Effective Use of Geospatial Tools in Highway Construction

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FOREWORD

Various sectors of highway project and service delivery, including highway construction, have witnessed an increasing use of geospatial technologies. However, the uses have largely been opportunistic and driven by a maturity of understanding in specific application areas. There is a need to develop a more holistic and cross-functional use of the technologies that benefit highway asset creation and service delivery. Focusing on this need, the Federal Highway Administration (FHWA) conducted a study to assess how state departments of transportation (DOT) and contractors were using the various geospatial technologies. Several state DOTs, contractors, vendors, and service providers were interviewed to document the state of the practice and identify challenges for implementing geospatial technology. Four specific case studies were conducted to document the innovative uses of the available technology as well as capture the benefits and costs associated with implementation. The emphasis of the research was on creating an approach that state DOTs can use to evaluate geospatial technology both from a technical and investment perspective, which will enable making informed decisions for implementation. The research documented the state of the practice for using unmanned aircraft systems (UAS), light detection and ranging (lidar), photogrammetry, structured from motion (SfM), and global navigational satellite systems (GNSS) for highway applications. This research yields effective practices for implementing geospatial technologies in a number of construction applications. These effective practices include a benefit-cost analysis (BCA) approach for determining return on investment (ROI) for implementing geospatial tools for different types of project applications and data collection needs. Lastly, this final report discusses current technological, regulatory/legal, and financial challenges and opportunities regarding their use.

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16. Abstract

Geospatial technologies such as photogrammetry and global navigation satellite systems (GNSS) have been an integral part of highway mapping for decades. However, geospatial technologies continue to evolve, and new technologies are becoming more accessible for a wide range of highway construction applications. Tools such as unmanned aircraft systems (UAS), lidar, aerial imagery, GNSS, automated machine guidance, and their derivative products offer many benefits to the highway construction industry. These benefits include improved efficiencies and streamlined processes, as well as more accurate and reliable data. The key to using these technologies successfully to optimize benefits is to correctly select the appropriate tool for the application and understand limitations. In many cases, data from each of these technologies will be integrated for a project to develop the necessary survey products.

This research investigates effective uses of geospatial technology for a wide variety of highway construction and maintenance applications; identifies a number of tools and their related accuracies; offers recommendations for tool selection, workflows, and strategies for conducting benefit-cost analysis (BCA); and analyzes future directions of these technologies in highway project and service delivery applications. The research explores several case studies using these technologies to document their benefits and limitations. In particular, the research determines the return on investment (ROI) associated with using these technologies in several of those case studies.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

3DEP	3D Elevation Program
AGL	above ground level
ALS	Airborne Lidar Systems
AMG	Automated Machine Guidance
ASPRS	American Society for Photogrammetry and Remote Sensing
AUVSI	Association for Unmanned Vehicle Systems International
BCA	benefit-cost analysis
CADD	Computer-Aided Design and Drafting
Caltrans	California Department of Transportation
CFR	Code of Federal Regulations
cm	centimeter
COA	Certificate of Authorization
CORS	Continuously Operating Reference Stations
COTS	commercial off-the-shelf
DEM	digital elevation models
DGNSS	differential global navigation satellite systems
DOT	Department of Transportation
DSM	digital surface models
DTM	digital terrain models
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
Ft	feet
FTE	full-time equivalent
GCS	ground control station
GIS	Geographic Information System
GLONASS	Global Orbiting Navigation Satellite System
GNSS	global navigation satellite systems
GPR	ground-penetrating radar
INS	inertial navigation system
KDOT	Kansas Department of Transportation
km	kilometer
mm	millimeter
MSL	mean sea level
MTLS	mobile terrestrial lidar system
NCHRP	National Cooperative Highway Research Program
NGS	National Geodetic Survey
OCRS	Oregon Coordinate Reference System
ODOT	Oregon Department of Transportation
OPUS	Online Positioning User Service
ORGN	Oregon Real-Time Network
OSU	Oregon State University
Pactrans	Pacific Northwest Transportation Consortium
PPP	precise point positioning
QA/QC	Quality Assurance/Quality Control

LIST OF ABBREVIATIONS (CONTINUED)

RGB	red-green-blue
ROI	return on investment
RTK	real-time kinematic
RTN	real-time networks
SAR	synthetic aperture radar
STLS	stationary (or static) terrestrial lidar system
sUAS	small unmanned aircraft systems
sUAV	small unmanned aircraft vehicle
UAS	unmanned aircraft systems
UAV	unmanned aircraft vehicle
UDOT	Utah Department of Transportation
UHF	ultra high frequency
USGS	U.S. Geological Survey

CHAPTER 1. INTRODUCTION

BACKGROUND AND SIGNIFICANCE OF WORK

State DOTs are charged with providing a safe, efficient, accessible, and convenient transportation system that meets vital national interests and enhances the quality of life for the American people, today and into the future. To that end, project delivery must efficiently provide a high standard of quality, produce adaptable and scalable components for future innovations, and be effective at meeting public expectations and state DOT goals.

Geospatial technologies have rapidly evolved in recent years given the proliferation of public interest in and use of global navigation satellite systems (GNSS)-enabled mobile devices, connected and automated vehicles, and unmanned aircraft systems (UAS). Leveraging geospatial technology such as UAS, lidar[1], aerial imagery, GNSS, and derivative products has proven to accelerate the achievement of organizational objectives through optimizing technological capability, improving process maturity, and delivering accurate geospatial data near real-time.

Technology plays a critical role in connecting the design of a highway project (the digital world) with its construction (the physical world). The hybridization of the physical and digital world is already occurring and will continue to strengthen as technological capability improves. Geospatial technology is a foundational element of technological capability in the built environment and continues to bring deeper meaning and insight to data through improved sensors (e.g., single photon lidar and Geiger-mode lidar, rapidly deployable platforms, and effective data governance). It is essential for state DOTs to understand their position and capability with respect to geospatial technology.

Process maturity of emerging technology often takes years to be optimized, but a continuous state of disruption enriches process improvement, which can accelerate maturity. For example, UAS imagery processing builds from the well-established field of traditional photogrammetry while also leveraging recent SfM techniques from the field of computer vision to leapfrog the technological advancement. Similarly, terrestrial lidar technology processes have evolved from aerial lidar. The industry will continue to be in a state of disruption, especially with the proliferation of connected and automated vehicles, robotics, and artificial intelligence.

Accurate real-time geospatial data is desired by the state DOT decision support system, and geospatial technology is rapidly achieving this level of maturity. Through the integration of advanced communication networks, information technology infrastructure, and geospatial technology, state DOTs are more quickly able to make decisions using near real-time geospatial data.

Geospatial technologies such as UAS and lidar require a strong information technology infrastructure to collect, process, and manage large datasets. Information technology infrastructure serves as a foundational component of geospatial technology and drives the need

[1] Note that *lidar* is sometimes referred to as LiDAR, LIDAR, LADAR, or laser scanning, which mostly refer to the same technology. The format *lidar* is adopted for this report since it is the predominant convention used in the industry.

for robust data governance policy. The ability to share datasets through cloud platforms and peer-to-peer networks, and to provide on-demand, near real-time access to geospatial data will allow state DOTs to focus more on intelligent transportation systems, cybersecurity, and data collaboration platforms such as a Common Data Environment application that enables mining and harvesting of the required geospatial data from data sources.

Geospatial data is a critical component across all levels of the government, including Federal, State, and local agencies. Over the past few decades, several advanced geospatial technologies have emerged that are used to collect, develop, store, manage, and disseminate data referenced to the earth by some type of georeferenced coordinate system (e.g., a map projection.) (Federal Highway Administration n.d.). These tools include the following:

- Total stations.
- GNSS.
- Geographic Information Systems (GIS).
- Advancements in digital imaging (e.g., sUASs).
- Lidar.
- Synthetic aperture radar (SAR).

These tools enable the capture of data with varying degrees of accuracy and density. Furthermore, these tools provide detailed mapping of infrastructure and topography across varied landscapes. Data that is captured by these tools is vital for many aspects of highway construction, including digital terrain models (DTM) and 3D models, planimetrics, as-built captures, spatial analysis, progress tracking, clash detection, and many other derivative products. Current high-accuracy, high-precision mapping is critical to avoiding or responding to issues in the field.

Geospatial technologies are widespread and have numerous benefits to the highway construction sector. The focus of this report is on geospatial data collection tools, but it should be noted that these tools are dissolving the traditional geospatial data lifecycle segments into more effective solutions (Figure 1). For example, geospatial data collection tools are writing data directly into databases using predefined schemas or collecting consumable geospatial data natively and sharing it across the enterprise for near real-time decision making.

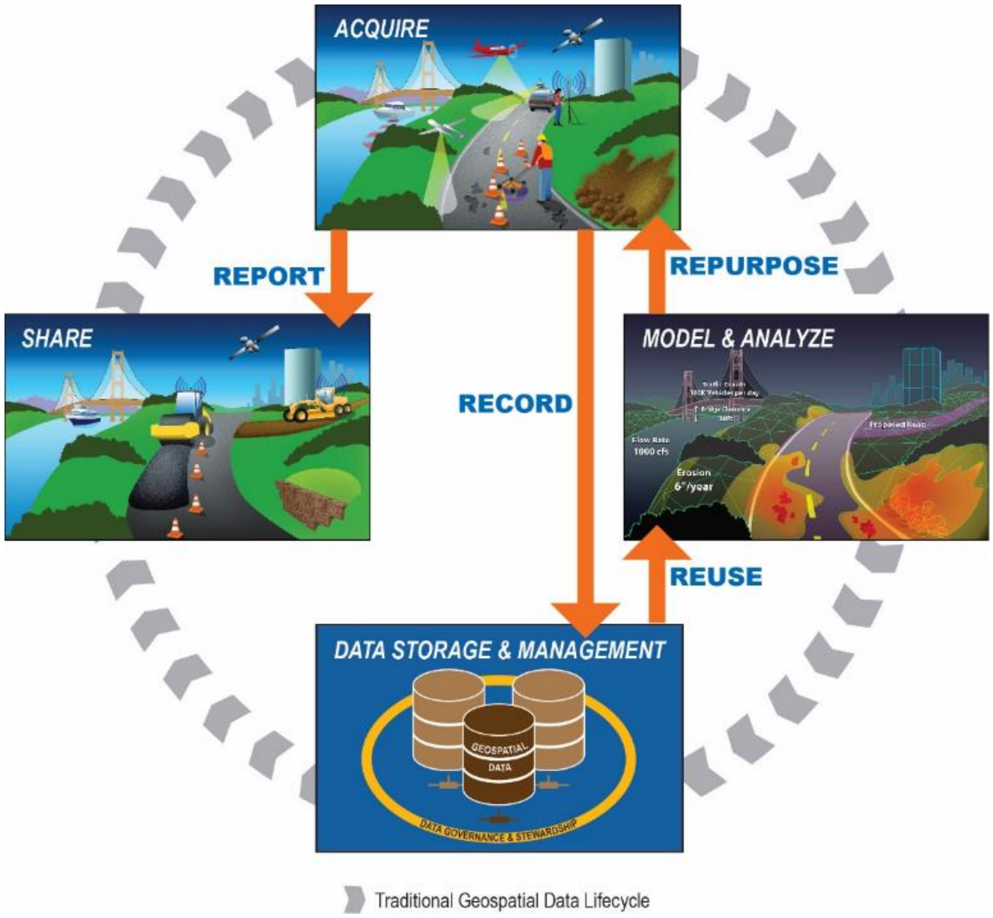


Figure 1. Illustration. Modified geospatial data lifecycle. (Modified from Olsen et al. 2013).

Topographic mapping is the most common application of geospatial technology used for highway construction. However, as GNSS and high-accuracy robotic total stations have become predominant technologies, applications have emerged that synthesize construction equipment, 3D design, and geospatial tools. Examples of this synthesis include roadway design, paving, earthwork, automated machine guidance (AMG), site monitoring, and progress monitoring. With the proliferation of GIS, emphasis has been placed on retaining geospatial data for reuse and effective practices in making decisions as it relates to the lifecycle of infrastructure. This has led to improvements in asset management applications, construction verification, as-built surveys, and quality assurance/quality control. As new geospatial technologies continue to improve or emerge, applications will expand that add value to the highway construction sector.

Technologies such as lidar and GNSS are becoming more commonplace in the area of highway construction, and the body of existing literature on these technologies is expanding rapidly (e.g., Navon and Shpatnitsky 2005; Slattery et al. 2011; Karan et al. 2013; and Olsen et al. 2013). Many state DOTs have seen benefits from the utilization of these tools. However, due to budget constraints, state DOTs in the United States are under increasing pressure to achieve a higher level of performance with fewer available resources. A recent study (Olsen et al. 2013) documented that many state DOTs see geospatial technologies as a potential solution to a declining budget and staff reductions in order to maintain the expected level of productivity. The aforementioned synthesis summarizes the practices and applications of geospatial technology usage across various state DOTs. Geospatial technologies and information provide fundamental support across most transportation operations. These technologies can help integrate fragmented sources of data distributed across multiple divisions and offices. Geospatial technologies also provide the framework to link and share each division's data into a unified geospatial transportation model (i.e., Common Data Environment). These geospatial technologies are not limited to design or construction, but are valuable at all phases of infrastructure projects, including routine maintenance and operations (Singh 2008).

Singh (2008) provides a framework for engineering automation where various disparate pieces of technology can be seamlessly integrated to evolve current state DOT operations. In addition to discussing the importance of geospatial technologies such as lidar and GNSS, Singh focuses on the importance of data management and technologies to support automation. In particular, Singh points out the necessity for an Engineering Data Management System that provides a clearinghouse for all data as it relates to the engineering process. Singh provides a data management philosophy: "*to ensure that the Right People see the Right Version of the Right Information at the Right Time*" (Singh 2008). This concept is crucial to providing a complete integration of geospatial technology and geospatial data into highway construction. The Oregon DOT (ODOT) has used this guide as a framework to help develop the appropriate legislation necessary to fully implement this concept. In fact, it recently established a new Engineering Automation Division to focus on implementing the remaining portions of that plan.

The linkage between the geospatial technologies and geospatial data to highway construction should be considered together with the ongoing national emphasis on 3D Engineered Models and use of Intelligent Construction Systems and Technologies. Owners and contractors need site-specific topographical survey and other survey products to build accurate 3D models in design, which, in turn, can be accomplished using appropriately selected geospatial technology platforms. Construction automation (e.g., AMG) requires rigorous geospatial survey, network control, and intelligent machines. Timely construction inspection and intervention, earthwork and other quantity estimation, digital as-builting, acceptance of bid items, and propagation of digital models of record to the asset management are aided by various geospatial survey platforms.

While these technologies are becoming increasingly important and useful across a state DOT, there is a limited number of standards, specifications, or effective practices available. Olsen et al. 2013 describe that different users have varying end-requirements based on their applications that require some flexibility in order to obtain the highest ROI. Nonetheless, some recent work on national standards, guidelines, and specifications has emerged:

- Guide for Efficient and Effective Utility Asset Data Collection Using Geospatial 3D Techniques. (Federal Highway Administration 2016)

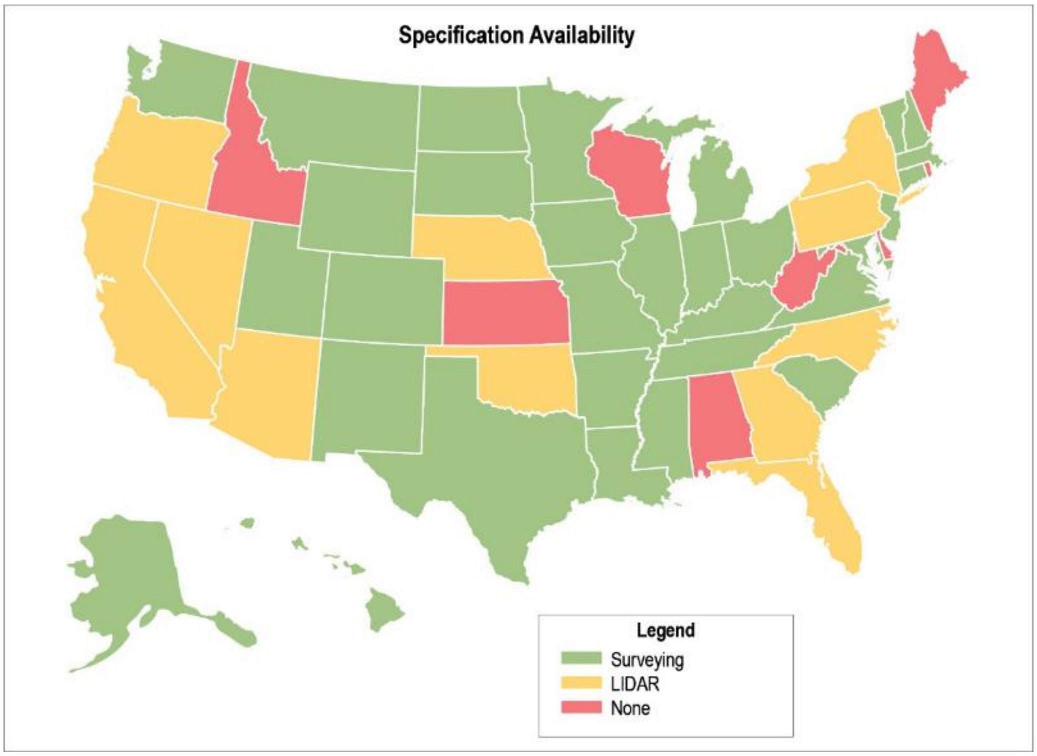
- Guide for Using 3D Engineered Models for Construction Engineering and Inspection. (Federal Highway Administration 2017)

- Guide for Optimizing Survey Data for 3D Design. (Federal Highway Administration 2017)

- NCHRP Report 748. (Olsen et al. 2013)

- ASPRS Geospatial Procurement Specifications

Individual state DOTs, such as the California Department of Transportation (Caltrans), have also been active in developing their own standards and guidelines for practice. The website developed for *NCHRP Report 748* (Olsen et al. 2013) provides an interactive map with web links to specifications developed by state DOTs (Figure 2). While all of these efforts (national and local) are significant, it has proven difficult to keep pace with the evolution and availability of geospatial technologies.



Original Illustration: © 2014 Matt O'Banion, Michael Olsen, and Gene Roe

Figure 2. Map. Availability of state surveying specifications.[2] (Modified from O'Banion et al. 2014).

Overcoming the technical hurdles with technology adoption is only one of many considerations; implementation efforts to train and educate personnel are critical to ensure a high ROI with geospatial technologies. *NCHRP Report 768: Guide to Accelerating New Technology Adoption through Directed Technology Transfer* (Hood et al. 2015) and *NCHRP Report 831: Guide for*

[2] Note that states with lidar specifications also have surveying specifications. The website also tracks states with photogrammetry and GNSS specifications as well.

Civil Integrated Management in Departments of Transportation, Volume 1: Guidebook (O'Brien et al. 2016) provide effective practices on technology transfer both between and within an organization. This report documents several case studies to illustrate important steps in the technology transfer process. It also provides solutions for common situations and challenges that arise when adopting new technologies and integrating them into the standard operating procedure. Although not specific to geospatial technology, this report is highly relevant to state DOTs using geospatial tools.

RESEARCH OBJECTIVES

The objectives of this study were as follows:

- Present the benefits, challenges, and future opportunities of the use of geospatial technologies to support highway construction.
- Investigate and document the effective use of geospatial technology in the highway construction sector.
- Analyze use of UAS and lidar technology in sectors with higher levels of maturity.
- Provide a summary of current regulations for operating UAS for construction.
- Address the level of detail needed during highway construction in various scenarios and contexts, as well as how this data is incorporated into digital as-builts for use in operations and maintenance.

This research study attempted to answer the following questions:

- How do tools support highway construction (e.g., topographic surveys, earthwork quantity take-offs, visual inspection, etc.)?
- Where does each technology fit within the spectrum of geospatial technologies already available?
- What is the resolution and accuracy (network and local) achievable through each technology or tool?
- How does an owner/contractor/consultant choose which tool is best for a given construction scenario or situation?
- What benefit can the owner realize by using the tool (in terms of ROI)?

The study included documenting the use of select technologies through four case studies, specifically:

- ODOT Use of Multiple Geospatial Technologies for Project Delivery.
- ODOT Use of UAS for Bridge Inspections.

- Utah DOT (UDOT) Use of Geospatial Technology for Design and Construction of State Route 20 (SR20).

- Construction Contractor Use of UAS.

The case studies focus on the use of technology and the processes to use the data for the intended use as well as a benefit-cost analysis (BCA) that served as the foundation for developing an ROI framework for guiding technology investments.

REPORT ORGANIZATION

This report summarizes the results from the investigation and analysis of the effective use of geospatial technology for a wide variety of highway construction applications. It discusses the geospatial tools and related accuracies, geospatial tool selection and workflow effective practices, a BCA approach for calculating ROI, documentation of four case studies, and a discussion on the future directions of geospatial technology.

Chapter 2 provides an in-depth look at geospatial tools, including the importance of geospatial data, the types of geospatial data collection platforms, UASs and their evolving context, and discusses the ranges and accuracies of specific geospatial tools.

Chapter 3 describes highway construction scenarios and applications of geospatial tools, offers workflow effective practices, provides geospatial tool selection effective practices, and discusses the ROI framework used in this study. While geospatial tools present important benefits to the highway construction sector, some limitations still need to be discussed. This chapter offers important considerations and recommendations on when certain tools are suitable given certain project constraints.

Chapter 4 summarizes each of the four case studies, including the processes for data collection and integration, and the BCA for calculating the ROI for most scenarios. In addition, this chapter provides the results of a desk scan of the use of UAS in construction and an evaluation of operating under 14 CFR Part 107 are discussed, along with lessons learned.

Chapter 5 concludes the report with a discussion of emerging trends and future directions on how to integrate geospatial data into state DOT and contractor data systems, as well as anticipated advancements in geospatial technology.

The report also contains several appendices. Appendix A provides a sample statement of work outline state DOTs can use during their procurement process for using UAS technology on their projects to ensure high-quality services are being provided. Appendix B provides a sample of the interview guide for the case studies. Appendix C provides the findings of preliminary interviews conducted during the first phase of this research project with state DOTs, construction companies, and vendors, which helped guide the research and select the case studies. The questionnaires for these interviews are provided in Appendix D and E.

GEOSPATIAL TECHNOLOGY OVERVIEW

Geospatial technologies are far reaching as they relate to highway construction. Many critical highway design and construction decisions are based upon the data representing existing conditions, which is collected using geospatial tools. The existing condition data is collected using topographic surveying techniques and is likely the most common application of geospatial tools for highway construction. As GNSS and high-accuracy robotic total stations have become predominant technologies, applications that augment construction equipment, 3D design, and geospatial tools have emerged. Examples of how this integrated technology is applied include roadway design, paving, earthwork, AMG, site monitoring, and progress monitoring. With the proliferation of GIS as a visualization and data management aid, emphasis has been placed on retaining geospatial data for reuse as a critical component in making decisions as it relates to the lifecycle of infrastructure. This has led to improvements in asset management applications, construction verification, as-built surveys, and quality assurance/quality control. As new geospatial technologies and processes emerge, applications will continue to evolve and expand.

The geospatial technologies identified for this study include UAS, lidar, photogrammetry and SfM, and GNSS. These technologies provide substantial benefit to project delivery, but recent advancements in processes and regulations necessitated a thorough analysis of the specific applications of each tool, the development of a mechanism that will help with suitable tool selection, and a discussion on ROI for using these tools.

This report also briefly discusses capabilities and limitations of other relevant geospatial technologies such as AMG, satellite imagery, ground penetrating radar (GPR), and total stations.

Unmanned Aircraft Systems

UAS has quickly become a versatile geospatial data collection tool that is transforming how highway facilities are planned, designed, built, and operated and maintained. Inspection, monitoring, and low accuracy applications benefit well from the use of UAS. Higher accuracy applications, such as engineering design mapping, still need further investigation and technology maturity before becoming an acceptable application. UASs are not only becoming commonplace among surveying and mapping professionals, but also are increasingly popular for other engineering and construction professionals in making quick and effective decisions because of their ease of use and rapid deployment. However, it should be noted and stressed that even though UAS can be easily leveraged for many applications, understanding the data characteristics for proper use and the regulatory considerations for safe operation are paramount.

In 2013, the Joint Planning and Development Office[3] and industry representatives developed an *Unmanned Aircraft Systems (UAS) Comprehensive Plan* that details efforts needed (including strategic goals) to achieve safe integration of UAS into the National Airspace System (Joint Planning and Development Office 2013). Since then, test sites were selected to conduct critical research into the certification and operational requirements; thousands of commercial UAS exemptions under Section 333 of the FAA Modernization and Reform Act of 2012 have been

[3] Joint Planning and Development Office consists of representatives from the Next Generation Air Transportation System (NextGen) – the US Departments of Transportation, Defense, Commerce, and Homeland Security, the National Aeronautics and Space Administration, and the FAA.

issued (Federal Aviation Administration, 2015b); new rules for sUAS have been finalized (14 CFR 107, known simply as "Part 107") (Federal Aviation Administration 2016a); and commercial operators in many industries have created successful businesses leveraging this technology.

As expectations of the technology become stable and the maturity of the processes is attained, the more valuable the technology will become.

This report also provides the findings of a literature review and seven phone interviews conducted with highway contractors and mapping/surveying service providers that are using UAS. Interviewees explained how they use the technology on highway projects, which includes monitoring construction and progress, monitoring stockpiles, earthwork volume calculations, surveying, and mapping. The UAS experience for the interviewed highway contractors ranges from "none to exploring/testing the technology" to "routinely using" it on their projects. Some construction companies outsource the UAS data collection, while others have procured UAS equipment and perform the entire process in-house.

Light Detection and Ranging

Lidar (also known as 3D laser scanning) can be used to acquire critical geometric information efficiently and with exceptional detail. Lidar sensors emit beams[4] of light (at speeds ranging from thousands to millions of points per second) to acquire X, Y, Z (3D) positions of points within an area of interest, producing a point cloud. The powerful, high-resolution, 3D point cloud provides a digital representation of the physical world that engineers, inspectors, asset managers, and others can repeatedly explore, query, and analyze to mine important information. With advancements in sensor miniaturization and power supply alternatives, Lidar is being adapted to fit many platforms, both airborne and terrestrial.

Airborne Lidar Systems (ALS) mounted to fixed-wing or rotary aircraft can acquire data fast and cover large areas of terrain quickly once flight logistics have been put in place. Depending on a variety of factors such as ground control density and aircraft behavior, ALS can quickly produce high accuracy bare-earth[5] data over a large area. ALS sensors have evolved from traditional linear-mode sensors, to more advanced sensors such as linear-array, single-photon, and Geiger-mode sensors. The more advanced sensors are prevalent in experimental settings and still require improvements to reach the same level of maturity as linear-mode.

Terrestrial lidar systems can be mounted on a mobile platform (MTLS) or a stationary platform (STLS) depending on the application. Typically, MTLS require additional components to compensate for movement of the platform, such as an inertial measurement unit, but can achieve equivalent accuracies and precisions depending on the sensor itself. MTLS sensors can be classified as either survey-grade or asset-grade given the differences in capabilities (density and accuracy) and costs. *NCHRP Report 748* provides performance-based guidelines for the use of MTLS in transportation applications (Olsen et al. 2013). STLS entered the engineering industry in the early 1990s but only became a popular tool for surveyors in the early 2000s. These

[4] Beams can be singular, continuous, or arrayed.
[5] Bare-earth data are data from traditional linear-mode lidar sensors that are filtered to remove vegetation, buildings, and other objects. Typically, represents terrain below vegetation.

systems are typically mounted on a stationary survey instrument tripod and collect data for a large area much slower than MTLS, but these systems offer improved resolution (mm to cm level) and accuracy (mm to cm level) for analyzing small sites or buildings (interior and exterior) compared to MTLS and ALS.

Lidar technology will continue to advance and transform the highway construction sector but understanding the benefits and challenges will ensure these tools are appropriately selected. This report presents research that assists state DOTs in understanding this technology for specific highway construction applications.

Photogrammetry and Structure from Motion

Photogrammetry is the practice of extracting precise geometric measurements from photographs. The photographs are typically acquired from an aircraft or other airborne platform, which enables efficient and cost-effective data acquisition over a large area. The use of airborne photogrammetry can minimize—although typically not eliminate—the need for ground-based surveys, which can be expensive and, on a construction site, potentially dangerous and/or disruptive to other operations. Photogrammetry was thought by some to have become been largely obsolete in favor of the wide-spread use of lidar, but there are still cost advantages to using traditional photogrammetry in certain applications—even film photographs are still being used in photogrammetry and arguably produce better ROI than digital imagery in certain situations.

SfM is a photogrammetric approach that has emerged relatively recently in the construction industry. The basic principles underlying SfM are not fundamentally different from those of conventional photogrammetry, but SfM uses advanced image matching algorithms and procedures developed in the field of computer vision. Detailed descriptions of SfM algorithms and workflows are beyond the scope of this report but can be found in Snavely et al. (2006), Snavely et al. (2008), and Westoby et al. (2012). Additional characteristics of SfM include ease of use, which is achieved through a high level of automation, and the ability to generate very high-resolution point clouds and orthoimages because the input imagery is often collected from close range (e.g., from the ground or by a sUAS at an altitude of a few hundred feet or less).

This report contextualizes photogrammetry and SfM in the use of UAS and offers effective practices on the benefits and limitations of this technology. Even with its current shortcomings, SfM is very promising, and this technology will be transformative for mapping from UAS imagery.

Global Navigation Satellite Systems

GNSS is a satellite system that provides geospatial positioning anywhere on earth. To date, two GNSS constellations are fully operational: the United States' GPS and the Russian Federation's GLONASS. GPS reached worldwide civilian capability in 1995 (Van Sickle 2015), and GLONASS reached the same capability in 2014. In addition, other GNSS constellations are under development, including China's BeiDou and the European Union's Galileo. Research is ongoing for making all of these systems interoperable and fully available for civilian applications. Upon completion of these systems, future GNSS receivers will be capable of tracking over 100 available satellites for pinpointing their location anywhere in the world. This will result in reduced delays in finding adequate satellites for determining the location of a receiver.

Many methods of collecting GNSS data provide substantial benefit to the highway construction sector. This report details the various methods and presents recommended uses for each method. The decreased cost and increased availability of this technology will become increasingly important tools for construction progress monitoring and connected site integration.

CHAPTER 2. DETAILED REVIEW OF GEOSPATIAL TECHNOLOGIES

This chapter provides detailed information on various geospatial technologies, including achievable accuracies. Applications of these technologies, as well as capabilities and limitations, are described in Chapter 3.

UNMANNED AIRCRAFT SYSTEMS

Unmanned aircrafts were originally developed for military applications. Barnhart et al. (2012) noted that the first successful, modern unmanned aircraft was developed under a U.S. Navy contract in 1918. Over time, increasingly advanced unmanned aircraft were developed for military applications, including for realistic aircraft targets, radar decoys, long-range reconnaissance, and weapon platforms. Civilian use of unmanned aircraft has recently become popular for many applications given the wide range of sizes and types of unmanned aircraft.

The miniaturization and improvement in the quality of computer processors, inertial navigation technology, batteries, and remote sensing technology, as well as the proliferation of GNSS technology, has greatly reduced the cost and size of UASs. Because of these recent advancements, UASs are becoming increasingly affordable and popular for civilian applications. Pajares (2015) summarizes dozens of recent studies that discuss a large number of civilian areas of application, including agriculture and forestry, search and rescue, surveillance, environmental monitoring and research, vegetation classification, photogrammetry, atmospheric research, cultural and archaeological studies, wildlife inventorying, and urban infrastructure mapping. Europe, Japan, Canada, and Australia have performed a number of investigations on the use of UAS for civilian applications. For example, the European Union's COMETS project forecasts considerable market growth in the civilian use of UAS based on an assumption that the UAS will be a part of the integrated airspace by 2015 (Frost and Sullivan 2007). In generating this forecast, Frost and Sullivan (2007) divided civilian applications of UAS into six categories.

- Government
  - Law Enforcement (public, civil, security)
  - Board security
  - Coastguard
- Fire Fighting
  - Forest fires
  - Other major incidents
  - Emergency rescue (e.g., mountain rescue)

- Energy Sector
    - Oil and gas industry distribution infrastructure
    - Electricity girds/distribution networks
- Agriculture Forestry and Fisheries
    - Environmental monitoring
    - Crop dusting
    - Optimizing use of resources
- Earth Observation and Remote Sensing
    - Climate monitoring
    - Aerial photography, mapping, and surveying
    - Seismic events
    - Major incident and pollution monitoring
- Communications and Broadcasting
    - VHALE platforms as proxy-satellites
    - MALE /S/ MUAS as short-term, local communications coverage

Basics of Technology

UAS is defined as a system to include unmanned aircraft vehicles (UAVs) and all of the associated elements related to safe operations, which may include control stations (ground, ship, or air-based), control links, support equipment, payloads, flight termination systems, and launch/recovery equipment. The payload of an unmanned aircraft can be equipped with a variety of passive or active sensors, such as video and red-green-blue (RGB) cameras, near infrared, hyperspectral, radar, thermal, and lidar sensors, as well as combinations of these sensor types. Because of this payload versatility, UASs can economically collect a variety of remote sensing data. In general, UASs can perform tasks similar to those that can be done by a manned aircraft, but often faster, safer, and at lower cost for smaller areas (Puri 2005). Unmanned aircraft are also generally capable of collecting high-resolution remote sensing data at much closer standoff distances and at significantly lower altitudes than manned aircrafts.[6] Manned aircrafts can generally cover larger areas more effectively than unmanned aircrafts while unmanned aircrafts are typically more advantageous for covering smaller areas.

[6] 14 CFR Part 107.51 limits the maximum allowable altitude to 400 ft. AGL, and higher if the UAS remains within 400 ft. of a structure.

Basic Components of UAS

While there is a wide range of different types of unmanned aircrafts (as discussed below), all UASs typically consist of the following basic components (Figure 3):

- **Aircraft**: The aircraft is the flying portion of the system, often referred to as a “platform” or a UAV. In addition to the airframe, the aircraft includes the motor(s) and fuel, such as batteries or gasoline.

- **Ground Control Station (GCS)**: The GCS is the control center for the operation of the UAS. It is usually the center in which the UAS mission is pre-planned. A typical GCS allows the operator to fly the aircraft and control the payload. For many systems, mission plans can be pre-loaded into the aircraft prior to takeoff so that the operator can control the aircraft without a joystick and can monitor its performance and movement on a digital map. A GCS typically includes a computer, laptop, mobile device, and/or radio remote controller.

- **Data Link:** The data link is the data transmission system enabling uplink and downlink between the GCS and the operator. The operator uses an uplink to transmit the mission plans to the aircraft prior to takeoff. These mission plans are then stored in the automatic flight control system of the aircraft. The uplink is also used to communicate real-time flight control commands to the aircraft when needed and to send commands to the payload sensor. Using the downlink, the aircraft returns status information on the performance of the aircraft’s system (e.g., fuel level, engine temperature), sends its positioning data, and, depending on the system, the data from the payload sensor back to the operator.

- **Navigation System:** The navigation system allows the operator to monitor the aircraft’s 3D position (as well as its velocity, altitude, and possibly other variables) in real-time. The aircraft uses its navigation system in real-time when flying a pre-programmed mission or when triggered to return to its takeoff position as a safety feature during an unexpected emergency. Furthermore, the data collected by the aircraft uses the navigation system data to georeference the data and correct errors in the raw data through post-processing routines. The navigation system may comprise one or more GNSS receivers, inertial sensors (gyroscopes and accelerometers, typically mounted in orthogonal triads), barometers, and magnetometers.

- **Payload:** The payload is any equipment transported by the unmanned aircraft. Geospatial professionals will attach remote sensing equipment to the aircraft, such as video, RGB, thermal, infrared, and/or multispectral cameras. Lightweight video and RGB cameras are commonly used today; however, some UASs can carry heavier payloads, such as lidar sensors. The payload sensors are frequently attached to the airframe on two- or three-axis gimbals to reduce vibrations and motion blur, as well as enabling the operator to point the sensor at an object of interest.

- **Launch, Recovery, and Retrieval Equipment:** The launch, recovery, and retrieval equipment are necessary equipment for aircraft that are incapable of vertical takeoffs and landings. Launch equipment may include ramps, catapults, rubber bungees, compressed air, and/or rockets. Recovery equipment may be required for bringing a flying aircraft safely down, such as a parachute, a large net, or a carousel apparatus. Retrieval equipment is necessary for transporting the aircraft from its landing point to the launch position.

- **Human Operator(s)**: The human operator(s) are necessary to supervise the safe and efficient operation of the unmanned aircraft, including a pilot, payload operator, and/or a spotter.

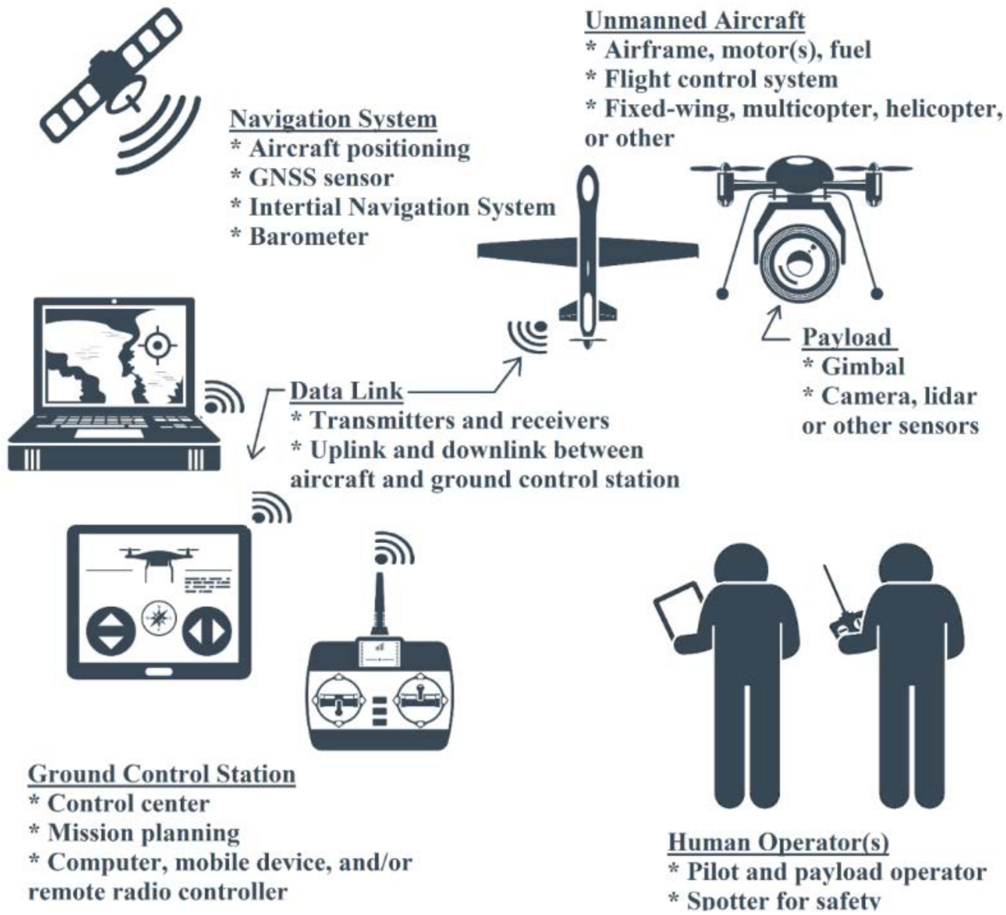


Figure 3. Illustration. Basic components of a UAS.

Basic Types

Technically, unmanned aircrafts include any type of vehicle that flies without a human onboard. Examples are fixed-wing gliders, quad-, hexa-, or octocopters (also known as multicopters), helicopters, airships, balloon systems, and more broadly, any unmanned vehicle with the ability to fly autonomously by using onboard processors, remote controls with human engagement, or another aerial vehicle under coordination (Pajares 2015) or consensus control (Jamshidi et al. 2011).

Although there are many different types of unmanned aircraft, sUAS are most commonly used today for civilian applications. Table 1 divides sUAS into three categories: small fixed-wing gliders, multicopters, and helicopters. This table summarizes the advantages of each of these categories based on a study by Otero (2015) and it provides examples of survey-grade, turn-key systems that are currently on the market. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

Table 1. Advantages and examples of various types of sUAS.

Category	Advantages	Examples
Fixed-wing gliders	• Capable of flying at greater speeds • Able to carry larger payloads than multicopters • Able to glide in flight which reduces battery or fuel consumption (longer endurance and capable of flying greater distances)	• Trimble UX-5 • senseFly eBee • Topcon Sirius Pro
Multicopters (e.g., quadcopters, hexacopters, octocopters)	• Highly maneuverable (can make sharp turns in flight) • Able to hover in place • Capable of vertical take-offs and landings and do not require runways or catapults	• Leica Geosystems Aibot X6 • senseFly albris • Riegl RiCOPTER • Trimble ZX5
Helicopters	• Capable of near vertical take-offs and landings • Capable of carrying larger payloads than multicopters • Longer flight endurance than multicopters—particularly if using gasoline powered engines	• Pulse Aerospace Vapor • Swiss UAV KOAX X-240 MK II

Figure 4 through Figure 6 present examples of each of these three categories of sUAS: fixed-wing glider, multicopter, and helicopter.

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Figure 4. Image. Example of sUAS fixed-wing glider.

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Figure 5. Image. Example of sUAS multicopter.

© 2017 Pulse Aerospace

Figure 6. Image. Example of sUAS helicopter.

Regulations

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration. The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

LIGHT DETECTION AND RANGING

Basics of Technology

Lidar is a relatively recent geospatial technology that can be used to acquire critical geometric information efficiently and with exceptional detail. Scanners emit pulses of light (at speeds ranging from thousands to millions of points per second) to acquire X, Y, Z (3D) positions of points within an area of interest, producing a point cloud. The powerful, high-resolution 3D point cloud provides a digital representation of the physical world that engineers, inspectors, asset managers, and others can repeatedly explore, query, and analyze to mine important information. Figure 7 shows examples of the detail available with 3D laser scan point clouds, showing the Spencer Creek Bridge in Oregon.

Figure 7. Image. Example of 3D laser scan point cloud of the Spencer Creek Bridge on Highway 101 in Oregon.

Image and video recordings/logs can also be obtained simultaneously with the lidar data acquisition. This ancillary data can provide greater detail than the laser scanner alone (C. K. Toth 2009). In many cases, these cameras are also calibrated so that the point cloud could be rendered with RGB color values. McCarthy et. al (2008) describe multiple advantages to using combined lidar and image information for transportation applications, including improved measurements, classifications, workflows, quality control checks, and overall usefulness. The geometric linkage between images and the scan data enables for measurements directly on the images, which can be more efficient and intuitive than working with point clouds separately. The scan data is important for measurements on large objects such as bridges and embankments, while the images are generally most helpful for discerning smaller objects.

In addition to co-acquired images, lidar provides a measurement of the return signal strength for each pulse, which is termed “intensity”. The primary benefit of lidar intensity is that it is representative of the object’s surface reflectance and other surface characteristics, which can be useful to distinguish between material types. Figure 8 shows an example intersection that is rendered with intensity values. Pavement markings, poles, and other objects can be easily distinguished. Intensity information has been used for several applications, including distinguishing painted stripes from pavement (Toth 2008, Yang et al. 2012), damaged sections of pavement, reflective sign extraction, and manhole detection (Guan et al. 2014). However, there are also a number of confounding variables to which intensity is related, including parameters related to the data acquisition geometry (e.g., range and angle of incidence), scanning environment, and sensors themselves. To overcome these issues, several intensity processing techniques have been developed and implemented to calibrate, normalize, or otherwise correct the recorded intensity values to produce values that are more useful and more closely related to true surface characteristics. Kashani et al. (2015) provided an overview of effective parameters on intensity measurements, basic theory, applications, and current intensity processing methods.

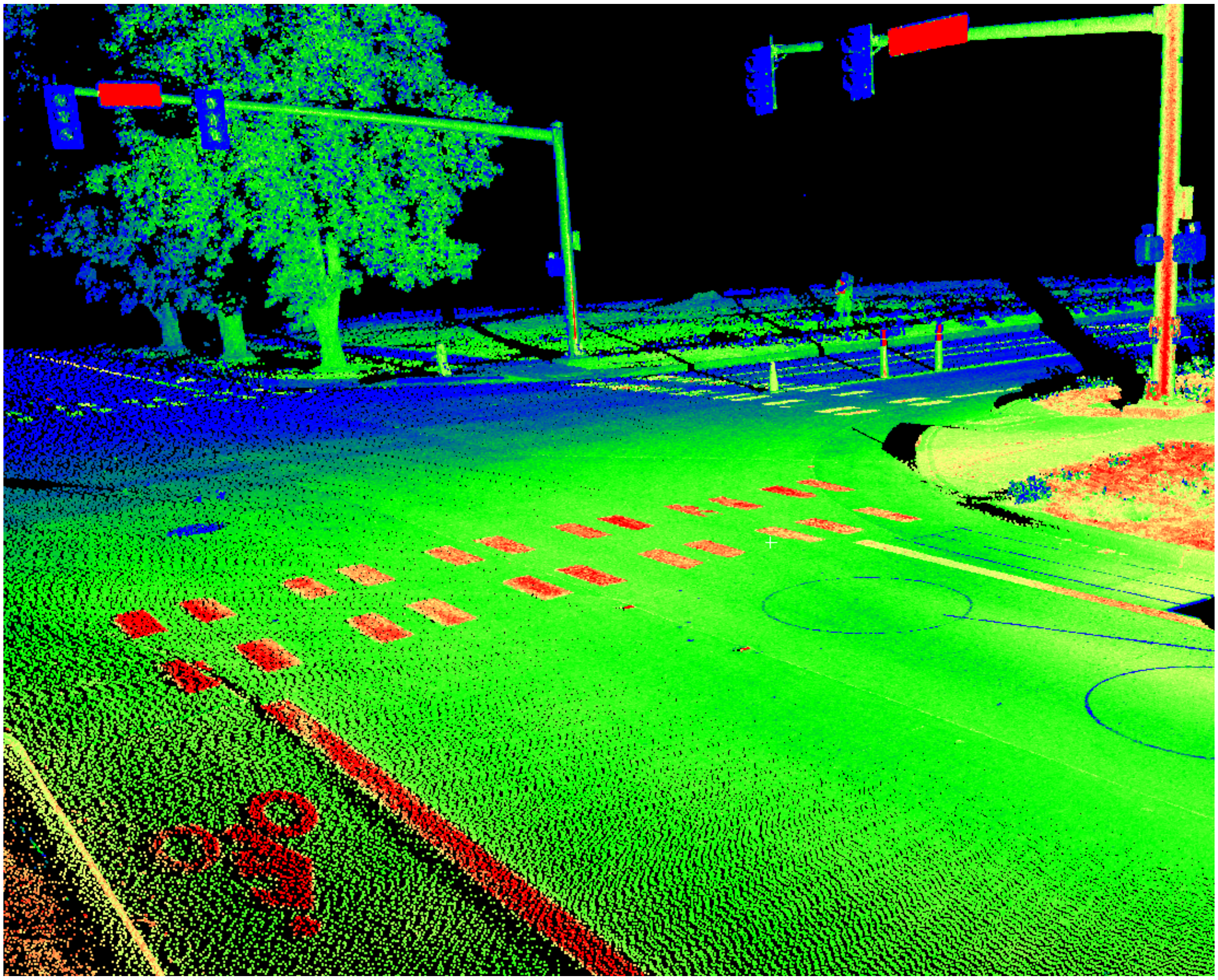

Figure 8. Image. Terrestrial laser scan point cloud of an intersection colored by intensity values.

It is worthwhile to note that although significant strides have been made, the dissemination of point clouds rendered with intensity information and RGB values is still in its infancy and is used in conjunction with geometric information for development of automatic and semi-automatic feature extraction processes.

Lidar is capable of high accuracies similar to traditional surveying methods, but it is capable of much higher resolution. While a traditional survey instrument (e.g., total station) may obtain higher accuracy (+/- 2 mm, 1-σ) for a single point, static lidar obtains several orders of magnitude more points at slightly lower accuracies (3-6 mm, 1-σ). The additional information that can be resolved in lidar data enables topography and other features to be modeled at a higher level of detail and accuracy over traditional techniques. This detailed, 3D virtual world provides personnel in the state DOT with a much better understanding of the field conditions and variability throughout the area of interest. The reduction in field time and ability to acquire data from the sides of the road with static lidar or at traffic speeds with MTLS provides significant safety benefits over typical surveying.

Lidargrammetry

Lidargrammetry is a technique that generates stereo-pairs from lidar intensity images for input into photogrammetric analysis for mapping. While the derivative digital elevation models (DEM) and other models have lower resolution and detail compared to lidar point data, they still retain its accuracy level. A key benefit of lidargrammetry is that it enables lidar data to be used in traditional photogrammetric workflows. It also improves on photogrammetry since lidar can better discern ground surface in densely vegetated areas, break lines are more clearly defined, and data can be acquired any time of day or night, if desired (Ward 2006). Additional details for this process can be found in the *ASPRS DEM User's Manual*, 2nd Edition (Maune 2007) and *ASPRS Manual of Airborne Topographic Lidar* (Renslow 2013).

Platforms

Lidar data can be acquired from a wide variety of platforms (Table 2), each with their own associated capabilities and limitations. Figure 9, Figure 10, and Figure 11 show examples of terrestrial and MTLS platforms. In many cases, data from multiple platforms may be fused together to enable complete coverage. Vincent and Ecker (2010) evaluated multiple lidar platforms—airborne, static terrestrial, and mobile for Missouri DOT to compare accuracy, cost, and feasibility. An important note is that MTLS can sometimes require supplemental static terrestrial scans to fill in the gaps; however, the data can be integrated relatively easily. It was also discovered that scanning significantly reduces field time, but significantly increases office processing time. In order to efficiently process the data, upgrading hardware and software capabilities may be required.

Table 2. Summary of available types of lidar survey platforms with their associated capabilities and limitations. (Modified from Olsen and Gillins (2015) and Vincent et al. (2010)).

Type of Lidar System	Typical Uncertainty (3D, 1-σ)	Description	Capabilities	Limitations
Airborne (ALS)	0.5 m (V: <0.1 m)	Sensor attached to fixed-wing aircraft at 1000 m or more above ground; co-acquired photographic images are becoming more common	• Rapid coverage over large areas • Fairly uniform sampling • Can collect other remote sensing data simultaneously	• Large footprint • Poor coverage on vertical faces • Flight logistics
sUAS (ULS)	0.1-0.3 m	Lightweight sensor mounted to an unmanned aerial system; flight heights are typically less than 150 m	• Detailed information for a site • Pre-programmed flight paths • Nadir and oblique scanning possible	• Short flying time limits to relatively small areas • Few systems available, experimental •
Handheld/ backpack (hhLS)	0.1-0.3 m	Sensor carried in hand or on a backpack frame	• Flexible system • Indoor/outdoor • Only one person required	• Slower than most other methods for large areas
Helicopter (HLS)	0.05-0.2 m	Sensor mounted to a helicopter flying closer to the ground	• Similar to airborne, but closer to ground	• Flight logistics may be complicated
Mobile (mTLS)	0.05-0.3 m	Sensor mounted to a vehicle and data are collected kinematically while a vehicle is in motion	• Fast coverage along highways	• Limited to navigable paths • Obstructions from traffic
Static (sTLS)	0.005-0.05 m	Instrument is mounted to a tripod. Photographic images are often co-acquired; typically implemented only for smaller sites	• Highest resolution • Highest accuracy • Some flexibility • Indoor/outdoor	• Slower than other techniques • Non-uniform sampling

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Figure 9. Photo. STLS unit with GNSS receiver surveying a damaged road after the 2016 Amberley Earthquake in New Zealand.

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Figure 10. Photo. MTLS system operated by ODOT for a pavement striping retro-reflectivity analysis.

Figure 11. Photo. Operation of a terrestrial scanner in Alaska "stop and go" mode for improved efficiency over static scanning.

Airborne Lidar System

ALSs mounted to fixed-wing or rotary aircraft can acquire data fast and cover large areas of terrain quickly once flight logistics have been put in place. Helicopter (rotary) based systems can fly closer to the ground and acquire data of higher resolution and accuracy. Recently, bathymetric lidar systems have become available, which enable mapping of submerged topography below the water surface, although actual capabilities are dependent on water clarity and turbidity.

ALS is best suited for mapping large areas of terrain. ALS datasets typically have lower accuracy and resolution compared to STLS or MTLS. Further, with the sensor angled to a point on the ground surface directly below the sensor head, it is typically not suitable for detailed scans of vertical features such as retaining walls or underneath structures such as bridges. However, researchers such as Hinks et al. (2009) have evaluated flight path configurations that enable improved coverage on vertical faces by flying at a 45-degree angle to the vertical object.

Stationary Terrestrial Lidar System

STLS are typically mounted on a tripod; however, they can also be mounted to a wagon or other portable platform for efficiency in moving the system from one location to another. The STLS system is not in operation during transport STLS is typically a slower method of collecting data for a large area, but it offers improved resolution (mm to cm level) and accuracy (mm to cm level) for analyses of small sites or buildings compared to airborne systems. For larger datasets, STLS can fill in gaps/voids from mobile or airborne lidar datasets. However, STLS will usually be applied locally for specific areas, one at a time. Within each area, multiple scans are often completed to optimize overlap in order to avoid data gaps/voids. In many cases with current systems, each scan setup can be completed in 5 to 10 minutes and provide sufficient detail on the object of interest. In general, basic analysis can be completed within a few days. However, this significantly depends on the amount of detail required for the analysis as well as the size and complexity of the dataset.

Hiremagalur et al. (2007) developed a set of standards and specifications for the consistent use of STLS in Caltrans projects. A concise version of these standards can be found in Chapter 15 of the Caltrans Survey Manual. The manual provides the background and supporting information for those standards and describes test procedures to validate the accuracy of lidar works in Caltrans survey projects. In addition, it clarifies limitations of common STLS in transportation applications and recommends appropriate methods for mitigating the limitations. This information helps surveyors select the right STLS and optimal acquisition settings for their specific applications. The standards also outline the CAD data format that should be used for archival and exchange purposes once features are extracted from the STLS data. In addition, Caltrans has developed STLS survey instructional materials and has conducted training classes with its surveyors (Yen et al. 2008).

Mobile Terrestrial Lidar System

MTLS systems can acquire detailed georeferenced 3D data efficiently from a moving vehicle at highway speeds with traffic. These systems are a complex arrangement of various components and subsystems that serve different, but critical functions. Puente et al. (2013) describe and compare configurations of various MTLS and notes that MTLS systems are typically comprised of a lidar sensor, IMU, GNSS receiver, and a control unit. Some systems integrate digital cameras, pavement sensors, and/or ground penetrating radar. While these systems are versatile and are a popular method for collecting vast amounts of geospatial data along a roadway, certain aspects discussed in the coming pages will bring necessary clarity for deployment activities.

A wide range of MTLS systems are used throughout the industry that could greatly impact the procurement of MTLS data acquisition depending on the requirements of the scope of work. Scrutinizing what accuracy levels the MTLS data needs to meet will drive what system is appropriate. Lower cost asset management and mapping systems (~$400k) can achieve sub-meter accuracies at the network level and decimeter accuracies at the local level. Survey-grade systems (~$1 million) can achieve cm-level accuracies at both the network and local level. While achieving the highest accuracy has required the use of dense targets, similar accuracy and reliability can be obtained by performing multiple passes of the area of interest, enabling improved verification of GNSS quality as well as trajectory enhancements by averaging multiple passes (Nolan et al. 2015).

NCHRP Report 748 provides performance-based guidelines for the use of MTLS in transportation applications (Olsen et al. 2013). Based on interviews with state DOTs and service providers, the report indicates that state DOTs have a strong interest in MTLS going forward, but there are very few examples of best practices and/or in-depth discussions of results. This guideline establishes nine data collection categories that are appropriate for the specific transportation applications based on resolution and accuracy requirements. The guidelines also provide general recommendations concerning the critical issue of data management. The guidelines are divided into two main sections: Management and Technical. The management portion contains a discussion of applications, workflows, data mining, the procurement process, decision making, an implementation plan, and currently available guidelines. The technical section describes the components of MTLS, error sources, calibration and correction, accuracy and resolution requirements and specification, quality control methods, considerations for common applications, information management, deliverable specification, and future trends. Appendices also contain sample calibration reports and templates for developing scopes of work. O'Banion et al. (2014) developed this work into an e-learning website (Figure 12), which includes online, interactive learning modules, a detailed and searchable reference list, and user forums to help educate about MTLS usage to support transportation applications.

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Figure 12. Screenshot. The learnmobilelidar.com website. (O'Banion et al. 2014).

Related work has been completed by the Queensland DOT and Main Roads and Austroads. It has developed three key documents: the *Mobile Laser Scanning Technical Guideline* (*Technical Guideline*) (AusPos 2014), the *Best Practice for Mobile Lidar Survey Requirements* (*AP-T269-14*) (Austroads 2014a), and *Applications of New Technologies to Improve Risk Management* (*AP-T268-14*) (Austroads 2014b). Notably, the *Technical Guideline* provides survey requirements for the capture and processing of MTLS data. It also provides specific ground and feature model requirements and provides a helpful checklist to ensure that product deliverables meet the appropriate specifications. This *Technical Guideline* enables contractors to apply new techniques provided they have a clear and reliable plan to validate the quality of the collected data to meet the requirements. *AP-T269-14* provides a review of applications for MTLS and covers positioning accuracy, point density, multiple passes, control and validation points, and deliverables and documentation requirements in several case studies. Lastly, *AP-T268-14* assesses 11 recent technologies for asset management, including lidar. The document prioritizes technologies into several levels based on factors such as cost, maturity, and applicability. The goal of this document was to create a business case for the use of technologies such as lidar and improve the dialogue between DOTs and private industry stakeholders. It also provides effective practices for implementation.

Nolan et al. (2015) and Nolan et al. (2017) describe the multi-pass approach to obtain similar accuracies with MTLS as are achieved through the widely-accepted practice of using multiple targets with a single pass. By performing multiple passes through a corridor, GNSS multipath errors can be detected and reduced. This method also provides safety benefits since less manual surveying is required to establish survey control targets along the highway. Lastly, the method results in a higher resolution point cloud.

Other

Note that other "mobile" lidar system platforms such as helicopter, all-terrain vehicle, or boat may be more suitable and faster for acquisition, depending on the object(s) of interest. Nonetheless, the technology operates similarly across these platforms. For example, helicopters allow for flights closer to the ground, which improves accuracy and resolution compared to fixed-wing aircraft that requires flights at a much higher altitude. Lightweight lidar systems can be installed on UASs and coupled with an inertial measurement unit system. However, to meet weight requirements, these systems will often be of lower accuracy compared to those used on larger devices. Handheld and backpack lidar systems are also available.

PHOTOGRAMMETRY AND STRUCTURE FROM MOTION

Photogrammetry is the practice of extracting precise geometric measurements from photographs. The photographs are typically acquired from an aircraft or other airborne platform, which enables efficient and cost-effective data acquisition over a large area. The use of airborne photogrammetry can minimize—although typically not eliminate—the need for ground-based surveys, which can be expensive and, on a construction site, potentially dangerous and/or disruptive to other operations. Close-range photogrammetry is another form of photogrammetry in which terrestrial photographs acquired at relatively short ranges enable detailed 3D models and measurements of objects. The discipline of photogrammetry is mature, with many of its methods and mathematical underpinnings dating back to the mid-19th century (Hilton 1985; Wolf and Dewitt 2000; Mikhail et al. 2001). It is closely related to other surveying and mapping techniques and technologies and is often grouped with them under the broader term "geospatial."

SfM is a photogrammetric approach that has emerged relatively recently in the construction industry. Interestingly, the majority of algorithms and techniques in SfM originated in the field of computer vision, and many important developments were made independently—and perhaps initially without knowledge—of related techniques in conventional photogrammetry (Daniilidis and Spetsakis 1997). The advanced image matching algorithms that form the basis of SfM afford much greater flexibility in data acquisition than conventional photogrammetry. Specifically, many requirements are reduced, such as those for highly calibrated, metric cameras, imagery acquired from a similar viewpoint, and nearly constant image scale. Hence, SfM lends itself well to UAS imagery acquisition and ground-based imagery acquisition using affordable, consumer-grade cameras. Additional characteristics of SfM include ease of use, which is achieved through a high level of automation, and the ability to generate very high-resolution point clouds and orthoimages because the imagery is often collected from close range (e.g., from the ground or by a UAS at an altitude of a few hundred feet or less).

Technology Overview

Stereo photogrammetry uses images acquired from multiple perspectives to create precise 3D information. In a typical airborne deployment, a camera on a manned aircraft is configured to acquire images with a specified amount of overlap as the aircraft flies over the area of interest (Figure 13). These overlapping photographs allow a human analyst (photogrammetrist) to stereoscopically reconstruct the geometry in the photographs and extract necessary 3D measurements. Today, the process of reconstructing the geometry is almost always done on a computer (as opposed to using the mechanical or optical-mechanical instruments that were common throughout most of the 20th century) and can be assisted with airborne GNSS or GNSS-aided inertial navigation systems (INS).

A fundamental task in photogrammetry is to establish the geometric relationship between image coordinates and ground coordinates, which is achieved using the so-called collinearity condition equations. These equations express the condition that, in a correctly oriented image, the camera station, an object point (i.e., a point on the ground) and its corresponding image point all lie on a straight line after accounting for lens distortion and other effects. A set of such sight lines connecting many ground points to their corresponding image points and camera stations is known as a bundle of rays. In a process referred to as bundle block adjustment (or analytical aerotriangulation), this bundle of rays is simultaneously adjusted to solve camera station positions and orientations, as well as ground coordinates of points.

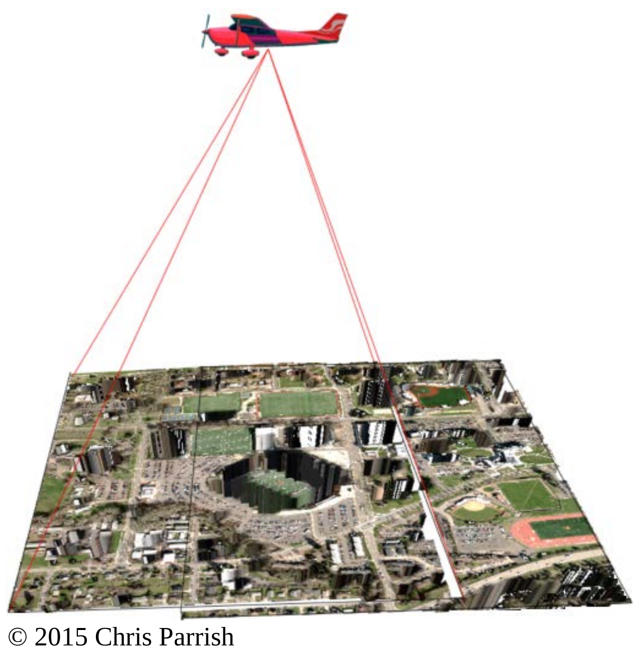


Figure 13. Image. Use of multiple, overlapping photographs in photogrammetry.

Common tasks in photogrammetry, following aerotriangulation, include the following:

- Measuring 3D spatial coordinates.
- Mapping topography, including generating DEMs.
- Producing orthoimages, which are images that have been corrected to remove distortions and have correct scale throughout.

Georeferenced orthoimages and DEMs produced photogrammetrically and having georeferenced coordinates (e.g., state plane) can be overlaid with other spatial data layers in a GIS to be used for project planning, change analysis, and myriad of other tasks in construction and transportation.

The basic principles underlying SfM are not fundamentally different from those of conventional photogrammetry noted previously, but SfM makes use of advanced image matching algorithms and procedures developed from the field of computer vision. Detailed descriptions of SfM algorithms and workflows are beyond the scope of this report but can be found in Snavely et al. (2006), Snavely et al. (2008), and Westoby et al. (2012). Briefly, the processing consists of an image matching step, carried out using algorithms such as the scale invariant feature transform key point detector (Lowe 2004), followed by recovery of camera parameters and 3D reconstruction (typically employing a bundle adjustment), and dense point cloud generation. After reconstructing the geometry in a relative sense, ground control points are introduced and used to transform the point cloud to georeferenced coordinates (e.g., state plane or a local project coordinate system), using a *Helmert* (also known as 7-parameter) transformation. Figure 14 shows the computed camera positions for a set of images. The blue rectangles indicate reconstructed camera positions in an arbitrary, image-space coordinate system. Following this step, ground control points will be used to compute and apply 3D conformal transformation to a georeferenced coordinate system.

Figure 14. Photo. Example of photograph locations for UAS SfM acquisition.

Because SfM is typically performed using high-resolution, close-range images, as compared to conventional photogrammetry from manned aircraft, it lends itself well to extraction of detailed 3D spatial information of individual objects on a construction site. Interestingly, the technology to which SfM is most frequently compared is not conventional photogrammetry, but rather STLS. In particular, several researchers have compared the spatial resolution—if not the spatial accuracy—achievable with SfM to that of STLS (Fonstad et al. 2013; Westoby et al. 2012; Mancini et al. 2013).

SfM algorithms rely on a large number of image correspondences (or "conjugate" image points, in conventional photogrammetry vernacular) to both reconstruct the geometry of the area of interest and solve for unknown camera parameters. Hence, a requirement in SfM is for a relatively large amount of overlap. The typical requirement is that each point must be visible in a minimum of three images (Westoby et al. 2012; Rothmund et al. 2013), but five to ten, or more, is preferable. In traditional photogrammetry, images overlap by 60 percent; whereas in SfM, overlaps of 80 to 90 percent are common. Additionally, control survey work is still required for accurate, georeferenced models.

GLOBAL NAVIGATIONAL SATELLITE SYSTEMS

GNSS is a satellite system that provides geospatial positioning anywhere on earth. To date, two GNSSs constellations are fully operational: the United States' GPS and the Russian Federation's GLONASS. GPS reached worldwide civilian capability in 1995 (Van Sickle 2015), and GLONASS reached the same capability in 2014. In addition, other GNSS constellations are under development, including China's BeiDou and the European Union's Galileo. Research is ongoing to make all of these systems interoperable and fully available for civilian applications. Upon completion of these systems, future GNSS receivers will be capable of tracking over 100 available satellites for pinpointing their location anywhere in the world. This will result in reduced delays in finding adequate satellites for determining the location of a receiver.

Even though other worldwide systems have just been deployed or are under development, GPS has been fully operational for over 20 years and has been applied for countless numbers of civilian applications. Originally developed for U.S. military applications, GPS has become an indispensable tool in every sector of the global economy (Ogaja 2011). Because GPS has been widely available for such a long time, information from a large number of articles, textbooks, and other publications is readily found. The following sections provide a brief overview of GPS and its applications in construction and transportation engineering. Recent advancements and future applications of GPS, including other GNSS technology, will also be discussed.

Source: FHWA

Figure 15. Photo. Use of a GNSS base receiver to provide control for AMG during the Design to Paver workshop at Camp Adair, Oregon.

Basics of Technology

GPS and other GNSS technologies consist of three basic segments:

- **Space segment:** The space segment consists of satellites that continuously broadcast position and time data to receivers. A complete constellation consists of a minimum of 24 satellites and is required to orbit Earth at a nominal altitude of 20,000 km.

- **Control segment**: The control segment is made up of ground stations scattered around Earth that monitor and track all of the satellites in view and collect the satellite broadcast signals. The master ground station collects this information and then computes precise satellite orbits that are then transmitted to each satellite. This process enables each satellite to broadcast current and reliable data to the user.

- **User segment:** The user segment includes receivers, processors, and antennas that allow operators to receive satellite broadcast signals that determines the position, velocity, and time of the operator's location on Earth. This is a passive segment capable of only receiving data from the satellites and incapable of transmitting information back. A passive system enables countless GNSS users without any danger of overburdening the system.

The position of a GNSS receiver is found by trilateration. For a successful trilateration routine, the receiver must determine its distance (known as a “range”) from a minimum of four satellites; the position of these satellites must also be accurately known. Distance is understood to be a function of the speed of light and the time elapsed for a signal to travel from the satellite to the receiver. Thus, time is an extremely important variable in satellite positioning. The satellite marks the moment the signal departs using a high-accuracy atomic clock. The receiver determines the moment the signal arrives by decoding the binary GNSS codes of the satellite signal. Carrier waves in the microwave spectrum transport these special GNSS codes and are modulated at specific frequencies.

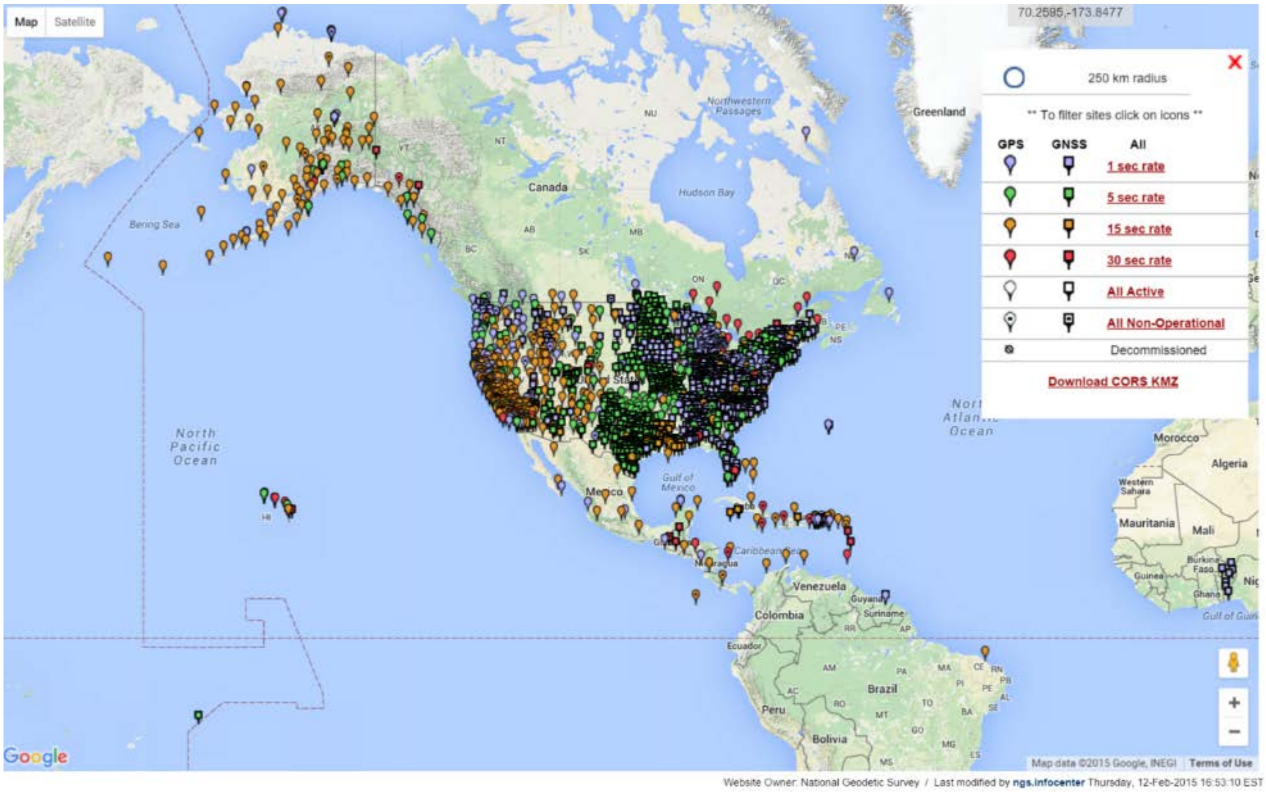
Consumer-grade, inexpensive GNSS receivers find ranges by only making use of the binary GNSS codes. Such receivers can be found today in cell phones and other mobile devices, cameras, and most consumer navigation devices. Under normal conditions and under an unobstructed sky, the positional accuracy of these code-based receivers is limited to roughly 5 to 15 meters at 1-standard deviation (1-σ).

Instead of only relying on GNSS codes, survey-grade GNSS receivers also make use of the aforementioned carrier waves for determining ranges to the satellites. Today’s survey-grade GNSS receivers find ranges by resolving the phases of two carrier wave frequencies modulated on the satellites, known as “L1” and “L2” frequencies. Carrier phase-based positioning typically requires longer observation time than code-based positioning with resultant accuracies being roughly less than one meter (1- σ) without applying relative positioning techniques or precise point positioning, as discussed below. Surveyors, geodesists, geophysicists, and other geospatial professionals most often use carrier phase-based GNSS receivers capable of resolving both the L1 and L2 frequencies (also known as dual-frequency receivers).

Differential GNSS

Several system-wide errors affect the accuracy of GNSS positioning, primarily due to atmospheric refraction and clock biases. A number of techniques have been developed for acquiring GNSS data and minimizing these errors. A common technique for minimizing system-wide GNSS errors is to set up a base GNSS receiver over a known point and differencing its known position with the position of the rover GNSS receiver as estimated from the satellites. Such an error estimate is described as a *differential correction* that can be made available to other users in the nearby area. Differential corrections are correlated both spatially and temporally. Such corrections can be applied to the positioning of other nearby static GNSS receivers or rover receiver that are logging data simultaneously with the base. This technique, known as differential GNSS (DGNSS), reduces errors of code-based rover receivers to less than 1 to 5 meters (1- σ).

Users can set up a temporary base receiver over a known point or they can make use of GNSS data from a permanent base station. For example, the National Geodetic Survey manages a global network of dual-frequency, permanent GNSS base stations known as Continuously Operating Reference Stations (CORS). Data from the CORS are freely available and can be downloaded for post-processing. Figure 16 is a map showing the locations and data rates for CORS.



Source: NGS

Figure 16. Map. Location of CORS and data logging rates. (NGS 2017).

It is also possible to receive differential corrections in real-time by using an ultra-high frequency (UHF) radio, a Wi-Fi connection, a satellite augmentation system, or a cellular signal. The U.S. Coast Guard provides a local-area augmentation service known as Maritime DGPS, by which they send differential corrections from their GPS base stations using UHF radios. The FAA has the Wide-Area Augmentation System (WAAS) that broadcasts the differential corrections from geostationary satellites (Federal Aviation Administration WAAS Frequently Asked Questions).

Static Relative Positioning

DGNSS with code-based receivers improves the accuracy of satellite positioning and navigation; however, many construction and engineering applications require cm to sub cm level accuracies. These levels of accuracy require the use of carrier phase-based GNSS receivers and, similar to DGNSS, generally requires the use of at least two GNSS receivers. Differencing the carrier phase measurements of two GNSS receivers greatly reduces spatially and temporally correlated errors and is referred to as *relative positioning*.

Static GNSS surveying is the most accurate type of relative positioning and is often used to establish geodetic control networks. A static survey typically requires construction of a control network with multiple, long-duration observations between multiple survey marks. Most governmental agencies have specific standards and guidelines for performing static surveys.

A static survey session involves setting up survey-grade receiver(s) over project control marks in order to simultaneously collect GNSS data from four or more satellites for a lengthy period of time for high-accuracy relative positioning. A static survey session often lasts longer than two hours and is later post-processed in the office to compute baselines or 3D vectors between each receiver to accuracy levels that can be less than 1 to 2 cm vertically and 0.3 to 1 cm horizontally (1- σ).

The control used for a static geodetic control network is typically found by post-processing GNSS data collected simultaneously at project control marks and nearby published[7] control marks. Often, surveyors will download and use GNSS data from nearby CORS and will then compute baselines between the CORS and their project control marks. They will also commonly use the published positions of the CORS as control for their static geodetic control network because the CORS are widely considered the backbone of the U.S. National Spatial Reference System.

In 2001 the National Geodetic Survey (NGS) released an online tool known as the Online Positioning User Service (OPUS) [8] (NGS 2017): This online tool improves efficiency in post-processing positioning data and has become very popular as users simply upload a raw GPS file and specify the antenna type and height above a project control mark. OPUS Static (OPUS-S) then post-processes the raw GPS data by computing baselines to three CORS, and then it emails the resulting solution to the user in a few minutes. For a four-hour observation, the accuracy of OPUS-S is roughly less than 2 cm vertically and 5 mm horizontally (1- σ) (Soler et al. 2006).

In 2014, NGS released another free online tool for GNSS network processing known as OPUS-Projects.[8] (NGS 2017). OPUS-Projects provides data management and post-processing tools for developing geodetic control networks involving multiple marks and multiple static survey sessions (Armstrong et al. 2015). This cloud-based software program provides options for quickly adding GPS data from multiple CORS, and it produces several plots for visualizing post-processing results. Table 3 lists some of the freely available tools provided by the NGS.

[7] Geodetic control marks are considered "published" when the mark meets NGS requirements for inclusion in the NSRS.
[8] All OPUS products may allow measurement data from other constellations such as GLONASS or Galileo to be included, but only GPS will be used to generate the positioning solution.

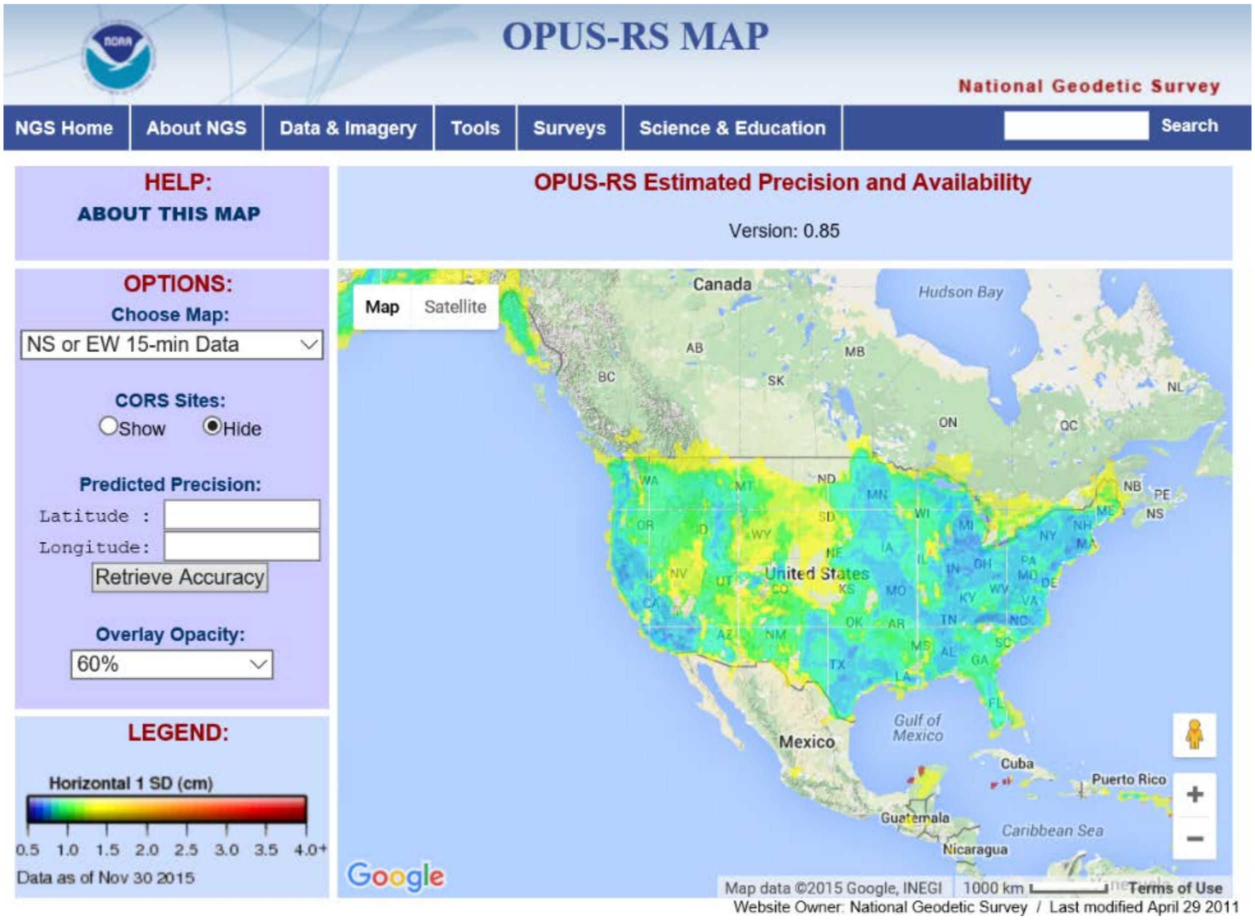
Table 3. Partial list of geodetic tools and data offered by the National Geodetic Survey.

NGS Tools	Description
DEFLEC (versions 99, 09, 12A)	Computes deflections of the vertical from a plumb bob and the ellipsoid
DYNAMIC_HT	Computes dynamic height from an orthometric height and a gravity value
GEOCON	Performs three-dimensional coordinate transformations
GEOID (99,03,06,09,12A)	Model of geoid undulations used to compute ellipsoid height to orthometric height
Horizontal Time-Dependent Positioning	Enables users to update geodetic coordinates due to time-dependent horizontal displacement
Leveling Online Computations User Service	Provides least squares adjustment of orthometric heights with corrections
Online Positioning User Service (OPUS)	Provides post-processing for static and fast-static GPS data; provides coordinates based upon the high-accuracy National Spatial Reference System
OPUS Projects	Provides GPS data management and post-processing for projects requiring multiple occupations
VERTCON	Computes modeled difference in orthometric height between NAVD88 and NGVD29

Rapid-Static Relative Positioning

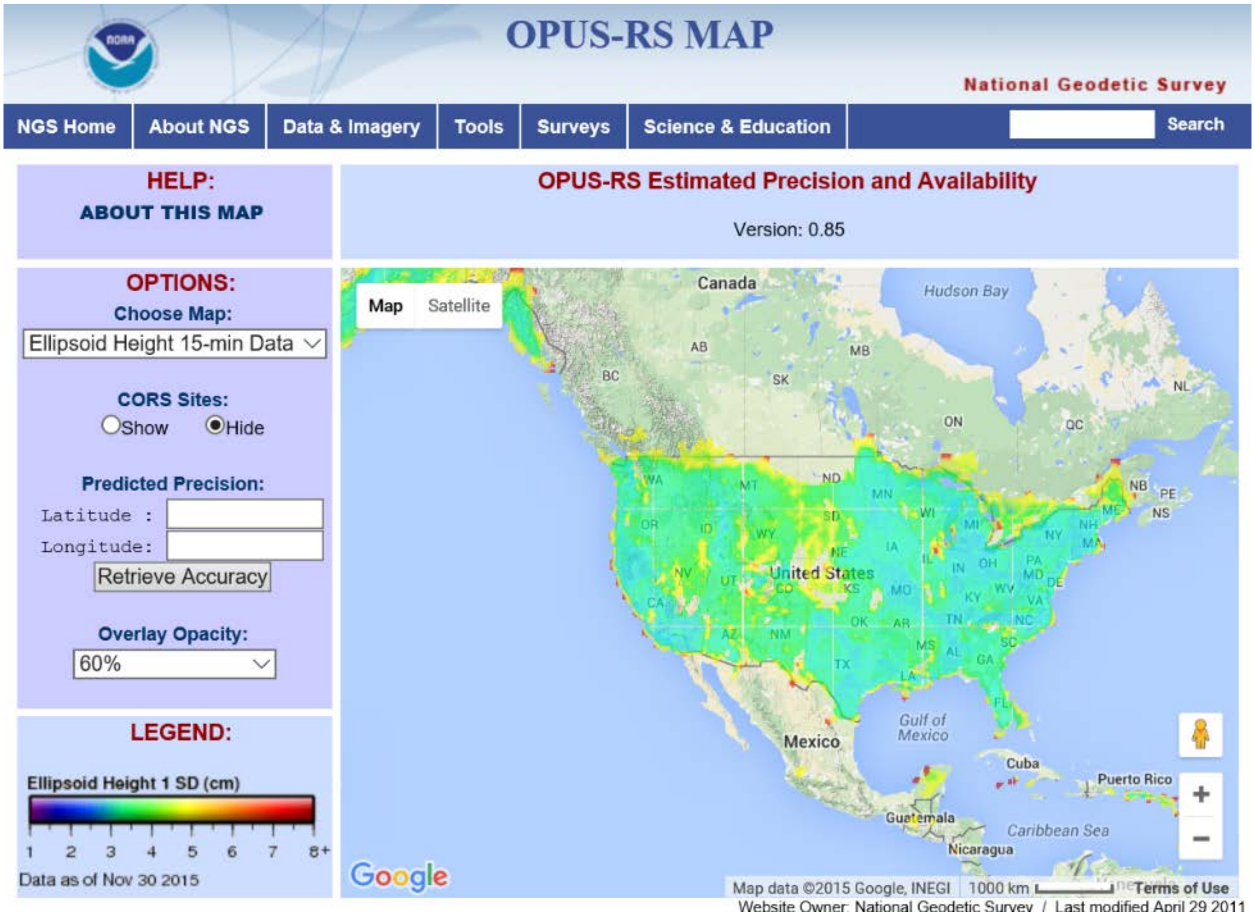
Rapid-static GNSS surveying is similar to static GNSS surveying, but it is typically limited to surveying baselines less than 20 km in length. The advantage to rapid-static surveying is that sessions can be as short as 15 minutes. However, rapid-static surveying is somewhat more susceptible to errors from atmospheric refraction and overhead obstructions than static surveying.

In 2006, NGS released another free online tool known as OPUS-RS for post-processing rapid-static GPS data. This tool functions similar to OPUS-S, but it uses a different processing algorithm, up to 9 CORS, and allows as little as 15 minutes of raw GPS data. The estimated accuracy of an OPUS-RS solution varies according to the geometry of the nearby CORS, but a tool is available for predicting the accuracy of OPUS-RS at sites with unobstructed view of the sky. NGS (2017) provides an online map that often predicts accuracies less than 2 cm (1- σ) horizontally (Figure 17) and 4 cm vertically (Figure 18) for observations of at least 15 minutes.



Source: NGS

Figure 17. Image. OPUS-RS horizontal error estimate. (NGS 2017).



Source: NGS

Figure 18. Image. OPUS-RS vertical error estimate. (NGS 2017).

Kinematic and Real-Time Kinematic Positioning

Although both static and rapid-static relative positioning are highly accurate, these techniques require a receiver to observe points for long periods of time. In many construction and transportation engineering applications, there is a great need to determine accurate positioning over points in a matter of a few seconds. For example, highly accurate measurements may be desired for mobile mapping systems or guidance of cars, trucks, boats, and heavy machinery. In kinematic relative positioning, dual frequency GNSS rover receivers are either in periodic or continuous motion. Data from the rover receivers can be post-processed with static data from a GNSS base receiver.

A more useful, efficient, and popular method of positioning is to perform kinematic positioning in real-time. This technique enables users to layout designs on the ground, perform quality assessment and quality control of the construction, and conduct other checks immediately in the field without the need to perform post-processing in the office. In Real-Time Kinematic (RTK) positioning, GNSS corrections from a base receiver over a known point are broadcasted to the rover receiver using a datalink, usually with a UHF radio, Wi-Fi, or cellular signal. The resulting position or velocity at the rover receiver are stored and reported to the user nearly instantaneously on a data collector.

RTK relative positioning is nearly as accurate as static positioning. Typically, accuracy levels can be found in real-time to less than 2 cm horizontally and 4 cm vertically (1- σ) when occupying a point for 2 to 3 minutes. Because of its high accuracy and efficiency, RTK positioning has become the most popular GNSS surveying technique. As listed below, RTK GNSS is used for numerous construction and transportation applications. For best results, rovers should be kept within 20 km of the GNSS base station (Van Sickle 2015). In addition, it is important to note that RTK positioning is much more susceptible to errors from atmospheric refraction and overhead obstructions than static relative positioning. Thus, static and rapid-static GNSS relative positioning are better suited for high-accuracy control work than RTK GNSS relative positioning.

Real-Time Networks

RTK GNSS has become the most popular type of relative positioning for surveying and engineering applications. However, the method requires setting up a base receiver over a known point, establishing a data link between the base and rover receiver(s), and possibly even hiring a person to attend to the base to prevent unexpected problems or theft. As noted above, for best results the rover receiver must also be kept within 20 km of the base receiver.

To alleviate these difficulties, many counties, states, municipalities, and commercial GNSS vendors are developing or have developed Real-Time Networks (RTNs). An RTN consists of a dense network of permanent, professional-grade base receivers (spaced typically every 50 km or less) that are established, monitored, and maintained either by government agencies, service providers, or vendors. These base receivers are linked together and broadcast their data to a central server. By connecting a rover receiver to the RTN server using a cellular modem, a user can receive an interpolated correction in real-time based on data from the multiple RTN base receivers.

The RTN eliminates the need for setting up an individual, temporary base station as well as enables the measurement of longer baselines. Rather than relying on a single base receiver, the multiple base receiver configuration in the RTN improves redundancy and more accurately estimates atmospheric refraction errors over a wider area. In addition, the performance of each base station can be monitored remotely and the control coordinates of each base receiver can be calculated. Another advantage is that users of an RTN can perform RTK GNSS work without the need to purchase or maintain a base receiver.

Numerous RTNs are under development or have been deployed in the U.S., including some that are operated by a state DOT (e.g., ORGN by ODOT). Recent advances in the coverage and capacity of cellular signals have increased the popularity of RTNs, which have led many users to favor RTNs over RTK techniques. Gakstatter (2014) has published a list of states that maintain RTNs.

Precise Point Positioning

Although RTNs are advantageous, there is a high initial outlay and costs to maintaining it over time. Precise positioning with GNSS would be more cost-effective if it were possible to do it with a single GNSS rover receiver without the use of corrections from a base receiver. Unfortunately, the aforementioned relative positioning techniques require a minimum of two survey-grade GNSS receivers. Positioning with a single GNSS receiver is challenging, because in doing so, the user is entirely reliant on the signals broadcasted from the satellites. Errors from the satellite signals accumulate due to orbital errors, satellite clock errors, and atmospheric refraction, which increases the level of positional uncertainty.

Over the past 15 years, researchers have developed a method to use data from global networks of GNSS base receivers in order to estimate much more precisely the satellite orbits and clocks, as well as model atmospheric conditions. This data, or precise-point corrections, can be obtained from the International GNSS Service and global GNSS vendors (e.g., Trimble®).

Using precise-point corrections, a new, high-accuracy technique has been developed known as precise point positioning (PPP). In PPP, baselines are not computed so there is no limitation in baseline lengths. In addition, the user only needs a single receiver and does not need to establish communication with a base receiver. A few online PPP tools are available for post-processing static GNSS data from a single receiver. A few online sites are listed in Table 4. Similar to OPUS, a user submits a raw GNSS file and specifies their antenna height and type; solutions are emailed back within a few minutes.

Table 4. Examples of online PPP service providers.

Service Provider	URL
Natural Resources Canada (CSRS-PPP)	http://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php
University of New Brunswick (GAPS)	http://gaps.gge.unb.ca
Trimble (CenterPointRTX)	http://www.trimblertx.com/UploadForm.aspx

Although PPP is on the cutting edge, it faces several challenges before it can become a mainstream GNSS positioning method. The primary challenge is that it may take over 20 minutes before a cm-level solution can be obtained. In addition, results may confuse some users because they are generally reported in a global reference system instead of relative to a local or regional reference system (e.g., relative to the CORS in the U.S.).

Achievable Accuracies

Consumer-grade GNSS receivers are most often used for quickly geotagging data in the field. For example, a GNSS digital camera can be used to geotag photographs, or a handheld receiver can be used to quickly collect the approximate location of assets.

For construction, mapping-grade receivers are useful for mapping objects that only require a general location. These handheld receivers may be used for mapping points, lines, and areas. As discussed above, professionals will frequently use GNSS to reduce errors to less than 1 to 5 meters. The collected data can be input and stored in a GIS along with attribute information to produce visualizations or maps quickly and accelerate geospatial analysis.

Survey-grade, dual-frequency GNSS receivers are necessary when users desire cm to sub cm levels of accuracy. Often, these levels of accuracy are needed for construction layout, surveying, and documenting as-builts.

As summarized in Table 5, a large number of techniques are available for collecting and processing GNSS data. Users should select the appropriate technique depending on the desired level of accuracy and the desired application.

AUTOMATED MACHINE GUIDANCE

Although not technically a geospatial tool in and of itself, an AMG system is a synthesis of 3D models, geospatial technologies (total stations, GNSS, and GNSS augmented with a laser for vertical control), accelerometers, an onboard computer, and software installed on highway construction equipment. The AMG system provides guidance to the operator for grade control or can be used to control the hydraulics of the equipment to maintain grade or steer a paver. AMG systems are found on a range of construction equipment that requires grade control, from bobcats to large excavators, as well as on slip-form median and curb pavers to multi-lane pavers.

In a typical workflow scenario, a 3D model is loaded into the AMG system. The computer analyzes the 3D model and harvests the vertical and horizontal positional data from the geospatial technology in real time. As a result, the computer provides feedback to the operator through use of a computer monitor or other means about the behavior of the highway construction equipment in relation to the 3D data. Currently, guidelines and specifications are being developed through the NCHRP Project 10-77 (White 2013).

Technology Overview

In order for AMG to be successful, all components need to be functioning properly and efficiently and the 3D models are of sufficient detail. In most cases, AMG relies upon geospatial technologies to determine the location of the machine. With stake or hub-based construction, the construction surveyor corrects any issues with precision in advance. Similarly, with AMG, these issues need to be corrected in advance through establishing higher network precision in the control and existing topography. The 3D models also require more precision than is typical of those used to create construction plans. With AMG construction, the level of detail with which transitions and hard tie-ins are explored prior to mobilization is usually significantly higher. However, there is always an option to turn off the AMG control and return to manual grade control.

Table 5. Summary of available GNSS data acquisition techniques (according to grade of the equipment).

GNSS Receiver and Technique	Typical Uncertainty[9] (1-σ)	Description	Capabilities	Limitations
Consumer-grade without differential corrections	H: 5 – 10 m V: 10 – 15 m	Often available in some phones, cameras, tablets, and handheld devices	• Fast and easy to use • Useful for geotagging data and navigation	• Lower accuracy • Only coarse coordinates provided
Consumer-grade with differential corrections	H: 1-2 m V: 2-5 m	Same as above but capable of receiving differential corrections from a local or wide area augmentation system	• Same as above but with some improved accuracy	• Same as above but with some improved accuracy
Mapping-grade with differential corrections (DGNSS)	H: < 1 m V: < 1 m	Handheld GIS units that can be integrated with an external antenna	• Fast mapping of points, lines, and areas • Easy insertion in GIS	• Low accuracy but better than above
Precise Point Positioning (PPP-GNSS)	H: < 2 -5 cm V: < 4 -10 cm	A new post-processing technique that uses only one survey-grade receiver and precise clocks and orbits calculated from a global network of GNSS base stations	• Does not require a second receiver over a known point (base receiver)	• Requires a minimum of 15- to 30-minute-long occupations for best results; often requires over 1 hour

[9] Under ideal conditions.

GNSS Receiver and Technique	Typical Uncertainty[9] (1-σ)	Description	Capabilities	Limitations
Real-time or post-processed kinematic relative positioning (K-GNSS)	H: 1-2 cm V: 2-4 cm	At least one survey-grade receiver/ antenna is set up over a control or base point, and another rover unit is moved to points of interest; measurements are made relative to the base unit(s)	• High acquisition rates, usually from 5 to 180 seconds • High accuracy • Establishment of real time networks with fixed base stations further improves data quality	• For best results, a base unit(s) should be within 10 km of the rover • Real-time corrections require communication devices (e.g., UHF radio, Wi-Fi, cellular signals)
Rapid Static relative positioning (RS-GNSS)	H: 1-2 cm V: 2-4 cm	A survey-grade receiver is set up over points of interest; the data is post-processed against data collected simultaneously with units at other nearby stations in a control network or against permanent GPS reference stations	• Higher accuracy • Less prone to position dilution of precision or multipathing than the above technologies	• Requires at least 15-minute-long occupations • Precise satellite orbits must be downloaded 1 to 3 weeks after a survey • Some projects may require multiple units with simultaneous occupations
Static relative positioning (S-GNSS)	H: 0.3 - 1 cm V: 1 – 2 cm	Same as above but requires longer occupations; used for establishing geodetic control networks	• Same as above and considered the most accurate GNSS survey technique	• Same as above but typically requires 2-hour or longer occupations

Note: H = horizontal accuracy and V = vertical accuracy

AMG systems provide an opportunity to control earthwork and paving quantities through the precise grade control. It is imperative that the engineers' design is based upon a survey that suitably represents existing conditions both to control earthwork quantities and to identify and resolve potential issues with how the design ties into the existing conditions. If not, the 3D model (based upon the engineers' design) will not coincide with existing conditions. This, frequently can lead to redesign and cost overruns. AMG operations for high value materials such as stone base, asphalt, and concrete require total station-derived control to control the material quantities. These optical systems use a resection routine to determine the position of the construction equipment. This requires a high level of consistency in the vertical control. Otherwise, when the AMG system switches from one total station setup to the next, there will be a significant shift in the blade or screed. In summary, a higher precision survey is customary for AMG, and there is an opportunity for savings in construction survey costs (among other costs) if this accuracy is achieved prior to design.

OTHER GEOSPATIAL TECHNOLOGIES

This section summarizes the capabilities and limitations of other available geospatial technologies that are beyond the scope of this project but still relevant. The emphasis of this discussion is to provide estimates of the typical measurement uncertainty of each technology (at one standard deviation or 1-σ). When such systems are used and rigorous geospatial data collection and processing techniques are used, data from multiple sources can be geospatially integrated with a high level of accuracy. The data acquired from these techniques can then be readily incorporated into a GIS database. Such integration enables rich comparisons of datasets, both spatially and temporally, and enables improved analyses of uncertainties. It also helps link fragmented projects together into a common framework to produce robust sources of information for future studies.

Satellite Imaging

Satellite imaging technology relies on modern satellite sensors to capture data for very large regions. The imagery is often available relatively quickly, and new smaller satellite systems may result in more timely images and broader coverage. There are number of service providers for this type of data acquisition (e.g. Quickbird, Worldview-1 and 2, GeoEye). The typical uncertainty (1-σ) for satellite imaging is 1-meter. Some of the limitations for this technology include: images having low spatial resolution, imagery is downward view only (not 3D), cloud cover can adversely affect image quality (Olsen and Gillins 2015).

Airborne Imaging from Manned Aircraft

Similar to satellite imaging, aerial imagery from a manned aircraft relies on imaging sensors. However, the sensors are attached to airborne platforms that capture ground deformations for large regions at higher accuracy than satellite systems. The typical uncertainty (1-σ) for airborne imaging from manned aircraft is 0.3-0.7 meters. Cameras require careful calibrations and increased coordination with airspace managers are some of the disadvantages for this technology (Olsen and Gillins 2015).

Oblique Imaging

Oblique imagery is collected at angles oblique to features of interest via various platforms, such as low altitude aircraft, mobile or terrestrial platforms. 2D images can be perceived in 3D, and overlapping images can be converted into 3D point clouds using photogrammetry techniques. The typical uncertainty (1-σ) for this technology is 0.3 meter. Increased data acquisition and processing time are among the disadvantages over other methods to acquire imagery. Also cameras must be carefully calibrated and ground control points are needed (Olsen and Gillins 2015).

Structure from Motion with Handheld Camera or with UAS

Structure from Motion with handheld camera (hSfM) or with unmanned vehicle (uSfM) is a computer vision technique for creating mosaics and processing overlapping images by at least 80% and producing 3D point clouds. The typical uncertainty (1-σ) for this technology is 0.1-0.3 meter. Imagery can be collected using consumer-grade cameras, sUAS. The solution requires ground control points for applying a real-world scale (Olsen and Gillins 2015).

Ground Penetrating Radar (GPR)

Ground penetrating radar technology (GPR) uses radar pulses to image the subsurface with a GPS sensor for 2D positioning of the device to map subsurface conditions. The typical uncertainty (1-σ) for this technology is 0.1-0.2 meter. Lines of systematic collection provide tomographic images; however, the sensor must generally be in physical contact with ground. Heterogeneous soil types affect the results and will require increased scrutiny to achieve the necessary level of quality (Olsen and Gillins 2015).

Air or Space Borne Interferometric Synthetic Aperture Radar

Interferometric synthetic aperture radar technology emits and receives narrow beam radar signals, and differences in returning wave phases from two images are then used to map surface deformations. It is possible to monitor surfaces for years. Also active sensors can be used at night or in cloud cover, and airborne and satellite systems are available for data collection. The typical uncertainty (1-σ) for this technology is 0.01 meter. Varying topography and vegetation distort the phase angle of the return signal, and ground control points may be necessary to achieve desired results (Olsen and Gillins 2015).

Ground-Based Radar (GBR)

Ground-Based Radar (GBR) technology is similar to the air or space borne interferometric synthetic aperture radar, but the device is mounted on terrestrial platforms and can monitor areas up to 2 km^2 at high spatial resolution. This is the ideal tool for monitoring and measuring very small displacements at high frequency. The typical uncertainty (1-σ) for this technology is less than 0.001 meter. This technology is limited to only targets directly in line-of-sight, and shares some of the same disadvantages as mentioned above (Olsen and Gillins 2015).

EVOLUTION OF DIGITAL SURVEYING DEVICES

Many automated surveying practices have been commonplace in state DOTs for some time, and new features are continually available (Olsen et al. 2013). Such techniques require less field time, reduced crew sizes, and minimize human error. This section describes digital levels and total stations, as well as their application to structural assessments. Figure 19 and Figure 20 show good examples of these devices in operation.

Digital Levels

Levels can be used to accurately determine cross slopes and road slope, as well as settlements, displacements, and rotations on a structure such as bridge decking, a beam, or a foundation. Digital levels provide both a distance to the reading as well as the elevation difference with sub mm accuracy. Systems capable of 0.3 mm accuracies over short (<50 m) ranges are available.

In many cases, digital levels have replaced many traditional dumpy and automatic levels resulting in improved speed and precision. This system uses a vertical rod with a barcode that can be read by the Electronic Distance Meter from a digital instrument. To ensure this rod is kept vertical, a level bubble is in place on the rod itself, similar to traditional leveling techniques. The difference is that the machine person no longer has to read values from a rod through a scope, thus reducing human error and improving efficiency.

Total Stations

Total stations are a well-established surveying technology used by most state DOTs (Olsen et al. 2013). Total stations measure angles and distances electronically to determine coordinates of objects of interest. While capabilities of total stations continue to evolve, total stations generally include one or more of the following capabilities:

- **Prism measurement:** The total station is sighted (horizontal and vertical angles) to the center of a prism and the electronic distance meter measures the distance to the center of the prism, enabling the measurements of angles and distances between points as well as coordinates. For structural monitoring, prisms, total stations, or both can be mounted permanently for time series measurements.

- **Reflectorless measurement:** Enables measurements to be collected more rapidly and on features not accessible with a prism. Although these measurements are generally not as accurate as prism measurements, they still can be achieved with 2 to 3 mm accuracy. These are useful for obtaining measurements on the sides of bridges, steep slopes, or other areas that are not easily accessible. Displacements with time can be tracked across a structure when inexpensive targets are placed at strategic locations.

- **Robotic:** Robotic systems have a tracking system to follow the reflective prism and collect survey points as the prism moves. Surveys can be completed more efficiently since a single person can operate the equipment and one does not lose time sighting the instrument to an object.

- **Imaging:** Enables georeferenced, 360-degree (panoramic) digital images to be collected with the total station data so that data can be placed in context. The imaging capabilities also aide the instrument operator during collection.

- **Integrated GNSS:** Both static and RTK GNSS measurements can be recorded for the instrument location, providing added flexibility in georeferencing total station data.

- **Integrated lidar scanning:** New multi-function systems have built-in scanners to acquire small point clouds that are directly linked to the total station data.

Figure 19. Photo. Operation of a total station to set control points for a highway project in Alaska.

Figure 20. Photo. Operation of a total station in robotic mode to acquire survey points in Oregon.[10]

[10] Note the GNSS receiver is being used simultaneously to log static data to provide control coordinates. The photo also shows the operation of a retro-reflectometer.

CHAPTER 3. HIGHWAY CONSTRUCTION SCENARIOS AND APPLICATIONS

This chapter discusses how geospatial technology is used in the highway construction sector, provides effective practices on workflows and tool selection, and discusses the ROI framework used in this study. Understanding the workflows of using geospatial technology during design, construction, and asset management will allow state DOTs to deploy geospatial tools more effectively. Furthermore, geospatial tools offer substantial benefits to project delivery but can also be detrimental to project costs and quality if not applied correctly. Later in this chapter, a framework is presented that offers effective practices on when to deploy certain tools given a specific scenario.

USES OF GEOSPATIAL TOOLS IN HIGHWAY CONSTRUCTION

This report focuses primarily on geospatial technologies used for highway construction, such as UAS, lidar, photogrammetry (including structure from motion), GNSS, and AMG. After each technology is discussed in detail, it is compared against other available technologies. This information provides a foundation to develop effective practices on selecting the appropriate technologies based on accuracy, resolution, and spatial coverage requirements.

Geospatial technologies also have significant value across a wide range of applications. This report focuses on common highway construction applications, including the following:

- 3D Highway Modeling.
    - Data collection for corridor mapping (e.g., topographic mapping).
    - 3D modeling to support construction automation (e.g., AMG).
    - Calculation of quantities (e.g., earthwork).
- Construction Engineering and Inspection.
    - Real-time verification.
    - Site or progress monitoring.
    - Measurement of quantities.
    - As-built records.

The study also documented the use of geospatial tools for bridge inspections. Other applications are discussed, as relevant; however, they were not a focus of this study.

An important part of this study was to investigate the use of geospatial technologies with state DOTs, construction contractors, and instrument developers/service providers. This was accomplished through a series of interviews (see Appendix C for the full results of the interviews) and follow-up discussions that captured information on how geospatial technology is used for highway construction, what geospatial technology is used for collecting data, what processes and products are developed, lessons learned in using geospatial technology, and benefit-cost data.

Table 6 illustrates the geospatial applications for highway construction, as reported by state DOTs. Selecting the right tools and proper application and use of those tools will yield the desired results (e.g., for spatial resolution and accuracy, time savings, cost savings). However, state DOTs have expressed the challenges of being able to quantify the benefits. Wyoming DOT indicated that the use of geospatial technologies has improved staff utilization—the state DOT is able to do more work with fewer resources. Florida DOT cited that photogrammetry and GNSS are meeting desired results for accuracy and ROI. Although lidar is also meeting the desired accuracy, the initial investment in the technology is costly. Arkansas DOT indicated that although its tools are meeting most requirements, it is difficult to quantify the cost savings.

Table 6. Geospatial Applications by State DOTs for Highway Construction

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUASs	Ground -based Radar	AMG	Robotic Total Stations	Sonar
Topographic surveying	x	x	x	x	x	x	x	x	-	-	x	x
Earthwork	x	x	-	x	x	x	x	x	-	x	x	-
Paving	x	x	x	-	-	-	-	-	-	x	x	-
Roadway design	x	x	x	x	-	x	-	-	x	-	x	-
AMG and control	x	x	x	-	-	-	-	-	-	x	x	-
Verification	x	x	x	-	-	x	-	-	-	-	x	-
As-built surveys	x	x	x	-	-	x	-	-	-	-	x	-
Site/progress monitoring	x	x	-	x	-	x	-	-	-	-	x	-
Inspection	x	x	x	-	-	x	-	-	-	-	x	-
Quality assurance/quality control	x	x	x	-	x	x	x	x	-	x	x	-
Asset management	x	x	x	x	-	x	-	-	x	-	x	x

- Not commonly used

Table 7 illustrates the geospatial applications for highway construction, as reported by construction companies. Compared to state DOTs, construction companies are using sUASs/sUAVs more frequently across construction applications; however, state DOTs are using conventional photogrammetry across more applications than contractors. Construction companies agreed with state DOTs on the importance of selecting the right tool for the project requirements in order to yield cost and time savings.

Table 7. Geospatial applications by construction companies for highway construction.

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUASs	Ground Penetrating Radar	AMG	GPS	Conventional Surveying Tools
Topographic surveying	x	x	x	x	-	x	x	x	x	x	-	x
Earthwork	x	x	x	x	-	-	-	x	-	-	x	x
Paving	-	x	-	-	-	-	-	-	-	x	x	x
Roadway design	x	-	-	x	-	x	-	-	-	-	-	-
AMG and control	x	-	-	x	-	-	-	-	-	-	x	x
Verification	x	x	-	-	x	x	-	x	-	-	-	x
As-built surveys	x	x	x	x	x	x	-	x	-	-	-	x
Site/progress monitoring	x	-	-	-	-	-	-	x	-	-	-	x
Inspection	x	-	x	-	x	-	x	x	-	-	-	-
QA/QC	x	x	x	x	x	-	x	x	x	x	-	-
Asset management	x	x	x	x	x	-	-	x	-	-	x	x

- Not commonly used

Table 8 illustrates the application of the technologies identified above for highway construction, as reported by instrument developers and service providers. Again, the application of sUASs/ sUAVs is more prevalent among instrument developers/service providers than state DOTs.

Table 8. Geospatial applications by instrument developers and service providers for highway construction.

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUAVs	Conventional Surveying Tools
Topographic surveying	x	x	x	x	x	x	x	x	x
Earthwork	x	x	x	x	-	x	-	x	-
Paving	x	x	x	x	-	-	-	-	x
Roadway design	-	-	x	x	-	x	-	-	-
AMG and control	x	-	-	-	x	-	-	-	x
Verification	-	x	-	x	-	-	-	x	x
As-built surveys	x	x	x	-	x	-	-	-	-
Site/progress monitoring	-	-	-	-	-	-	-	x	-
Inspection	-	x	-	-	-	-	-	x	-
QA/QC	-	x	-	x	-	-	-	x	x
Asset management	x	-	x	-	-	-	-	-	-

- Not commonly used

Unmanned Aircraft Systems

sUASs have been investigated for a number of specific transportation engineering and construction applications. As summarized in Table 9, researchers have applied sUAS for monitoring traffic; inspecting structures, such as bridges and towers; assisting with construction safety inspections; inventorying roadside conditions; surveying and mapping topographic features; monitoring construction progress and updating building information models; estimating earthwork volumes; identifying potential avalanches near roadways; monitoring unstable slopes and mapping landslides; and reconstructing and documenting crash scenes. Currently, research projects are being funded by ODOT and the Pacific Northwest Transportation Consortium (Pactrans) to evaluate the capabilities of sUAS for bridge assessments (Gillins 2016). Another project funded by Pactrans is evaluating the suitability of SUAS and SfM techniques for assessing rockfall hazards along highways will be published in the near future. Information about this project can be found on the Pactrans website under the title, *"Unmanned Aircraft System Assessments of Landslide Safety for Transportation Corridors."*

Table 9. Transportation engineering and construction applications of sUAS.

Application	Benefits	Limitations
Traffic Monitoring and Surveillance (Irizarry and Johnson 2014); (Brooks et al. 2014)	Inexpensive and repeatable image and video capture	Potential collision hazards and restriction on flights above traffic
Structural Inspection (Zink and Lovelace 2015); (Brooks et al. 2014); (Eschmann et al. 2013); (Hallermann and Morgenthal 2013); (Khan 2015); (Otero et al. 2015); (Gillins et al. 2016)	Increased efficiency; expanded access to difficult areas; permanent digital records.	Potential collision hazards; unable to do hands-on assessments
Construction Safety Inspection and Security (Gheisari et al. 2014)	Increased efficiency; permanent digital records	Potential distraction and collisions hazards
Roadside Condition Inventorying, Assessment, and Inspection (Barfuss et al. 2012); (Hart and Gharaibeh 2011); (Zhang 2008)	Permanent digital records; bird's view not possible by vehicle-mounted imaging systems	Data collection of visible assets via "bird's view" only
Topographic Mapping and Estimating Earthwork Volumes (Judson 2013); (Siebert and Teizer 2014); (Hugenholtz et al. 2015); (Brooks et al. 2014)	Quick data collection to produce preliminary 3D mapping products	Less accurate than other technologies

Application	Benefits	Limitations
Monitoring Construction Progress and Status (Zollman et al. 2014); (Wang et al. 2014); (Lin et al. 2015)	Quick data collection to produce 3D as-built models; permanent digital record	Lack of automation tools to create building information model components
Identifying Potential Avalanches (McCormack 2008)	Enables rapid collection of remote sensing data in steep, inaccessible, snow-covered terrain	Restrictive regulations for maintaining line-of-sight of the operator, not suitable for mountainous terrain
Monitoring Unstable Slopes (Lucieer et al. 2014); (Niethammer et al. 2010)	Inexpensive and quick data collection over uneven terrain	Requires ground control points or aerial targets
Crash Reconstruction (Brooks et al. 2015)	Inexpensive and quick data collection and production of high-resolution, digital, 3D model of a crash site	Requires ground control points or aerial targets

Benefits

The main benefit of sUAS in construction and transportation engineering applications is that they can carry a variety of payload sensors for remotely collecting a diverse range of data. Remote sensing reduces the amount of time someone needs to physically contact or occupy areas of interest; therefore, it can minimize safety risks as well as possible impedance on construction progress. Remote sensing with a sUAS can provide a unique “birds-eye” view of objects of interest. It is possible to access and collect a wide range of data with a sUAS across locations that are difficult or even dangerous to reach from the ground. In addition, because a sUAS can be flown at very close standoff distances, high-resolution remote sensing data can be collected efficiently across areas of interest.

Remote sensing with a sUAS is also generally economical. The cost of purchasing and operating a sUAS can be orders of magnitude less than the corresponding costs for manned aircrafts. sUAS can generally be launched and recovered roughly from the same location, thereby reducing fuel consumption and time because of the lack of travel back and forth from an airport or airstrip. Finally, repetitive flights of small areas over time can be performed inexpensively with a sUAS, which allows for efficient collection of a time-series of remote sensing data.

Limitations

Although some large UASs can rival or out-perform manned aircraft in terms of flight endurance, most sUASs can only fly for a limited amount of time before needing more fuel or energy. A small portion of UASs are powered by gasoline and can fly for longer periods of time (e.g., > 1 hour). However, the majority of sUASs are powered today by lithium batteries that have very high energy densities. The high density energy in a lithium battery provides the necessary high discharge rate for powering the motor(s) and enabling a sUAS to fly for a short period of time. Of course, flight endurance depends on the size, weight, and type of sUAS. In general, however, the typical flight endurance for a battery-powered, small fixed-wing glider is less than 60 minutes; the typical endurance of a battery-powered multicopter is approximately 10 to 45 minutes. For flights longer than 45 minutes, the aircraft will need to land several times in order to exchange its drained battery with a charged battery. Users must also take proper precautions when charging, discharging, and storing lithium batteries.

Light Detection and Ranging

As stated previously, lidar can support a wide range of activities within a transportation organization. NCHRP Report 748 (Olsen, Roe, et al. 2013) describes many of these applications (Figure 21) and provides detailed references. This report will summarize those that are most relevant to construction (Table 10). In this section it is important to discuss additional background on various applications of lidar compared with the other technologies because of the versatility and efficiency of lidar to support many applications and given its widespread use. However, it should be noted that some of these applications may benefit more from UAS technology as it matures. The following are additional sources that cover and summarize various applications of lidar:

- *Synthesis of Transportation Applications of Mobile Lidar* (Williams et al. 2013) and the *NCHRP Report 748* website (Olsen, Roe, et al. 2013) provide a review of several reports, papers, and presentations as well as a substantial reference list of various transportation applications using MTLS. Applications discussed in this literature review include project planning, development, construction, operations, maintenance, safety, research, tourism, and asset management.

- *Infrastructure Investment Protection with Lidar* (Chang et al. 2012) provides a one-page case study of transportation projects using lidar for many applications. Each summary includes a synopsis of the project, major findings, and lessons learned.

- The ASPRS *Manual of Airborne Topographic Lidar* (Renslow 2013) contains a subchapter that describes a variety of applications of lidar technology for transportation operations, including highway surveys, bridge clearances, pavement analysis, and construction. In addition, a discussion of considerations for the use of lidar technology in transportation operations is provided and includes traffic, environmental conditions, scanning geometry, minimal guidelines and standards, and varying accuracy and resolution needs.

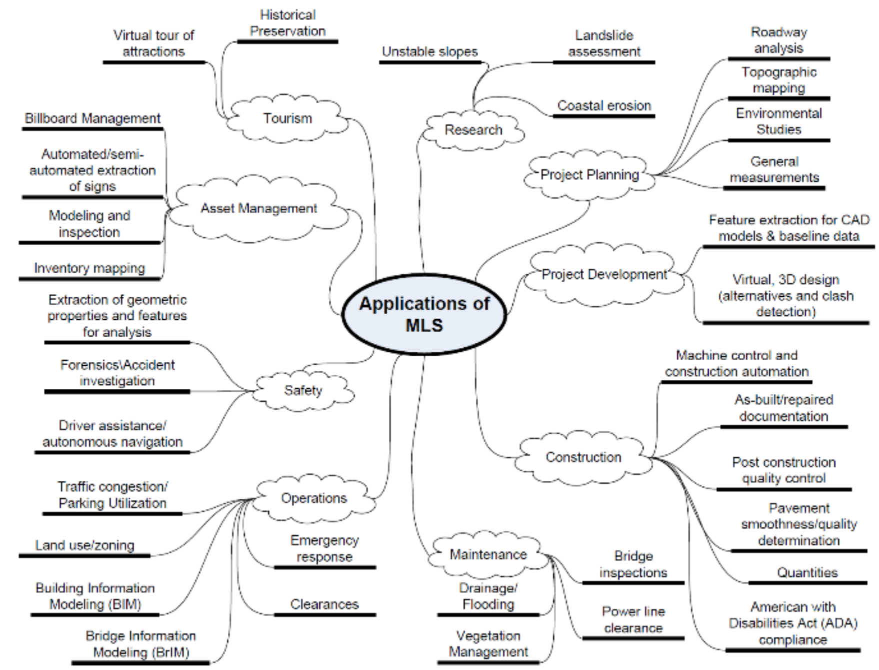


Figure 21. Illustration. Sample applications of MTLS in transportation. (Olsen et al. 2013).

Table 10. Summary applications of MTLS for construction and respective sources.

Application	Examples and Description
Topographic surveying (Uddin 2008); (Grafe 2008); (Yen et al. 2010)	Topographic terrain mapping Contour mapping
Earthwork (Jaselskis et al. 2003); (Duffell and Rudrum 2005); (Slattery and Slattery 2011)	Earthwork volume calculation
Roadway Design (Mabey 2009)	Collecting baseline data
Machine guidance and control (Grafe 2008); (Singh 2008)	Automated machine control (e.g., pavement milling machine)
As-built surveys (Olsen et al. 2012); (Whitfield 2012); (Vasquez 2012); (Singh 2008); (Su et al. 2006)	Rood grade and cross slope determination Clearance check for highway overpasses Obstructions detection
Site monitoring or progress monitoring (Rybka 2011); Olsen (2015)	Estimates of percent completion Earth movements and in-situ infrastructure monitoring
Paving Inspection (Herr 2010); (Johnson and Johnson 2012); (Chin and Olsen 2011)	Pavement condition assessment
QA/QC (Kim et al. 2008); (Tang et al. 2011); (Glennie 2009); (Puente et al. 2013)	Pavement flatness control assessment of road grade and cross-slope attributes Measurement of pavement thickness
Asset management (Duffell and Rudrum 2005); (Kingston et al. 2006); (Burns and Madin 2009); (Metzger et al. 2014); (Cunningham et al. 2015)	Roadside feature inventory Americans with Disability Act feature inventory Geotechnical asset management

Topographic Surveying and Earthwork Volumes

Yen et al. (2010) provides a detailed background on using MTLS to produce DTMs of pavement surfaces and proposed recommendations for data quality assurance (QA) and quality control (QC). A repeatable pilot test and control procedures was developed to evaluate accuracy and usability of MTLS data in highway pavement surveys. They indicated that the MTLSs used at the time of the research have difficulty meeting the Caltrans vertical specification and recommended adjustment methods to improve the overall accuracy.

In a research project for the Illinois DOT, Slattery and Slattery (2011) evaluated the accuracy of lidar measurements for earthwork removal, pavement surface analysis, evaluation of damaged bridges, and as an as-built design aid. They determined that lidar was more efficient and provided accurate earth volume calculations compared with traditional survey techniques.

Bethel et al. (2006) evaluated airborne lidar for transportation corridor mapping and found that it provided mapping-level accuracies. Rigorous ground-control techniques would need to be employed to obtain survey-grade accuracies. Ohio DOT has performed similar research and come to similar conclusions.

As-built Surveys

Many researchers and commercial entities have developed tools that enable rapid development of models from lidar point clouds, primarily for infrastructure management. For example, Tang et al. (2010) describes how as-built models can be created from point clouds.

Several state DOTs (e.g., California, Kentucky, Oregon, and Texas) have used lidar to create accurate models of bridges or other structures, which enables them to effectively verify dimensions, analyze the structural elements, assess settlements, evaluate clearances, and check for deteriorations. These models can help aid in emergency efforts or for periodic bridge inspections. DeMann (2010) provides a summary of STLS done for Utah DOT for as-built modeling. Indiana DOT used lidar to model two different bridges on I-70 (Bethel and Van Gelder 2005). Indiana DOT explored georeferencing techniques with GPS and IMU systems, as well as integration of point cloud data into a GIS.

Watson et al. 2011 conducted research for South Carolina DOT and determined that STLS is a precise method of gathering bridge clearance measurements. They found that temperature and live traffic had little impact on these measurements. Johnson and Johnson (2012) discussed operational consideration for using STLS in highway construction applications, including comparisons of scans of asphalt and concrete surfaces. They also compare STLS results to GPS and total station measurements for accuracy evaluation. Finally, this study evaluated the various configurations of target placement on the accuracy of the resulting point clouds.

Yen et al. (2008) presented a vehicle-based system using scanning laser rangefinder for the Caltrans measurement of roadway structure profiles. Measurement capabilities include horizontal and vertical clearances, which can be used to support issuing permits based on vehicle height.

ODOT has used lidar for assessing clearances in bridges and tunnels (Olsen et al. 2012). In one case study, they scanned both the vehicle and the tunnel so they could digitally verify that it would be able to pass through. The information from their mobile scans has been helpful for verifying clearances and issuing permits for large trucks traveling the highway system.

David Evans and Associates performed a detail analysis of MTLS data collected in Los Angeles to ensure that the space shuttle *Endeavour* would be able to be routed to a museum through the City. (Vasquez 2012). As a result of the pre-analysis and clash detection performed with the MTLS data, the operation was successful in efficiently transporting the shuttle through the City. Critical infrastructure could be dismantled in a logical way avoiding damages or problems that would have led to costly delays and an increased footprint on the public.

Feature Extraction for Asset Management

Singh (2008) proposes that the most detailed survey should be collected immediately post-construction to document what was completed such that this information can be used throughout the maintenance and operations phase of the highway lifecycle. This database should be updated when modifications are made. When a new project is set to start, only minimal survey work would be required to verify the models that were previously generated. In the Design to Paver workshop (see Case Study 1 in Chapter 4), a demonstration showed how STLS could be used to survey pipes being placed under ground such that their location is well documented prior to backfilling.

Previously, extracting features from lidar data for asset management required highly trained technicians. Recent software advancements have become available to bring basic digitization and feature extraction from the point cloud to a more common level of proficiency. Additionally, many new automated workflows have been developed to extract features of interest.

Soni et al. (2011) evaluated several software packages (e.g., Innovmetric PolyWorks, Leica Cyclone, MicroSurvey PointCloud CAD, Trimble Realworks Survey, and VG4D) for integration into Caltrans lidar workflows. They provide a step-by-step workflow in "virtual geomatics", including importing, viewing, and extracting features from lidar. The report also describes how to use this data for project tracking and creating reports. Additional work done by Caltrans includes developing workflows for data processing in Leica Cyclone.

McQuat (2011) discusses how several different structures (signs, facades, bays, automobiles, curbs, et al.) can be automatically detected within a point cloud. McQuat also provides insight on how these structures can then be converted for use in a GIS. Trojak (2011) describes Washington DOT's use of this information for asset management.

Caltrans District 4 used MTLS to map 600 miles of freeway assets in the San Francisco Bay Area (Boyer 2015). This project emphasized that using MTLS makes the surveying process safer and more efficient for the surveyors. Several applied research projects are being completed to improve upon this feature extraction project. Researchers (Coifman 2013) at Purdue University are developing segmentation algorithms to extract vehicles from lidar data and subsequently group and track them. In addition, Oregon State University is currently conducting a National Science Foundation funded research project (National Science Foundation 2014; Kashani et al. 2015) to develop advanced classification feature extraction algorithms of transportation assets within lidar datasets.

Monitoring and Construction Quality Control

Olsen (2015) presents a method and implementation for in-situ change detection and analysis using STLS. This method can be used to aid a structural inspector to view damages directly in the field. Figure 22 shows an example of an in-situ change analysis that was done a few minutes following the scan in the field. The area shaded in purple indicates >10 cm of displacement.

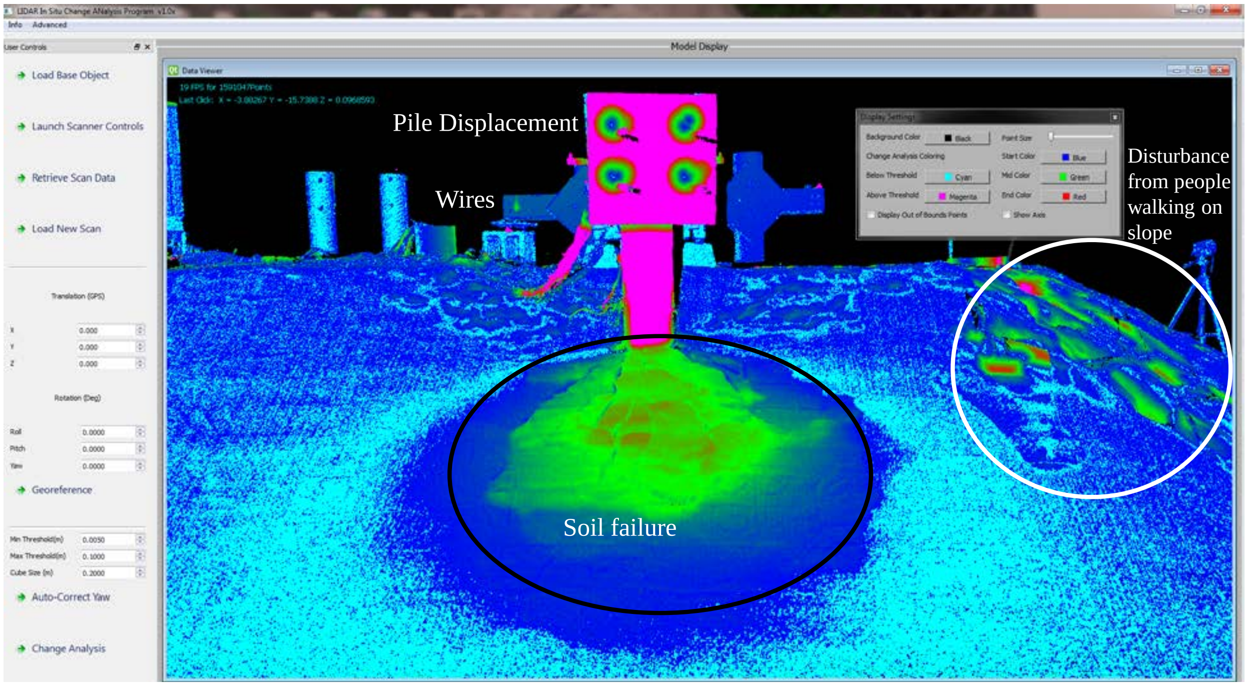


Figure 22. Image. Example of in-situ change detection analysis for a Field test of pile lateral load capacity on a slope. (Modified from Olsen 2015).

Tang et al. (2011) presents an approach for identifying flatness defects in concrete surfaces that can be used for a structural evaluation. Finally, Anil et al. (2013) discuss an approach for performing deviation analysis for construction quality evaluation.

Chin and Olsen (2015) evaluated the use of STLS, digital levels, and inertial profilers in pavement profile analysis for ODOT. The research indicated that STLS shows advantages because of its ability to relatively quickly collect a large and dense dataset that enables verification across the entire road surface compared to distinct profiles. However, it does require significantly more processing than the inertial profilers.

Slope Stability Assessment

ALS has proven to be an important tool for landslide delineation (Burns and Madin 2009). Leshchinsky, Olsen, and Tanyu (2015) developed a tool to detect and classify landslide deposits from ALS data for highway risk assessment. Landslides have been a significant problem on the US20 Highway Pioneer Mountain to Eddyville reconstruction project which is scheduled to be completed in 2017 after many delays. ODOT used ALS, MTLS, and STLS for many aspects of the project to help mitigate these problems. Unfortunately, ALS data was not available prior to the start of this design-build project to enable detailed landslide mapping. The availability of this information would have resulted in drastically different design and construction procedure to help avoid and mitigate the impacts of active and retriggered landslides more efficiently, yielding significant cost savings and fewer delays. Several bridges were under construction and were subsequently demolished due to significant landslide damage, resulting in costs that were on the order of tens of millions of dollars.

Combs et al. (2011) describes the results of a pooled fund study to map geotechnical conditions of unstable slopes, including rock mass characterization, surficial slope stability, rockfall analyses, and displacement monitoring. The report (soon to be released) provides an overview of ground-based lidar and processing software, discusses how lidar can be integrated into geotechnical studies, and includes case studies in Arizona, California, Colorado (two sites), New Hampshire, New York, Pennsylvania, Tennessee, and Texas. The authors also discuss best practices and procedures for data acquisition to ensure it provides reliable data for geotechnical analyses.

Turner (2006) discusses processing procedures to use STLS to evaluate the stability of rocky slopes and how scan data can be integrated into geotechnical and geologic investigations. Kemeny and Turner (2008) evaluated the use of STLS for highway rock slope stability analysis and found that ground-based lidar offered several advantages compared to traditional techniques, including safety, accuracy, access, and analysis speed. Kemeny et al. (2008) used STLS to evaluate several rockfall sites near highways in Utah and Colorado with lidar.

Lato, et al. (2009) demonstrate how rock fall hazards along transportation corridors can be monitored using MTLS on both railway and roadway-based systems. In both situations, MTLS provided increased efficiency, safety, and ability to more thoroughly investigate hazards both instantaneously and during subsequent analysis without revisiting the site. Two recent studies (Metzger et al. 2014; Cunningham et al. 2015) have evaluated the use of mobile and static lidar for rock slope stability along highway corridors. The project focused on using this information in a risk-based, proactive geotechnical asset management framework.

Safety and Visibility Analysis

Researchers at Oregon State University are conducting research for Pactrans to explore the feasibility, benefits, and challenges of a safety analysis for sight distances based on state DOT MTLS data. This research also develops a systematic MTLS data analysis framework to evaluate sight distances in different practical scenarios. The use of high-resolution MTLS data for sight distance analysis provides a data-driven solution to aid decision making for safe transportation operations.

Expanded Applications

Lidar provides several benefits and, as a result, is being widely adopted by state DOTs across the country. (Olsen, Raugust and Roe 2013) One of the key benefits of lidar is the fact that the same lidar dataset can be used by multiple people for a wide variety of applications, minimizing the need for additional data collection. This has resulted in the phrase, “Collect once, use many times.” Additionally, one can remotely survey a site from safe locations, minimizing the danger to field crews and the traveling public. Lidar also enables a much more efficient and thorough field survey, minimizing the need for costly revisits to the site to collect additional information. Finally, the comprehensive information provided by lidar greatly improves the detail in models used throughout the design process and, hence, reduces risks in design and construction.

The 3D Elevation Program (3DEP), led by the U.S. Geological Survey (USGS) summarizes many of the important benefits of ALS data collection (Sugarbaker et al. 2014). The USGS was able to document that the use of ALS data resulted in a 5:1 ROI, with more than $690 million in new revenue annually to the private sector. As highlighted through 3DEP, ALS data is very useful for applications such as natural hazard assessment and infrastructure protection. 3DEP also provides maps showing the status of ALS data collection across the country with updates from individual states, which allows for a transparent view of the program performance and provides notice of what ALS data is available.

Lidar data can also be acquired and shared between agencies, which is a key reason for the high ROI of 3DEP. Several states have formed lidar consortiums where each member agency (Federal, State, or local) contributes a portion of the cost toward the data collection. (Puget Sound Lidar Consortium 2010; Idaho Lidar Consortium 2017; Alaska Department of Natural Resources 2011), This also helps to ensure that experts within the consortium can perform quality control on the data, rather than each agency needing its own lidar QA/QC experts. More details on lidar data collection status can be found at the USGS 3DEP website. (USGS 2017)

A primary advantage of ALS data over photogrammetry and most remote sensing techniques is the ability to “penetrate” vegetation cover through acquiring multiple returns of a single laser pulse. This enables detailed mapping of the ground in dense forests as well as collecting data on the forest canopy. However, there are limitations to ALS data in vegetated areas, including lower accuracy and resolution when compared to open terrain.

Another key benefit of MTLS data is the ability to integrate other sensors onto a single mobile platform. (Olsen et al. 2013) This enables the collection of a wide variety of important metrics needed for various applications from a single data collection effort. Table 11 outlines the key strengths and weaknesses of lidar.

Table 11. Summary of lidar strengths and weaknesses. (Modified from Olsen et al. 2013).

Strengths	Weaknesses	Common Transportation Applications
• Survey-grade measurements • High-resolution capabilities • Intensity measurements • Multiple end uses and opportunities to share data • Increased safety for surveyors • Efficiency—Reduced number of field visits (collect once, use many times), as well as faster field collection	• Relatively high up-front cost • Data can be cumbersome • Technical staff may be required • Mobilization may be difficult • Line-of-sight limitations creates occlusions • Points require processing to be classified, which is generally a semi-automatic process	• Asset management • Pavement analysis • Bridge analysis • Geotechnical analysis • Construction applications • Design aid

Limitations

The limitations of lidar are as follows:

- **Line of sight:** While lidar is an active sensor enabling it to map areas that are not illuminated by other light sources, it does not have the ability to penetrate objects. Objects that block the line of sight of the scanner create occlusions and shadows. However, this can be minimized with good planning or rolling slowdowns (Singh, Olsen, and Roe 2013). Data can also be supplemented with other techniques to fill in critical features that cannot be captured with lidar directly.

- **Expensive up-front cost:** Systems, software, and data collection can be relatively expensive; however, as discussed in Yen et al. (2011), the systems can provide a high ROI. This requires a significant investment in the technology and training of appropriate staff.

- **Data explosion:** The large volume of data can be disruptive to existing workflows and organizations. Managing and storing the extremely large datasets that result from lidar can be a challenge. This has been a major issue holding back the true integration of this technology into transportation workflows; however, many promising advances have been recently made to enable integration.

- **Technical staff/expertise may be required**: Performing lidar processing requires specialized training.

- **Evolution of technology is rapid**: Hardware can become obsolete quickly compared with the current state of the art. Nonetheless, a lidar unit still can be more efficient than other technologies even if it is not the latest model.

- **Semantics:** Lidar points require substantial processing to be classified/labeled, which is generally a semi-automatic process. Often for full feature extraction, a wide variety of software packages are required.

- **Wet, dark surfaces:** Lidar uses near infrared light, which means that it does not reflect well on wet or dark surfaces.

- **Sampling intervals:** Sampling intervals for lidar are also not uniform and resolution will degrade with distance from the scanner. However, processing techniques can enable the data to be filtered to produce a model with uniform sampling (e.g., a grid), if desired.

Cost Considerations and Analysis

As described in the limitations section, an issue associated with purchasing a lidar sensor is the relatively high upfront cost ($50,000 to $200,000 for STLS, $300,000 to $1 million for MTLS, >$1 million for ALS). The time savings, improved data quality, and reduced site visits often quickly offset these initial costs. *NCHRP Report 748* (Olsen, Roe, et al. 2013) provides guidance on important considerations for a state DOT deciding whether to purchase a MTLS. Washington DOT (Yen et al. 2011; Yen et al. 2014) evaluated the integration and efficiency achievable in transportation workflows with MTLS data. Results are provided for seven separate benefit-cost analyses performed on the contracting, renting, or purchasing of a MTLS for mapping or surveying grade data output. This report considers several implications of the purchase, such as QA/QC benefits, roadside asset management investigation, bridge clearance quantification, and Americans with Disabilities Act feature inventory. It was determined that the purchasing option for a MTLS created the highest cost benefit of these options for Washington DOT; however, this analysis was dependent on the frequency of data collection required. The BCA indicated that purchasing and operating a survey-grade MTLS produced the highest savings of $6.1 million in six years.

ODOT recently upgraded to a survey-grade MTLS after using a mapping-grade system for approximately three years. Although detailed ROI information has not been published, ODOT has rapidly found applications and uses for the data. ODOT targets acquiring data on an annual basis for all major highways. Many of these benefits were discussed in the Design to Paver Workshop hosted by ODOT (Case Study 1 in Chapter 4).

In addition to deciding whether the purchase of a MTLS is appropriate for a state DOT, there are many parts in the lidar processing workflow aside from acquisition. *NCHRP Report 748* (Olsen, Roe, et al. 2013) outlines relative costs for major stages of the workflow and cost considerations to help decide which processing is more cost effective to conduct in-house rather than externally.

Photogrammetry and Structure from Motion

There is a number of published research available that discusses transportation and construction applications of photogrammetry, which is shown in Table 12. In addition to the journal and conference papers and reports listed in Table 12, a number of state DOTs maintain detailed standards for photogrammetric surveys, which are commonly used in contracted and/or in-house photogrammetric surveys performed for topographic mapping, reconnaissance, transportation planning, design, construction, maintenance, and other uses.

Table 12. Construction and transportation applications of photogrammetry and SfM.

Construction and Transportation Applications of Photogrammetry/SfM	Notes
Visualization and progress monitoring of construction projects	4D models generated from SfM and close-range photogrammetry. (Golparvar-Fard et al. 2009)
Quality control	SfM using site photos for 3D modeling and quality control. (Dai and Lu 2012)
As-built data, quantity surveying in construction management, real-time 3D construction field data, intelligent jobsites	Close-range photogrammetry using off-the-shelf, portable digital cameras. (Dai and Lu 2010)
	Combination of mobile computing, lidar, and webcam-based, close-range photogrammetry. (Trupp et al. 2004)
Construction project progress tracking	Close-range indoor photography using a handheld camera. (Ahmed et al. 2012)
	Data collection with a Nikon D90 camera; use of photo-modeler scanner. (Kim et al. 2011)
	Close-range photogrammetry and Automated Construction Project Monitoring system. (Memon et al. 2012)
	Integration of lidar, RFID/barcode and close-range photogrammetry for progress measurement on construction sites. (El-Omari and Moselhi 2008)
	Photogrammetry, CAD modeling for construction progress monitoring and visualization. (Bayrak 2008)
Monitoring of structures for damage during construction	Close-range photogrammetry for monitoring buildings for damage during construction. (Luhmann and Tecklenburg 2001)
	Close-range photogrammetry for bridge deflection measurement. (Hilton 1985)
Condition evaluation	Synthesis report with a number of relevant references. (Olsen et al. 2013)
Topographic mapping/DEM creation	Synthesis report with a number of relevant references. (Olsen et al. 2013)

Construction and Transportation Applications of Photogrammetry/SfM	Notes
Volumetric change analysis; site/route planning	UAV-based proof of concept study; applications cited include volume estimation and route planning. (Peterman and Mesaric 2012)
Automated construction site modeling	Photo-based approach to modeling construction space for planning. (Gore et al. 2012)
Photogrammetric mapping along highway corridors for transportation engineering planning and design	Report on standards for control for photogrammetry using airborne GPS; minimizing ground control can reduce hazards associated with survey crews working within the highway right-of-way. (Munjy and Hussain 2010)
Bridge inspection and historic bridge documentation	Close-range photogrammetry for bridge inspection and historic bridge documentation. (Jáuregui et al. 2006)
Accident investigation and reconstruction	Close range photogrammetry for accident investigation; study conducted for Virginia DOT. (Arnold 2007)

Benefits

The main benefit of conventional aerial photogrammetry is the ability to efficiently and economically acquire data over large areas. Additionally, by acquiring imagery from an aircraft, photogrammetry can reduce safety risks and avoid the need to interrupt operations to acquire data. The safety risks of ground-based surveys can be significant when survey crews are required to work near vehicular traffic. Photogrammetric surveys can also provide data products that simultaneously support multiple transportation-related needs, such as orthophotos and DEMs. Many of these benefits are summarized in the Caltrans *Survey Manual*, Photogrammetry Surveys section (Caltrans 2006). As noted above, SfM adds additional benefits, including ease-of-use, cost savings (due to the ability to avoid manned aircraft and expensive, metric-grade cameras), highly-automated workflows, and the ability to perform data collection from a UAV.

Limitations

Conventional photogrammetry is fairly well established as a tool for supporting some design and construction-related tasks. Limitations of conventional photogrammetry include the expense of mobilizing an aircraft to the project site and a fairly steep learning curve. Additionally, using typical operational procedures, airborne photogrammetry does not always satisfy the spatial accuracy requirements of the most demanding engineering applications.

Although SfM has tremendous upside (including the potential to perhaps overcome some of the challenges associated with conventional photogrammetry for construction and transportation applications), there are a number of limitations that need to be addressed through ongoing research and development. While a number of recent studies have examined the accuracy of SfM (e.g., Mancini et al. 2013; Fonstad et al. 2013; Tonkin et al. 2014), additional work is needed to rigorously assess the uncertainties and the conditions that can lead to poor reconstructions in SfM (Fonstad et al. 2013). Moreover, this technology is still new enough within the geospatial industry that robust standards and effective practices for its use in construction have not yet been developed.

Another limitation of SfM is the requirement for ground control to reference the point clouds and orthoimages to georeferenced coordinates. Although direct georeferencing using GNSS-aided INS is under development, SfM currently typically requires a significant amount of georeferenced ground control. Furthermore, any nonlinear distortions in the point cloud due to faulty image matching cannot be eliminated by the seven-parameter transformation used to fit to ground control (Fonstad et al. 2013) and, therefore, will persist in final data products.

Global Navigation Satellite System

As summarized in Chapter 2, a large number of techniques are available for collecting and processing GNSS data. Users should select the appropriate technique depending on the desired level of accuracy and the selected application. This section summarizes common applications of GNSS.

Construction Quality and As-builts

RTK or RTN GNSS technology can be used for construction quality control and assurance activities, progress documentation, and creation of digital as-builts. For example, GNSS can be used for real time verification and quantity measurements and can easily store the 3D position of features for subsequent documentation of as-built conditions. Using RTK or RTN GNSS results in improved efficiency, efficient documentation of inspection process, and a permanent digital as-built record. However, surveying staff must be available to perform task or construction inspectors must be trained in the use of GNSS equipment and only discrete points are measured.

Automated Machine Guidance

RTK or RTN GNSS technology can be used during AMG operations to guide positioning of heavy construction equipment including the blade and bucket relative to 3D surface in real time. Using RTK or RTN GNSS for AMG results in improved efficiency and increased safety by removing crew workers around heavy equipment as well as reduced construction costs by > 50%. However, RTK or RTN GNSS is less accurate vertically than horizontally and other sensors may be needed to augment vertical positioning for precise work. (Townes 2014; Singh 2010)

Deformation Monitoring

RTK or RTN GNSS technology can be used during deformation monitoring by taking measurements over time to track deformations (semi- and fully permanent receivers may be used). Using semi- and fully permanent RTK or RTN GNSS receivers can be collected near continuously for structural health and ground monitoring. However, RTK or RTN GNSS data is only collected at discrete points and is more accurate horizontally than vertically.

Topographic Surveying and Mapping

RTK or RTN GNSS Technology can be used for topographic surveying and mapping mainly by locating features, break lines, and elevation changes quickly. RTK or RTN GNSS has been shown to be 40% to 90% more cost-effective than conventional surveying tools. However, RTK or RTN GNSS only measures discrete points that are physically occupied with a receiver and photogrammetry and lidar are more efficient for higher-resolution.

Estimating Earthwork

RTK or RTN GNSS technology can be used to estimate earthwork through measuring with rovers to estimate volumes of stockpiles and pits. RTK or RTN GNSS results in improved efficiency and transparency for quantity measurements. However, volumes must be interpolated from discrete point measurements.

Geodetic Control Networks

Static or rapid-static GNSS techniques can be used to establish geodetic control networks. For example, static receiver(s) are used to accurately determine the geodetic position (i.e., latitude, longitude, ellipsoidal height) of control marks. Static or rapid-static GNSS does not require line-of-sight between marks, enabling efficient measurement of long lines and provides highly accurate geodetic positioning. However, static or rapid-static GNSS requires long occupation sessions and post-processing and usually multiple GNSS receivers.

Site Control

Static or rapid-static GNSS techniques can be used to establish site control surveys. For example, static or rapid-static relative positioning may be used to determine high accuracy geodetic coordinates on some marks for controlling a construction project. Static or rapid-static GNSS provides a method to accurately georeference 3D construction designs and as-builts of constructed works. However, since static or rapid-static GNSS is less accurate vertically than horizontally, surveyors often also use levels or total stations to check vertical control points.

Height Modernization

Static or rapid-static GNSS techniques can be used for height modernization, which is a specialized type of static surveying where heights can be determined on benchmarks across large areas. Static or rapid-static GNSS provides significant cost savings over differential leveling for determining or "modernizing" heights on benchmarks, but static or rapid-static GNSS is less precise than differential leveling.

Benefits

Although continually improving and evolving, GNSS has become a mainstream geospatial technology, enabling data to be linked together into a common coordinate system and provided in context with surroundings. Significant research and development have enabled GNSS measurements to produce survey-grade results in real-time or with post-processing techniques. GNSS surveys are particularly useful for surveys over large extents (several miles) where error propagation would be significant for most traditional surveying techniques. This enables information to be presented in context with its surroundings. It also enables data to be acquired at remote sites. Lastly, GNSS is often integrated with many other technologies and techniques whenever georeferenced positioning is essential.

Limitations

GNSS results are limited by the quality and quantity of the satellite constellation, which can vary throughout the day and by location. For optimal results and particularly for highest accuracy, GNSS requires a clear view of the sky, and quality degrades when trees, buildings, and other objects obstruct this view, resulting in multi-pathing of satellite signals.

Moderate, up-front investments are required to acquire GNSS receivers depending on the desired capabilities. Further, because there are a variety of available GNSS receiver types with varying accuracy, it is important to document which receiver was used for the data collection and what the observation quality was to ensure that future users of the data understand its limitations. This information can be captured in the metadata record, which is an effective way to store important descriptive information about the dataset.

Automated Machine Guidance

ODOT has developed a document outlining "Key Concepts for a 25-Year Time Horizon" in regard to the automation of engineering and highway construction. Much of this document discusses the synthesis of geospatial tools, geospatial data, 3D models, and construction automation. This document, written in 2008, has served as a broad vision for the ODOT to implement emerging technologies, including AMG (Singh 2008). ODOT has subsequently hosted two demonstration workshops "Design to Dozer" (Oregon Department of Transportation 2010) and "Design to Paver" (Oregon Department of Transportation 2014). Materials for both of these workshops are available online as well as videos of machinery in action. ODOT has also updated its survey and design manuals to proactively address the needs of AMG construction.

The Mississippi DOT and the University of Southern Mississippi have developed a report that outlines the implementation strategy for the use of AMG and GNSS on construction projects, including specifications, quality control, and business policies and procedures (Hannon 2010). The research provides a framework of effective practices for special considerations in contract workflow processes. This study identifies the need to share 3D design models on projects with AMG earlier in the procurement process.

Benefits

Some of the benefits of AMG are as follows (Olsen et al. 2013):

- Reduced human errors and therefore reduced rework.
- Reduced size of labor force.
- Reduced field time.

- When perfected, seamless integration with design.

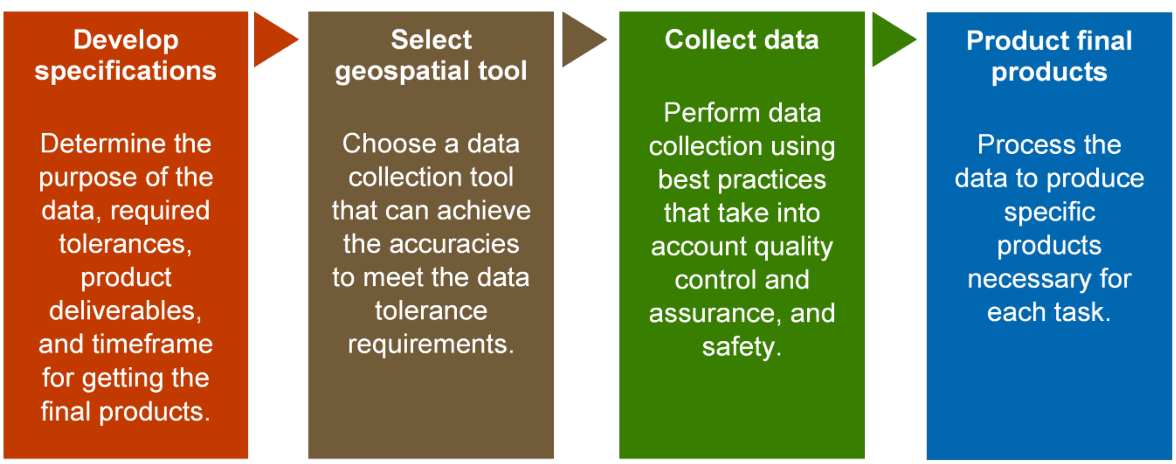
Limitations

Some of the limitations of AMG are as follows (Olsen et al. 2013):

- High upfront costs.
- Few experts available.
- Technology not fully developed.
- Rapidly changing platforms.
- Data interoperability.
- Designer unfamiliar with needs of contractors.

EFFECTIVE PRACTICES

The workflow for using the appropriate geospatial tool is heavily dependent on the function for which the data are being collected. The effective practices presented herein is based on the findings of the literature review and the documented case studies. The information is offered as general effective practices to help state DOTs deploy geospatial tools effectively. The areas covered in this section include Design, Construction Engineering and Inspection, and Asset Management. The workflow for using geospatial tools for highway construction projects is illustrated in Figure 23.

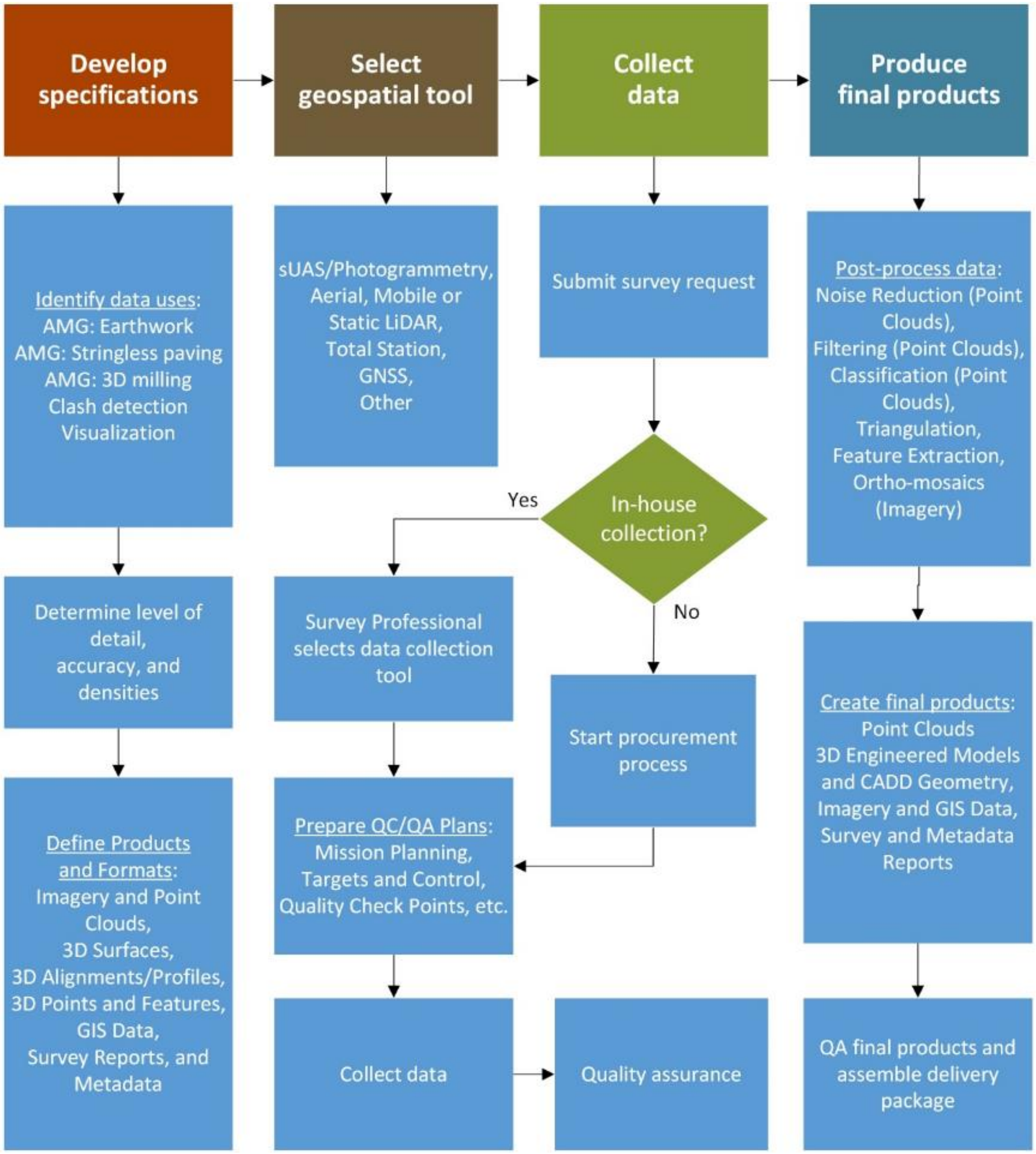


Source: FHWA

Figure 23. Flowchart. General effective practices for the use of geospatial technology in highway construction projects.

Design

During the pre-construction phase, geospatial tools are used to collect data to support 3D design. The process starts when a designer requests a pre-construction survey, which becomes the foundation map to model the project, calculate quantities, and produce digital data to support AMG construction methods and construction engineering and inspection processes. The design team should communicate the purpose and need for the data to the surveying professional who has the expertise to select the appropriate data collection tool to meet the needs of the project. A general workflow for using geospatial data to support 3D design is illustrated in Figure 24.



Source: FHWA

Figure 24. Flowchart. General workflow for effective use of geospatial technology to support 3D design.

Identify Data Needs and Develop Specifications

The first step is to determine the purpose of the data as this is the primary factor in selecting the tolerances for meeting the needs of the project. For example, if the purpose of the data is to calculate earthwork quantities, the specifications dictating the tolerances for measurement of earthwork determine the accuracies of the data. Once the needed accuracies have been determined, the survey professional is the appropriate party to write the performance-based specifications for a pre-construction survey contract or select the geospatial tool for the data collection task.

Select Geospatial Tools

Once the data needs have been identified and the specifications developed, it is time to select the data collection method. It is not necessary to stick to one platform for capturing the existing conditions. In fact, it is common for geospatial professional to choose a variety of tools to acquire the information to meet the required tolerances while keeping the cost of the data collection low. It is entirely possible to select MTLS to collect pavement surfaces and aerial photography, lidar, or sUAS to do the side-slope conditions. However, proper documentation of the dataset characteristics and collection methods are key factors to consider when deciding on a multi-platform acquisition and data fusion approach. Table 13 provides known vertical accuracies for different geospatial tools used for data acquisition. Note that these methods may be affected by a number of factors (some more sensitive to error than others) causing these accuracy values to be unachievable.

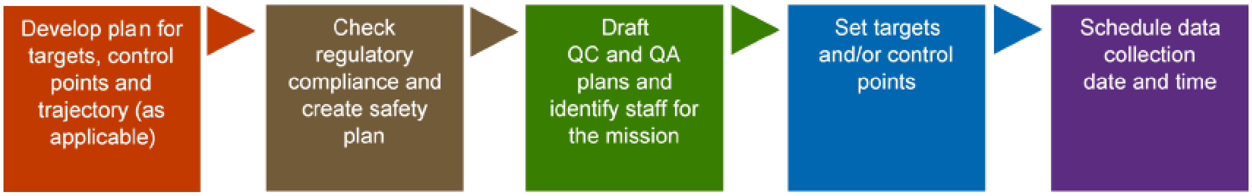
Table 13. Geospatial data acquisition tools and associated network accuracies[11].

Data Collection Method	Optimal Achievable Network Accuracy (RMS)
Aerial photogrammetry – sUAS	0.03 m (3D)
Aerial photogrammetry – Fixed-wing aircraft	0.05 m (3D)
Aerial lidar – Fixed-wing aircraft	0.05 m (Vertical)
Aerial lidar – Low altitude helicopter	0.04 m (Vertical)
Mobile lidar	0.03 m (3D)
Terrestrial static lidar – Tripod mounted	< 0.01 m (3D)
GNSS – RTK	0.01 m (Hz), 0.02 m (Vt)

[11] Note that these values represent the best results achievable with current technology on hard, well-defined surfaces. Lower accuracy would be expected in more complex terrain and locales with heavy vegetation.

Pre-Construction Data Collection

Once a tool has been identified for data collection, the mission planning starts followed by the actual mission to produce the final deliverables. Figure 25 illustrates the mission planning workflow.



Source: FHWA

Figure 25. Flowchart. Mission planning workflow.

Pre-mission: This task consists of preparing for the mission, location of targets and control points, safety considerations, and QA/QC plans for the operation. All these sub-tasks should be clearly documented in a pre-mission plan to share with the data owner. Diagrams are particularly helpful for communicating the target and survey control plan and trajectory of the mission (Figure 26). Note that the recommended number and spatial distribution of ground targets varies as a function of spatial extent, terrain, cover types, project accuracy requirements, and other variables. Figure 27 shows the placement of a ground control target for a sUAS flight (the flight plan is illustrated in Figure 28).

Source: FHWA

Figure 26. Photo. Example of ground control point layout plan for a sUAS flight mission.

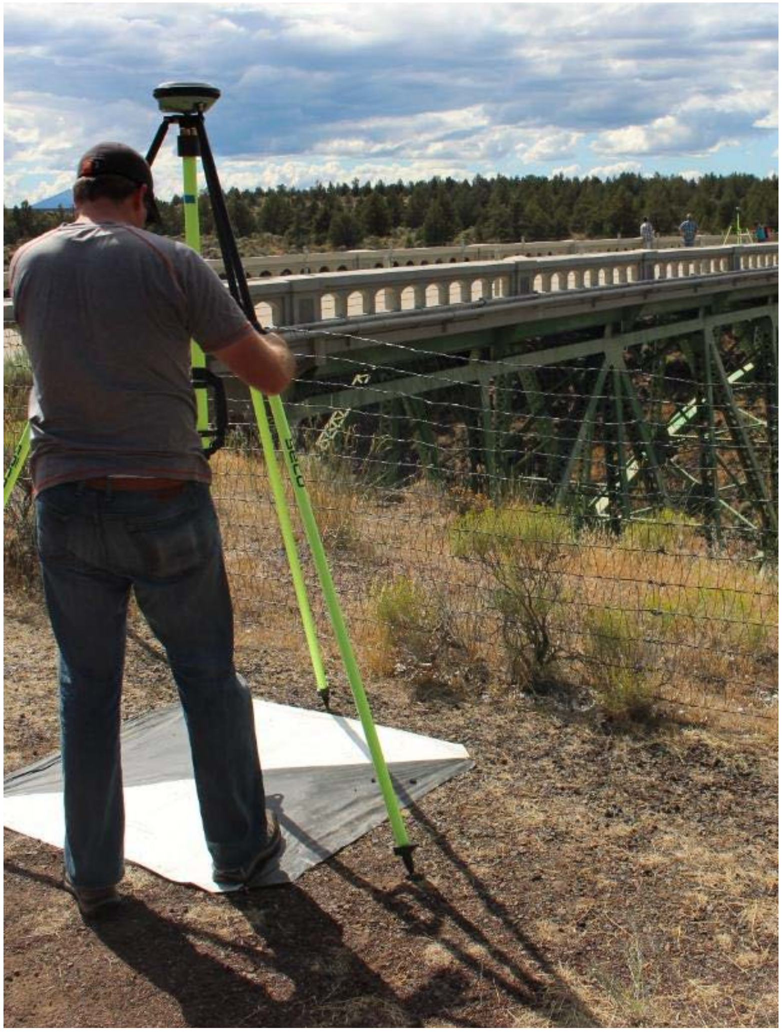
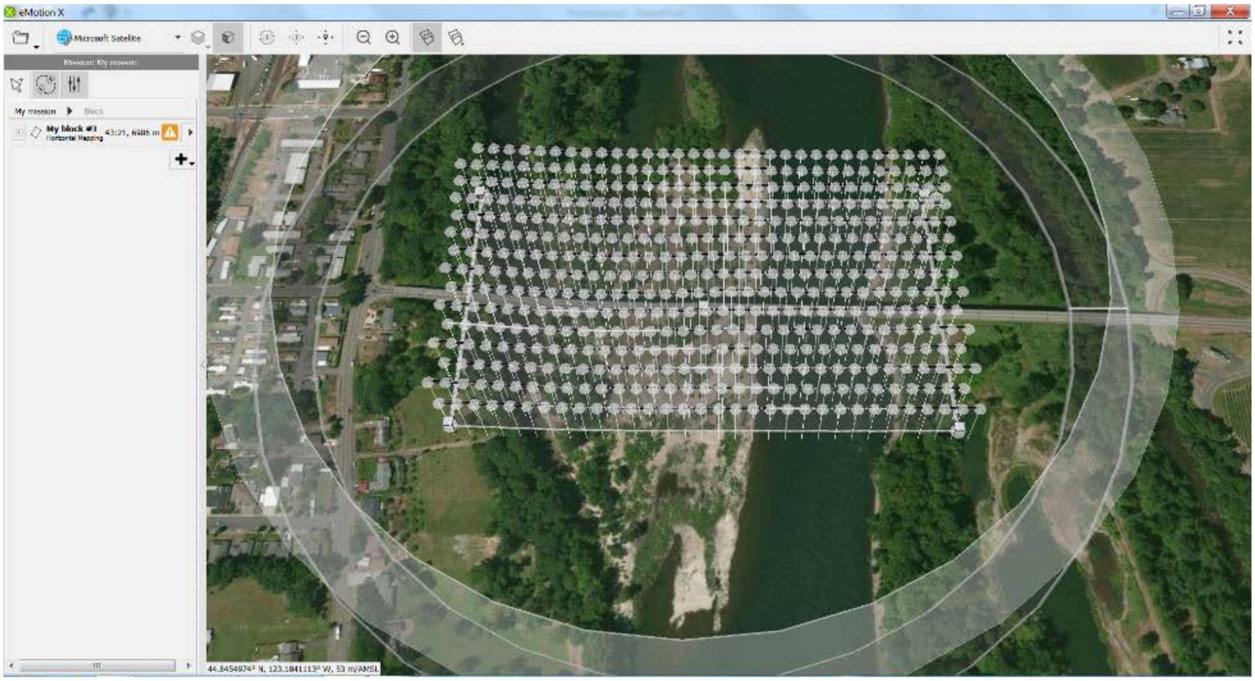


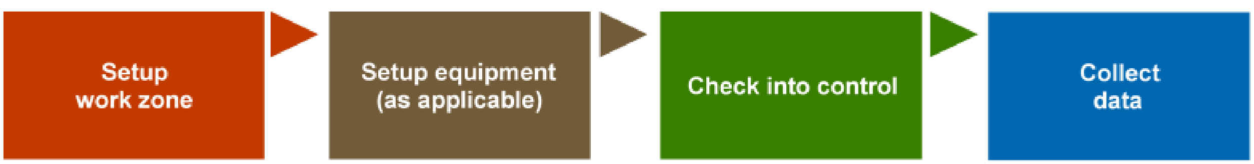
Figure 27. Photo. Establishing photo control for sUAS flight.



Source: FHWA

Figure 28. Photo. Flight plan for horizontal mapping mission. Circles denote planned photo centers.

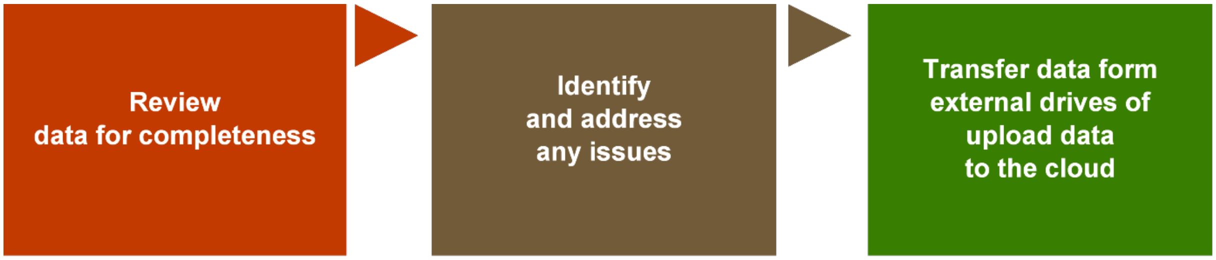
The mission: This task is the actual collection of the data using the geospatial tools previously selected. Figure 29 presents the mission workflow. It includes setting the safety work zone (as applicable), targets and survey control points, instrument locations, and operating equipment. In addition, the quality control measures previously established are used to ensure the data are being collected in accordance with the requirements.



Source: FHWA

Figure 29. Flowchart. Data collection mission workflow.

Post-mission: This task occurs immediately after the data collection ends. Figure 30 presents the post-mission workflow. It includes final quality assurance of the collected data and uploading datasets to external hard-drives or cloud-based storage for post-processing.

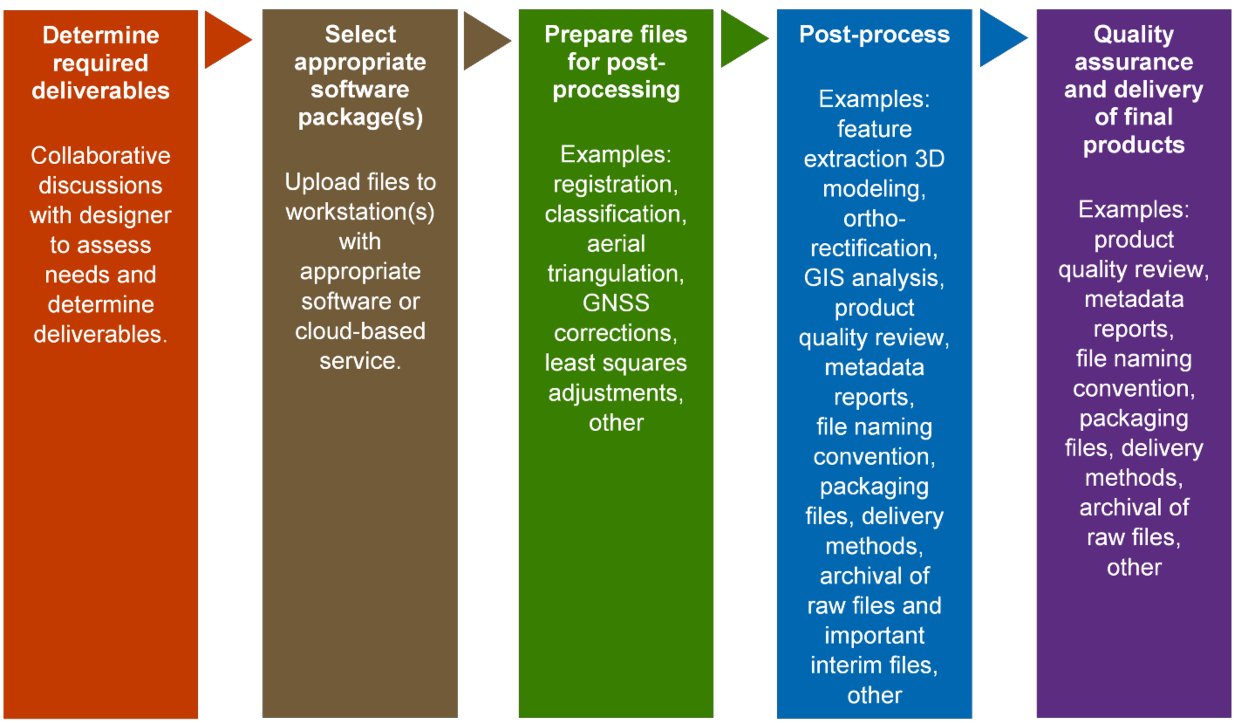


Source: FHWA

Figure 30. Flowchart. Post-mission workflow.

Produce Final Products

The last step is to post-process the data to create the final deliverables in accordance with the specifications. Figure 31 presents the production workflow. Post-processing of the data depends on the collection approach and instruments used, and each of the workflows for producing the final products are dictated by proprietary software that is compatible with the hardware. Table 14 lists some of the most commonly used commercial off-the-shelf (COTS) software packages for post-processing geospatial data.



Source: FHWA

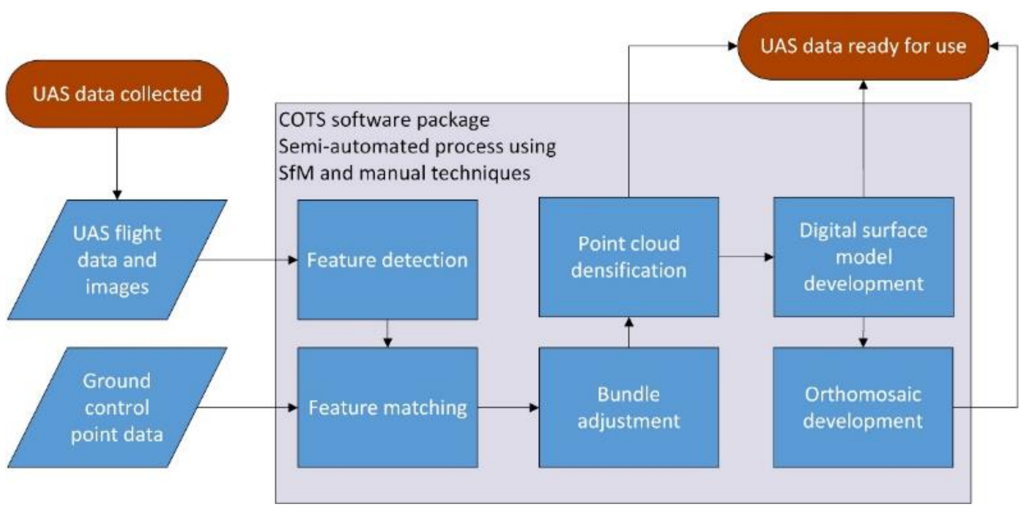
Figure 31. Flowchart. Workflow to produce final products to support design.

Table 14. Commonly used COTS geospatial software packages.

Functionality of the Software	Common COTS Software Packages[12]	Geospatial Data Collection Platform
Point cloud post-processing	Leica Cyclone, Riegl Riscan Pro, Maptek I-Site Studio, Faro Scene, TopoDOT	Lidar (all platforms)
Imagery post-processing/aerial-triangulation/photogrammetry	Leica Photogrammetry Suite, Erdas Imagine, Agisoft Photoscan, Pix4D	Aerial photography and UAS/sUAS
Photography orthorectification	Leica Photogrammetry Suite, Erdas Imagine, Agisoft Photoscan, Pix4D	Aerial photography and UAS/sUAS
Survey data collection and post-processing	Leica Geo-Office, Leica Infinity, Trimble Business Center, OPUS, OPUS Projects	Total stations and GNSS equipment

UAS Data Processing

Figure 32 illustrates the semi-automated workflow of processing UAS imagery and related products. A number of cloud-based, server-based, and computer-based COTS platforms follow this general process.



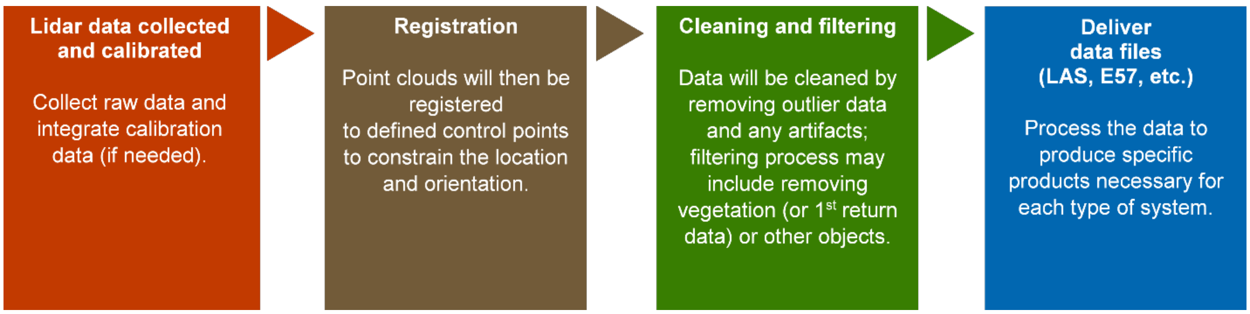
Source: FHWA

Figure 32. Flowchart. UAS imagery processing workflow.

[12] Software packages listed are not all inclusive.

Point Cloud Processing

Figure 33 illustrates the generic workflow for developing lidar data into formats consistent with the type of lidar system. This data is point data that can be used as-is or further modeled into surfaces for use in CAD or interacted with directly to obtain intelligence about features for applications such as asset management.

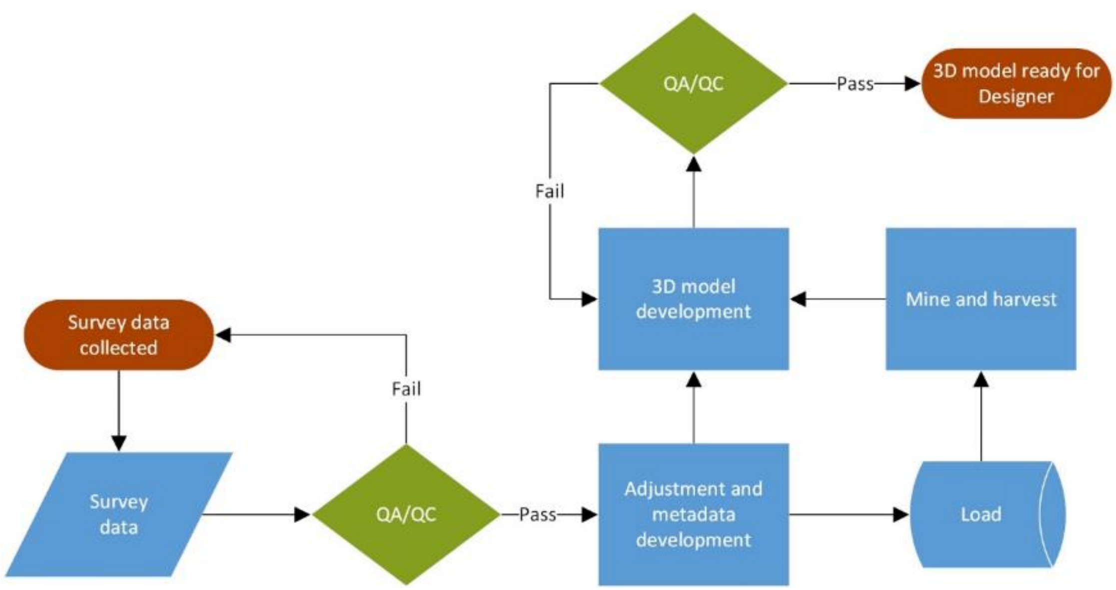


Source: FHWA

Figure 33. Flowchart. Point cloud processing workflow.

Survey Data Processing

Figure 34 illustrates the workflow for processing survey data for use in 3D models. While the survey data processing workflow is well-known, the workflow presented here improved upon the need for more robust data governance. Metadata and database interaction are critical pieces that need to be institutionalized to optimize the value of survey data for subsequent data needs.



Source: FHWA

Figure 34. Flowchart. Survey data processing workflow.

Construction Engineering and Inspection

Construction engineering and inspection can benefit from the use of geospatial tools, specifically for tasks such as documenting progress, measuring quantities, and real-time verification. These tasks rely on the data-collection process described in the design workflows. The most commonly used geospatial tools in construction inspection are GNSS rovers and total stations, although sUAS are starting to be used by contractors to document progress and create as-builts. Lidar technology is also being used for generating as-built documentation and for QA/QC. Further, many of these geospatial tools are an integral part of implementing AMG or construction automation.

Construction Inspection

A combination of geospatial technologies are used to collect the data needed to develop the surfaces and other model features the inspector can use for measuring quantities and real-time verifications, as shown in Figure 35.

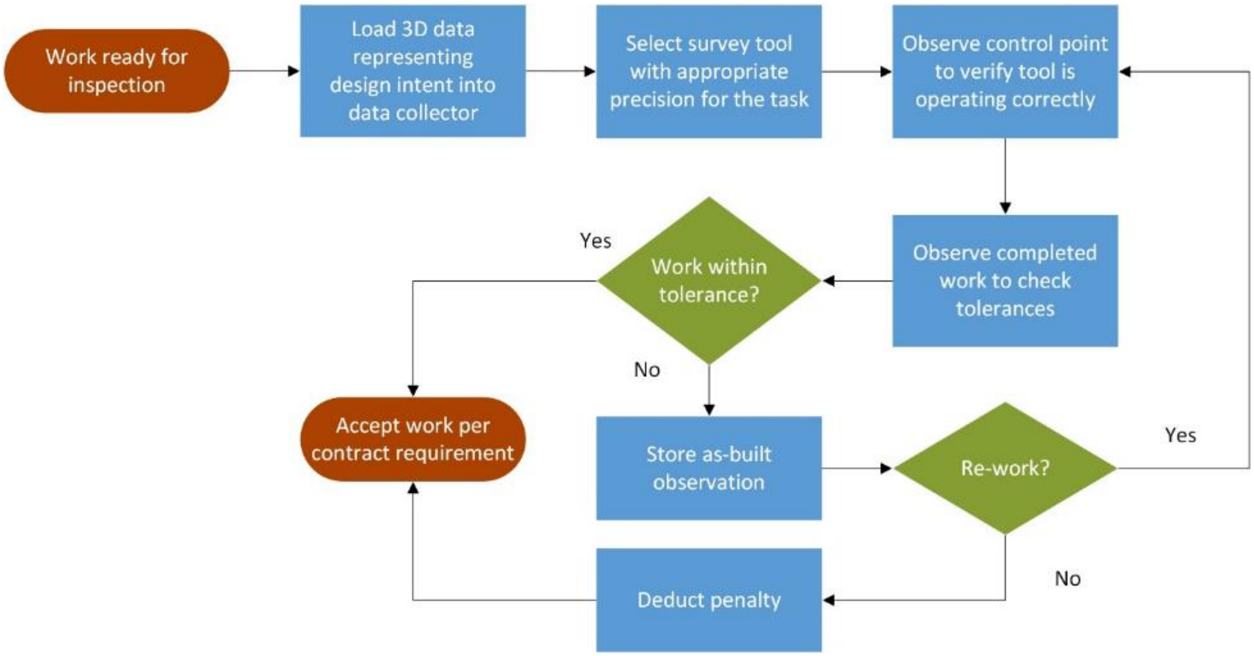
Source: Utah DOT

Figure 35. Photo. Inspector using GNSS rover to check grade.

The process for data collection for construction inspection is the same as that described for design applications. The right tool has to be selected to collect the data to meet the tolerances for the quantity measurements. The processes for using geospatial tools for construction inspection are illustrated in Figure 36 and Figure 37.

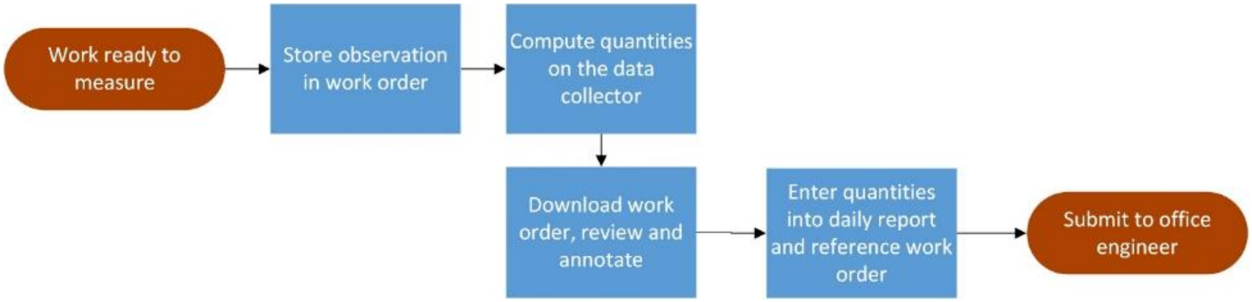
The use of sUAS for construction management is limited to creating low altitude photogrammetric 3D models that can be used for calculating earthwork quantities and visualization models for public outreach (Figure 38).

The construction staff or the contractor can launch a mission at specified intervals to document progress of work and calculate earthwork quantities.



Source: FHWA

Figure 36. Flowchart. Process for using a geospatial tool for real-time verification. (Maier et al. 2016).



Source: FHWA

Figure 37. Flowchart. Process for using a geospatial tool for measuring quantities. (Maier et al. 2016).

Source: Utah DOT

Figure 38. Photo. 3D model created from sUAS data collection and low-altitude photogrammetry post-process.

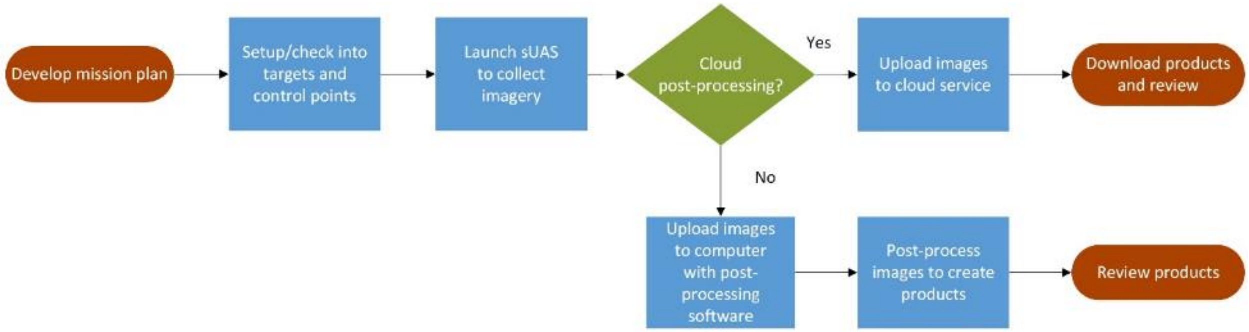
Table 15 shows recommendation for selecting the appropriate geospatial tool to perform a particular inspection task.

Table 15. Geospatial tool recommendations per inspection task.

Inspection Task	Geospatial Tool
Measure excavation, earthwork, seeding, and linear items	GNSS rover
Check slopes and distances	GNSS rover
Check fine grade	Total station
Check steel erection location	GNSS rover
Check steel erection elevation	Digital level
Check structural concrete	Total station

Progress Documentation

The use of sUAS is increasingly popular with construction contractors due to the low cost for obtaining accurate data quickly. While sUAS are used to collect data necessary to extract features and surfaces for quantity computations, the most prevalent use of the technology is to document the progress of the work and use the videos and imagery captured for public information outreach (Figure 39). The contractor can take a snapshot of the project to create a time lapse and show the owner what has changed every day.

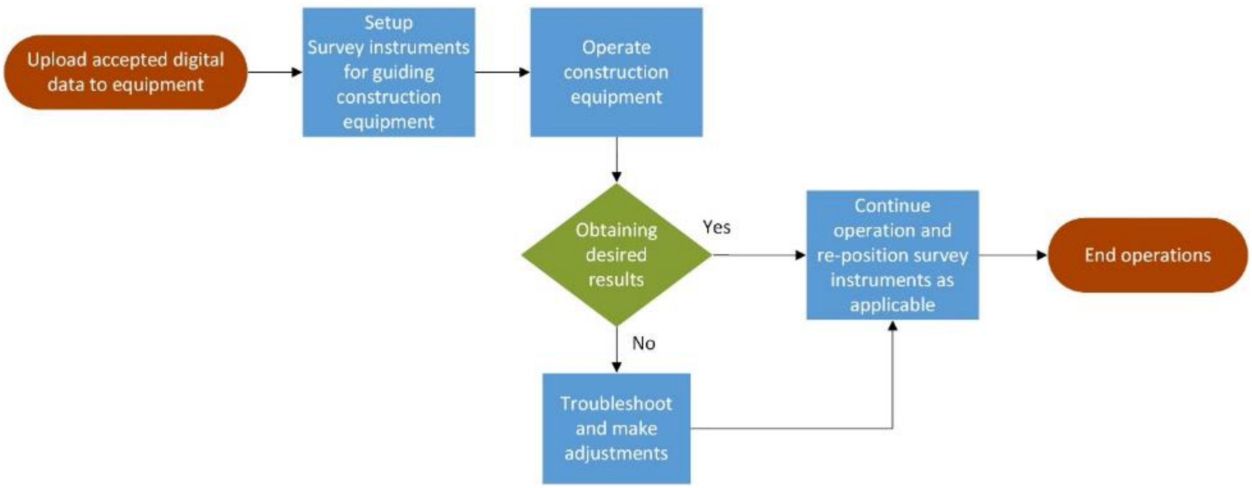


Source: FHWA

Figure 39. Flowchart. Workflow for producing progress documentation from sUAS mission.

AMG Construction Methods

AMG is a construction method that relies on geospatial tools for positioning. The most common and mature applications of AMG include excavation and grading, and concrete (stringless) paving. Depending on the precision needed for the activity, the equipment will be guided by either GNSS, laser-augmented GNSS, or robotic total stations. The workflow for using geospatial tools for AMG is illustrated in Figure 40.



Source: FHWA

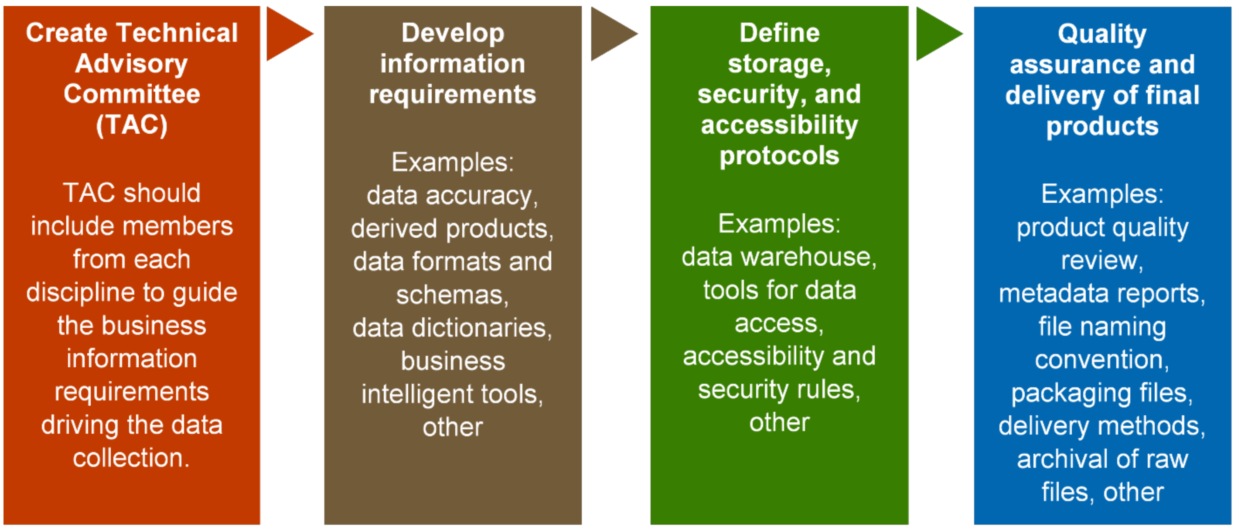
Figure 40. Flowchart. Workflow for using geospatial tools in AMG construction equipment.

Asset Management

An asset register is the systematic recording of all assets owned or operated by an organization. It serves as a repository of all pertinent data associated with an asset collected over its lifecycle, including its inventory, location, physical attributes, historical and current conditions, performance, life-cycle costs, and detailed history of maintenance and renewal/replacement activities.

Irrespective of the size of a state DOT's asset portfolio, an asset register is central to an asset management system supporting various activities. At their basic level, an asset register is a database for an asset type, while in enterprise level solutions, asset registers are integrated with GIS-enabled systems. In either case, each asset register serves a "single source of truth" for state DOTs for managing their assets (Taggart, 2014). Typical sources of information for asset registers include as-built and/or design drawings, condition assessment data, roadway survey data, schedule of quantities, bid documents, video, and photo logs.

While almost all state DOTs have some kind of asset information, an asset management system involves establishing a managed process to identify, collect, organize, and continually improve information for asset registers. Figure 41 illustrates the process for geospatial data collection in support of asset management.



Source: FHWA

Figure 41. Flowchart. Generic process for using geospatial tools in transportation asset management.

Understanding the architecture and schema of the target asset management database is critically important prior to initiating the data collection. This requires collaboration with the DOT and a thorough understanding of the asset management system to avoid data deficiencies and conflicts. Once the schema is developed for the project, data and attribution are collected (asset-grade MTLS with cameras is recommended). For smaller, more focused asset mapping, such as signs or adding/updating features in an existing asset management system, GNSS and cameras may be sufficient to collect the required data. After the data is collected, the data will be verified for completeness and quality. The data can be uploaded from the field using cloud platforms or FTP transfer for requirements validation before going through a final quality check. When the data passes the required quality checks, the data is then loaded into the target database for final validation.

TOOL SELECTION FOR PROJECT PHASES

Given the wide array of capabilities of geospatial technologies, selecting the appropriate tools can be challenging. In many cases, multiple technologies can be used together to generate more complete models efficiently by capitalizing on the strengths of each technology or platform. The analysis should focus on the end needs and applications that are immediately supported by the technology, as well as potential applications.

While pilot projects are important to evaluate the capabilities of new technologies (and are strongly encouraged), those technologies should generally not be used heavily in production work until they can confidently produce satisfactory results. In many cases, these can be done in parallel by collecting redundant data with a trusted system so that the ROI, benefits, and limitations can be clearly documented by comparing the new technology with the current state of practice. If the new technologies prove unreliable during the test, one should consider why and if those limitations are likely to be resolved with near future advancements of the technology or with additional training and experience. In such a case, the technology could be tested again at an appropriate time. ROIs determined from pilot studies often may not capture efficiency improvements or additional applications of geospatial technology that occur when an organization becomes more mature in technological utilization.

NCHRP Report 748 provides effective practices on the geospatial survey resolution and accuracy requirements for MTLS for a wide range of applications, including 3D design and highway construction (Olsen et al. 2013). Note that although this was developed for MTLS, data collected from UAS SfM technology would follow similar requirements. The accuracy requirements shown in Figure 42 would be similar across the broad spectrum of geospatial technologies; however, most other technologies would not be able to efficiently achieve as high a resolution. Hence, those resolution (point density) requirements should not be applied for other technologies such as GNSS. It is also important to note that some applications in the figure are specific to MTLS and would not be efficiently completed using technologies such as GNSS.

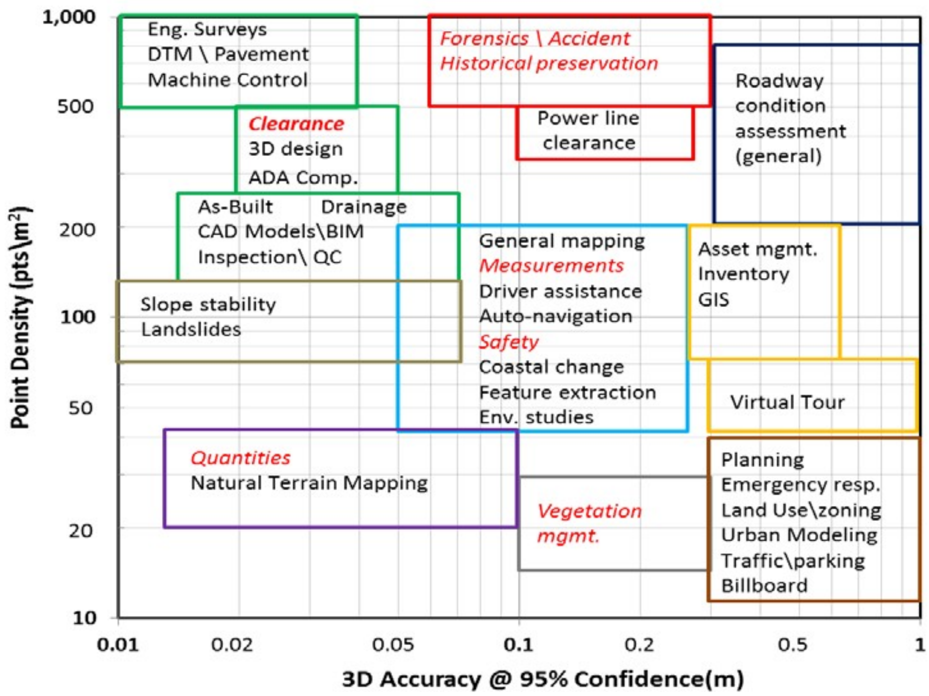


Figure 42. Graph. Resolution and accuracy requirements for a wide range of transportation applications for MTLS. (Olsen et al. 2013).

Traditional highway project survey products include right-of-way and adjacent property legal descriptions, existing ground DTMs, Computer Aided Design and Drafting (CADD) line work and point symbols, digital photography, control description and metadata describing the map projection, vertical datum, horizontal scale factor, and rotation. These survey products constitute a streamlined set of data that are sufficient to perform design, right-of-way acquisition, and construction layout. Furthermore, these survey products and the associated geospatial data will be sufficient to support 3D modeling and digital construction operations provided that they also meet the project’s accuracy requirements. Accuracy requirements, particularly network-level accuracy, are often a major driver of project cost.

With respect to the data, unnecessarily high network survey accuracy requirements can be costly to collect and process, but a low network accuracy of certain constraining features can lead to expensive redesign and change orders. Tie-ins to hard surfaces (e.g., existing pavements, existing bridge structures, or existing curbs and gutters) are often constraints on the design. For instance, CADD software will interpolate between points. Much like accuracy, unnecessary point cloud density (from geospatial data capture tools) increases cost, but too little point density can miss necessary detail. For example, superelevation at a tie-in may be miscalculated if the distance between points is greater than the lane width. Oversampling can also lead to processing bottlenecks.

Topographic accuracy needs can be differentiated based on whether the feature is a constraint, a design feature, a location feature, or a planning feature. Table 16 defines the feature types and outlines minimum horizontal and vertical accuracies for constraint, design, location, and planning features (from Maier et al., under review). These recommendations are based on the ease and efficiency of the technology (e.g., total stations can be used in every category, but they are not very efficient for topographic surveying compared to other techniques such as lidar).

Table 16. Minimum network survey accuracies and recommended geospatial technologies for different feature types to support construction automation. (Maier et al. 2015).

Feature Type	Description	Minimum Network Accuracy	Maximum Distance between Points	Example Feature, and Recommended Geospatial Technology
Constraint	Feature constraints the design and cannot be modified	Hz: 0.04 ft. (0.012 m) Vt: 0.02 ft. (0.006 m)	5 ft. (1.52 m)	Tie-ins to existing sewers, curbs, culverts, pavements, utility covers, bridge elements Hz: Total stations; static or rapid-static GNSS Vt: Digital levels; total stations
Design	Changing this feature affects design or constructability	Hz: 0.1 ft. (0.03 m) Vt: 0.04 ft. (0.012 m)	10 ft. (3.05 m)	Minimum grades on pavements or ditches, stream thalwegs, existing pavements that will be modified Hz: Rapid-static or kinematic GNSS; total stations; terrestrial laser scanners Vt: Total stations; terrestrial laser scanners
Location	Feature can be modified without affecting design or constructability	Hz: 0.25 ft. (0.076 m) Vt: 0.1 ft. (0.03 m)	25 ft. (7.62 m)	Stream banks, tops and toes of slopes, ditches, natural ground, retaining walls, storm/sanitary sewer inverts (not tie-ins) Hz: Mobile, handheld, or helicopter lidar systems; oblique photogrammetry; UAV-SfM; Kinematic GNSS Vt: Kinematic GNSS; terrestrial laser scanners

Feature Type	Description	Minimum Network Accuracy	Maximum Distance between Points	Example Feature, and Recommended Geospatial Technology
Planning	Feature is for reference and it does not affect design or constructability	Hz: 0.5 ft. (0.152 m) Vt: 0.5 ft. (0.152 m)	50 ft. (15.2 m)	Utility poles, landscaping, woods lines, wetland limits, fences; features to be demolished Hz and Vt: UAV-SfM; mobile, handheld, or helicopter lidar systems; oblique photogrammetry

Hz. = horizontal; Vt. = vertical; UAV-SfM = Structure from Motion with UAV.

Survey tools are constantly evolving. If a survey specification describes the outcomes of the topographic mapping, the surveyor can select appropriate tools to capture the necessary data efficiently and safely, depending on the site conditions. Recent work by Olsen and Gillins (2015) shows achievable resolution and accuracy capabilities of a wide variety of geospatial technologies (Figure 43). The number of spatial dimensions in this figure is indicated by blue (1D – elevation only), red (2D – coordinates only), and black (3D – elevation and coordinates) text. This figure can facilitate the decision-making process to select the appropriate technology based on the accuracy and resolution requirements for a specific application.

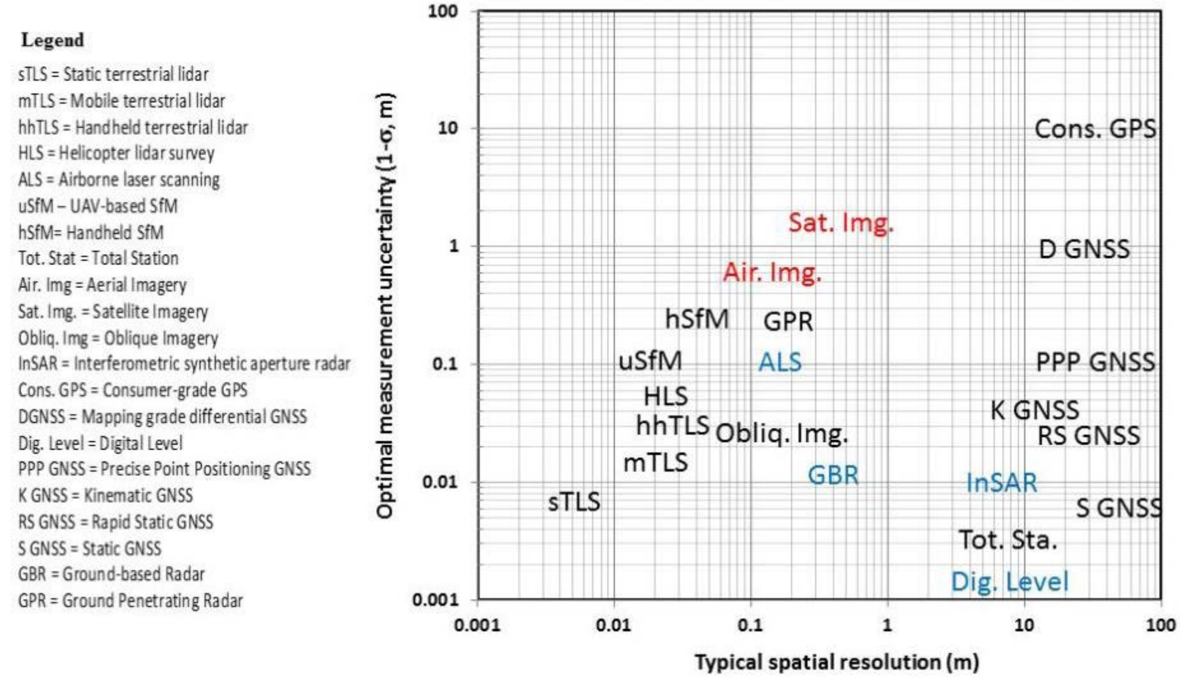
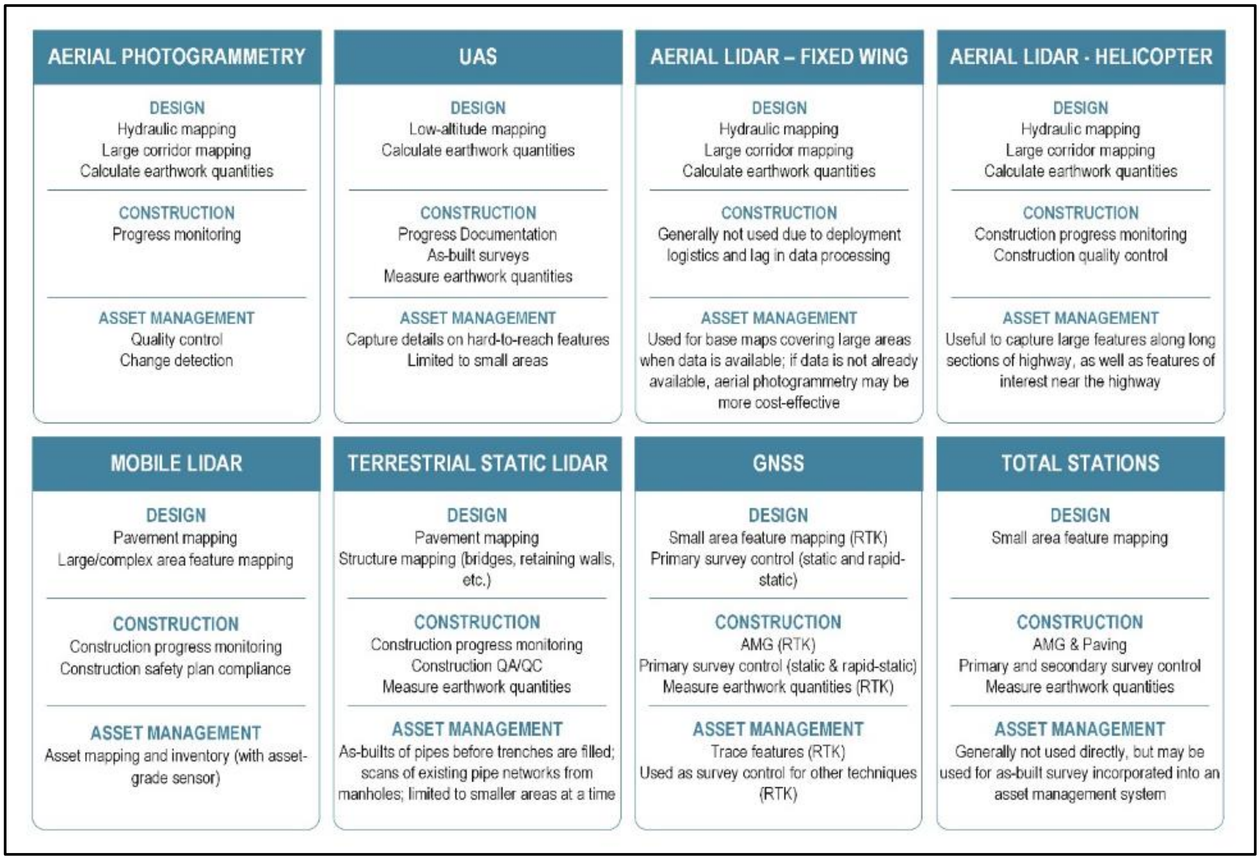


Figure 43. Graph. Optimal measurement uncertainty (1-σ) and typical spatial resolution of sample points achievable by geospatial technologies. (Olsen and Gillins 2015).

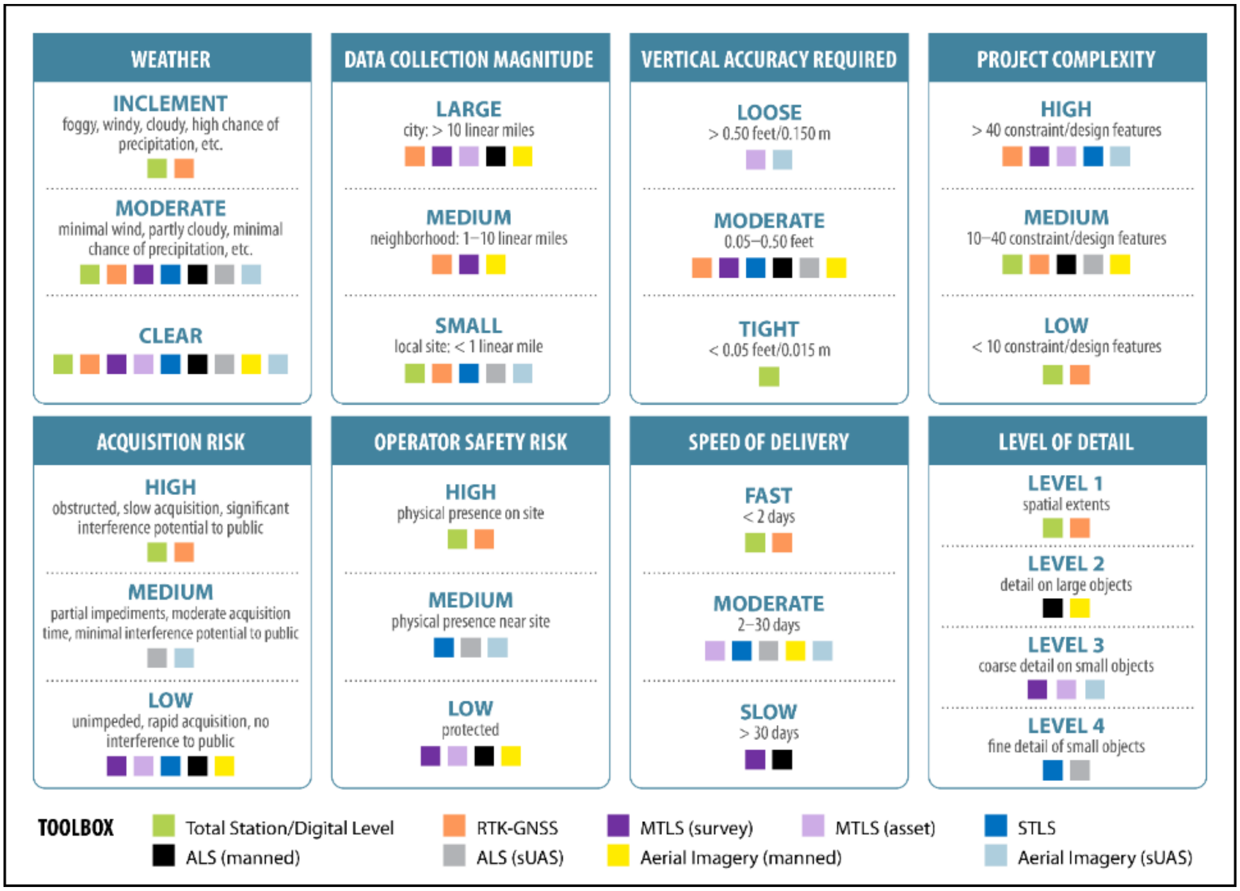
The technologies, of course, can be used outside of these ranges but may not be recommended. Figure 44 provides some examples of applications best suited for each geospatial tool during specific project phases. While there are many tools that can achieve similar results, there is typically a primary tool that is considered for a given application. Furthermore, it must be stressed that in most cases, a combination of tools is required to arrive at the final product. For example, all mapping for design will require some level of survey control to validate accuracies for the final product. Survey control is measured using GNSS or total stations and digital levels, while the mapping may be derived from lidar or imagery.



Source: FHWA

Figure 44. Illustration. Examples of applications best suited for each geospatial tool during specific project phases.

Figure 45 builds on aforementioned criteria to narrow down suitable tools for specific project requirements. As stated previously many factors should be considered before selecting a tool or combination of tools. Static and rapid-static GNSS are not listed because this technology is mainly used for establishing survey control for the project and is used on all types of projects, large or small.



Source: FHWA

Figure 45. Illustration. Criteria for selecting geospatial technologies to meet specific requirements.

ROI CALCULATION FRAMEWORK

The framework presented below was created to help DOTs develop a BCA by tracking different cost categories and benefits through a pilot project that can be scaled up to the annual construction program in order to calculate a five-year ROI. The replacement lifecycle for hardware is dependent upon the type of geospatial technology (e.g., sUAS and GNSS rovers). However, an average depreciation cycle for geospatial hardware is five years. Hence, the five-year ROI calculation was used for this BCA and may be used for planning purposes.

General Information

BCA and ROI calculations should consider general information such as inflation, discount rates, and program specifications, as shown in Table 17. Inflation rates are established by the U.S. Bureau of Labor Statistics and are typically applied to costs to be incurred in future years. Discount rates are those used in calculations to compute the present value of projected benefits. A three percent discount rate is used as a standard value in these types of calculations. Lastly, a base year should be selected for determining the inflation and discount rates. The base year is the year prior to technology implementation.

Table 17. BCA example of general user input information.

Parameter	Data Input	Units	Comment
Inflation base year	-	Year	Year prior to technology implementation (e.g., 2016)
Inflation rate	-	Percent	From Bureau of Labor Statistics website (e.g., 1%)
Discount base year	-	Year	Year prior to technology implementation (e.g., 2016)
Discount rate	-	Percent	3% is a standard industry assumption
Contract value for the project	-	Dollars	Input the contract value for pilot project
Construction program annual amount	-	Dollars	Input the annual construction program amount

- Data to be added during BCA.

Costs

The costs of geospatial technologies are as diverse as the applications for which they are used. Furthermore, multiple geospatial tools can be used simultaneously during highway construction, thus the BCA process should be flexible enough to track the costs of multiple technologies. The cost categories recommended herein include hardware, software, maintenance, and training. Moreover, each technology may have different replacement cycles; for example, a GNSS rover may be replaced every five-to-eight years while a sUAS may be replaced every three years. Thus, specifying hardware replacement cycle per technology may be useful. It is important to note that the hardware may be acquired through direct purchase, lease, or as a programmatic annual cost for hardware as a service.

Other costs to consider in a BCA and ROI calculation should include the DOT staff dedicated for engineering automation tasks, such as research and development, technical support, and training. Examples of cost categories to track in a BCA are shown in Table 18, Table 19, and Table 20.

Table 18. Example equipment cost framework used in BCA calculations.

Costs	Data Input	Units	Comments
sUAS equipment	-	Dollars	Cost to own or lease the equipment
sUAS replacement cycle	-	Years	Years between replacing equipment (or leasing contract terms)
sUAS training	-	Dollars	Total cost for initial training. Assumes a one-time cost
GNSS rover equipment	-	Dollars	Cost to own or lease the equipment
GNSS rover replacement cycle	-	Years	Years between replacing equipment (or leasing contract terms)
GNSS rover training	-	Dollars	Total cost for initial training; assumes a one-time cost
Total station equipment	-	Dollars	Cost to own or lease the equipment
Total station replacement cycle	-	Years	Years between replacing equipment (or leasing contract terms)
Total station training	-	Dollars	Total cost for initial training; assumes a one-time cost
Mobile lidar equipment	-	Dollars	Cost to own or lease the equipment
Mobile lidar replacement cycle	-	Years	Years between replacing equipment (or leasing contract terms)
Mobile lidar training	-	Dollars	Total cost for initial training; assumes a one-time cost
Total maintenance for all equipment	-	Dollars	Input total maintenance for all surveying equipment, assumed to be an annual cost

- Data to be added during BCA.

Table 19. Example software costs framework used in BCA calculations[13].

Costs	Data Input	Units	Comments
sUAS software package	-	Dollars	Assumed to be a one-time cost
sUAS annual maintenance/subscription	-	Dollars	Assumed to be an annual cost
sUAS training	-	Dollars	Total cost for initial training; assumes a one-time cost
Surveying software package	-	Dollars	Assumed to be a one-time cost
Surveying annual maintenance/subscription	-	Dollars	Assumed to be an annual cost
Surveying training	-	Dollars	Total cost for initial training; assumes a one-time cost
Point clouds software package	-	Dollars	Assumed to be a one-time cost
Point clouds annual maintenance/subscription	-	Dollars	Assumed to be an annual cost
Point clouds training	-	Dollars	Total cost for initial training; assumes a one-time cost
Photogrammetry software package	-	Dollars	Assumed to be a one-time cost
Photogrammetry annual maintenance/subscription	-	Dollars	Assumed to be an annual cost
Photogrammetry training	-	Dollars	Total cost for initial training; assumes a one-time cost
Other package	-	Dollars	Assumed to be a one-time cost
Other annual maintenance/subscription	-	Dollars	Assumed to be an annual cost

- Data to be added during BCA.

[13] Industry is moving toward a software subscription business model.

Table 20. Other cost categories used in BCA calculations.

Miscellaneous Costs	Data Input	Units	Comments
Computer/tablets	**-**	**Dollars**	**Initial purchase price for these items**
Replacement cycle	**-**	**Years**	**Years between replacing computers or tablets**
Insurance	**-**	**Dollars**	**Assumed to be an annual cost**
Other one-time costs	**-**	**Dollars**	**Optional input; include any one-time costs not captured in other categories.**
Other annual costs	**-**	**Years**	**Optional input; include any one-time costs not captured in other categories**
Automation staff (FTE)	**-**	**Dollars /hour**	**Average full-time loaded hourly rate for automation staff**
Automation FTE hours spent per year	**-**	**Hours**	**Average hours spent on automation per year; assume number of FTEs times 2,080 hours**

- Data to be added during BCA.

Benefits

The best approach for tracking benefits accurately is through comparing the benefits observed through a pilot project case study to some baseline comparison. The baseline comparison should be a project of similar scope and size in which the technology is not being used. Due to the different applications of geospatial technologies, it is recommended to only include the benefits as those shown in Table 21. The benefits related to time savings due to staff efficiencies are as follows:

- Data collection (all applications).
- Data post-processing (all applications).
- Quantity measurements and calculations (for construction inspection) or other staff efficiencies.

Table 21. Benefit categories used in BCA calculations.

Benefits (Quantifiable)	Data Input	Units	Data Needed
Data collection efficiency - data collector hourly rate	-	Dollars per hour	Average full-time loaded hourly rate
Data collection efficiency - tradition duration of data collection	-	Hours	Total hours spent on data collection (pre-implementation)
Data collection efficiency - percent time savings	-	Percent	This value should be tracked during the pilot project; however, a default of 50% time savings may be assumed if data is unavailable
Data post-processing efficiency - staff hourly rate	-	Dollars per hour	Average full-time loaded hourly rate
Data post-processing efficiency - traditional duration of data post-processing	-	Hours	Total hours spent on data collection (pre-implementation)
Data post-processing efficiency - percent time savings	-	Percent	This value should be tracked during the pilot project; however, a default of 75% time savings may be assumed if data is unavailable
Quantity measurements and calculations efficiency - staff hourly rate	-	Dollars per hour	Average full-time loaded hourly rate
Quantity measurements and calculations efficiency - traditional duration of quantity measurements and calculations	-	Hours	Total hours spent on data collection (pre-implementation)

Benefits (Quantifiable)	Data Input	Units	Data Needed
Quantity measurements and calculations efficiency - percent time savings	-	Percent	This value should be tracked during the pilot project; however, a default of 50% time savings may be assumed if data is unavailable
Other productivity efficiency - staff hourly rate	-	Dollars per hour	Average full-time loaded hourly rate
Other productivity efficiency - traditional duration of other productivity task	-	Hours	Total hours spent on data collection (pre-implementation)
Other productivity efficiency - percent time savings	-	Percent	This value should be tracked during the pilot project; however, a default of 50% time savings may be assumed if data is unavailable

- Data to be added during BCA.

Calculations

There are a number of formulas used in BCA and ROI calculations that include the standard terms listed in Table 22. Once a pilot project is concluded, the documented benefits can be used to estimate overall savings for the entire construction program. Once the benefits for the pilots are calculated, Equation 1 can be used to find the percent savings. Benefits for the entire construction program in year one can be derived using Equation 2.

Similarly, the costs incurred during the pilot can also be used to derive statewide costs. The initial costs for the pilot would need to be scaled up for statewide deployment using the values tracked during the pilot for hardware, software, maintenance, and training taking into account replacement cycles for hardware. One-time purchases would be included in the initial cost, and any reoccurring costs would need to be summarized for each year as appropriate. There will be years where the costs will be higher than others due to hardware replacement cycles. The costs for each year during the five years will need to be summarized to plug into Equation 5. Thus the total cost for the initial year will be the one-time cost of the pilot. It is highly recommended to phase-in the cost of large items such as hardware over the five-year STIP cycle when building initial inventory of equipment, then replace the initial inventory using a programmatic replacement cycle starting with the oldest units.

A spreadsheet model may be created to automate the BCA and ROI calculations using the framework presented herein, but the development of such a tool was beyond the scope of this project.

Table 22. Definitions of terms used in BCA calculations.

Term	Description	Equation
Discount factor	Factor used in calculations for present value of benefits to incorporate discount rate for each year in the BCA	Equation 3
Inflation factor	Factor used in calculations for present value of benefits to incorporate inflation rate for each year in the BCA	Equation 4
Total costs	Includes initial cost plus any reoccurring costs by including inflation and discount factors	Equation 5
Total benefits	Includes total estimated benefits by including inflation and discount factors	Equation 6
NPV	Net present value (of future benefits)	Equation 7
ROI	Return on investment (for specific time period)	Equation 8

$$Percent\ Pilot\ Savings = \frac{Pilot\ Project\ Total\ Benefits}{Pilot\ Project\ Contract\ Amount}$$

Equation 1. Percent pilot savings.

$$Construction\ Program\ Savings\ (Bi) = Percent\ Pilot\ Savings\ x\ Annual\ Construction\ Program\ Amount$$

Equation 2. Average construction program savings.

$$d_n = \frac{1}{(1 + r_d)^{n - n_0}}$$

Where:

d_n = current year's discount factor
r_d = discount rate
n = current year
n_o = base year

Equation 3. Discount rate factor.

$$i_n = i_{n-1} * (1 + r_i)$$

Where:

i_n = current year's inflation factor
i_{n-1} = previous year's inflation factor
r_i = inflation rate

Equation 4. Inflation rate factor.

$$Total\ Cost = (1 + r) \sum_{i=0}^{n} \frac{C_i}{(1 + q)^i}$$

Equation 5. Total costs.

$$Total\ Benefits = (1+r)\sum_{i=0}^{n} \frac{B_i}{(1+q)^i}$$

Where:

r = inflation rate factor
n = number of years past the base year minus one, for our model n=4
C_i = uninflated, undiscounted cost for the ith year
B_i = uninflated, undiscounted benefit for the ith year
q= nominal discount rate factor

Equation 6. Total benefits.

$$NPV = Total\ Benefits - Total\ Costs$$

Equation 7. Net present value.

$$ROI = \frac{(Total\ Benefits - Total\ Costs)}{Total\ Costs}$$

Equation 8. Return on investment.

Example BCA and ROI Calculation

A DOT is conducting a pilot project to document the costs and benefits of implementing the use of GNSS rovers for construction engineering and inspection. The tasks include real-time verification and calculation of quantities.

- A total of four GNSS rovers will be purchased in 2017 to equip each inspector on the project with a piece of equipment
- The contract value for the pilot is $5 million
- The average annual construction program is $900 million
- A total of 150 GNSS rovers would be needed for statewide deployment
- The efficiency observed in the pilot project was 35 percent higher than the baseline comparison

- All general information, costs, and benefits are tabulated in Table 23, Table 24, and Table 25

- The output of the results is shown in Table 26

Table 23. Example of general information for calculating BCA and ROI.

General Information	Data Input	Units	Comment
Inflation base year	2016	Year	Year prior to technology implementation (e.g., 2017)
Inflation Rate	1%	Percent	From Bureau of Labor Statistics website (e.g., 1%)
Discount base year	2016	Year	Year prior to technology implementation (e.g., 2017)
Discount rate	3%	Percent	3% is a standard industry assumption
Contract value for the project	5,000,000	Dollars	Input the contract value for pilot project
Construction program annual amount	900,000,000	Dollars	Input the annual construction program amount

Table 24. Example costs of technology implementation.

Costs	Data Input	Units	Comments
GNSS Rover equipment	80,000	Dollars	Cost to own or lease the equipment for the pilot project. This translates into a $3 million initial investment for statewide deployment assuming a cost of $20,000 per GNSS rover. Replacement cycle used for calculations was five years.
GNSS Rover replacement cycle	5	Years	Years between replacing equipment (or leasing contract terms)
GNSS Rover training	1,500	Dollars	Total cost for initial training; assumes a one-time cost for a train-the-trainer statewide implementation
Total hardware maintenance for all equipment	2,000	Dollars	Input total maintenance for all surveying equipment, assumed to be an annual cost. This is the cost for the pilot. Assuming $500 per GNSS rover, this translates into a $75,000 annual cost for statewide implementation.
Surveying software package	14,000	Dollars	Assumed to be one-time cost. This translates into a $525,000 one-time purchase for 150 units.
Surveying annual maintenance/ subscription	2,800	Dollars	Assumed to be an annual cost. This translates into a $105,000 annual cost for 150 licenses.
Surveying training	0	Dollars	Assumed to be included in the hardware training
Technical support staff - automation FTE	40	Dollars per hour	Average full-time loaded hourly rate for automation staff
Technical support staff - total hours worked on automation per year	4,160	Hours	Average total hours spent on automation (assumes 2 FTE)

Table 25. Example benefits of technology implementation.

Benefits (Quantifiable)	Data Input	Units	Data Needed
Quantity measurements and calculations efficiency - staff hourly rate	35	Dollars per hour	Average full-time loaded hourly rate
Quantity measurements and calculations efficiency - traditional duration of quantity measurements and calculations	2340	Hours	Total hours spent in one year to perform this task pre-implementation
Quantity measurements and calculations efficiency - percent time savings	35%	Percent	This value should be tracked during the pilot project; 35% is a conservative estimate based on case study findings

Table 26. Example of BCA and ROI calculation outputs[14]

Value	Output	Measure	Description
Project savings	28,665	YOE $[15]	These are the savings tracked during the pilot project
Contract value	5,000,000	YOE $	This is the contract value for the pilot project
Percent savings	0.57%	Percent	This is the percent of savings during the pilot project
Program savings over five years	24,815,882	YOE $	This is the projected savings for the five-year construction program based on the pilot project
Program spending over five years	5,192,531	YOE $	This is the projected cost over five years to implement technology in every project based on the pilot results
Net present value	19,623,351	YOE $	This is the net present value of the savings
Return on investment	378%	Percent	This value represents the five-year return on investment

[14] The values in this table are examples only and not representative of any particular study.
[15] Years of expenditure in dollars.

CHAPTER 4. RETURN ON INVESTMENT CASE STUDIES

DATA COLLECTION APPROACH

The previous work of this project including the literature review and interviews served as the basis for identifying DOTs and contractors who are leading the way in the use of geospatial technology in highway construction applications. Both ODOT and UDOT were identified as two leading DOTs using a variety of geospatial technology for developing 3D engineered models for construction, embracing contractor's use of AMG construction methods, investigating the use of GNSS equipment for inspection work, and piloting sUAS as another geospatial data collection tool that can be used in both project delivery and bridge inspection.

This chapter describes four case studies in detail. Case Study 1 details a demonstration workshop hosted by ODOT. Although not a traditional case study, much of the structure and conclusions resulting from the workshop illustrate the benefits and considerations of deploying innovative technology in highway construction. There were no baseline data to compare against given the high level of technology maturity at ODOT and the lack of quantifiable data to evaluate, such as the other case studies analyzed. However, during the demonstration, there were apparent inefficiencies and clear benefits observed that are discussed below.

Case Study 2 presents an Oregon State University (OSU) research project evaluating the use of sUAS for bridge inspections by ODOT. Many of the baseline costs of performing bridge inspections using traditional workflows are well-documented, which helps develop an accurate ROI. As noted below, sUAS provides substantial benefit for visual inspections but lacks in "arm's length" and probing-type inspection requirements. However, the benefits were able to be quantified to the extent that a comparative analysis of workflows allowed.

Case Study 3 describes a UDOT highway project that used sUAS for construction progress and development of DTMs, and GNSS rovers for real time verification and quantity measurements. UDOT was interviewed by the research team to capture their innovative use of geospatial technology during design and construction. The costs and benefits were quantified, and an accurate ROI was developed.

Case Study 4 provides a contractor's account of using sUAS for measuring quantities at a quarry for a mining project. It was important to look outside the highway construction sector to a more mature industry using UAS technology as a means to capture cross-industry similarities in addition to costs and benefits. The costs and benefits were quantified, and an accurate five-year ROI was developed to emphasize the programmatic impact.

Lastly, this section concludes with a desk scan of the use of sUAS in construction. The desk scan provides results from a secondary independent literature search and interviews with contractors and service providers. The purpose of the desk scan was to strengthen the research team's assumptions and to solidify the current perceived value of using sUAS for construction purposes.

For the aforementioned case studies, the research effort attempted to capture the benefits and costs for implementing geospatial tools at the project level. The team worked with each participant to collect costs and benefits categories listed in Table 27 using the following pre-defined confidence scores: 1 = Documented; 2 = Educated Estimate; 3 = Guess. However, as shown below, Case Study 1 did not use the specific categories or confidence scores due to the lack of quantifiable data. Case Study 2 had fully documented baseline costs (confidence score of 1), but the benefits were largely based on assumptions gathered from comparative analysis of workflows.

Table 27. Benefit cost categories used for case studies.

Benefit Categories	Cost Categories
Improved efficiency	Surveying equipment (including maintenance)
Improved safety	Software (including maintenance)
Increased data quality	Technical support staff
	Miscellaneous costs

CASE STUDY 1: GEOSPATIAL TECHNOLOGIES FOR DESIGN TO PAVER WORKSHOP

ODOT hosted the Design to Paver Workshop was held from July 9-10, 2014 in Oregon. The demonstration event showcasing the innovative geospatial technologies was held at Camp Adair and the topical presentation was held at Oregon State University in Corvallis.

Overview

Design to Paver (Figure 46 and Figure 47) was an innovative event organized by ODOT and the FHWA to promote the use of Intelligent Construction Systems and Technologies for highway construction. The workshop provided information and training covering 3D Design, AMG, and related technologies. The workshop included classroom presentations, field demonstrations of AMG for road construction, and an implementation guidebook. The materials, including the video and other media, are available at http://designtopaver.org.

The workshop brought DOT leadership together from across the country (with a focus on the Western Association of State Highway and Transportation Officials states) to see and learn more about these technologies and the efficiencies and benefits they can provide as well as discuss limitations. In total, there were approximately 300 attendees with several industry leaders donating their time and use of equipment for the workshop. The event was hosted by ODOT and FHWA funded the demonstration as part of the “Every Day Counts” initiative as well as assisted with organizing the event.

The event consisted of presentations by DOT and industry personnel with expertise in these systems, followed by live demonstrations of equipment and technologies onsite.

The primary idea for this event was to showcase an actual project demonstrating various technologies in construction automation. Figure 46 shows many of the technologies that were showcased. Due to safety considerations, it is not possible to bring people to an actual construction project. However, for this workshop they could design the demonstration project in a controlled environment such that there would be ample room for people to watch safely from the sidelines while still maintaining authenticity of the processes that occur on an actual construction site.

The intent of this workshop was to provide live demonstrations of geospatial technologies and construction automation. Hence, there were additional costs associated with the project including slowing down progress (as compared to what would be achieve during an actual project) for maximum attention to how the technologies affected performance.

This workshop builds off of a smaller event, *Design to Dozer*, which ODOT hosted in 2010 near Eugene, Oregon (ODOT 2010).

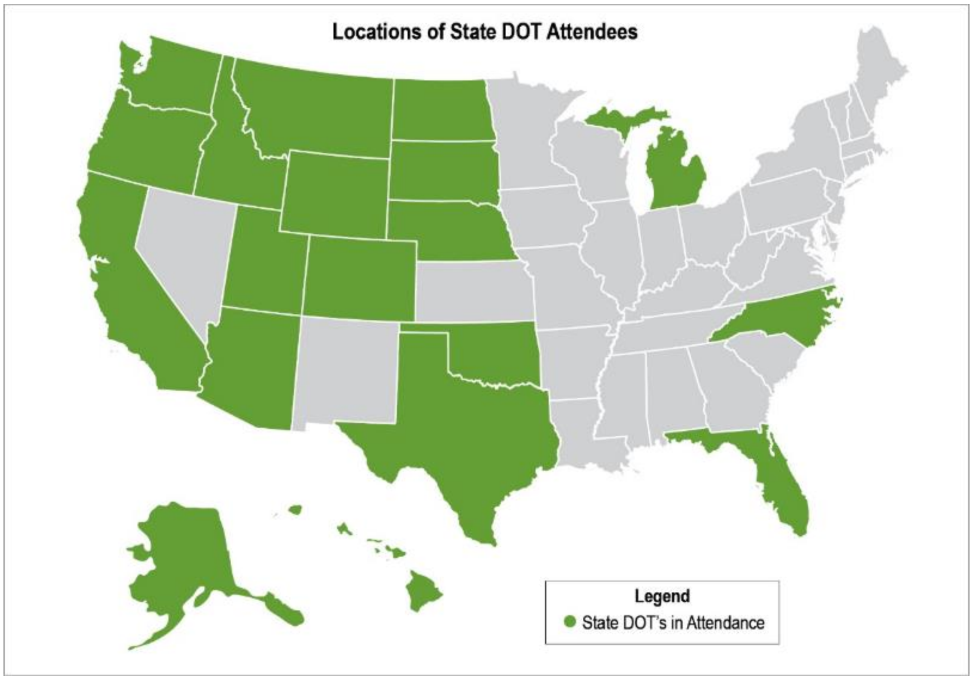
The concepts for both of these workshops were based on an engineering automation document developed by Ron Singh, who was the Chief of Surveys at the time for ODOT (Singh 2008). This pivotal document, which outlines a 25-year technology implementation plan, was important in standing up this event, as well as a variety of uses of geospatial technologies throughout ODOT. It also sets the direction for expanding usage of these technologies at ODOT after the event.

Source: FHWA

Figure 46. Photo. AMG grading equipment being demonstrated during the Design to Paver workshop at Camp Adair, Oregon.

Source: FHWA

Figure 47. Photo. AMG paving equipment being demonstrated during the Design to Paver workshop at Camp Adair, Oregon.



Source: FHWA

Figure 48. Map. Locations of state DOT attendees.

Methodology

While the event was primarily a demonstration, several relevant activities from a normal project were completed. These included data gathering, site survey, 3D design, construction, and QA/QC. This section describes activities and technologies used for each stage. ODOT has specifications for the use of all of these technologies in its survey manual.

Data Gathering

ODOT gathered available information, such as airborne lidar and photographs of the site during the planning stage. Airborne lidar was available, but it was unclear whether it was used directly in the planning.

Site Survey

A complete site survey was completed using a variety of technologies, including total stations, STLS, GNSS, and photogrammetry. These surveys followed ODOT's standards.

- GNSS survey control points were established using a combination of static occupations and the Oregon Real-Time Network (ORGN). Leica Geo-office was used for GNSS processing.

- The project was completed using the Oregon Coordinate Reference System (OCRS) (Armstrong 2010). The OCRS is a set of low-distortion projections developed by ODOT such that grid and ground distances are nearly identical. This system has been used on all of its projects since its creation.

- Traditional photogrammetry was used to generate orthoimages. Leica Photogrammetry Suite and Erdas Imagine were used for these products.

- The base map and DTM were generated from several components:

    - Traditional photogrammetry to create topo points across the site.

    - STLS (Leica C10) to capture detail in areas of interest. Leica Cyclone was used for lidar processing.

    - A total station and GNSS were used to capture line and grade and identify specific feature points or objects to include in the DTM.

- MTLS was also used for general information for the site. However, at the time, ODOT had an asset-grade system, so they were hesitant to use it for the DTM given its accuracy limitations.

Extra work was also completed as part of the program to provide a demonstration of the ORGN. ODOT integrated an additional base station into the ORGN, which remained on site for the duration of the workshop and served as a base station for some of the contractors.

3D Design

The DTM and base map were provided to the designers who then created the 3D design model following ODOT design standards. ODOT has been using 3D design for roadways since the 1990s, so the level of process maturity is fairly high. Given that this was a demonstration, certain design elements were exaggerated, such as super-elevation and curvature, to show the capabilities of the equipment.

The data and model itself were used as the authoritative source of design information instead of the plans. However, for the workshop, plans were provided to attendees as a reference. This resulted in additional work during the design that was unnecessary for the actual construction using AMG. The contractors were included as part of the team in the design to ensure that data formats would be consistent from design to construction.

Construction

The 3D models were uploaded into a variety of equipment with construction automation capabilities and were used to build the roadway based on the model. The construction followed ODOT's standards and specifications.

Just prior to starting work, validation of the DTM was completed using a process ODOT calls confidence points (randomly acquired points) to validate original ground surface. In this process, the terrain is characterized based on what types of accuracy they expect. For example, a higher accuracy should be achieved on a hard pavement surface compared with general topography.

Quality Management and As-built Surveys

Despite the fact that this was a demonstration, contractors were still held to ODOT's standard specification. Various quality management strategies were implemented, including the following:

- Importing the models into rover GNSS units as well as tablets.
- GNSS rovers were used for evaluating subgrade.
- The total station was used for concrete or asphalt pavement surfaces given the requirements for higher accuracy.
- A sUAS (Trimble UX5 Fixed Wing) was used to capture project progress for surveying and monitoring purposes.
- Two video cameras were onsite continuously recording for construction site monitoring.
- Pre-construction surveys were also used as references for QA/QC purposes.

- Even though some quality metrics from intelligent compaction such as stiffness measurements still require a substantial amount of work before being usable, the information regarding the number of passes and temperature are important QA/QC information that can be obtained.

- A potential usage of AMG is for rapidly generating as-builts for asset inventory directly out of the machines. This capability was not used on this project; however, a MTLS was used for as-built documentation.

- Quantity estimations were also not performed on the project. ODOT's process was to obtain the design intent elevation and compare it to the as-built elevation such that the roadway was built to the intended surface rather than check the quantities. However, the data collected could be used to quickly obtain quantities, if desired. If there was a reason to deviate from design, then ODOT would pay based on the measurement, otherwise they make payments based on compliance with the design.

Technology Advancement

After the workshop, ODOT began using inspection tablets that connect to ORGN to obtain standard RTK accuracies. The 3D models are now loaded onto these tablets for the inspectors.

Inefficiencies Observed

During the workshop, some inefficiencies were observed, such as contractors using geodetic tools, but not taking advantage of geodetic algorithms. For example, the hardware vendors teach the contractors to perform a local site calibration with the GNSS. Another contractor set up their own base station. However, these processes are no longer necessary with the ORGN.

The project was also designed on a low-distortion projection system (OCRS) instead of tate plane coordinates, which was difficult for one contractor. This contractor converted everything to state plane and performed a site calibration. However, after the experiences of the *Design to Paver* workshop, this same contractor successfully moved away from site calibration to using the ORGN on another project with a large time crunch.

Benefits and Costs

Because this project was a demonstration, analysis BCA or ROI calculation was not completed. Efficiencies on the project were below normal because this was a demonstration. In fact, the contractors had to slow down so that they could be at the appropriate locations to showcase the work they were doing.

Another difficulty in directly calculating ROI for this project is that ODOT has a high level of technology maturity and has already integrated many of these technologies into their standard workflows and practices. Hence, there is no cost information for a "baseline" comparison of performing surveys in the traditional sense. ODOT has found a steady-state approach to integrating the new technology as it becomes available and appropriate.

Nevertheless, the *Design to Paver* demonstration project was critical to expand interest within ODOT in these technologies. As a result, ODOT commissioned researchers at OSU (Dr. David Sillars, Principal Investigator) to complete a detailed ROI study for the DOT, with results to be available in 2017. This study covers five different technologies, including 3D design, AMG, MTLS, engineering data management, and tablets.

Data Sharing Considerations

Data interoperability was smooth on this project with minimal disruptions. The LandXML format was used to transfer data between stakeholders. Both Trimble and Leica Geosystems technology were used and the data integrated well between both systems.

While data was not provided directly to the field crews on the project until the day of the workshop, preliminary discussions occurred with the leadership of those industry partners about logistics.

For *Design to Dozer*, Bentley wrote direct software to convert InRoads results into a format for the machines in 2010. However, they did not use this software for *Design to Paver* since the LandXML format was sufficient.

Following receipt of the models from ODOT, the contractors segmented the models for the various stages of construction to optimize their processes. These processes are only documented internally by the contractor since they provide their competitive edge. However, it is worth noting that the operators themselves saw the data (i.e., plans) for the first time their first day in the field, resulting in a plug and play approach. The contractors were able to quickly review the model and go straight to work with minimal questions regarding what they needed to complete.

Primary Lessons Learned

ODOT learned several important lessons through this event including significant benefits of doing workshops that highlight uses of technologies, continued engagement of management is important, improved collaboration between design and construction staff. These lessons learned alone provided a significant ROI for ODOT against the cost of the workshop itself.

Have a plan in place (e.g., Singh 2010) that carefully outlines how the technology will be implemented and used. The FHWA saw this document, which is how it became interested in supporting the event. However, the document has also served as a guide to ODOT for implementation.

Have a Plan B (and other backup plans) when things do not go according to plan. Challenges will always arise in using new technologies. It is important to work with manufacturers to let them know what is needed and what the priorities are.

Benefits of Workshops Highlighting Uses of Technologies

The demonstration and educational aspects of this workshop were critical to the AMG implementation. Once people see the technology in action, the benefits become apparent and they are easily convinced of the value. Obviously, organizations cannot perform these workshops all the time, but they can perform some, perhaps smaller in scope, periodically. They can also use the educational materials from the workshop itself and other efforts to reduce costs. For such an event, contractors were willing to donate their time since the audience was national. However, this would be harder to implement for a limited, local audience.

Engage Management

Showing upper management the technologies and enabling them to participate are also important to implementation. Without their support it is very difficult to gain traction. At the time of the workshop, upper management was unaware of the capabilities that already existed within ODOT. The Director attended the demonstration and was given the opportunity to operate a machine. He first tried it manually, then he flipped on automation so that he could experience and understand the improvement firsthand. This had a significant impact in the implementation since the director immediately could see the benefit.

Continued communication with leadership is important to convince them of the benefits. They need to be informed and recognize the benefits. They need groups of people to champion technologies that they trust. A key to showing them the benefit is to demonstrate the impacts and value beyond a project—Think beyond the Project. The workshop highlighted the importance and further uses of the data downstream for maintenance, operations, and future projects.

Coordination

Although one can download the 3D models on site directly to the machine, coordination is needed between the design and construction teams beforehand to ensure data are converted into the appropriate format for each system, as well as divided into the appropriate tasks.

Value of New Technologies

Although there is still a lot of concern about obtaining reliable stiffness values from intelligent compaction, the systems still provide a host of additional benefits, particularly for QA/QC. For example, they provide geospatial information as to the number of passes over each section of pavement, information on where the roller sat idle, and other information that would be useful to have recorded for the future should a section of pavement experience structural problems at a later date. They also provide reliable temperature estimates.

Additional Opportunities

Future projects and activities at ODOT have benefited from this workshop including standing up a new Engineering Automation Division that is responsible for implementing these new technologies in their practices. ODOT also held a subsequent meeting with the Oregon Transportation Commission regarding the event. In order for an idea to gain traction, it needs to have the support of leadership and it needs to be understandable to leadership. In this case, the leadership saw clear ROI benefits from the demonstration of these technologies and have rapidly pursued implementation.

Further, one of the designers who attended the workshop is currently using AMG for a large concrete paving project south of Eugene, Oregon. This decision was made when the attendee realized the benefit at the workshop.

As another example, ODOT used MTLS data to compute sight distances following the recent increase in speed limits in Eastern Oregon by the Governor. ODOT estimates that for this one project, using already available MTLS data saved approximately $250,000.

There were a lot of lessons learned given that many of the attendees had limited exposure to these technologies. Attendees continue to use the information available at the event website and it is likely that there has been a much broader impact on the event than what ODOT can track.

ODOT Future Plans

ODOT shows no signs of slowing down in implementing these technologies. For several of the technologies used, there have been refinements made since the workshop because of their continued use. Below are some of the activities they are currently pursuing, which build on the efforts from this workshop:

- Evaluating the use of augmented reality for construction engineering and inspection.
- Looking at ground penetrating radar to capture information about pavement.
- Integrating their MTLS with GIS.
- Integrating geospatial data with asset management data
- Looking at replacing video logging with MTLS.
- Expanding the use of sUAS for surveying tasks,
- Creating internal policy for the use of sUAS.
- Exploring underutilized areas that will benefit with the use of MTLS.
- Exploring 3D bridge design.
- Exploring e-Construction practices.
- Looking at how engineering automation can help with QA through plotting all QC information.
- Exploring subsurface utility engineering practices and related legislative changes.
- Exploring the use of the data as the prevailing contracting order or precedence and not the hardcopy plans.
- Working with manufacturers to develop solutions and customized workflows.

- Trying to create a dashboard for the ODOT's Engineering Technology Advancement Unit that shows each initiative underway in ODOT's Engineering Automation Division, the status, and point of contact, as a way to improve internal communication and connect interested parties.

- Raising the visibility and attraction of intelligent compaction to ODOT leadership.

CASE STUDY 2: UAS FOR BRIDGE INSPECTIONS

Overview

OSU is currently conducting a research project for ODOT titled "Eyes in the Sky: Bridge Inspections with Unmanned Aerial Vehicles" (Gillins and Parrish n.d.). The purpose of the project is to evaluate the effectiveness of sUAS in bridge inspections and to provide recommendations to ODOT on operational use of sUAS in inspections.

To date, the OSU team has conducted sUAS flights at four bridges: Independence Bridge, River Road South (bridge number: OR 05789A); Crooked River Bridge, Highway 4 (pedestrian bridge); Mill Creek Bridge, US 26 (bridge number: OR 01660); and St. Johns Bridge, US 30 Bypass (bridge number: OR 06497). Flights have been conducted under FAA Certificate of Waiver or Authorization: 2016-WSA-101-COA (Parrish, 2018).

The results of the project, to date, have shown that sUAS can assist in satisfying some requirements of a bridge inspection. sUAS are most effective for visual and routine bridge inspections (non-fracture critical inspections). However, sUAS are less beneficial in inspections of fracture-critical or functionally obsolete bridges, since sUAS cannot currently provide comparable results to a physical inspection or satisfy the "arm's length" requirements for these types of inspections.

sUAS also cannot be used to probe and scrape the bridge, which is required in some types of in-depth inspections. However, the OSU team determined that, in some cases, nearly all expectations of a visual inspection can be achieved using a sUAS. Defects such as cracks, pack rust, and loose and missing hardware were easily identifiable in the imagery acquired at the four bridges listed above. Additionally, sUAS can often improve viewing angles and resolution over what can be achieved visually (including with binoculars) standing on the bridge deck or at one end of the bridge looking up given to the ability to maneuver the sUAS near the bridge and use optical zoom, if available on the camera.

This report presents a preliminary BCA for the use of sUAS in bridge inspections based on the work of the OSU project team and relevant information provided by ODOT.

Methodology

The first step in assessing the potential cost savings achieved through use of sUAS in bridge inspections involves the determination of baseline costs for bridge inspections conducted without sUAS technology. Erick Cain, ODOT Bridge Inventory Coordinator, provided 33 financial spreadsheets with budgetary information for recent bridge inspections contracted by ODOT. These spreadsheets contain itemized costs for bridge inspections. To protect the interests of the firms responsible for the work, the OSU team redacted all company names and proprietary information and used only aggregated data for the baseline cost estimates.

The cost portion of this preliminary ROI analysis was completed based on OSU's equipment and data collection costs under the assumption that a ODOT would use similar equipment and procedures. The validity of this assumption is, at present, unknown; however, OSU's costs provide the best information currently available for this portion of the analysis.

Benefits and Costs

The primary benefit of using sUAS for bridge inspections is representative of the cost savings from decreased field time, which reduces the costs for the following:

- Equipment rental/usage (e.g., snooper cranes).
- Traffic control.
- Travel (e.g., lodging, meals, and incidental expenses).

It is important to note that decreased field time also increases the safety of the inspectors and the general public, although a quantitative assessment of this cost benefit is beyond the scope of this preliminary ROI analysis. In particular, safety can be improved through a reduction in the use of snooper cranes, climbing on the structure, lane/shoulder closures, and associated traffic control.

To quantify the value of implementing a sUAS for bridge inspections, 15 previous bridge inspection cost breakdowns were compiled from the 33 financial spreadsheets provided by ODOT. The bridges that were inspected range in size, type, and inspection duration. The savings from using a sUAS is assumed to reduce inspection field time by 20 percent and increase office time by 30 percent. Even though the office time increased, the time savings from inspection field time was much greater and resulted in an overall average time savings of 10 percent, as shown in Table 28.

The increase in office time is a result of sUAS mission planning and processing/analyzing the collected datasets. It is assumed that if the average in field time savings per project is 20 percent, then equipment rental and traffic control costs will also decrease by 20 percent per project. At an estimated cost of $2,000 per day for snooper truck rental and $2,500 per day for traffic control, there is a noticeable decrease in field inspection costs.

For determining the average savings for equipment use and traffic control, the average bridge inspection duration is assumed to be seven days (with two people). This estimate is based on information from Erick Cain, who noted that, while there is tremendous variability in the time required to complete an inspection, bridge size, material, etc., the bridges flown by the OSU project team in Central Oregon would typically take approximately five to six days with a team of two, with much of that being night work if lane closures are necessary. The bridges on the Columbia River were complex bridges and took six people two weeks to inspect, with half of that being night work with lane closures. These considerations lead to a very rough estimate of two people and seven days to inspect an average, large bridge of the type for which sUAS would add value to the inspection.

Table 28 summarizes the savings for 15 different bridge inspections if sUAS was used.

Table 28. Estimated savings from use of sUAS.

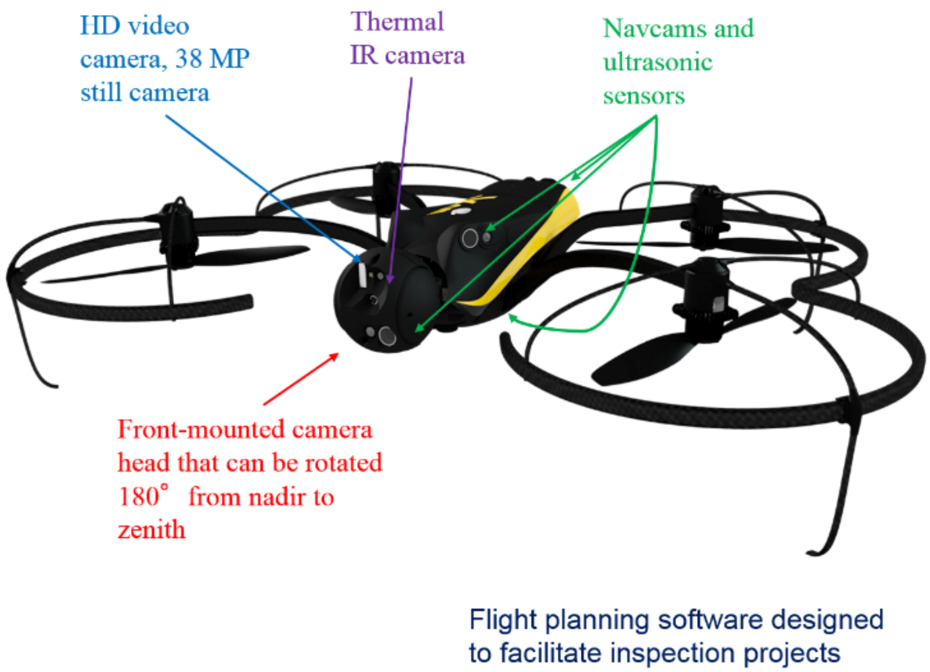
Statistic	Personnel Time Saved (%)	Dollars Saved ($)
Average:	10%	$ 3,900
Std. Dev:	3%	$ 2,700
Min:	3%	$ 200
Max:	15%	$ 10,500

The average payout cost for the 15 bridge inspections was $73,800 without using sUAS in the inspection process. By using sUAS, there is an estimated average savings of approximately $3,900 for personnel time (overall average of 10 percent, as stated previously), $2,800 for equipment rental, and $3,500 for traffic control, which decreases bridge inspection costs by $10,200 per project for those bridges suitable for UAS data acquisition.

sUAS Costs

After an extensive market study, the system that OSU selected the senseFly albris (Figure 49), which met the majority of needs for the bridge. The main characteristics that the OSU team sought in a sUAS included the following:

- Multirotor design, enabling vertical takeoff and landing, as well as hovering in place.
- Ability to fly close to structures while maintaining a fixed, safe stand-off distance.
- Flight planning software designed for inspection work.
- In-flight, adjustable camera pointing angle.



Original Photo: © 2017 senseFly

Figure 49. Illustration. senseFly's albris sUAS.

The cost of the sUAS and accessories (batteries, propeller set, radio modem, remote control, etc.), as well as operator training and software, was $39,079. It is important to note that, as with all technology, sUAS costs (including accessory costs) are decreasing with time, and the cost for this and similar systems is expected to decrease. Although not part of this analysis, investigating an effective replacement program for keeping sUAS technology fresh and effective is necessary for any organization. Additionally, this analysis concluded that the break-even point for investing in this technology occurs quickly.

Travel Costs

If a dedicated pilot with a remote pilot certificate, as specified in Part 107 of the FAA regulations is needed, one additional person is added to the inspection team, increasing lodging and per-diem costs. However, if at least one member of the inspection team is certified and can serve as the pilot in command, then there are no additional personnel or travel costs.

Office Costs

As noted above, while the use of sUAS is expected to decrease the overall field time for a bridge inspection, there is an anticipated 30 percent increase in office time. Image/video processing time is highly variable depending on the required deliverables for the project, but this analysis focused on datasets that aide in visual inspection work, which is included in the analysis. This increase in office time is already accounted for in Table 28, and it is more than offset by the estimated 20 percent decrease in field time. Furthermore, it is worth noting that a general shift in project time from field to office, in addition to resulting cost savings, is also anticipated to improve safety.

CASE STUDY 3: GEOSPATIAL TECHNOLOGIES FOR HIGHWAY DESIGN AND CONSTRUCTION

Overview

UDOT used a roadway project on State Route 20 (SR20) as a pilot to evaluate multiple innovations that rely on geospatial technology. The scope of the project was to add climbing lanes on a steep hillside with significant geometric complexity. The following innovations were evaluated:

- 3D model as contractual "document".
- Topographic mapping using sUAS for calculating earthwork quantities during construction.
- Use of sUAS for monitoring construction progress.
- Real-time verification and quantity measurements with GNSS rovers.

The project delivery method for this pilot project was Construction Management/General Contractor to allow flexibility during the evaluation of innovative technologies. The contract was awarded a medium-sized contractor with vast experience using geospatial technologies.

Methodology

The research team first developed an initial interview guide to document the case study. The interview guide (see Appendix B) had the following five categories:

- General Information.
- Highway Application.
- Data Collection.
- Workflows and Products.
- Cost and Benefits.

The initial interview lasted approximately one hour, but several follow up phone calls and emails were necessary to get all the information needed to obtain benefit-cost information. Because the case study was conducted after the pilot project was completed, it was challenging to compile accurate benefits and costs. The information gathered during the data collection phase of the research was helpful to develop the effective practices in Chapter 3 and the details described in this chapter.

Applications

Highway Design

The original topographic mapping was created using a variety of technologies and workflows to develop a model used as the foundation for developing the design that met UDOT's standards, as required by the department's Survey and Geomatics Manual. The initial survey control network was established by UDOT in accordance with this manual.

Upon receiving the contract award, the contractor conducted a topographic survey using additional points to validate the existing ground surface in the model. This new existing ground model was provided to the design team to update the design with the most accurate existing ground model available. The contractor also established the construction survey network that would be used for AMG construction activities.

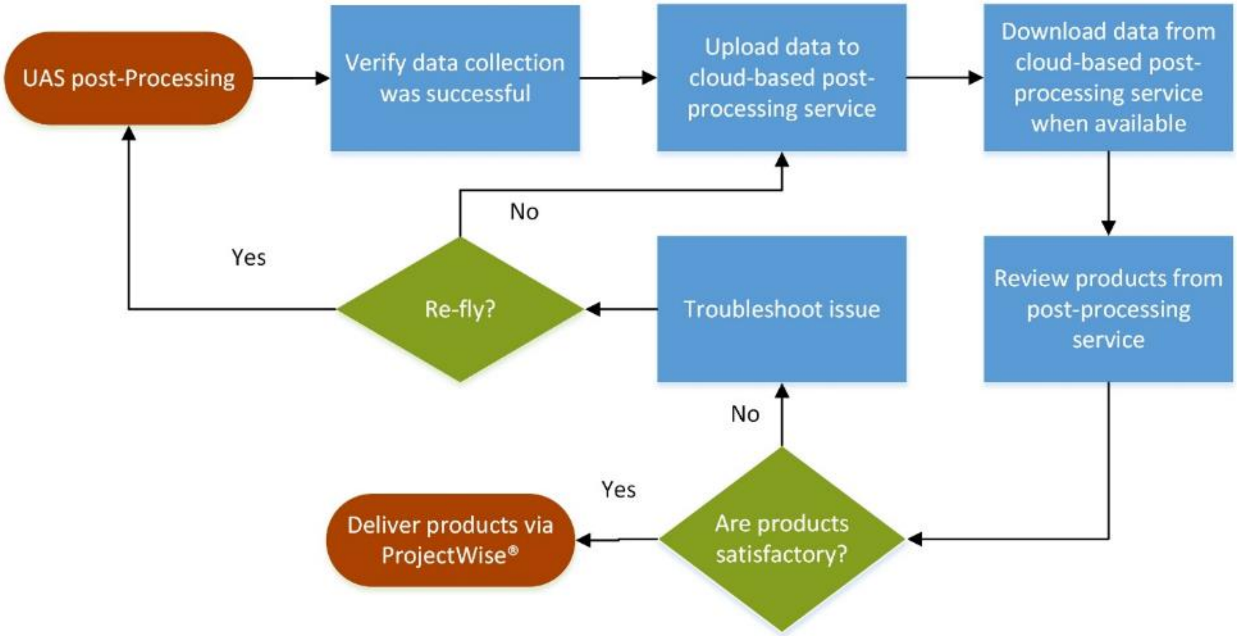
Construction Engineering and Inspection

All existing and proposed surfaces were provided to the construction inspection team to be used during real-time verification and quantity measurements using GNSS rovers. The survey equipment used for construction inspection was provided by the contractor but operated by UDOT's construction staff.

Inspectors were able to check grades against tolerances specified in the contract requirements in real-time and measure quantities quickly by comparing the actual measurements to the original design values. This new process drastically reduced the time spent on this particular task. It also allowed the team to address errors much more effectively and efficiently when needed.

Data Collection, Workflows, and Products

The case study also investigated the use of sUAS for data collection to create surfaces that inspectors could use for real-time verification and measuring quantities, as well as for monitoring progress. Although UDOT used the sUAS purchased for the pilot for collecting data, it was not used for production because the contractor was responsible for providing all data collection for production work. The workflow used for post-processing data collected using the sUAS is illustrated in Figure 50. The final deliverables are listed in Table 29.



Source: FHWA

Figure 50. Flowchart. Workflow to post-process data collected by sUAS.

Table 29. Final deliverables from data collection using sUAS.

Final Products Delivered	Format Delivered
Point clouds of interim and final surfaces	LAS
Final 3D models (as-built conditions)	3D PDF, InRoads DTM, MicroStation CAD drawing

Lessons Learned and Future Direction

The following challenges were encountered during construction inspection:

- The proprietary nature of the software programs prevented the team from seamlessly transferring the models from design to construction; thus, requiring vendors, UDOT, and the contractor to work together to develop workarounds to make the process work.
- The design models were too complex for construction applications and had to be simplified to be consumed by downstream users (e.g., contractor and inspector).
- There was no effective practices for conducting inspection tasks with geospatial technology, which identified the need for updating specifications to be more in line with using modern technology and techniques.

- The level of development was not sufficiently accurate in certain areas of the model, which required addressing discrepancies between design and actual construction quantities.

Overall, the pilot project was considered a success. The collaboration among UDOT, the contractor, and vendors was a key success factor for this project. Other success factors included UDOT support for taking risks, the availability of technical resources, and buy-in from the construction staff. The project was completed nearly 25 days ahead of schedule, which was attributed to the use of intelligent design and construction methods that rely on geospatial technology.

UDOT plans to implement intelligent design and construction methods and use geospatial tools on other highway construction projects as well as investigate the use of these technologies in asset management applications, specifically bridge inspection and maintenance.

Benefits and Costs

Estimates for both benefits and costs were provided by UDOT based on their knowledge of the use of GNSS rovers for real-time verification and sUAS data collection, post-processing workflows, and the efficiencies of using digital data during construction. It is difficult to isolate the use of one geospatial tool as the indicator for all the benefits gathered during this case study given the combined use of geospatial technologies used during this pilot project that resulted in the overall benefits. Additionally, it is important to note that UDOT purchased multiple sUAS for the purpose of testing numerous projects and applications. While this investment was not tied directly to the SR20 project, the BCA shows that technology was purchased and tested as part of UDOT's pre-implementation planning efforts. The technology is relatively inexpensive compared to the numerous applications and benefits that can be realized.

The sUAS was used for the following projects or applications:

Cutler Dam Bridge Inspection: UDOT tested the senseFly albris, Phantom 4, and the 3DR Solo systems for bridge inspections. The bridge has weight limit restrictions that prevent a boom truck being used for inspection, which required inspectors to climb the bridge and find any problem spots. The use of sUAS technology was tested to provide a solution to improve safety and save cost of this type of bridge inspection. The sUAS technology was able to capture 4K resolution imagery that bridge inspectors can use to see key areas under the bridge.

Veyo Arch Bridge Inspection: UDOT tested the senseFly albris and the Phantom 4 to investigate the usability of this tool for bridge inspections. UDOT captured thermal and standard 4K resolution imagery of the bridge deck, which showed stress cracks in the beams. Some of the challenges encountered during this test was having to maneuver around some scaffolding.

Logan Canyon MSE Wall Movement Analysis: UDOT tested the senseFly albris and the Phantom 4 in conjunction with STLS to monitor wall movement over the winter. UDOT is planning to fly the sUAS in the spring to determine the amount of movement since the first data collection mission.

Eagle Canyon Arch Bridge Inspection: This is a large and tall arch bridge. UDOT tested the Phantom 4 sUAS primarily to investigate the behavior of the sUAS during high winds during a mapping mission. The Phantom 4 proved to be the best sUAS to use in high winds. UDOT collected data to create a point cloud of the area to help determine drainage concerns.

Weber Canyon Survey: UDOT tested the Phantom 4 for an aerial survey of the area, which is difficult to survey due to the road having narrow shoulders and difficult terrain. UDOT also planned to test the SenseFly albris, but due to inclement weather, the mission was postponed until the snow melts. UDOT is using the point cloud and imagery to create a report that documents the need for replacing the bridge.

US-6 Survey: UDOT is currently testing the viability of using sUAS for determining earthwork pay quantities for construction projects. The sUAS data was compared to traditional survey, and it was determined the sUAS can achieve better detail on soft surfaces. The construction of this project has not yet started, but UDOT plans to test the sUAS capabilities for determining pay quantities when the project begins.

Qualitative and quantitative benefits are show in Table 30 and Table 31, respectively. Costs are shown in Table 32. The summary BCA for UDOT's implementation of sUAS and GNSS rovers for construction inspection for project SR20 is presented in Table 33.

Table 30. Qualitative benefits from using sUAS and GNSS rovers in UDOT's SR20 project.

Qualitative Benefits	Description
Improved safety by reducing exposure	It is assumed that documentation of a project will be conducted using a combination of geospatial technologies such as sUAS, GNSS rovers, and tablets. sUAS and tablets can capture photos and videos that can be used later for reviewing progress in the office.
Improved data quality of daily reports	Having imagery and/or video capture of the daily progress provides an extra level of information for documentation.
Improved data measurements for quantities	Being able to automate post-processing of data needed for calculating certain types of quantities reduces errors due to transposing numbers, etc. Also, the use of GNSS rovers in the field to take measurements during verification provides a higher level of accuracy.
Visualization of project progress for public information	Being able to record videos and create visualization models of the progress for public outreach are invaluable.
sUAS will enable data collection for multiple applications	The purpose of purchasing sUAS technology was to be able to collect data for multiple purposes that can benefit the entire enterprise.

Table 31. Quantitative benefits from using sUAS and GNSS rovers in UDOT's SR20 project.

Benefits	Measure	Data Needed	Data Input	Confidence Score	Comments
Efficiencies - construction inspector productivity	Dollars	Average full-time loaded hourly rate	$34.66	1	Loaded rate = 1.6 x average hourly rate
Efficiencies - construction inspector productivity	Percent	Time saved	50%	2	Increased efficiency due to combined use of technologies including sUAS, tablets, and GNSS rovers for real-time verification.
Efficiencies - construction inspector productivity	Each	Number of construction staff in the field	4	1	Two Trans Tech (Inspectors) One Rotational Engineer One Field Engineer
Efficiencies - construction inspector productivity	Hours	Hours worked per week	45	1	Average provided by UDOT
Efficiencies - construction inspector productivity	Weeks	Duration of project	13	1	Provided by UDOT
Survey setup productivity	Hours	Time saved	0	2	No changes observed due to no change in survey setup for other technologies.
Data post-processing – traditional survey	Hours	Time staff spent performing task	4	2	Traditional workflow: manually upload files to software, process, QA, and producing deliverables.
Data post-processing – sUAS	Hours	Time staff spent performing task	1	2	New workflow: automated photogrammetric process, QA and create workflow.

Table 32. Costs for using sUAS and GNSS rovers in UDOT's SR20 project.

Costs	Measure	Data Needed	Data Input	Confidence Score	Comments
sUAS- albris senseFly	Dollars	One-time cost	$34,990	1	sUAS (three-year replacement cycle)
sUAS- DGI Phantom 4	Dollars	One-time cost	$2,500	1	UDOT has plans to procure more devices in the future. Intended use: photogrammetric surveys.
sUAS- 3DR Solo	Dollars	One-time cost	$2,000	1	Additional antennas will be purchased to fix range of live video feed limitation.
Training (all-inclusive)	Dollars	One-time cost	$4,000	1	None
1-year product support (sUAS)	Dollars	Annual cost	$1,500	1	None
sUAS spare parts and labor warranty	Dollars	Annual cost	$979	1	None
Pix4D Mapper Pro	Dollars	One-time cost	$4,990	1	Software for sUAS
Software annual maintenance	Dollars	Annual cost	$0	1	Chose not to purchase now; upgrades are additional costs, which are unknown
Survey contract pay item	Dollars	Contract bid cost	$62,000	2	Contractor provides 3D as-built surfaces and GNSS rovers for inspection
Technical support staff	FTE	Loaded rate/hr.	$48	1	Dedicated staff for technical support of geospatial technologies $30/hour. Loaded rate = 1.6 x $30

Table 33. Summary of BCA for UDOT's implementation of sUAS and GNSS rovers for construction inspection for project SR20.

Value	Output	Measure
Project savings	$82,672	Year of expenditure in dollars
Contract value	$3,200,000	Year of expenditure in dollars
Percent savings[16]	2.58%	Overall percent savings for implementation of technology
Program savings over five years	$99,404,209	Year of expenditure in dollars; assumes an annual construction program of $800,000,000 in 2015 dollars
Program spending over five years	$70,568,060	Year of expenditure in dollars; assumes an annual construction program of $800,000,000 in 2015 dollars
Net present value	$21,836,150	Year of expenditure in dollars; assumes an annual construction program of $800,000,000 in 2015 dollars
Return on investment	28%	Percentage

Conclusions

The use of sUAS and GNSS technology for construction engineering and inspection has resulted in a positive ROI for UDOT. It is important to note that UDOT introduced a new pay item for construction survey never used before for construction projects, thus the real benefits realized for using this technology are potentially much greater. The benefits realized by UDOT's use of geospatial technology are far greater than those documented in this case study.

CASE STUDY 4: UAS FOR MEASURING QUANTITIES

Overview

Contractors use a variety of survey tools for multiple purposes including to improve utilization of their equipment fleet. Two of the more important business drivers for implementing sUAS in the mining industry are to improve the management of quarry quantities and for calculating quantities. This investment in sUAS allows contractors to have access to the technology as another geospatial tool to collect survey data and document progress of the work. Thus, it is fair to state that mining projects are also benefiting from contractors investing in sUAS.

It is important to note that sUAS are just another geospatial tool used by contractors and will not completely replace the need for collecting data with other geospatial technology. The data used

[16] Percent savings was calculated using Equation 1 from Chapter 3.

in this BCA only considers the use of sUAS for quarry quantity management. However, similar benefits could be applied to highway construction in terms of safety and efficiency.

While the value of using a sUAS was not quantified on this project, the contractor recognized that improved communication, improved data quality, and customer satisfaction are three major qualitative benefits from using this technology.

Methodology

The research team first developed an initial interview guide to document the case study. The interview guide (see Appendix B) had the following five categories:

- General Information.
- Highway Application.
- Data Collection.
- Workflows and Products.
- Cost and Benefits.

The initial interview lasted approximately one hour. There were several follow-up phone calls and emails that were necessary to get all the information needed to obtain benefit-cost information. This case study was specific to the use of measuring quarry quantities; however, contractors reportedly use sUAS to completely replace more expensive surveying tools in mining projects for specific tasks where payment is based on lump sum.

Applications

Measurement of Quantities using sUAS

Contractors use sUAS to map stockpiles of materials in quarries and mining projects for the purpose of calculating quantities. sUAS was exclusively used as a replacement for other more expensive technology. The cost of implementing this technology was minimal compared to the time efficiencies when considering the high labor rates associated with data collection.

Benefits and Costs

Estimates for both benefits and costs were provided by the contractor's knowledge of sUAS data collection, post-processing workflows, and time savings based on productivity rates. Qualitative and quantitative benefits are show in Table 34 and Table 35, respectively. Costs are shown in Table 36. The ROI summary is presented in Table 37.

Table 34. Qualitative benefits from using sUAS for mapping and calculating material quantities.

Qualitative Benefits	Description
Improved data quality of reports	Having imagery and/or video capture of the daily progress provides an extra level of information for documentation.
Improved data measurement for quantities	Being able to automate post-processing of data needed for calculating certain types of quantities reduces errors due to transposing numbers, etc. Also, the use of GNSS rovers in the field to take measurements during verification provides a higher level of accuracy.
Improved communication and customer satisfaction	sUAS data is quickly captured and shared with stakeholders for rapid decision making as well as situational awareness. This data can also be effectively visualized to meet customer expectations of quality and resolution.

Table 35. Quantitative benefits from using sUAS for mapping and calculating material quantities.

Benefits Category	Data Input	Measure	Confidence Score	Comments
Data Collection Efficiency Gains - employee hourly rate	85	Dollars	1	Average full-time loaded hourly rate
Data Collection Efficiency Gains - traditional duration	40	Hours	1	Total hours spent on quantity measurements (pre-implementation)
Data Collection Efficiency Gains - percent time savings	90	Percent	2	Total hours spent on quantity measurements (post-implementation)
Data Post-Processing Efficiency Gains - employee hourly rate	64	Dollars per hour	2	None.
Data Post-Processing Efficiency Gains - data post processing - traditional survey	6	Hours	2	None.
Data Post-Processing Efficiency Gains - data post processing – sUAS	2	Hours	2	None.

Table 36. Costs of using sUAS for mapping and calculating material quantities.

Costs	Data Input	Measure	Confidence Score	Comments
Surveying Equipment - albris senseFly (sUAS-RTK)	$49,590	Dollars	1	One-time cost
Surveying Equipment - maintenance for sUAS	$3,500	Dollars	1	Annual cost
Surveying Equipment - spare parts and labor warranty (sUAS)	$2,245	Dollars	1	Annual cost
Surveying Equipment - training	$3,132	Dollars	1	One-time cost
Software - Global Mapper	$1,850	Dollars	1	Includes post-processing service
Software - Pix4D Mapper Pro	$9,000	Dollars	1	750 subscription
Miscellaneous costs - computers/iPads	$10,000	Dollars	1	Replaced every three years
Miscellaneous costs - Insurance	$2,100	Dollars	1	Annual cost

Table 37. ROI Summary.

Value	Output	Measure
Five-year efficiency savings	306,256	Year of expenditure in dollars
Spending over five years	24,242	Year of expenditure in dollars
Five-year ROI	147%	Assumes no more purchases

DESK SCAN: UAS FOR HIGHWAY CONSTRUCTION

The purpose of this desk scan was to review secondary independent literature and other sources relevant to the use of sUAS in construction and investigate the use of sUAS with highway construction contractors and geospatial service providers. This information was then synthesized into a summary of the various applications, incurred costs, and realized benefits of using sUAS technology. This desk scan illustrates that sUAS is a valuable and versatile tool adding value to the highway construction sector.

Literature Search

The majority of the information found during the literature search consists of publications by state DOTs researching and implementing sUAS and some industry magazines highlighting geospatial professional companies expanding their services to include sUAS. Limited information was found regarding the use of sUAS by highway contractors; mostly the information came from industry magazine articles and sUAS service provider blogs. The most relevant publications, including highway construction applications and sUAS technology implementation costs, are summarized below.

Highway Contractors

In the newsletter of *Construction Executive* magazine, McCann (2016) provides an overview of emerging sUAS applications in heavy/highway construction, including the following:

- Creating topographic maps with images for planning, bidding, and estimation.[17]
- Using sensors and surveying equipment to capture details on density and rock formations for excavation and blasting purposes.
- Measuring and monitoring materials stockpiles and asphalt plants.
- Pit planning for highways traversing forested and mountainous terrains.
- Road and bridge inspections.[17]

McCann (2016) discusses how contractors that own sUAS equipment need to insure it and the ones that outsource sUAS services need to verify that their providers have the appropriate licensing and insurance. In addition, contractors or their sUAS providers should have aviation liability insurance.

A case study by *Identified Technologies* (2016) highlights the use of its eeDaaS (end-to-end Drone as a Service) by a contractor to survey a dangerous, mountainous site for a new section of highway in Kentucky. The use of the sUAS technology translated into significant time savings for both survey data collection and processing. The website for *I Build America* (2016) highlights sUAS among several new technologies used during the earthwork construction phase of a new 11-mile section along the US 29 highway in Somerset, Pennsylvania. The contractor used a sUAS service provider to document the as-built conditions, remotely view the site, take photos, and generate progress reports. They found sUAS technology to be particularly helpful surveying high elevated slopes.

State DOTs

McGuire et al. (2016) conducted a study for the KDOT to determine whether it is beneficial for KDOT to implement sUAS in its routine operations. The study included a detailed review of

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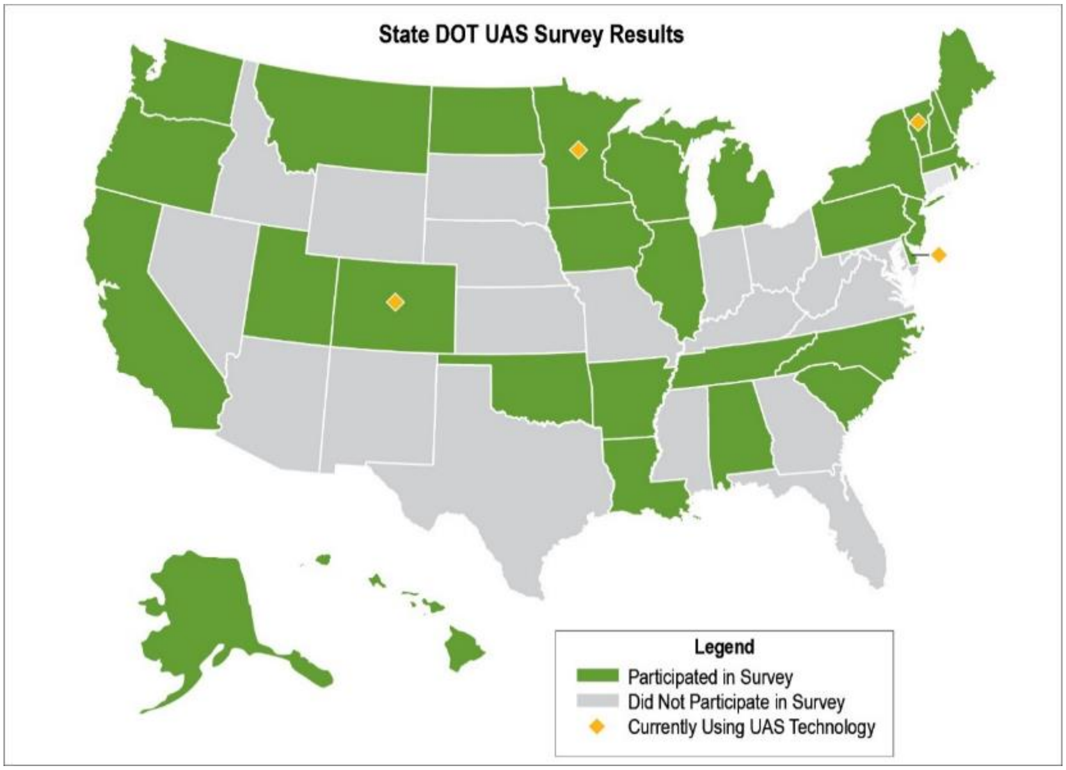
[17] Note that these applications are limited to new highway construction projects (vs. reconstruction) due to current restrictions that prevent flying UAS in certain areas.

sUAS research done by other state DOTs (Utah, Georgia, Washington, Arkansas, and North Carolina) and a survey that was sent to all state DOTs. Figure 51 shows the survey results.

Of the state DOTs that responded to the survey, four indicated that they are currently using sUAS: Colorado, Delaware, Minnesota, and Vermont. None of these four state DOTs reported currently using sUAS for highway construction-related activities but rather for other transportation applications such as environmental, mine, and highway inspections (landslides and rock fall). The following sUAS applications were recommended for KDOT: bridge inspection, radio tower inspection, surveying, road mapping, high-mast light tower inspection, stockpile measurement, and aerial photography.



Source: KDOT

Figure 51. Map. State DOT sUAS survey results. (McGuire et al. 2016).

McGuire et al. (2016) provides a cost estimate for their specific recommendations for KDOT to launch a sUAS program, as shown in

Table 38. As discussed later in this report, these startup costs are similar to the costs reported by the highway contractors interviewed. Note that McGuire et al. (2016) discuss the cost of creating a position for a sUAS pilot at KDOT; however, it appears that contractors typically have someone available on staff to operate the sUAS equipment and are not hiring a person specifically for this task. McGuire et al. (2016) also discuss the cost of software for data processing when doing more technical tasks such as surveying, but it appears that most contractors are not accurately tracking this expense.

Highway contractors and service providers interviewed mentioned that several state DOTs are currently conducting research on sUAS technology, including Florida, Maine, Nevada, and Ohio.

Table 38. Estimate of sUAS program startup costs. (McGuire et al. 2016).

Item	Price per unit	Recommended units	Total
Honda EU2000 Generator	$999.00	1	$999.00
Revolectix 24VDC 55A Power Station 1320W	$250.00	1	$250.00
Battery iCharger 308DUO 1300W Dual Channel	$259.00	1	$259.00
DJI S900 sUAV, A2 controller, Z15 gimball	$3,400.00	1	$3,400.00
DJI S900 sUAV – backup unit and extra parts	$1,350.00	1	$1,350.00
Li-PO battery 1500mAh	$373.00	4	$1,492.00
Futaba 10CAG 2.4 GHz Airplane MD 2 with R6014HS Receiver	$629.00	2	$1,258.00
DJI Inspire 1 – with controllers (a complete kit)	$3,498.00	1	$3,498.00
iPad Air 3 Mini or Samsung Galaxy Tab S2 – 8”	$499.00	2	$998.00
Sony a5100 camera with a standard lens	$598.00	1	$598.00
Sony a5100 camera with infra-red conversion	$798.00	1	$798.00
Total	**$12,653.00**	**16**	**$14,900.00**

Industry magazine *Inside Unmanned Systems* (Choi 2016) reports that ODOT is starting a sUAS program to help survey areas for construction efforts. ODOT is starting the program with an Aibotix Aibot X6 Hexacopter with traditional RGB cameras to create 3D maps. It reports that there is a learning curve when using sUAS technology for surveying, especially for processing the imagery captured with the sUAS. ODOT notes that current regulations limit the applications for highway projects since it is not allowed to fly over nonparticipants, and also the vertical accuracy achieved with the technology today is limited to certain applications.

State DOTs Outsourcing sUAS Services

Recently, companies that provide geospatial professional services are expanding their fleets to include sUAS, recognizing the potential applications for many industries, including transportation. Press releases from different highway consultants promoting their addition of sUAS services were identified during this search. (Michael Baker International 2016) (Woolpert 2016)

While some state DOTs are doing research and/or testing to start sUAS programs, other state DOTs are procuring professional services to test and implement the use of sUAS. One example is the Nevada DOT which recently awarded a statewide contract for digital aerial imagery and video and/or other remotely sensed data (Lillian 2016). Another recent example is a request for proposals recently issued by the Montana DOT (MDT 2016) for a two-year contract to conduct "as needed" sUAS testing. Figure 52 below shows a snapshot of the scope of work advertised, which indicates that one of the goals is to aid construction administration staff in determining earthwork quantities.

SCOPE OF WORK

MDT intends to investigate the viability and usefulness of utilizing unmanned aerial systems (UAS) to map highway construction projects during and after construction to aid construction administration staff in determining earthwork quantities. The initial strategy is to utilize the services of the consultant selected for this term contract to map two projects slated to begin construction in 2016. The specific projects have not yet been finalized. The projects will likely be rural in nature and in the range of 5-8 miles in length.

The scope of services to be provided includes using an Unmanned Aerial System (UAS) to perform photogrammetric mapping and orthophoto production using a digital camera. The consultant will be expected to deliver a digital terrain model for use in calculating earthwork quantities, along with orthophotos. The scope of work will encompass all phases of data acquisition, data processing and final product development and delivery. Deliverables will need to meet MDT requirements for accuracy, format, timeframe, etc. The Consultant will also be responsible for the ground survey work necessary to correlate and verify the collected data, using a Montana-licensed land surveyor. Concerning accuracy requirements, MDT's goal is to evaluate the capabilities of this technology. The proposal must contain details regarding the levels of accuracy and precision that will be achieved, specifically the vertical tolerance. In order to achieve the goals and intent of this data acquisition, an acceptable level of ground sample distance must be met. Expectations regarding ground sample distance are in the range of 2.5 cm to 5.0 cm. Anything greater than 5.0 cm is generally not deemed acceptable for this work. A ground sample distance less than 2.5 cm will result in a higher proposal score. Regarding horizontal and vertical accuracy, MDT targets 0.20' – 0.35' at the 95% confidence level for this type of work, and should be achieved.

Source: Montana DOT

Figure 52. Image. Screenshot of a Scope of Work advertised for professional services using sUAS.

The *North Carolina Unmanned Aircraft Report* (Estes 2014) discusses the pros and cons of either purchasing sUAS equipment or using a third party. The benefits include cost efficiency for state DOTs with aerial asset needs, while costs include increased needs for specialized staff and infrastructure. As for using a third party for sUAS operations, benefits include access to the latest technology and no burden to operate and maintain the sUAS equipment, while it possibly increases costs.

Phone Interviews

To accomplish the phone interviews, a combination of emails and brief phone calls were made to interview highway contractors. The team was able to contact four large highway contractors and all four responded that they are using sUAS. Three provided contact information to discuss their sUAS operations, and two contacts were available for phone interviews, which are summarized below. A regional highway contractor based in Akron, New York, responded that as of now, it has limited experience with sUAS from using a company to fly over gravel pits and generating contour maps.

The team also contacted seven highway contractors in Texas. Three interviews are summarized below. Two other Texas contractors responded that they are not using sUAS but are discussing or investigating their use. For example, one contractor tried to hire a sUAS provider to obtain progress photos for its 183 South Project in Austin but ended up using helicopter flights due to the proximity to the airport and also not being satisfied with the quality. A sixth Texas contractor responded that it is not using sUAS at all, and one contractor did not reply.

Lastly, for this desk scan, three interviews were conducted with geospatial services companies. The notes for these interviews are summarized below.

Large Highway Contractor #1

A Construction Technology Engineer at a large highway contractor was interviewed. This engineer is also a certified pilot who operates their sUAS out of the Nevada regional office. The firm has five sUAS in different offices and all the data processing and management is conducted in-house. Initially, the equipment was leased, but proceeded with purchasing the equipment and doing research and development in-house. It was noted that figuring out the processes for establishing ground control and achieving the accuracies needed for project surveys was more challenging than anticipated.

All of this firm's sUASs are multi/quadcopters, and their main application is surveying their large earthwork projects. In addition, this firm uses the technology in smaller projects for the following:

- Monitoring stockpiles; note that this application does not require precise ground control and they could scan every other week.

- Construction and progress monitoring (images).

- Environmental inspections: accessing environmentally sensitive areas and other hard to access places.

- Some pre-site inspections: not for photogrammetry but images. More accurate than Google Earth and less expensive then purchasing images from counties.

As for the new sUAS Rule (Part 107), the engineer feels that it clearly outlined regulations for the use of sUAS technology. There is the limitation of not flying sUAS over live traffic, but contractors could apply for an exemption and fly up to traffic from both directions and cover most of the project. In addition, traffic control could be used to complete sUAS surveys. Some challenges that still remain for sUAS surveys include the following:

- Lead time for "permits." For example, if flying near an airport, it can take from 60 to 90 days to obtain approval.
- Reflective surfaces: snow, water, etc.
- Vegetation; lidar sensors help but integrating to sUAS is extremely costly.
- Limitations when trying to inspect bridges/structures.

Large Highway Contractor #2

The Director of Virtual Design and Construction (VDC) for a large highway contractor was interviewed and explained that the firm has been exploring the use of sUAS for a year. The firm has a yearly agreement with a sUAS manufacturer that markets sUAS for the construction industry. The sUAS manufacturer offers a rental agreement that includes processing of the data captured with the sUAS. The benefits for this type of agreement include not having to keep up with the sUAS maintenance, "if it fails, you get a new one," and also the staff can import the information already processed into CAD for modeling.

The Director suggested that there are other companies with slightly different business models that do not manufacture sUAS but offer Drones as a Service (DaaS). The firm has licensed pilots that find the right sUAS for each job and also conduct the data processing and create 3D surfaces for contractors. One benefit of this service is that the firm's remote pilots take care of obtaining the right notifications/permits and complying with relevant federal, state, and local regulations. One of the main challenges identified for contractors with the sUAS technology currently is understanding the legal requirements and regulations. Working with sUAS and DaaS companies ensures they are not breaking the law, they are operating safely, and are good stewards to the community.

The firm is currently renting a multi/quadcopter with the main goal being capture images for photogrammetry and creation of 3D surfaces. These 3D surfaces can then be used for the following:

- Construction and progress monitoring.
- Earthwork volume calculations.
- Monitoring stockpiles (e.g., volume and movement of materials).
- Videos and images for public information (project updates).
- Logistics planning; traditionally, contractors would use Google Earth for this purpose, but those images can be two or three years old and not represent current conditions.

Some of the challenges when implementing the sUAS technology include the large size of the files for the data captured with UAVs and the need for computing power to process those images. There is also a learning curve to figure out the process to establish job-level ground control.

Lastly, the firm has more than 300 projects at one time in North America, so the knowledge of what the firm is doing with sUAS is limited. Many operations are more regional and local. Project teams are allowed to procure sUAS or sUAS services as they see fit.

Highway Contractor #1

The Director of the Surveying Department at a highway contractor was interviewed. The firm has been using sUAS for about a year through an agreement with a sUAS manufacturer. They trained a staff member (pilot) to operate sUAS and their surveying department processes the imagery received from the manufacturer. Now the firm is going to dedicate a second person to sUAS operations. It is noteworthy that they do a lot of commercial/high-rise construction and conduct sUAS surveys for those projects as well.

The sUAS currently being renting from the manufacturer is a quadcopter, and its main applications in highway construction are as follows:

- Monitor stockpiles (monthly).
- Survey borrow pits.
- Survey areas with significant excavations planned.

The Director suggested that the broader contractor community is very excited about the sUAS technology and are always looking for new applications. The firm conducted a sUAS survey for a Farm to Market Road in Texas and a highway project in north Texas with very steep slopes. The sUAS surveys gave them a rough estimate of the quantities and progress for these projects. Similar to the previous interviewees, it was noted that the sUAS limitations for highway projects are typically where you can fly (e.g., live traffic). In addition, the Directot explained that the sUAS technology the firm is using currently is not accurate enough for engineering surveys. For a large highway project, the firm is exploring the use of fixed-wing sUAS with longer flight times and also lidar as a separate tool (not integrated to the sUAS).

Highway Contractor #2

An executive for a highway contractor based in Houston, Texas, was interviewed. The executive noted that the firm purchased a multicopter sUAS and trained staff to operate it in-house. The firm’s main application is to take high-definition progress photos of their projects. The executive anticipates that their future applications will be creating 3D/surface models and monitoring stockpiles.

Highway Contractor #3

The contact with a highway contractor referred the research team to one of their affiliates. The affiliate firm interviewed produces recycled concrete and asphalt materials. The firm has been using sUAS for about 1.5 years for measuring stockpiles. The firm has looked at other applications for the highway contractor, but noted limitations of operations, such as flying over moving traffic. The firm has someone in-house that operates UAVs, about once a month. This person was acquiring a pilot’s license as a personal hobby, and the firm helped him complete the certification to use it at work as well.

The firm owns two sUAS, a fixed wing (eBee from senseFly) and a multi/quadcopter (Indago from Lockheed Martin). The firm’s main application is to measure material stockpiles. This application does not require tying the data to project coordinates or very high accuracy as required for design applications. In addition, they mainly fly over private property (stockyards) versus public areas as required for other highway construction applications. It was noted that since their systems are on the higher end, they are able to program them to land safely if they encounter issues/run out of battery.

As a materials producer, the firm’s yards/stockpiles are significantly large and there are major safety benefits when having sUAS surveys versus a surveyor climbing piles. There is increased coverage and accuracy with aerial surveys of material piles. There is also major time savings. For example, it used to take approximately two to three weeks for a surveyor to measure the different yards/stockpiles scattered around Houston since in one yard they can have up to 10 large piles. With sUAS surveys, this process is down to approximately one week since flying over an entire yard takes about 15 minutes, and there is also a time savings with the data processing and calculations.

Geospatial Services Company #1

A Project Manager from a national geospatial services firm that operates a fleet of planes, sensors, and sUAS was interviewed. The firm operate multiple sUAS, including multicopters, fixed wing, and an aerial imaging system that integrates a Cessna-piloted aircraft (Figure 53-A) and sUAS equipment (Figure 53-B). The benefit of this type of system is that it captures similar data as with a UAS and it is not affected by FAA Part 107 sUAS regulations such as not operating near “non-participants”/live traffic or the wait periods to obtain authorizations/waivers (Federal Aviation Administration 2016b).

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A. Subfigure photo of a Cessna. (Schneider 2016).

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B. Subfigure photo of a sUAS equipment mounted on the Cessna. (Schneider 2016).

Figure 53. Photos. Cessna-mounted UAS alternative. (Schneider 2016).

The Project Manager explained that many highway contractors are exploring sUAS technology and some of them are purchasing sUAS equipment. However, it was suggested that many of them are still in the research stages and are not fully implementing the technology in their projects. One example is a highway contractor who purchased sUAS equipment for a 17-mile project, but had to hire the geospatial services company to fully implement the technology for that project.

When asked about the different applications of sUAS technology in highway construction projects, the Project Manager explained that it is important to understand the accuracy required for the different uses and what are the appropriate sUAS systems. The Project Manager noted that based on the current technology it is not feasible to complete engineering surveys for design plans or final as-builts, and that the main applications in highway construction are as follows:

- Construction monitoring.
- Earthwork volume calculations.

- Intermediate-as builts, monitoring progress for partial payments, etc.

Geospatial Services Company #2

The Director of Aerial Services at a geospatial services company, was interviewed and explained the firm has used sUAS technology for engineering and as-built surveys for Pennsylvania DOT projects. The Director emphasized that the person conducting and analyzing the surveys needs certain skills and qualifications. Also, it was noted that sUAS are another tool and that for some applications can be more efficient than ground surveys in terms of both time and cost. Similarly, for some applications it can be less expensive than conventional aerial surveys.

Geospatial Services Company #3

An executive for a geospatial services company noted that the firm is a full-service mapping firm that provides geospatial data collection and processing services, including imagery and lidar acquisition for generation of mapping and site documentation products in Arizona, California, Pennsylvania, and Texas. The executive explained that they have used the sUAS technology for inspection and 3D reconstruction for various bridge and construction projects. It was noted that what used to take a bridge inspector one week to physically inspect only takes an hour for a sUAS and only a couple of days for an inspector to review the data in the office with large format and high-resolution monitors.

Cost of sUAS

Table 39 summarizes the cost information provided by highway contractors and service providers during the phone interviews. All companies provided a rough estimate for the sUAS purchase, but none of them reported detailed costs for their entire sUAS operations. Two contractors pay $25,000 for a rental agreement with a sUAS manufacturer; two contractors purchased sUAS ranging from $20,000 to $60,000 each; and one contractor purchased a less expensive system for $2,000 to take project photos. Both service providers reported a cost of $50,000 each for their professional sUAS systems.

Table 39. Summary of sUAS cost information.

Company	UAS Cost	Other Cost Information/Comments
Large Highway Contractor #1	Multicopters: $30,000 to $60,000	The technology is evolving so fast that companies are likely to purchase new systems in two to three years. Safety benefits are hard to quantify but are significant. For example, there are fewer minor injuries, especially for people measuring stockpiles, etc.

Company	UAS Cost	Other Cost Information/Comments
Large Highway Contractor #2	sUAS manufacturer agreement: $25,000	None.
Highway Contractor #1	sUAS manufacturer agreement: $25,000	Typically compare the costs between sending a crew for a particular project and conducting a sUAS survey. There are 1-2 staff members operating sUAS full time.
Highway Contractor #2	Multicopter: $2,000	Main use of sUAS is to take project photos. Costs for operating and maintaining the system have not been tracked.
Highway Contractor #3/Affiliate	Fixed wing and multicopter: $20,000 to $30,000 each	None.
Geospatial Services Company #1	Estimated cost of $50,000 for sUAS versus $1 million for conventional aerial systems for photogrammetry/ remote sensing	Estimate of $150/hour for sUAS survey versus $1,500/hour for conventional aerial survey. Most savings are due to the differences in cost for mobilization and data capture.
Geospatial Services Company #2	Fixed wing: $50,000	None.
Geospatial Services Company #3	Multicopter: $13,000 each	Stated that the sUAS filled a space that was not covered by their current business model. The cost effectiveness came into play on small sites; however, the larger the project, the less compelling the sUAS became. Safety benefits are hard to quantify but are significant.

Desk Scan Conclusions

Based on the information provided by the highway contractors interviewed and collected during the literature review, the use of sUAS technology is increasing. The conclusions gathered for the use of sUAS by highway contractors are as follows:

- All large highway contractors contacted use sUAS.

- Of the seven regional highway contracting offices contacted, three use sUAS, one has limited experience, two are discussing their use, and one has no experience at all.

The types of sUAS used by highway contractors are as follows:

- Out of the five contractors interviewed, four use multi/quadcopters.
- One of the contractors owns a fixed-wing sUAS.
- One of the contractors is considering the purchase of a fixed-wing sUAS for a large highway project.

Highway contractors use sUAS for the following purposes:

- Earthwork volume calculations.
- Monitor stockpiles (volume and movement of materials).
- Construction, progress monitoring, and project updates (images).
- Environmental inspections.
- Pre-site inspections and logistics planning (images).
- Survey borrow pits.
- Survey areas with significant excavations.

The benefits of using sUAS are as follows:

- Improved safety benefits, although this is difficult to quantify. For example, there are fewer minor injuries, especially for people measuring stockpiles, climbing slopes, etc.
- Increased coverage and accuracy with aerial surveys of material piles.
- Significant time savings for survey data collection and data processing and calculations.
- Videos and images of places not easily accessed before (e.g., steep slopes).

The highway contractors interviewed did not report detailed costs or ROI information—only rough estimates for the initial sUAS equipment purchase, as shown in Table 39. One contractor reported one to two people dedicated to sUAS operations but noted that they also conduct surveys for commercial construction projects and not just highways. The contractors that lease equipment expressed that the lease pays for itself.

CHAPTER 5. SUMMARY OF KEY OBSERVATIONS AND CONCLUSIONS

This study focused on documenting how geospatial technologies are being successfully implemented by state DOTs for multiple applications. The comprehensive literature review identified four applications for further investigation through case study documentation. Each case presented unique perspectives, challenges, and opportunities; however, the use of geospatial technology was led by the need to streamline processes, improve efficiency, and increase safety.

The most significant finding during this study was that contractors are more progressive with using geospatial technologies such as high precision survey tools (e.g. total stations, GNSS) for AMG construction methods and sUAS data collection for measuring earthwork quantities and construction progress monitoring. This is mainly due to the fact that these tools have become essential in providing innovative solutions for construction means and methods that result in accelerated project delivery and increased safety through reduced exposure to traffic and heavy construction equipment.

Nevertheless, state DOTs are not far behind in using geospatial technologies. In fact, photogrammetry, aerial and mobile lidar, and GNSS have been successfully used for many years, even decades, during the pre-construction phase of a project for many state DOTs. The challenge state DOTs face for expanding the use of geospatial technologies beyond pre-construction is the perceived cost and lack of resources needed for implementation. However, it was found that state DOTs are expanding the use of geospatial technologies, specifically MTLS for collection of asset inventory, GNSS rovers for construction inspection (real-time verification), and sUAS for collecting data on as-built construction surfaces and for bridge inspections.

Given how fast geospatial technology changes and being pressured to do more with less resources, it is becoming more difficult for state DOTs to invest in this technology. Developing a sound business case using the tools in this study can start a thoughtful discussion on evaluating potential technology improvements that benefit not only organization effectiveness, but also stewardship of the taxpayer’s money.

Lastly, the main key findings of the study can be summarized as follows:

- Continuing research, investment, and experience in geospatial technologies will lead to increased efficiency and cost savings as the technology becomes integrated.
- Appropriate tools should be selected based on the job requirements and then applied properly in order to meet the accuracy and efficiency expectations.
- Institutionalizing processes and workflows for incorporating geospatial data into digital models improves effectiveness of project delivery.
- Maintaining an appropriate level of geospatial technology understanding internally is necessary to ensure outsourced geospatial services meet project requirements.

- As technology matures lessons learned can be tracked and leveraged to sharpening ROI calculations as well as improve operational effectiveness.

- ROI for sUAS is difficult to quantify due to the current maturity level of the technology, but the ability to collect massive amounts of data quickly and safely are weighted highly.

- There is uncertainty in the ability of using Structure from Motion (SfM) algorithms for high accuracy mapping using sUAS, non-metric cameras. Significant work remains to fully test and document strengths and limitations of SfM.

- sUAS regulation changes driven by public engagement have improved capability and technology transfer in the highway construction sector.

- 1Part 107 clarified the regulatory requirements for sUAS practitioners and allowed for reduced start-up costs as well as flexibility in operating constraints, but it also has identified a need for state DOTs to implement safeguards that ensure qualified surveying and mapping services are provided. Part 107 compliance should be viewed as a minimum requirement and considered with other qualifications depending on the application.

- Professional organizations and jurisdictional licensing boards will need to urgently consider how sUAS impacts minimum standards of practice to limit unqualified practice. However, state DOTs have an opportunity to be more progressive then these organizations by ensuring specifications include the relevant qualification requirements.

EMERGING TRENDS AND DIRECTION

The geospatial technologies discussed in this report have opened the doors to many future opportunities for state DOTs. While one can only speculate about the future, this section describes the trends that are likely to occur based on past and current advances. It also discusses some of the challenges and opportunities associated with these trends. Specifically, the research team anticipates the following:

- Sensor capabilities will improve with respect to resolution, accuracy, and speed.

- Multiple sensors will integrate on a single platform.

- Software programs will allow for more data types, handle larger datasets, and expand automation abilities.

- Geospatial technology will proliferate areas and applications with limited exposure to geospatial technology.

- UAS technology will mature and find a place in the toolbox as platforms, sensors, operational capabilities, and regulations improve.

- GNSS and the National Spatial Data Infrastructure will strengthen through continued advancements in accurate and precise geodetic positioning.

- Use of AMG will expand and 3D models will become widely used in both design and construction.
- Connected and automated vehicles will rely heavily on geospatial technology for accurate situational awareness.
- ROI information contained in this report will enable state DOTs to share lessons learned, costs, benefits, and technology management best practices so stewardship of taxpayer funds are held paramount.
- FHWA's Every Day Counts initiative will resonate with state DOTs so strategic planning of effective use of geospatial technology goes beyond just the immediate project needs.

Improved Sensor Capabilities

First and foremost, recent experience has shown tremendous improvement in sensor capabilities. Future sensors will continue to have improved resolution and accuracy capabilities. The speed and efficiency at which they can collect data will also continue to improve. The size, weight, and power consumption of these sensors have decreased, enabling more flexibility in using them in platforms such as sUAS. *NCHRP Report 748* (Olsen et al. 2013) discusses emerging technologies for lidar, including full-waveform capabilities, flash lidar, and photon-counting lidar, which have opened new doors for improved data analyses with lidar systems.

The key challenge of this proliferation of capabilities is determining what level of data quality (accuracy and resolution) is optimal from an ROI standpoint. While there are certainly benefits to higher data quality, the actual accuracy and resolution requirements for optimal ROI needs further study for various transportation applications. Too high a resolution will often result in data processing bottlenecks for limited added value to a particular project, and in some cases, may result in significant delays on the project, resulting in lower ROI. Alternatively, in some cases, it may be worth obtaining data of higher quality than needed for a project if that data may be used for an application in the future that requires higher quality. Furthermore, as state DOTs gain more experience with these technologies, including improved IT infrastructure and trained employees, higher ROIs can be achieved. These capabilities will also directly influence the accuracy and resolution requirements for a dataset to yield the optimal ROI for the intended (and unintended) applications.

Integration of Multiple Sensors on a Single Platform

Currently, many geospatial technologies exist as single, distinct systems. However, a trend is developing to combine multiple sensors into a single platform that can be linked through the geospatial sensors (position and time). Currently, there are few commercial systems that combine these sensors, and users must develop custom solutions for sensor integration. Current challenges include coordinating the various data streams and calibrating the individual sensors. *NCHRP Synthesis 446* (Olsen et al. 2013) found that many of the requirements in the *Manual on Uniform Traffic Control Devices* are geospatially related and can be collected from a single platform.

Software Enhancements

In addition to improvements with the hardware and sensors themselves, software will continue to improve in terms of integrating a larger range of spatial data types, handling larger datasets efficiently, and automating many tedious, manual tasks. Overall, with the proliferation of smart devices there is a trend toward smaller, more powerful mobile apps rather than larger, more complicated software packages installed on a desktop computer. It is likely that geospatial technologies will continue to improve in both of these realms. The smaller apps will make it simpler for a wider audience to use the data; however, the larger, more complex software programs will likely still be part of the data processing workflows for the geospatial professionals preparing the data for use by others.

Computer vision algorithms continue to result in improved capabilities, including object recognition and extraction from rich geospatial datasets. As more feedback is provided to vendors, these technologies will become tailored to provide additional capability to the data, resulting in robust datasets that can be more efficiently queried.

Another major enhancement related to software is the continued expansion of cloud computing. There will be less reliance on a state DOT having substantial computing hardware and powerful workstations. Cloud computing will provide more efficient access to computer clusters for rapid processing, data storage, and data backup solutions. Data storage and handling will be more effective in the cloud, and users will work from a terminal providing a connection to the data rather than the user transferring data across physical IT infrastructure. Although ROI will vary depending on each state DOT’s needs and current IT infrastructure, higher ROIs will likely be possible given continued advances and use of cloud computing. For example:

- State DOTs will not be required to spend as much on advanced hardware and software for employees. Upgrades and routine procedures would be handled via the cloud computing service.

- It will be easier for state DOTs to share and use the data throughout their organization. Less time will be spent in copying/transferring data in a full cloud computing solution.

- Improved access and continued usage of the data will likely lead to new innovation and applications realized for the technologies as more employees have the data at their fingertips.

Further, advanced geospatial data is being integrated more into mainstream engineering packages such as CAD and GIS, enabling more users to exploit the data for their needs. However, while many cloud computing solutions have advanced security mechanisms, data security protocols may be a concern with cloud computing depending on each state DOT’s legal requirements. Unless a full cloud computing service is used where data can be stored, processed, and analyzed in the cloud service, there can be inefficiencies with transferring data between the cloud and local storage.

Proliferation of Geospatial Technology

Because of the hardware and software enhancements described in the prior sections, ease of access throughout the state DOT will result in technologies being used for new applications and in divisions that currently have limited exposure to geospatial technologies. As an example, simpler versions of geospatial mapping software (e.g., Google Earth) have become widespread and reach a much larger audience than larger, more powerful software (e.g.., ArcGIS). Location-based services and information will be important to tie data together that have been traditionally collected in spreadsheets, data logs, or other forms that are not georeferenced. The location information will also be important for improving communication with the public on their smart devices.

Nonetheless, many challenges come with the proliferation of technology such as there being more options with various capabilities that make selecting the right tool to achieve an optimal ROI more difficult. For example, as discussed in Chapter 2, there are a wide range of GNSS sensors from consumer to high quality survey grade systems. The capabilities and applications of these sensors are very different. Education and training is important to help users understand fundamental geospatial principles, such as positional uncertainty, so that users understand the limitations of the sensors and do not attempt to use data from a lower accuracy system when higher accuracy is required. Data that is ease to use and readily available can present challenges where people inappropriately use that data for a task for which it is not suitable. Hence, state DOTs should ensure that they have adequate resources in terms of protocols, training, and geospatial professionals.

Prevalence of UAS Technology

UAS technology is rapidly decreasing in cost and becoming increasingly used in professional and non-professional activities. Ongoing improvements in battery technology will enable greater endurance and payloads. Enhanced hardware, firmware, and software will likely lead to continuous improvements in safety, reliability, and efficiency of UAS operations. Notwithstanding these enhancements, continued research is needed to effectively transition UAS into widespread operational use for construction and transportation engineering applications. Advancing beyond initial “proof-of-concept” studies, thorough empirical assessments will be needed to develop detailed operational procedures and safety plans for select use cases. Further work in statistical and empirical uncertainty analysis is needed to better understand and model uncertainties in data and information derived from UAS missions, including imagery processed using SfM software. Through ongoing research and development in these areas, as well as the recent trend toward easing the regulatory environment for commercial firms using sUAS, the future of UAS in construction and transportation engineering is extremely promising.

One emerging trend in UAS technology for surveying and mapping applications is the development of direct georeferencing capabilities to reduce the reliance on extensive ground control, which can be expensive and logistically challenging to achieve. This is being achieved through the development of low-cost, light-weight RTK/post-processed kinematic GNSS receivers and micro electro-mechanical system inertial sensors for use in GNSS-aided INS. Carrier-phase RTK-capable GNSS receivers are beginning to be marketed as original equipment manufacturer components for a few hundred dollars or less, and micro electro-mechanical system-based INS weighing as little as 10 grams are also being advertised. However, despite the excitement surrounding these inexpensive, light-weight, low-power components that appear to offer the ideal solution for direct-georeferencing of sUAS data, their performance must be rigorously investigated before they can be adopted for operational use in surveying and mapping applications.

While the types of sUAS-capable cameras and their specifications (e.g., spectral and spatial resolutions) continue to improve, work remains to be done to enable widespread use of lidar on sUAS. While a few companies currently market lidar sensors that are small enough and have low enough power requirements to be operated on sUAS, one of the limiting factors to date has been the lack of robust, reliable direct-georeferencing capabilities. Since, as noted above, this is a currently an area of rapid development, it is likely that sUAS-based lidar will also see rapid growth in the near future.

One of the key challenges in sUAS is the limited battery life; however, battery technology continues to improve with proliferation of smart devices or alternatives such as solar panel cells that will likely improve battery life for sUAS, enabling them to be more effective on larger projects. Additionally, smaller, lightweight sensors that consume less power will continue to evolve, which will help improve battery life.

Some new sUAS systems also have the ability to sense and avoid objects. These sensors will likely become more commonplace ensuring safer operation of UAS. Additionally, research is currently underway to quickly analyze the collected data *in situ* to make sure all of the appropriate data have been collected before leaving the site. Further, additional research is being completed for sUAS swarms to communicate with one another and work together to complete a task. These techniques will likely result in more efficient and effective data-gathering practices.

On the software side, SfM software is already seeing widespread adoption for 3D reconstruction and creation of point clouds and orthoimages from sUAS imagery with enhancements continuously underway. While conventional photogrammetry is already well established as a means of accomplishing certain construction and transportation-related tasks, the future of SfM is extremely promising, especially when integrated with UAS technology. However, while SfM is currently being referenced using such terms as "revolutionary" and "game changing," significant work remains to fully document both its strengths and limitations in surveying engineering applications. Future work should focus on the following:

- Rigorous uncertainty analysis for UAS-based SfM.
- Direct georeferencing of UAS-based imagery to alleviate some ground control requirements.
- Development of standards and specifications for construction applications.

Arguably, the greater need is for improvements to flight planning and data acquisition software depending on the software experience of the project team. For example, for the UAS bridge inspection project described in this report, the ideal planning software would enable the user to virtually enter bridge elements of interest and navigate through an existing point cloud (e.g., from airborne lidar or an earlier UAS overhead flight) to specify the safe standoff distance, identify the location of the takeoff and landing zone, and identify the locations of any obstructions or obstacles to avoid.

The software would then automatically generate a flight plan that could be flown semi-autonomously using ultrasonic sensors, lidar, and/or stereo vision to prevent the aircraft from ever getting closer to the structure than the specified stand-off distance. The pilot would then have the ability to take control manually at any time, or simply to have the multicopter UAS stop and hover in place at any point while zooming, panning, or tilting the camera(s). While UAS manufacturers are already working to develop this type of functionality in their planning and acquisition software packages, additional work is needed to make these capabilities fully operational.

GNSS and the National Spatial Data Infrastructure

GNSS infrastructure has rapidly progressed over the last several years with satellite launches by the European Union of its Galileo constellation and by China of its BeiDou constellation. Japan is also looking to develop a GNSS system. In the last few years, significant improvements have been made in consumer-grade GNSS devices, which are becoming more prevalent. It is likely that these systems will continue to improve and become less expensive, enabling use in a variety of new applications for highway construction. This allows for the use of georeferenced crowdsource data, which could be used for tracking vehicle congestion near construction zones. It will also be a critical component of connected and autonomous vehicles. The decreased cost and increased availability of these devices will become important for use in construction progress monitoring and connected site integration. Finally, improvements in GNSS technology will continue to improve the efficiency of AMG processes.

There has been an increase in CORS managed by the NGS and partners, as well as local real-time GNSS networks. The denser networks being created will continue to improve accuracy and reliability of the data collected. However, the cost of creating and maintaining these networks can be difficult for a single organization to bear. Some states, such as Oregon, have found a sustainable approach with partners to operate a real-time network (ORGN) through the state DOT. Others have found the cost to be too prohibitive with the perceived limited utilization within the state DOT. Nonetheless, cooperative agreements between various state DOTs and external entities can help produce a higher ROI using pooled resources to maintain these networks. States that operate RTNs often need cooperative agreements with surrounding states so that the network can cover the entire State. Some States can legally charge for the service, while others cannot, leading to some complications in implementation. However, considering the future in connected vehicles and smart cities, RTNs offer significant value to enable those technologies, which will result in more efficient and safer use of the highway network. These factors are worth considering for ROI if a state DOT is considering operating a RTN.

Surveyors performing work for a state DOT have been the predominate users of the RTN technology; however, a much broader pool of people involved in asset management (e.g., ODOT), construction inspection, and even the general public operating connected vehicles, will likely use the RTN for improved positioning. In other words, it is important to think beyond the project and ultimately to other potential services and practices that are likely to be empowered by the use of a RTN, which could yield higher ROIs.

At the national level, the spatial data infrastructure continues to improve. The NGS continually updates the NSRS, enabling higher accuracy work to be completed. It has also improved geoid modeling and will release a pure-gravimetric geoid in the future as part of its NSRS modernization program. Lastly, the NGS has been developing time-dependent positioning models to handle tectonic motion for improved positioning (e.g., horizontal time-dependent positioning). As geospatial technologies are capable of more accurate measurements, and as many state DOTs base payments on measurements that consider leveraging more accurate positional data, the dynamics of the planet become increasingly important to consider when performing geodetic survey work at high accuracies.

AMG and 3D Modeling

Although AMG has been used by contractors for several years, the designers, as a whole have been resistant to the adoption of the 3D engineered model as a "contract document". In the case where 3D models are provided on an "information only" basis, the contractors encounter data interoperability issues and significant data quality issues. Designers typically do not propagate manual plan edits to the 3D model that was used to create the plans. Designers also do not typically model intersections or provide more detail than is required to create cross-sections. However, some state DOTs have updated their design guidance to introduce these details to advance the use of 3D models in their workflows, including AMG. Usually the most significant data quality issue is with the existing ground survey and control accuracy. Contractors and service providers have adapted and developed workflows to overcome these obstacles so that they can use these tools more often, as in the case of Mississippi DOT, which sees the value in these technologies and has begun to adopt standard operating procedures for use in highway construction. 3D modeling has also been the subject of recent FHWA Every Day Counts initiatives.

Connected Vehicles

Improved integration with data acquired by geospatial technologies will enable advanced features to be developed through the connected vehicle program. Geospatial technologies combined with advanced feature extraction will enable more accurate data and more frequent real-time updates to required information, such as intersection geometry, locations of stop bars, lane boundaries, signal head locations, etc., that can be fed to vehicles in the connected vehicles system. Many lower cost versions of geospatial technologies are being integrated directly in these vehicles.

ROI Determination

NCHRP Synthesis 446 (Olsen et al. 2013) made the recommendation of improving the sharing and reporting of experiences between state DOTs, including the documentation of failures. Through the materials available in this report, state DOTs will also be able to share ROI findings with the use of these technologies. Because of all of the complexities of ROI and the experiences and capabilities of each state DOT with technology, one DOT may achieve a better ROI than another with the use of the same technology on the same types of projects. Hence, by sharing ROI information, state DOTs will be able to compare themselves with others that are in a similar position.

Each technology will have a different replacement cycle that will need to be carefully established and monitored. Creating a “refresh” plan for technology replacements and software upgrades will allow an organization to lean forward with respect to innovative use of geospatial technology. In some cases with rapidly evolving technology such as a sUAS, the ROI may need to be realized in a shorter time frame (a couple of years) since a better alternative will likely be available making the current systems obsolete. Note that even though older systems can still be used, they may not be as efficient as current systems. Organizations will need to determine the appropriate time to upgrade in order to take advantage of new efficiencies, reduce maintenance costs, and retain as high a resale value as possible to aid in subsequent investments in replacement technology. However, other technologies such as GNSS rovers have stabilized and ROI can be realized over a longer time frame. Each state DOT will have to decide whether it makes sense for them to purchase/own, lease, or have consultants readily available with the technologies.

FHWA Every Day Counts: Innovation

Lastly, the FHWA Every Day Counts is focused on promoting innovation. As with the five iterations of Every Day Counts rounds to date, geospatial technologies will continue play a vital role in promoting and enabling innovation. Standing up innovation groups within the state DOT plays an important role in exploring new technologies, their capabilities, and determining their appropriate role within a state DOT that maximizes ROI.

The key to making innovation a positive ROI within a state DOT is to have a strategic plan leaning forward with respect to implementing technology. Such a plan will help each state DOT look beyond the project into more effective enterprise strategies where the data will yield a higher ROI.

APPENDIX A: EXAMPLE STATEMENT OF WORK OUTLINE FOR USING SUAS ON HIGHWAY CONSTRUCTION PROJECTS

CONTACTS

List contact information for primary representative of data\service provider, full list of state DOT contacts with primary contact identified, and any other organization contacts involved.

BACKGROUND

The background will include the purpose and expected outcomes of the project. This will ensure the service provider understands the intent of the state DOT for data acquisition and the state DOT understands what is feasible. The intended application(s) and user(s) of the data should be discussed and a list of stakeholders in the project should also be provided.

PROJECT LOCATION

Insert graphic or link to project limits and annotations for areas of special consideration. Note the sections of interest, and estimated extents of the project (items should include extents of data collection and any deliverable driven implications).

Type of area to be captured (bridge site, water bodies, interstate through urban corridor suburban freeway, rural highway, natural area, etc.)

DEPARTMENT OF TRANSPORTATION STANDARD REFERENCES

List references (such as this *Guidelines* document, FGDC-STD-001-1998 and other applicable ISO specifications) that will be followed for completion of the work. What is reference or included here will be based on the needs of the project, the limitations of a technology and the application of appropriate specifications.

PROFESSIONAL LICENSURE AND CERTIFICATION EXPECTATIONS

Ascertain if the work requires a Professional Land Surveyor, Professional Engineer, Certified GIS Professional, Certified Bridge Inspector, Certified Tunnel Inspector and/or Certified Photogrammetrist.

Ascertain what certifications are required for the performance of the work (e.g., Part 61 or Part 107 pilot ratings, certification in thermography, HAZMAT, Confined Space Training, climbing certification, etc.)

DEPARTMENT OF TRANSPORTATION PROVIDED RESOURCES

What the data provider can expect from the state DOT (e.g., access, traffic control, shutdowns, right of entry to private property, provision of survey control, sample data from previous successful project, state DOT special insurance requirements, data ISO specs, etc.).

APPROACH

Details on equipment, instrumentation and sensors to be used and elaboration on the expertise of the service provider. This should include details on how the means and methods are applied in leveraging the proposed hardware and software to achieve the required deliverable.

WORK PLAN

Task 1 - Project Management

- Coordination (Meetings, Teleconferences, Milestone Reviews)
- Budget (Tracking, Reporting)
- Schedule (Tracking, Reporting) – should include phases such as planning, data collection, data reduction and product development to delivery.
- Quality Management Report
- Progress Reports (May include a preliminary deliverable for a small portion of the final deliverable)
- Survey Narrative Report (Outlines the means and methods used, findings and context clarifications for the deliverable)
- Calibration requirements (Part of meeting the ISO specification)

Task 2 - Project Planning

- Data Collection Plan (Survey Control, Logistics, Regulatory Review, Collection Routes and Patterns, GNSS Constellation Review, etc.)
- Safety Plan (Emergency Contacts, Protocol and Reporting; Safety Assessment Protocol, Traffic concerns, etc.)

Task 3 - Horizontal/Vertical Control

- Coordinate System definition to be used (includes Datum, Projection, Reference Frame, Epoch, Geoid and Units)
- Description of existing or baseline survey control expectations (includes monumentation existence, reference networks, reference marks, GNSS baseline lengths, etc.)
- Survey Control Report (Outlines the data used, adjustment applied and final statistical result)

Task 4 - Collection and Processing

- Imagery or LiDAR product accuracy and resolution expectations *(Data collection category)*
- Imagery or LiDAR deliverable format *(considers RGB, Intensity scales, multi-return, and versioning).*
- Imagery or LiDAR product requirements *(quality assurance)*
- Processing techniques *(means and methods, quality control)*

Task 5 - Mapping/Modeling

Data formats required for deliverables *(may include metadata requirements):*

- Extracted Lines, Objects, Polygons and Point Features with attributes *(classification)*
- Digital Terrain or Surface Model
- Orthometric or Oblique Imagery *(tiled, mosaic, georeferenced)*
- Oblique Video Files *(raw, edited, georeferenced)*
- Point Clouds *(SfM-constructed, optimized database, decimation, tiled)*
- 2D planimetric or vectorized mapping file
- 3D linework or vectorized mapping file
- 3D solid or object model *(parametric or not)*
- Software anticipated to use the deliverable
- Viewing or data visualization software, if needed.

PROJECT SCHEDULE AND TIMELINE

Graphic showing when each task will occur, including start and completion dates *(consider weather, lighting, traffic and temperature for the collection phase)*

DELIVERY SCHEDULE

When, how and to whom products should be delivered.

ACCEPTANCE CRITERIA

Discussion on what must be met for payment *(milestones)* and if milestone payments will be used, who will perform the QA/QC work *(data provider, state DOT, or external/independent), and* how the accuracy should be reported following industry standards and specifications

COMPENSATION

Discussion of direct and indirect costs involved with the project and how payments will be made.

APPENDIX B. CASE STUDY INTERVIEW GUIDE FOR EFFECTIVE USE OF GEOSPATIAL TOOLS IN HIGHWAY CONSTRUCTION

The purpose of this project is to document a case study utilizing geospatial technology to understand the effective use for highway construction applications and quantify the return on investment (ROI) provided by the technology. This project is funded by the FHWA with WSP | Parsons Brinkerhoff serving as the contractor for the work. The total interview should not last more than 60 minutes. Please use this interview guide to document each case study.

This interview guide is composed of six different sections shown below with approximate time allocations:

1. General Information (five minutes)
2. Highway Application (five minutes)
3. Data Collection (five minutes)
4. Workflows and Products (ten minutes)
5. Lessons Learned and Future Direction for Using Target Technology (ten minutes)
6. Cost and Benefits (ten minutes)

We would like to schedule a follow-up call (30 min) in a week or so after the interview to go over the cost/benefit data you are providing and any remaining questions.

SECTION 1: GENERAL INFORMATION

1. Project Identification Number:
2. Construction contracting method
   a. D-B-B
   b. D-B
   c. CMGC
3. Who is providing the sUAS data acquisition services?
   a. Contractor
   b. Owner
   c. Service provider
   d. Contractor and owner
   e. Other ______________________
4. Detailed Scope of Work: (Please attach any useful documentation).
5. DOT/Owner Contact:

6. Phone and Email:

7. Contractor/Service Provider(s):

8. Phone and Email:

9. What is the size of your organization?

10. How long have you been collecting data using a sUAS?

SECTION 2: HIGHWAY APPLICATION

1. What is the primary highway application for the case study? Select multiple as applicable.
   a. Pre-Construction Surveys (Design-to-Construction)
   b. Construction Engineering & Inspection
   c. Asset Inventory/Bridge Maintenance
   d. Other (please specify)

2. What's the purpose of data collection?

3. What accuracy and resolution (if applicable) were required?

4. Does the state DOT/owner have specifications for this type of data collection?

5. Were other standards, specifications, or guidance documents used in preparation of the scope of work and for certifying project deliverables?

6. How can we access these specifications?

SECTION 3: DATA COLLECTION

1. This case study is targeting the use of:

2. What sensors are used for the sUAS?
   a. Digital camera for imagery only
   b. LiDAR scanner only
   c. Digital camera and LiDAR
   d. Other (please specify)

3. What are the accuracy capabilities of the system?

4. Can you provide any photographs or video of the project?

SECTION 4: WORKFLOWS AND PRODUCTS

1. Did you have to get a COA for this work? How did new FAA regulations (Part 107) impact this project?

2. Can you describe the workflow used in the data collection process?
   a. Mission planning
   b. Field data collection
   c. Quality control and assurance
   d. Creation of required products (include process, software used, and required deliverables)

3. How many people are involved in the data collection and the post-process?

SECTION 5: LESSONS LEARNED AND FUTURE DIRECTION FOR TECHNOLOGY USE

1. How will you use FAA regulations (Part 107) moving forward?

2. Were there any public concerns regarding the use of UAS in this project?

3. What lessons did you learn during this project?

4. How will you incorporate these lessons learned in your next project?

5. Were the resolution and accuracy requirements sufficient? Overly prescriptive?

6. Did the project deliverables work satisfactorily for the project?

7. What kind of technical problems did you encounter? (e.g., data interoperability, size of files, etc.)

8. How were these products received by the project team? Were there any concerns?

9. What is the future direction for your organization in utilizing this technology?

10. Is there any documentation (e.g. project reports) that you could share with us?

SECTION 6: COST AND BENEFITS

The purpose of this exercise is to collect data to validate planning level estimates to be used in a high level benefit cost analysis (BCA)

1. How did you incorporate risk in your decision to enter the UAS market?
   a. Work liability
   b. Successful use of UAS for project conditions
   c. Safety considerations

d. Other ________________

2. Can you provide cost incurred to provide these services? More details are available in the spreadsheet
   a. Direct cost for equipment and other necessary items to run the operation
   b. Cost for staff to run operation
   c. Cost for software
   d. Cost for regulation compliance
   e. Cost incurred for training
   f. Other ______________

3. Can you provide qualitative and quantitative benefits (calculated or estimated values) by using this technology? More details are available in the spreadsheet
   a. Safety
   b. Improved efficiencies
   c. Improved quality
   d. Reduced re-work
   e. Risk avoidance

4. The data collection template has a number of line items with measures and data needed for calculations of ROI. If no actual numbers are available, estimates are ok to use. Please provide assumptions made. If no single number can be listed, please provide an estimated range.

Data collection template review (Table 40 and Table 41)

Thank you – this is the end of our interview

NEXT STEPS

We will reconvene in 1-2 weeks to review cost benefit data and ask any follow up questions we may have.

Our research team will send an invitation with details for the call. We greatly appreciate your assistance with this and will share the research results with you when available.

Table 40. Case study cost capture tool

Cost Category	Value	Measure	Comments	Other Assumptions/ Confidence Score
Hardware	-	Dollars	One-time cost	Please state the replacement cycle
Hardware Maintenance	-	Dollars	Annual	-
Software	-	Dollars	One-time cost	-
Software Maintenance	-	Dollars	Annual	-
Training	-	Dollars	One-time cost	-
Technical Support Staff	-	Average loaded hourly rate	FTE	-
Other Costs	-	Dollars	One-time or annual cost?	-

- Data to be added during interview

Table 41. Case study benefit capture tool.

Benefit Category	Data Input	Unit	Comments	Other Assumptions/ Confidence Score
Time savings for data collection	-	-	-	-
Time savings for producing quantities	-	-	-	-
Increased data quality - qualitative	-	-	-	-
Increased safety - qualitative	-	-	-	-
Other benefits?	-	-	-	-

- Data to be added during interview

APPENDIX C. STATE DEPARTMENT OF TRANSPORTATION, CONSTRUCTION COMPANY, INSTRUMENT DEVELOPER AND SERVICE PROVIDER OUTREACH

Building on the findings from the literature review, the outreach effort consisted of interviews with multiple government agencies, construction firms, and others within the geospatial technologies industry to understand the level of use, experiences, expertise, challenges, motivations, expectations, and successes with using geospatial technologies. The objective of the interviews is to determine the level of use, experience, expertise, motivations, and expectations of the interviewees as it relates to geospatial technologies. The interview process began with the development of two questionnaires for state DOTs and construction companies and instrument developers and service providers, followed by identifying and selecting interview candidates and conducting the interviews (Figure 54). Findings from this outreach effort were intended to supplement findings from the literature review and will be used to inform the selection of candidates for detailed the case study analysis.

Source: FHWA

Figure 54. Process. Outreach effort.

STATE DEPARTMENTS OF TRANSPORTATION

The project team identified ten state DOTs to obtain more information about their geospatial technologies:

- Arkansas State Highway and Transportation Department (Arkansas SHTD)
- California Department of Transportation (Caltrans)
- Florida Department of Transportation (Florida DOT)
- Michigan Department of Transportation (Michigan DOT)
- New York Department of Transportation (New York State DOT)
- North Carolina Department of Transportation (North Carolina DOT)
- Ohio Department of Transportation (Ohio DOT)

- Oregon Department of Transportation (Oregon DOT)
- Utah Department of Transportation (Utah DOT)
- Wyoming Department of Transportation (Wyoming DOT)

These state DOTs were selected based on the maturity and diversity of their geospatial practices (including the use of sUASs for inspection and monitoring), as identified through the literature review. Representatives from each state DOT participated in telephone interviews using the structured questionnaire to guide the conversation. A copy of the interview questionnaires for both state DOTs and construction companies is presented in Appendix D. In addition to these initial interviews, follow-up interviews were conducted with Wyoming DOT and Ohio DOT. An interview was conducted with the Minnesota DOT to find out more information about their use of sUASs for inspection and monitoring.

Overview

State DOTs take various approaches to researching and adopting new geospatial technologies ranging from proactive to cautious. The majority of the state DOTs interviewed noted that they proactively research and adopt new technology. The remaining state DOTs stated that they are more cautious and selective in their approach but see themselves as fully committed once a technology has been identified.

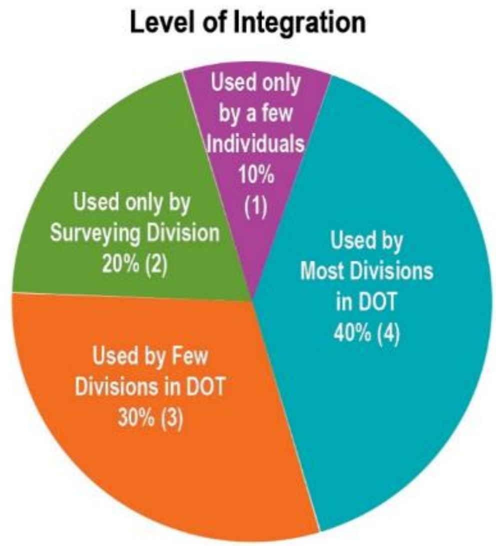
Most state DOTs reported that it is very important to investigate geospatial tools in connection with construction operations—New York State DOT cited that these tools will enrich its geospatial database, while Caltrans has established a geospatial governance board and geospatial information officer to aid in their investigations and advocacy. Michigan DOT envisions the future use of a Civil Integrated Management (CIM) System and believes that geospatial tools are a crucial part of that vision. One state DOT (Wyoming DOT) felt it was somewhat important.

Maturity

The level of expertise with geospatial data tools, technologies, and information across those state DOTs interviewed was fairly advanced. New York State DOT reported that it is transitioning to 3D modeling—however, it has not yet ventured into Civil Integrated Management (CIM) or 4D/5D modeling. Caltrans does 85 to 90 percent of its work in-house. Utah DOT is moving toward 3D digital submissions and understands the importance of geospatial data and tools in the success of their projects. Michigan DOT has a high level of expertise as it pertains to certain geospatial tools, but an overall lower expertise as it relates to integration and full implementation of these tools. Only one state DOT (Ohio DOT) reported a nascent maturity.

Integration

Figure 55 illustrates the level of integration of geospatial tools and data into daily construction workflows of the state DOTs. Four state DOTs responded that geospatial tools and data are used by most divisions in the state DOT and three state DOTs responded that they are used by a few divisions. Only one state DOT responded that geospatial tools and data are only being used by a few individuals.



Source: FHWA

Figure 55. Chart. Level of integration of geospatial tools and data.

Technology Usage

DOTs were asked to rate the frequency of use of specific geospatial technologies in the roadway design and construction process. Below is a summary of the findings:

- GNSS and conventional photogrammetry are the most widely used technologies reported by the state DOTs interviewed, which is to be expected given that they have been available for quite some time. GNSS is often integrated with other geospatial technologies to provide positioning capability.
- The use of STLS, MTLS, and ALS varies across state DOTs—while some state DOTs are using these technologies on a regular basis or increasing their use, others are not using these technologies at all.
- The use of AMG has an average level of use across state DOTs. Those reporting frequent use stated that utilization of AMG is typically driven by the contractor.
- Terrestrial photogrammetry and sUASs are seldom used (Wyoming DOT is the only state DOT that reported using both). Michigan DOT is in the second phase of sUAS research which includes deployment, ROI, and developing a guidance document. SfM (structure from motion) is not being used by state DOTs. Oregon DOT reported that consultants are still researching the use of sUASs and SfM.
- Other geospatial technologies that state DOTs are using include sonar, electromagnetic, magnetometers, semi-global matching (SGM), and digital ortho-photography.

Table 42 illustrates the geospatial applications for highway construction, as reported by state DOTs. Selecting the right tools and proper application and use of those tools will yield the desired results (e.g., for spatial resolution and accuracy, time savings, cost savings). However, state DOTs have expressed the challenges of being able to quantify the benefits. Wyoming DOT indicated that the use of geospatial technologies has improved staff utilization—the state DOT is able to do more work with fewer resources. Florida DOT cited that photogrammetry and GNSS are meeting desired results for accuracy and ROI. Although STLS is also meeting the desired accuracy, the initial investment in the technology is costly. Arkansas DOT indicated that although its tools are meeting most requirements, it is difficult to quantify the cost savings.

Table 42. Geospatial applications by State DOTs for highway construction.

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUASs	Ground Penetrating Radar	AMG	GPS	Conventional Surveying Tools
Topographic surveying	x	x	x	x	x	x	x	x	-	-	x	x
Earthwork	x	x	-	x	x	x	x	x	-	x	x	-
Paving	x	x	x	-	-	-	-	-	-	x	x	-
Roadway design	x	x	x	x	-	x	-	-	x	-	x	-
AMG and control	x	x	x	-	-	-	-	-	-	x	x	-
Verification	x	x	x	-	-	x	-	-	-	-	x	-
As-built surveys	x	x	x	-	-	x	-	-	-	-	x	-
Site/progress monitoring	x	x	-	x	-	x	-	-	-	-	x	-
Inspection	x	x	x	-	-	x	-	-	-	-	x	-
QA/QC	x	x	x	-	x	x	x	x	-	x	x	-
Asset management	x	x	x	x	-	x	-	-	x	-	x	x

- Not commonly used

Unmanned Aerial Vehicles/Systems

As discussed above, the use of sUAVs and sUASs is still relatively nascent—although the following state DOTs have made some strides in researching and using these technologies:

- **Wyoming DOT** has been using sUAVs almost exclusively for studying rock faces and not for construction specifically, although Wyoming DOT has used it for a few small gravel pits. A major challenge to using sUAVs is wind—Wyoming DOT currently uses a quadcopter for better control in windy conditions – and may be impractical for Wyoming DOT to monitor construction with UAVs. Wyoming DOT is getting LAS files from its contractor, who is using 60 percent overlap. Wyoming DOT is easily getting under a tenth of a foot of accuracy from flying at 400 ft.

- **Ohio DOT** had as UAS program that went through a brief start-up phase before it was shut down. Ohio DOT now has a joint sUAS program with Indiana DOT that both state governors are promoting as a business catalyst for the states' economies. Ohio DOT is working on the regulatory side of sUAS and is hoping to launch its first flight.

- **Minnesota DOT** implemented a pilot project for sUASs, but the state has a strict policy that requires that any investment in new technology must show a clear ROI; Minnesota DOT cannot invest in pure research projects. Minnesota DOT has been able to quantify the ROI of photogrammetry over large areas, but it has been more difficult to demonstrate the ROI for smaller areas flown with as UAS. The proposed FAA rules prohibit flight over traffic or people, which will be a very big challenge to overcome for highway construction projects. Minnesota DOT currently has a UAS policy which permits the use of sUAS for the purposes of conducting the business of Minnesota DOT, with FAA approval through a Certificate of Waiver or Authorization (COA) for a particular aircraft, for a particular purpose, in a particular area.[18]

- **Michigan DOT** is in the second phase of sUAV research which includes deployment, ROI, and developing a guidance document. The initial phase of research was finalized in 2015 and focused on the feasibility of the technology.

Future Use

State DOTs plan on using the following technologies in the future:

- Lidar
- GNSS
- UAVs/UASs
- Unmanned vehicles (e.g., boats)

[18] http://www.dot.state.mn.us/policy/operations/op006.html

- Terrestrial photogrammetry
- RTN
- SfM
- Ground penetrating radar (GPR)
- CIM applications

When asked to identify which technologies will be researched in the future for potential use, six state DOTs responded with sUAVs/sUASs. The state DOTs identified the following additional technologies:

- SfM
- Terrestrial photogrammetry
- RTN
- Geiger-mode lidar
- MTLS
- Automated vehicles
- Feature extraction
- CIM applications

Most state DOTs are not going to disregard any technologies in the future. One state DOT reported that their emphasis is on researching the most suitable geospatial tool for highway construction and therefore, they will not disregard any technologies.

Return on Investment

A majority of state DOTs interviewed indicated that ROI is very important, although it is difficult to quantify. Caltrans reported that its ROI information is largely anecdotal and the state DOT has very little quantifiable data.

State DOTs that reported that ROI was not important to the decision of adopting a new technology stated different reasons:

- For Arkansas DOT, safety and speed of acquisition are important factors in adopting a new technology.
- For New York State DOT, although ROI is not very important, New York State DOT still faces the challenge of determining which tool to use that will get the best return.

- For Ohio DOT, ROI is not a top priority.

State DOTs expect ROI in geospatial technologies to include:

- Increasing productivity.
- Delivering a better construction plan product.
- Increasing safety, efficiency, and speed of delivery.
- Long-term positive ROI and cost effectiveness.

Most state DOTs have not documented ROI. North Carolina DOT has historic data (mostly for sUASs), but there is interest in calculating time and schedule benefits. ODOT has not documented ROI, but the ODOT is starting a research project with Oregon State University to calculate ROI for AMG. Michigan has started to quantify some maintenance data.

State DOTs have realized the following non-financial benefits by using geospatial technologies:

- Increased collaboration.
- Increased visualization.
- Increased safety.
- Increased speed and accuracy.
- Increased density of data.
- Increased efficiency.
- Increased cost effectiveness.
- Decreased risk.
- Improvement of schedule.
- Increased certainty of quantities.
- Improvement of quality.
- Improvement of staff skills.
- Better product that is a closer fit with design intent.
- Increased access of data.

The majority of state DOTs collaborate with other departments and agencies to share costs and benefits:

- Florida DOT collaborates with TRB, AASHTO, and FHWA, North Carolina DOT shares MTLS data.
- North Carolina DOT shares MTLS data.
- Ohio DOT collaborates with the Attorney General and the Department of Natural Resources.
- Utah DOT shares data through UGate, a geospatially enabled data repository based on Oracle Spatial database, Esri SDE, and ArcGIS server.
- Michigan DOT is currently working on collaborating and sharing data with other agencies. Agencies include USGS, DNR, DEQ, and NGS.
- New York State DOT shares data with its contractors and the state is negotiating a statewide GIS contract.
- Oregon DOT is part of a statewide lidar consortium. In addition, its RTN network is available to the public and the state police is using the mobile lidar database.

Two state DOTs (Caltrans and Wyoming DOT) share data informally and another state DOT (Arkansas DOT) does not currently share any data.

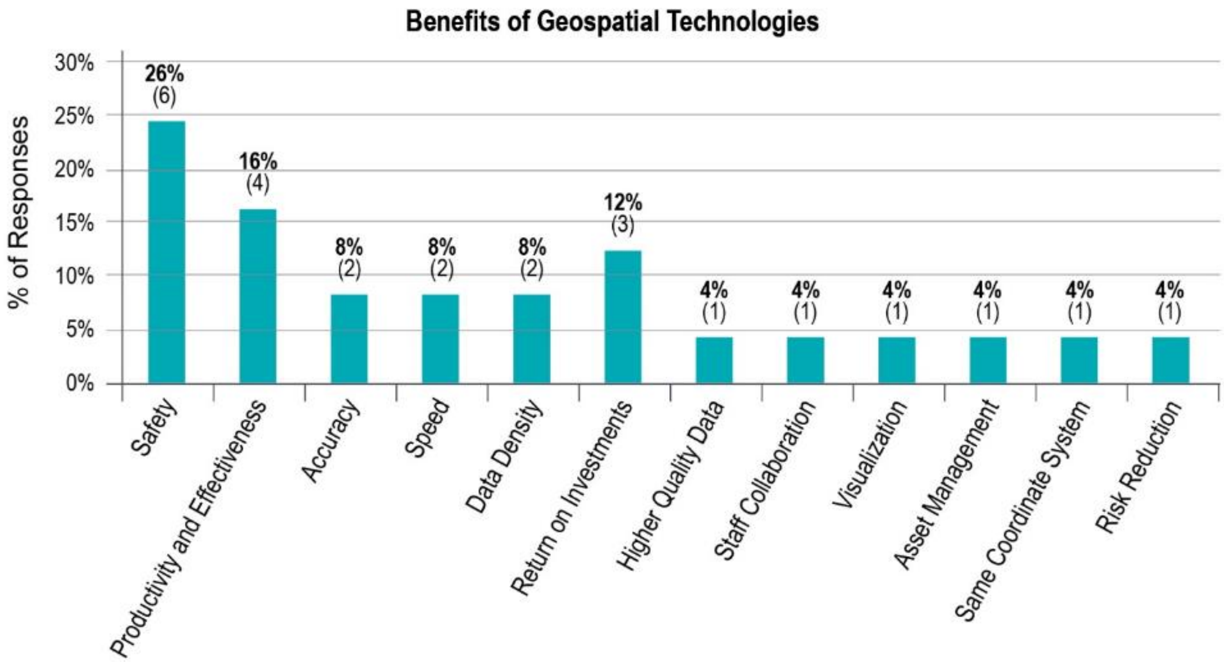
Benefits

State DOTs were asked to identify the top three benefits from using geospatial technologies and tools. Their responses are presented below:

- Safety.
- Productivity and efficiency.
- Accuracy.
- Speed.
- Data density.
- ROI (including reduced costs).
- Higher quality data.
- Staff collaboration.
- Visualization.

- Use of 3D data for asset management.
- Staff are on the same coordinate system.

Figure 56 illustrates the frequency of responses to the benefits of using geospatial technologies identified above with the top two benefits identified being improved worker safety and increased productivity and efficiency. Accuracy, speed, data density, and ROI tied for the third most common response.



Source: FHWA

Figure 56. Chart. Benefits of geospatial technologies.

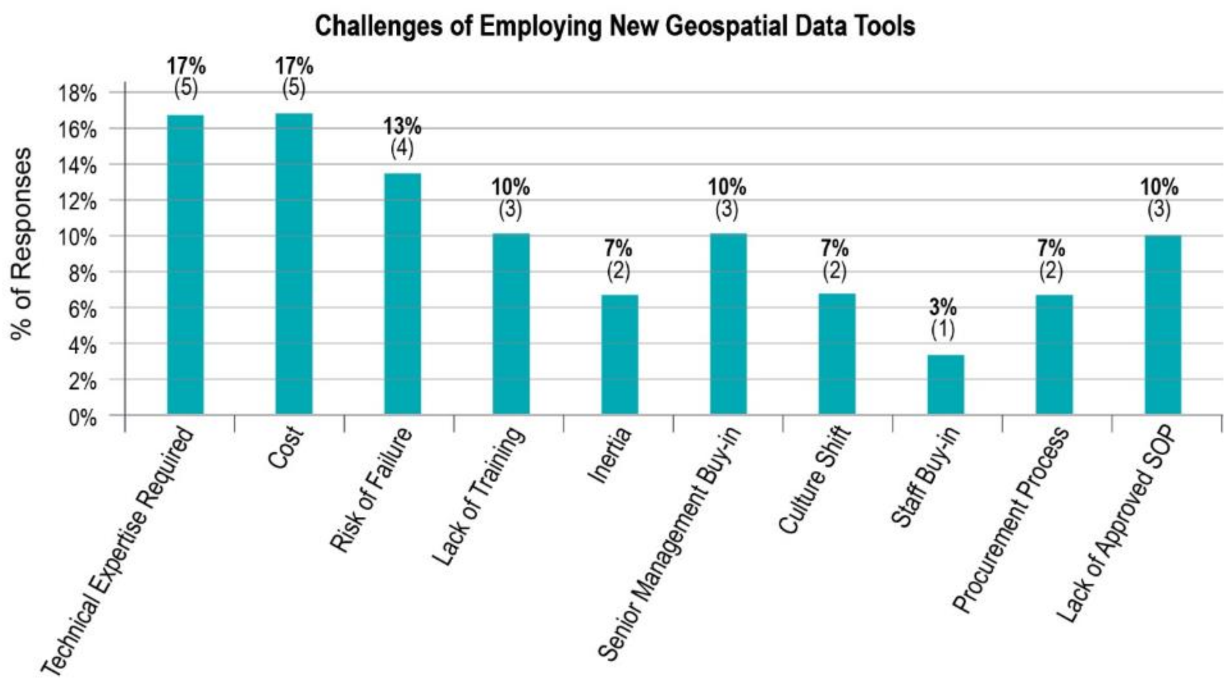
Challenges

Primary challenges of employing new geospatial data tools, as identified by state DOTs, include the following:

- Technical expertise required.
- Cost.
- Risk of failure.
- Lack of training.
- Inertia.

- Senior management buy-in.
- Staff buy-in.
- Culture shift.
- Procurement process.
- Lack of approved Standard Operating Procedure (SOP).

Figure 57 illustrates the frequency of responses to the challenges identified above. The top three challenges identified were technical expertise required, cost, and risk of failure.



Source: FHWA

Figure 57. Chart. Challenges of employing new geospatial data tools.

CONSTRUCTION COMPANIES

Overview

All of the construction companies interviewed (four in total) are taking a proactive approach to researching and adopting new technologies. Investing in these technologies is a critical component for gaining a competitive advantage and staying current in the highway construction sector. New and different technology solutions help these firms solve more challenging problems for their clients (including reducing costs and labor) and develop expanded deliverables. One constructor cited having strong relationships with equipment and instrument providers, which enables them to provide beta testing for developing technology.

Technology Usage

Construction companies were asked to rate the frequency of use of specific geospatial technologies in the roadway design and construction process on a scale of 0 (never) to 10 (routinely). The results are summarized below and illustrated in Table 43:

- GNSS is the most widely used technology reported by construction companies (which aligns with state DOT practices); other technologies were not as consistently used across construction companies.
- Half of the construction companies surveyed use AMG on a routine basis, while half do not use it at all.
- STLS and MTLS is used routinely by one construction company, occasionally by two others, and not at all by a fourth construction company. ALS is used routinely by one construction company, occasionally by another, and not at all by two construction companies.
- Terrestrial photogrammetry is the least used technology—the ratings ranged between 0 and 4—while usage of conventional photogrammetry ranged from not at all (2 construction companies) to frequent/routine use (2 construction companies).
- Usage of SfM, sUAS, and GPR technologies vary in frequency across construction companies.

Table 43. Frequency of use of geospatial technologies by construction companies.

Technologies	Frequency Rating
GNSS	9.5
AMG	6.7
GPR	5.5
TLS	4.5
MTLS	4.5
Conventional Photogrammetry	4.3
sUAS	4.3
ALS	3.3
SfM	3.0
Terrestrial Photogrammetry	1.8

Table 44 illustrates the geospatial applications for highway construction, as reported by construction companies. As compared to state DOTs, construction companies are using sUASs/sUAVs more frequently across construction applications, however, state DOTs are using conventional photogrammetry across more applications than construction companies are. Construction companies agreed with state DOTs on the importance of selecting the right tool for the project requirements in order to yield cost and time savings.

Table 44. Geospatial applications by construction companies for highway construction.

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUASs	Ground Penetrating Radar	AMG	GPS	Conventional Surveying Tools
Topographic surveying	x	x	x	x	-	x	x	x	x	x	-	x
Earthwork	x	x	x	x	-	-	-	x	-	-	x	x
Paving	-	x	-	-	-	-	-	-	-	x	x	x
Roadway design	x	-	-	x	-	x	-	-	-	-	-	-
AMG	x	-	-	x	-	-	-	-	-	-	x	x
Verification	x	x	-	-	x	x	-	x	-	-	-	x
As-built surveys	x	x	x	x	x	x	-	x	-	-	-	x
Site/progress monitoring	x	-	-	-	-	-	-	x	-	-	-	x
Inspection	x	-	x	-	x	-	x	x	-	-	-	-
QA/QC	x	x	x	x	x	-	x	x	x	x	-	-
Asset management	x	x	x	x	x	-	-	x	-	-	x	x

- Not commonly used

Unmanned Aerial Vehicles/Systems

The majority of construction companies are researching the use of sUAVs for the following:

- Site and progress monitoring (limited to discussions with providers and literature investigation).

- Inspection of bridges and structures.
- Verification and QA/QC.

Only one construction company reported a fair amount of experience with sUAVs, which is being used on 75 percent of its projects for imagery capture and processing using SfM. They noted their sUAV meets a tenth of a foot accuracy requirement on surface mapping for QA/QC and a +/- 2 to 3 percent accuracy requirement on stockpile quantities. This was qualified with the need for ground control to reinforce the SfM solutions from the sUAS imagery. For a stream restoration project spanning over 4 miles, 60 global positioning system (GPS) control points were used and then confirmed with approximately 300 confidence points. The overall expectation is 30 ground control points (GCPs) per mile surveyed with a total station for highways. The construction company is not yet using sUAV lidar systems regularly because the technology has not been developed far enough—and a photogrammetry solution from imagery provides the necessary data.

Future Use

Technologies that are being researched for use in the future include the following:

- sUAV/sUAS.
- Lidar as a STLS or as an MTLS.
- Hydrographic surveying associated with bridge construction (e.g., green lidar).
- GPR for identifying underground conflicts and utilities.
- SfM.

Construction companies are not going to disregard any technologies for potential use in the future.

Return on Investment

Although construction companies acknowledged the importance of ROI, none reported formally tracking it. Construction companies assume that a piece of equipment will pay itself off in one to two years, although it takes a little longer for conventional airborne systems (e.g., one construction company reported that its sUAS paid for itself in 2 to 3 years, which is essentially the life of the system). Construction companies have also estimated cost savings in labor—one construction company estimated a 20 percent increase in productivity and decrease in labor costs, while another construction company reported a reduction in filed labor by 50 percent since the inclusion of GNSS into its workflow in the late 1990s.

Benefits

Construction companies identified the following benefits:

- Reduced labor efforts and costs.
- Increased safety. Less field personnel are placed in harm's way in the right-of-way or active construction zones (e.g., GNSS enables mapping of the bottom of pits or ditches without having to put field personnel at risk).
- Reduced rework. The use of GNSS and conventional surveying reduces errors and change orders.
- Time and schedule savings. The reduced need for lane closures allows for a more rapid start up for projects; scanning via lidar results in extended working time since scanning can be accomplished at night.
- Risk management. The addition of sUAV imagery as a permanent record of preconstruction and process conditions enables risk management.
- Less impact on traffic. Lidar results in no lane closures, which translates to less cost and impact on traffic.
- Increased efficiency.
- Increased data volume to better inform decision making.
- Reduced errors.

Benefits realized specifically from sUAV/sUAS include schedule, time, safety, accuracy, and a permanent imagery record.

Unlike the responses of state DOTs, there was no benefit that stood out as more common among the rest.

Collaboration

The level of collaboration with other companies varies between organizations—whereas collaboration was quite common among state DOTs. One construction company does not collaborate with other companies to share the cost/benefits or risks/rewards of geospatial tools. It does, however, provide all of its data models to its client to ensure everyone is using the same data. Another construction company reported that it collaborates with clients to share costs and data—the construction company is currently in beta testing for a paving technology and has teamed up with New York State DOT to provide sUAS imagery over highways.

Challenges

Construction companies identified the following challenges that are holding clients back from using new geospatial data tools and technologies:

- Lack of technical expertise or understanding of the tools.

- Whether or not the cost will justify the time and money spent.
- Lack of understanding of SOPs for the systems.
- Cost for both equipment and service provided.
- Whether the technology meets the needs of the application.
- Lack of technical results and case studies.
- Lack of training in use of the data.
- Unclear understanding of the limitations of the accuracy of different geospatial tools.
- Inertia and the hesitation to try something new.
- Threat of positions being eliminated as a result of the new technology.
- Current regulatory environment for the use of sUAVs.

INSTRUMENT DEVELOPERS AND SERVICE PROVIDERS

The project team administered a questionnaire to instrument developers and service providers to assess their perspectives on geospatial practices. This questionnaire focused on identifying the tools and applications that instrument developers and service providers are delivering to clients for various highway construction applications, as well as the benefits and challenges associated with implementation and use. A copy of the questionnaire for instrument developers and service providers is presented in Appendix E.

Overview

Three of the four instrument developers and service providers interviewed are approaching new technology proactively; new technology is perceived as necessary to remain at the cutting edge to maintain a competitive advantage in a challenging market. However, one service provider is approaching cautiously and selectively—recognizing that technology is changing at a pace that is difficult to keep up with, but that not all technology will be adopted or able to survive in the long run.

Technology Usage

Collectively, these instrument developers and service providers provide the following technology to clients:

- GNSS
- STLS
- MTLS

- ALS
- Conventional photogrammetry
- Terrestrial photogrammetry
- sUAV/sUAS
- GNSS for machine guidance

Instrument developers and service providers interviewed all agreed that tools will meet the needs for accuracy and efficiency expectations as long as the tool is being applied properly, which aligns with the responses from state DOTs and construction companies. One service provider expressed that tools are chosen to meet project requirements, as opposed to using new tools to drive the project. Table 45 illustrates the application of the technologies identified above for highway construction, as reported by instrument developers and service providers. Again, the application of sUASs/sUAVs is more prevalent among instrument developers/service providers than state DOTs.

Table 45. Geospatial Applications by Instrument Developers and Service Providers for Highway Construction

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUAVs	Conventional Surveying Tools
Topographic surveying	x	x	x	x	x	x	x	x	x
Earthwork	x	x	x	x	-	x	-	x	-
Paving	x	x	x	x	-	-	-	-	x
Roadway design	-	-	x	x	-	x	-	-	-
AMG and control	x	-	-	-	x	-	-	-	x
Verification	-	x	-	x	-	-	-	x	x
As-built surveys	x	x	x	-	x	-	-	-	-

Applications	GNSS	STLS	MTLS	ALS	Terrestrial Photogrammetry	Conventional Photogrammetry	SfM	sUAVs/sUAVs	Conventional Surveying Tools
Site/progress monitoring	-	-	-	-	-	-	-	x	-
Inspection	-	x	-	-	-	-	-	x	-
QA/QC	-	x	-	x	-	-	-	x	x
Asset management	x	-	x	-	-	-	-	-	-

- Not commonly used.

When asked about the suitability (with regards to accuracy and cost) of using the tools for particular applications, instrument developers and service providers stated the following:

- ALS can be costly for projects unless they are appropriately sized—otherwise, STLS or MTLS could provide a more cost-efficient solution.
- STLS is best applied to earthwork and paving operations.
- sUAS is promising for small area data capture; at this time, beyond visual line of sight operations require a waiver. sUAS is also very promising for roadway and pavement data capture, however MTLS will outperform sUAS on large projects (i.e., greater than two miles).
- For a QA/QC application, STLS can be used for high accuracy, ALS for large areas, and sUAS for lower accuracy.
- For a verification application, ALS can be used for larger areas and sUAS can be used for lower accuracy.

Unmanned Aerial Vehicles/Systems

One service provider identified itself a leader in the deployment of sUAS and as an early adopter. The firm applied for and received an early Section 333 exemption to fly through rural areas in Ohio, enabling it to use both its fixed-wing and its rotary sUAS for projects and to develop the processes and procedures for its safe and appropriate operation. sUAS is a key area of development for broader application and is viewed as being able to reduce acquisition time for smaller sized projects as well as substantial savings in fuel and maintenance costs as compared to their manned aircraft fleet. sUAS is not viewed as a replacement to their other services or manned aerial platforms, but as complimentary for small areas or otherwise inaccessible sites.

Future Use

Technologies that are being researched for use in the future include the following:

- sUAS
- SfM
- Backpack and pushcart mobile scanning
- Aerial applications
- Flash lidar
- Photon lidar
- Geiger-mode lidar

Instrument developers and service providers are not disregarding any tools in the future; however, one service provider sees a reduction in the use of STLS and a diminished use of close range (terrestrial application) photogrammetry. STLS was most impacted by the mobilization and labor costs being overly burdensome to support the service.

Return on Investment

Service providers and instrument developers provided varying timeframes for yielding an ROI:

- Technology is expected to pay itself off in a reasonable timeframe proportional to the original cost. Airborne systems require two years, mobile systems require three years, and sUAS in one year (with the ROI initially slower due to research and development).

- Another service provider cited a two to three-year window for a technology to be profitable (most applicable for MTLS, ALS, and other airborne geospatial services), but not necessarily paid off. A payoff may be more immediate if there is a project big enough. Still, other clients may not be getting a rapid ROI, but they are still satisfied with using the technology since the intangible benefits associated with accessibility to other opportunities and improvement in safety.

- ROI anticipated for clients and users is directly related to the cost of the systems, which vary from $50,000 to $1.6 million. A ballpark expectation to pay off an instrument is 4 years.

The success of a tool is based on its application and how aggressive the use of the tool is pursued. Another factor is how efficiently the user is applying the tools or technology and whether it is appropriate for that application.

Benefits

Benefits identified by instrument developers and service providers include:

- Increased data density (more than is typically needed or used, but available when unforeseen issues in design or construction arise).
- Time savings.
- Increased safety.
- Schedule compression.
- Quicker extraction of information (reducing field time and increasing office time).
- Increased efficiency.
- Reduced lane closures and transit delays.
- Reduced labor and associated costs (e.g., personnel needed to support field operations).
- Reduce the risk of error and schedule impacts.

Other benefits that have been recognized for specific tools include:

- GNSS – Savings in efficiency, schedule, and labor time.
- MTLS – Increased safety by putting less personnel in the ROW, less lane closures, reduced labor in crew sizes, and accuracy to the design level.
- sUAS – Increase efficiency and safety; provides faster, more frequent ability to capture quantities and monitoring.

Challenges

Instrument developers and service providers interviewed consistently identified cost and technical expertise as major challenges for adopting geospatial technologies. The initial investment can be high—especially when other tools have the ability to provide similar data. Their clients are also waiting for mainstream maturity and acceptance of certain tools before adoption. Other challenges identified include:

- Lack of training and understanding of the value of the data from new tools.
- Risk of failure and unwillingness to try a new approach.

- Lack of approved SOP which can deter clients who are looking for the least impact to their existing workflows and operations.

In addition, instrument developers and service providers also identified challenges to adopting sUAS:

- Unqualified operators that do not understand the geospatial aspects of deliverables.

- Unclear about safety.

- A challenging regulatory environment that is not favorable to easy or early use in the highway industry.

APPENDIX D. INTERVIEW QUESTIONS FOR DEPARTMENTS OF TRANSPORTATION AND CONSTRUCTION COMPANIES

DEMOGRAPHIC INFORMATION

Name:

Title:

Years of Experience:

Licensure:

Education:

QUESTIONS

1. Which of the following best describes your state DOT;
   a. Proactive in researching and adopting new technology
   b. Cautiously and selectively research new technology
   c. Adopt new technology only after it is generally accepted within the community/industry

2. How important is it for your organization to be investigating geospatial data tools in connection with construction operations?
   (On a scale of 1-10, 1 being not at all important, 5 being somewhat and 10 being critical to the future)

3. What is your organization's overall level of expertise with advanced geospatial data tools, technologies and information? *(On a scale of 1-10, 1 being novice or new at all important and 10 being expert)*

4. What is the current level of integration of geospatial data tools, technologies and information into you organization's daily construction workflows?
   a. Used by most divisions in our state DOT/Company
   b. Used by a few divisions in our state DOT/Company
   c. Used only by our surveying division
   d. Used only by a few individuals
   e. Currently at the research\investigation level only

5. Is your state DOT using any of the following technologies in the roadway design and construction process or through subcontractors: *(rate each of the below on a scale of 0(never) to 10 (routinely)*
   a. GNSS
   b. STLS
   c. MTLS

d. ALS
e. Terrestrial Photogrammetry
f. Conventional photogrammetry
g. SfM
h. sUAV for imagery or lidar
i. GPR
j. AMG
k. Other (please specify)

6. *If the answer was yes to any of the above, reiterate that subject and ask:* What applications are you using (GNSS, lidar, sUAV, etc.) for:
   a. Topographic surveying
   b. Earthwork
   c. Paving
   d. Roadway Design
   e. Machine guidance and control
   f. Verification
   g. As-built surveys
   h. Site monitoring or progress monitoring
   i. Inspection
   j. QA/QC
   k. Asset Management
   l. Other (please specify)

7. Which of these technologies do you plan to use in the future and why?

8. Which of these technologies are you going to research in the future?

9. Which of these technologies are you going to disregard in the future?

10. Are the technologies you identified in the previous questions meeting the requirements (e.g., for spatial resolution and accuracy, time savings, cost savings) for the application areas you identified? *Prompt with reminders of affirmative responses to question 3.*

11. How important is return on investment in your decision to adopt any of these technologies?

12. What do you expect for a return on investment in geospatial technologies?

13. Have you documented the ROI from any of the above?
    a. *If affirmative, are they willing to share that information with us for the purpose of this study?*

14. What non-financial benefits has your organization realized by utilizing these geospatial technologies?

   a. *Follow up with (risk reduction, schedule improvement, certainty of quantities, site documentation, others?)*

15. Does your state DOT collaborate with other departments or agencies (Companies) to share the cost and/or benefits of using geospatial tools?

16. In your opinion what are the top 3 benefits from using geospatial technologies and tools

17. In your opinion what are the top 3 factors holding back the use of new geospatial data tools and technologies in your organization?
    a. Value proposition
    b. Procurement Process
    c. Doesn't meet accuracy specifications or other needs
    d. Cost
    e. Inertia
    f. Technical Expertise
    g. Lack of technical results/case studies demonstrating accuracy
    h. Lack of approved SOP
    i. Lack of training
    j. Senior management
    k. Risk of failure

18. Do you have or are aware of any recent projects that employed geospatial technologies that we have discussed and could be documented as a case-study? Are you willing to participate with us on documenting a project as a case study?

19. End of Interview, thank you

APPENDIX E. INTERVIEW QUESTIONS FOR INSTRUMENT DEVELOPERS AND SERVICE PROVIDERS

DEMOGRAPHIC INFORMATION

Name:

Title:

Years of Experience:

Licensure:

Education:

QUESTIONS

1. Which of the following best describes your company;
   a. Proactive in researching and adopting new technology
   b. Cautiously and selectively research new technology
   c. Adopt new technology only after it is generally accepted within the community/industry

2. How important is it for your organization to be investigating, using, and providing new geospatial data tools?
   (On a scale of 1-10, 1 being not at all important and 10 being critical to the future)

3. What is your organization's overall level of expertise with advanced geospatial data tools, technologies and information? *(On a scale of 1-10, 1 being novice or new at all important and 10 being expert)*

4. Which of the following technologies do you provide in the roadway design and construction process?
   a. GNSS
   b. STLS
   c. MTLS
   d. Terrestrial Photogrammetry
   e. Conventional photogrammetry and/or SfM
   f. ALS
   g. sUAV for imagery or lidar
   h. Other (please specify)

5. *Use the list of any technologies identified from above, reiterate that subject and ask:* What technologies are you using/developing (GNSS, lidar, sUAV, etc.) for application in:
   a. Topographic surveying

b. Earthwork
c. Paving
d. Roadway Design
e. Machine guidance and control
f. Verification
g. As-built surveys
h. Site monitoring or progress monitoring
i. Inspection
j. QA/QC
k. Asset Management
l. Other (please specify)

6. Which of these technologies do you plan to develop further *(Instrument*)/use *(Service Provider*) in the future and why?

7. Which of these technologies are you going to research in the future?

8. Which of these technologies are you going to disregard in the future?

9. Are the technologies you identified in the previous questions meeting your customers' requirements (e.g., for spatial resolution and accuracy, time savings, cost savings) for the application areas you identified? *Prompt with reminders of affirmative responses from question 3.*

10. ROI expectations.
    a. *(Instrument*) What expectation of ROI do you see for your customer? What do they expect? What have they reported?
    b. *(Service Provider)* Do you as a provider expect a return on the investment of geospatial technologies? If so, what are your expectations? If not, why is ROI not important?

11. Have you documented the ROI from any of the above?
    a. If affirmative, are they willing to share that information with us for the purpose of this

12. *(Service Provider)* What non-financial benefits has your organization realized by utilizing these geospatial technologies?
    a. Follow up with (*schedule improvement, certainty of quantities, site documentation, others?*)

13. What non-financial benefits do you envision for state DOT's or other clients?

14. Describe any risk in the construction process that is reduced by utilizing these technologies?
    a. Follow up with (*Insurance documentation, site monitoring, installation documentation, etc.....)*

15. What is your organization's overall level of expertise with advanced geospatial data tools, technologies and information? *(On a scale of 1-10, 1 being novice or new at all important and 10 being expert)*

16. In your opinion what are the top 3 factors holding back the use of new geospatial data tools and technologies in your customers' organization?
    a. Value proposition
    b. Cost
    c. Inertia
    d. Technical Expertise
    e. Lack of technical results/case studies demonstrating accuracy
    f. Lack of approved SOP
    g. Lack of training
    h. Senior management
    i. Risk of failure

17. Does your company believe it will gain a competitive advantage by being more involved with these technologies?

18. Have you completed or are you aware of any projects that employed the geospatial technologies that we have discussed and could be documented as a case-study? Are you willing to participate with us on documenting a project as a case study?

    End of Interview, thank you

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