LiDAR Surveying and the UAS Phenomenon:
Understanding How to “See the Wood for the Trees”

Craig Emrick, PSM
Vice-President of Mapping Services

Prepared For:
51st Transmission and Substation Design and Operation Symposium
Embassy Suites Dallas-Frisco Hotel
September 5-7, 2018
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Abstract

The goal of this paper is to introduce the transmission engineer to these different technologies, to enable them to see past the sales pitch, and to determine the right technology for their project.

Starting in the mid-1990’s, airborne LiDAR has been used with great success in surveying electric transmission lines. Since the 2010 NERC Recommendation, “Consideration of Actual Field Conditions in Determination of Facility Ratings”, the use of airborne LiDAR has matured and has proved to be indispensable in discovering discrepancies between design and actual conditions in the Bulk Electric System. However, transmission engineers potentially take this data for granted, without understanding the capabilities of LiDAR, the factors that drive accuracy, or the limitations of the technology.

In the last decade, the use of terrestrial LiDAR in the substation world is also maturing, giving utilities the ability to model in 3D for design, as-built, and retrofit purposes. This technology is more suited to small projects, such as substations or a few transmission spans. Airspace restrictions, where aircraft are not permitted to fly in specific areas, can also make this an indispensable tool. Like airborne LiDAR, this technology has certain capabilities, factors that drive accuracy, and technological limitations.

More recently, new technologies, such as Unmanned Aerial Systems (UAS), are being used as platforms to do some of the same work currently performed using manned aircraft, with varying degrees of success. As with the other technologies, the UAS-based survey comes with its own set of capabilities, accuracy drivers, and limitations. Among these are line-of-sight limitations and higher-than-expected costs.

This paper will explore the different technologies available for surveying the electrical system, including manned airborne LiDAR, terrestrial LiDAR, and UAS-based surveys. The fundamentals of the different technologies will be presented, along with platforms, data accuracies, technological limitations, cost drivers, and best-use applications. A commentary will also be presented on the impacts of the FAA’s recent decision granting Xcel approval to run inspection drones beyond line of sight.

(Note that for this paper, we will discuss only laser systems with time-of-flight technology, and do not address those with phase-based or waveform processing technology.)

Introduction

Pickett and Associates, Inc. is a privately-owned, surveying, mapping, and engineering firm, building on more than 50 years of success. With headquarters in central Florida, our primary service area covers the southeastern and midwestern U.S. and the Caribbean Islands. We provide a wide range of specialized services for public, private and industrial clients in the utility, mining, land development, solid waste, and transportation sectors.
Airborne LiDAR – Manned Aircraft

Commercially available airborne LiDAR (Light Detection and Ranging) systems have been around for more than two decades and the technology has proven to be a useful tool for a variety of applications: topographic surveys, volume computations, and transmission line surveys, to name a few. These systems have gone through transformative improvements over the years and can now measure up to 1,000,000 three-dimensional points per second from a single laser unit, and these dense sets of data allow us to capture detailed representations of many features of interest, including transmission lines.

Platforms

In the early days, sensors had lower pulse rate frequencies (PRF) as compared to today’s LiDAR sensors. These early sensors had a PRF of 50kHz (50,000 points per second) or less, while today’s sensors have a PRF as high as 1GHz (1,000,000 points per second). With the older sensors, helicopters were the chosen platform, as they allowed a lower and slower flight over transmission lines, enabling them to densify the point clouds to a usable level. With today’s higher PRF sensors, LIDAR data collection from a fixed-wing aircraft routinely produces results that meet or exceed the needs of the transmission line engineer. Since fixed-wing aircraft are less expensive to purchase, operate, and maintain, this results in a significant cost savings to the utility.
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Types of Airborne LiDAR

Airborne LiDAR systems can be divided into three main types: topographic, bathymetric, and multispectral. Topographic LiDAR typically uses wavelengths in the infrared spectrum (1064nm), which is good for detecting ground, vegetation, and other features, but it does not penetrate water. Bathymetric LiDAR typically combines the topographic laser with another in the green spectrum (532nm) and allows for penetrating water and reaching the bottom of water bodies, sometimes up to 60m in depth, though water conditions greatly affect the depth that these lasers can reach. Multispectral systems combine the first two lasers with a third infrared laser (wavelength of 1550nm), adding additional the capacity for land cover and vegetative classification.

Scan Patterns

There are three primary scan patterns for LiDAR sensors: (a) oscillating, (b) rotating, and (c) elliptical. Each of these produce a different scan pattern on the ground, with their own advantages and disadvantages. Oscillating scanners provide multiple angles of incidence, including straight down (at nadir) to help detect objects. Rotating scanners have similar look angles, but keep point spacing more evenly distributed. Elliptical scanners provide forward and rear looking angles of incidence, but not at nadir.

Figure 2: Topographic, bathymetric and multispectral LiDAR wavelengths
Source: Teledyne Optech (http://www.teledyneoptech.com/index.php/product/titan/)

Figure 3: LiDAR Scan Patterns
Source: MDPI (http://www.mdpi.com/2072-4292/6/10/9951/htm)
What’s Involved with Acquiring LIDAR?

In addition to the platform and LIDAR sensor, satellites (GPS, GLONASS, etc.) and the Inertial Measurement Unit (IMU) play important roles in the LiDAR acquisition. Positioning satellite systems orbiting at an altitude of 12,550 miles above the earth provide a means to compute the position of the aircraft, while the IMU measures the angular attitude of the aircraft (roll, pitch, and yaw). A GPS base station on the ground is used to provide differential corrections to the airborne GPS. These measurements, with subsequent post-processing to minimize errors, form the foundation from which the 3D LiDAR points will be computed.

Once the position and attitude of the aircraft is known for any point in time, laser range measurements are then processed. The laser is typically reflected off a moving mirror to scan below the aircraft. The first measurement is the angle at which the laser pulses are fired, or the angle of the mirror relative to the aircraft. The second measurement is the time of flight of the laser pulse from the ground and the returned signal to the sensor. This time is divided by two and multiplied by the speed of light to calculate the range, or distance, the laser pulse has travelled. Lastly, all these measurements are post-processed to create the final 3-dimensional point cloud.

Accuracy and what influences it

There are two forms of accuracy: relative and absolute. Relative accuracy is the accuracy from point to point, and from swath to swath. In other words, how these points fit themselves. Absolute accuracy is the accuracy of the LiDAR as compared to data sources of a higher order of accuracy. In other words, how the data fits to the earth.

Looking at relative accuracy and assuming a properly calibrated LiDAR system, altitude is the first parameter that influences the accuracy of LiDAR. Altitude affects both the horizontal and vertical accuracy of individual LiDAR pulses. As a pulse of light leaves the system’s emitter, the beam diverges, creating a larger spot size at further distance from the aircraft. A laser pulse with a 0.25mrad divergence will have a spot size, or footprint, of 0.25m at 1km altitude.
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Each laser pulse is measured to the center of the pulse and returns from objects can come from the edge of the footprint. In this case, the angle of the reflected pulse (at edge) differs from the angle being measured (center of pulse). Therefore, larger footprints can create a larger horizontal error for a given point.

Figure 5: Laser divergence and spot size (laser footprint)

Altitude also plays a role in the vertical accuracy of the individual laser pulses when combined with other error sources. The laser range measurements themselves (time of flight) are minimal, and the larger error sources come from the GPS/GNSS and the Inertial Measurement Unit (IMU) systems. When combined with the GPS positional errors and the IMU angular errors, the overall vertical accuracy decreases (gets larger) for the individual LiDAR pulses.

Figure 6: Horizontal and vertical accuracies in relation to altitude.
Source: Teledyne Optech
Post-processing of the data can also affect the relative accuracy of the data, swath-to-swath. In the initial processing, the points of a single swath of data are computed, and the point-to-point relative accuracy is typically consistent. When compared to adjacent overlapping swath data, the relative accuracy between these swaths may be greater than desired. There are multiple software packages that will assist in the refined processing to achieve a better relative accuracy. One example is a proprietary software from a LiDAR manufacturer that uses planar surface matching to minimize the relative errors between swaths. Whatever method a software utilizes, it invariably contains a mathematical least-squares adjustment, thereby minimizing the errors as much as possible.

The importance of absolute accuracy can not be overstated. As mentioned before, absolute accuracy is the comparison of the relatively accurate LiDAR data to a data source of higher accuracy. In practical terms, this typically means a ground-based conventional or GPS survey. The American Society for Photogrammetry and Remote Sensing (ASPRS) recommends a minimum of 20 vertical checkpoints of a higher accuracy to compare against the LiDAR data. This step is crucial to ensure the data is properly georeferenced to a published coordinate system or datum. When properly georeferenced, the LiDAR data will “fit” any past and future data that overlaps with the data set and will also be in it’s proper location when converted to other geographical formats.

**Capabilities**

LiDAR shines at creating 3D representations of those features seen from above. But better yet, it excels at showing what you can’t see from above. As some of these laser pulses find their way through the vegetated canopy, the ground surface and other features, like buildings, can be detected. These features can be seen and measured, as the tree canopy is stripped away to reveal what’s hidden below.

**Limitations**

Land cover (vegetation) can affect the ability to adequately capture the ground surface or other features of interest. If the laser pulses cannot strike the feature of interest, no measurement can be made on that feature. LiDAR manufacturers have helped with this problem by increasing the number of pulse returns the system can sense from a single laser pulse. As the pulse travels from the plane, a portion of the footprint may intersect the top of a tree, and that portion of the pulse is returned to the sensor and measured. However, the remainder of the pulse continues to travel until another portion of the pulse strikes a second object and is returned to the sensor. This continues until the last bit of energy is returned to the sensor. Early LiDAR systems were single-return systems, while new systems can sense up to 8 returns from a single laser pulse.
Having the ability to detect multiple returns from each laser pulse helps with penetrating vegetation and finding the ground, or other features, under canopy. However, there are still limitations with seeing through some land covers. Contrary to what may appear obvious, forested areas are not as problematic as other land cover classifications. Typically, there isn’t much low, thick growth under heavy tree canopy due to less sunlight reaching the ground. The nemesis of LiDAR, at least in this author’s experience, is thick grasses and short broadleaf plants. I like to say that if sunlight can reach the ground, LiDAR can reach the ground. However, two examples where sunlight (and LiDAR) cannot reach through to the ground are cogon grass and kudzu vines. These land covers are not conducive to LiDAR surveys and will likely need supplemental ground surveying to accurately survey the ground.
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**Cost Drivers**

While many factors can drive the cost of manned airborne LiDAR surveys, there are a few primary sources of costs that can be mitigated. First, the platform which will carry the LiDAR system greatly affects the overall cost of the survey. As previously mentioned, fixed-wing aircraft cost less to purchase, cost less to operate, and cost less to maintain. They also shorten the duration of flight on most projects.

Aircraft, by design, can go anywhere, and they do. Most companies travel and work in multiple states, as the number of commercial LiDAR vendors is small due to the initial cost of entry into the market. Therefore, the mobilization distance from where the aircraft is located to the project location plays an important role. This is another benefit of the fixed-wing aircraft, as they can travel the distance more economically than a rotor aircraft.

Lastly, when a long mobilization is required, it is best to have a very long project, or many small projects for the vendor to survey. This allows the utility to spread the cost of a single mobilization over more miles of transmission line, bringing the per-mile cost down to an affordable number.

**Terrestrial Laser Scanning (TLS)**

TLS systems use the same basic technology as airborne LiDAR systems, but are used from a static vantage point, most commonly mounted on a surveyor’s tripod. These systems are used for engineering-grade surveys of smaller sites, where fine detail is crucial, such as an electrical substation. TLS Systems commonly have laser pulse repetitions of up to 500kHz. Ranges are typically between 250m and 750m, much shorter than airborne LiDAR systems. Technology keeps advancing, with the most recent model on the market advertising up to 1GHz laser pulse repetition and a 1km range. Most scanners also have high resolution cameras that allow for the creation of photo-realistic point clouds.

*Figure 10: TLS system and target on tripods. Camera mounted on scanner.*
Applications

As stated, TLS systems are better suited for small projects due to their stationary nature and short-range capabilities. Their high-density point clouds offer the ability to model in 3D for design, as-built, and retrofit purposes. Common applications for TLS include deformation monitoring of dams, as-built surveys of industrial facilities, and surveying hard to reach features.

What’s Involved with Terrestrial Laser Scanning?

Since TLS systems are stationary, their line of sight is limited to what can be detected from a single position. Features of interest can be blocked fully or partially by other features, creating blind spots behind those objects. A single scan of a complex structure, such as an electrical substation, will not provide the complete dataset needed by an engineer. To resolve the blind spot issue, the surveyor will move the scanner around to different vantage points to capture the entire scene. The added benefit of multiple scans is the additional data collected during these scans, providing richer detail for the features of interest.

Another feature that TLS systems have is the ability to scan smaller areas of interest with greater detail than the overall scene. The surveyor can restrict the scan window and increase the granularity of a scan. This can produce a highly detailed representation of an individual feature, allowing the end user to better identify the feature and make precise measurements.
Accuracy and what influences it

Much like airborne LiDAR, angular errors can result in low-accuracy LiDAR points. Small angular errors at the emitter increase proportionally in relation to the distance between the LiDAR system and the feature being surveyed. Therefore, when surveying for engineering purposes, it is a best practice to maintain a short distance from the feature being surveyed. This distance will depend upon the capabilities of the TLS being used, but accuracy generally begins to suffer noticeably at distances greater than approximately 300 feet.

Again, like airborne LiDAR, the post-processing, or registering, of the scan data can affect the accuracy of the overall point cloud. There are two primary means of registering the multiple scans of a single survey. The first uses planar surfaces that are common in two or more scans to best-fit the scans together. This software also uses a least-squares adjustment process to minimize the errors and create a ‘best-fit’ solution, at least as it relates to relative accuracy. The second primary means of registering data is to use reflective targets while scanning. These targets will remain in the same position over multiple scans, and these scanned targets are used to register the individual scans together into a single point cloud. For absolute accuracy, a subset of these targets will be field-surveyed to provide georeferencing to a published coordinate system, allowing the data to fit with other georeferenced data sources.
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Limitations

The primary limitations of using TLS have already been discussed, namely the shorter distances needed between the scanner and the features surveyed, and the need to perform multiple scans to capture an entire scene and fill in blind spots. As also discussed, TLS is ideal for small projects. On larger projects, especially linear projects, errors can accumulate, causing accuracy to diminish.

Another limitation for the end user is the size of the data. TLS produces very dense point clouds which can be difficult to navigate and manipulate. As an example, the substation shown above represents almost a half billion points totaling 13GB of data. But we need not throw the baby out with the bath water. Several utilities and privately held companies are using these rich datasets to create accurate as-built models of substations and other industrial equipment, replacing the ‘heavy’ point clouds with ‘lightweight’ 3d objects with CAD and modeling software.

Cost Drivers

The cost of the system itself drives up the cost of data acquisition, but with the labor component reduced, the increase in cost is less than one might think. Like airborne surveys, mobilization to a project site increases expense. However, TLS is typically a local affair, as there is more than likely a surveyor with a TLS system within a reasonable distance from any project.

In practice, the use of TLS can reduce overall costs. It is not uncommon for an engineer to realize that they need more information than originally requested. With a conventional survey, the crew would need to revisit the project site to take additional measurements. Since laser scanning collects much more information than a conventional survey, it is not atypical for the additional requested information to already be ‘in the can’, which can be accessed quickly from the point cloud. This results in a time and cost savings to the surveyor and engineer.

One downward cost driver that should not be overlooked is the cost of safety. With TLS, the field crews no longer need to access and touch features to measure them. They don’t have to get close to electrified equipment. They don’t have to use manlifts to reach high above-ground features. The ability to measure from a distance reduces the safety risk to the field crew members, thereby reducing the cost of hazard mitigation and greatly reducing the risk of personal injury.

Figure 15: TLS survey of tower
Unmanned Aerial Systems

In the last several years, Unmanned Aerial Systems (UAS) have taken off, literally and figuratively, as platforms for some of the same work currently performed using manned aircraft, with varying degrees of success. These small platforms lend themselves to inspections and small-scale surveys and are providing new perspectives on old problems. As with the other technologies, the UAS-based survey comes with its own set of capabilities, accuracy drivers, and limitations.

Platforms

Much like manned aircraft, there are two basic UAS platforms: fixed-wing and rotor. Fixed-wing platforms excel at covering larger areas with lower power consumption. Construction materials range from fiberglass to low-cost foam, creating different price points and flying characteristics. These platforms are ideal for capturing high-resolution imagery or video along corridors or large tracts of land.

![Fixed-wing platforms: Rugged fiberglass (left) and lightweight foam (right)](image)

Multirotor UAS platforms come in a variety of configurations and price points. Small quadcopters typically come with an integrated camera and are compatible with inspections and image/video acquisition. Octocopters provide a greater flexibility in camera payloads, such as mapping-grade, IR, or thermal cameras, and are well-suited for small-scale photo-based surveys. Large (multi)rotor platforms provide greater flexibility, allowing multiple payloads at once, such as a survey-grade LiDAR system and mapping-grade camera.

![Multirotor platforms: Small quadcopter, octocopter, and large helicopter](image)

Payloads and Data

Integrated 4K cameras are standard issue for the small commercial UAS platforms. These cameras provide high-resolution video and still images and are ideal for inspections. These cameras are typically not able to produce accurate mapping data, but their imagery can produce great results, suitable for a variety of applications, such as bird-nest inspections and construction progress.
High-quality, consumer-grade cameras are commonly used on UAS platforms for mapping applications and meet accuracy requirements for most projects. Calibrated lenses are available that minimize lens distortion error and provide a greater level of clarity in the imagery and accuracy in photo-based measurements. Image GSD, or ground sample distance, can be less than 1cm, providing clarity from aerial imagery not seen before.

These consumer-grade cameras, along with automated photogrammetric software, afford the ability to create Digital Surface Models (DSM). A DSM is a point cloud derived from images only. The software utilizes automated photogrammetry methods to create 3-dimensional point clouds of the surveyed area. The resultant point clouds can be highly accurate, even when compared to the more mature technologies previously discussed.

In one comparison example, we surveyed small piles of material using the three technologies discussed so far: airborne LiDAR at 3,000 feet of altitude, terrestrial laser scanning at ground level, and UAS photography from 300 feet of altitude. From the resultant point clouds of all three sources, we computed and compared the volumes of five separate piles. For all five piles, the three volumes for each pile had a difference of only 2% or less, indicating an accurate DSM can be derived from photography.
In our example, the piles surveyed were devoid of vegetation. This is an important distinction, as cameras are passive sensors and can only detect the light being reflected toward them. This is a major drawback when surveying vegetated sites, as the DSM created will be representative of what it ‘sees’. As the name implies, the DSM is a ‘surface’ model, and the surface on a vegetated site is the vegetation itself. If the ground underneath the vegetation is your feature of interest, and it commonly is, this technology will not provide the desired results.

Very recently, manufacturers of manned LIDAR systems have been successful with making smaller systems that can be carried by the larger UAS platforms. These systems can produce point clouds with densities far greater than from a manned aircraft, creating rich detail from several hundred feet above ground. These have the same characteristics as the manned systems, making them an attractive choice.
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Accuracy and what influences it

For data from any of these payloads, there are three main components needed for accuracy: survey-grade GPS, a quality IMU, and survey ground control. For most small and medium UAS, the GPS accuracy hovers near the 1-meter mark, and the IMU has greater error in the angular attitude measurements than those in a survey-grade system. The errors in these fundamental measurements create longer post-processing times and uncertainty in the final output. The solution, as with other technologies, is to have a set of field-surveyed ground control for use in post-processing and quality control of the final data output.

Limitations

As with all technology, the various UAS platforms and payloads all have limitations, and some of these have been discussed above. For the platforms themselves, the greatest limitation is distance. Because they are generally battery-powered and have short flight times of 20-45 minutes, the UAS is constrained to small-scale survey projects. Power technology will continue to improve, and very recently, manufacturers are advertising flight times up to 1 hour.

The FAA line-of-sight regulation also limits the distance the aircraft can travel from the pilot. The UAS must always be in the pilot’s visual line of sight. However, several companies have been working with the FAA to research Beyond Visual Line of Sight (BVLOS) missions. In the utility sphere, Xcel Energy leads the way, working with the FAA since 2016 on BVLOS missions. In April 2018, they received FAA approval to fly BVLOS missions on a routine basis. As other companies follow in their footsteps, the niche that UAS currently occupies will continue to grow.

Conclusion

Understanding the capabilities, accuracies, and limitations of the available technologies helps to select the right tool for the right job. To summarize the technologies covered:

- Airborne LiDAR
  - Ideal for linear facilities and wide-area surveys
  - High detail suitable for modeling (powerlines, topography)
  - Mature technology

- Terrestrial Laser Scanning
  - Smaller footprint
  - Finer detail
  - Maturing technology

- Unmanned Aerial Systems
  - Small-scale projects
  - Variety of payloads
  - Growing technology