Evaluation of an Inexpensive Alternative to a Lidar-Based Aerial UAV Surveying Platform

Georgia Tech Space Systems Design Laboratory
School of Aerospace Engineering

AE 8900 MS Special Problems Report
Space Systems Design Lab (SSDL)
Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA

Author:
Will McNulty

Advisor:
Dr. Brian C. Gunter

May 15, 2021

Abstract

In this project, a UAV aerial surveying platform is built, integrated, and tested using inexpensive and readily available sensors. The goal is to evaluate its performance and accuracy in lidar-based mapping of terrain elevation, and to assess its potential for replacing commercial off-the-shelf lidar surveying platforms that are very expensive to purchase and operate. A fully integrated field test is performed on the experimental UAV, and the results of this test show that a standard GPS receiver does not provide adequate position accuracy to achieve most aerial surveying tasks. Next, a simulation of Real-Time Kinematic (RTK) GPS position accuracy is applied to the experimental data as a substitute for the standard GPS data, and this simulation shows that an upgrade to RTK GPS could provide sufficient accuracy for many surveying missions. Despite the potential improvement in accuracy using RTK GPS, there are some fundamental limitations of the low-cost experimental platform, especially with regards to the resolution and level of detail it is able to capture during a survey. With this in mind, the low-cost experimental platform has the potential to fill a niche for surveying missions that don't quite require the full fidelity of an expensive commercial lidar system, but could benefit from the significant reduction in cost and complexity. Finally, some general practical aspects for the experimental UAV are discussed, including regulatory issues and other considerations for field work.

Introduction & Motivation

This project examines an Uncrewed Aerial Vehicle (UAV) surveying platform built using an inexpensive and readily available lidar sensor. Industries, researchers, and governments are starting to rely more heavily on UAVs to complete missions faster and more efficiently. This project focuses on surveying missions, where the goal is to get an accurate digital representation of the topography in a certain region. There are a number of important scientific applications of UAV altimetry surveys. For example, they can provide scientists with mapping and elevation data of the world's ice sheets [1], volcanoes [2], and costal environments [3].

In the context of survey missions, UAVs often provide an advantage over conventionally piloted aircraft. They can be cheaper and easier to maintain, while also enabling more hazardous missions that would be impractical for a piloted aircraft. However, despite these advantages, UAV platforms can still be complex and expensive to operate. As an example, a full commercial off-the-shelf (COTS) integrated UAV and lidar system, such as the LidarUSA Snoopy Revolution, costs $59,000 to purchase, and the associated data processing software costs $15,000 [4, 5]. This does not include operational or training costs that would be required to get the system up and running.

The goal of this project is to explore an alternative to commercial grade lidar systems using inexpensive and readily available parts. The LidarUSA ScanLook Revolution 120, the sensor aboard the Snoopy Revolution, publishes an accuracy of 3.8 cm [4]. On the other end of the price spectrum, Garmin's LiDARLite v3, a compact and lightweight one-dimensional lidar sensor, publishes an accuracy of 2.5 cm [6]. In addition, the Here3 Real-Time Kinematic (RTK) GPS system with base station claims it can achieve accuracies up to 2.5 cm [7]. If the published accuracies for the LiDARLite and RTK GPS are realistic, it is possible that when coupled together, these sensors could provide accuracy comparable to the significantly more expensive COTS system. The purpose of this project is to investigate the capabilities of a simple and low cost lidar aerial surveying system using real hardware and simple data processing methods, and to see if there are applications where this system may provide an advantage.

UAV Platform Description

A working UAV system was assembled and tested to investigate the utility of an alternative surveying platform. The UAV itself is a 3D Robotics hexacopter in the Y6B configuration. A Y6B configuration has a frame with three arms, with one motor mounted on the top of each arm, and another motor mounted on the bottom. Power is supplied by a single 4S 6500 mAh LiPo battery. The autopilot is a Pixhawk 2.1 Cube Orange with ADS-B Carrier Board, which runs the ArduPilot Copter firmware. ArduCopter version 4.0.5 was used for the majority of this project. The system uses a SiK Telemetry Radio system (915 MHz) to communicate wirelessly with a ground station during flights and ground tests. The UAV airframe, along with many of its smaller components, are old and no longer available for purchase, so it is difficult to know the UAV's exact cost. However, the estimated cost for the airframe and baseline components is approximately $800. This estimate does not include an RTK GPS receiver upgrade, RTK base station, sensor payload, or radio control transmitter. ArduPilot provides the opportunity to program autonomous missions on the autopilot, or the pilot can fly it directly using a radio transmitter. For this project, test flights were performed using direct control with a Spektrum DX7 transmitter paired with a Spektrum satellite receiver. In the field on a real mission, an autonomous mission plan could provide a large benefit, but this is not investigated here. The assembled UAV platform can be seen below in Figure 1.

Figure 1. Fully Assembled UAV

The UAV serves as a platform for sensing instruments and payloads. The lidar and altitude sensing capability were of primary interest. In this particular setup, a LiDARLite v2 sensor is used, which is an older version of the v3 sensor mentioned above. This older sensor was used because it was already in our possession from a previous project, and serves as a good starting point for the analysis. The lidar sensor is mounted to a servo-stabilized gimbal that continuously points in the nadir direction regardless of vehicle attitude. The autopilot uses its internal gyros to control the gimbal and send stabilizing commands to the gimbal servos. An image of the assembled gimbal and lidar sensor is shown in Figure 2.

Figure 2. Lidar Sensor Mounted to Servo Gimbal

Accurate knowledge of the UAV's position and altitude is important for an aerial survey system, and this information is acquired through GPS. Unfortunately, the GPS system used for preliminary analysis is not an RTK-capable system. Again, this is due to the availability of existing hardware from previous projects. Although it's not state-of-the-art, it provides a useful starting point to characterize the accuracy of the system. A photo of the GPS receiver is shown in Figure 3.

Figure 3. GPS Receiver

When powered on, the lidar sensor continuously reads a one-dimensional distance measurement along the sensor's line of sight and reports the value back to the autopilot. The GPS receiver also connects to the autopilot, providing continuous position, velocity, and altitude information when a sufficient number of satellites are in view. The raw lidar distance measurements and GPS data can be processed after a mission to extract useful information.

Data Processing

A key aspect of survey missions is the data processing required after the flight. A goal of this project is to process the data in an intuitive and straightforward way without expensive software packages. This is achieved by extracting data logs from the UAV and processing the relevant data in Matlab.

There are two ways to access the flight data from the UAV. The first is through the telemetry logs (also called T-logs). When ground station software is connected to the UAV through a hard wire USB cable or telemetry system (such as the SiK Telemetry Radio used in this project), and the ground station is communicating to the UAV with MAVLink, the ground station records the message traffic over this interface in the T-logs. The common message set for MAVLink can be found on the MAVLink website [8].

The second option is to access the DataFlash logs. The DataFlash logs capture all of the internal message traffic within the autopilot itself. They are saved directly to the autopilot storage in a compressed binary format, and can be downloaded to a computer after each flight using ground control station software. The full ArduPilot message set can be found on the ArduPilot website [9].

For this project, the DataFlash logs are used as the primary source of data from the UAV. In general, the messages in the DataFlash logs are more stable and reliable than the MAVLink messages because they are not subject to packet loss or other telemetry connectivity issues. To quickly convert the raw binary files, a Matlab routine called Ardupilog is used. This converter quickly parses the raw binary log file into a useful Matlab format. It was developed by users within the ArduPilot community, and contributed to the community for use [10, 11].

To obtain information about the absolute surface elevation under the UAV, the GPS position and altitude of the UAV is required, along with the distance measured by the lidar. The GPS message (containing latitude, longitude, and altitude) is provided at 5 Hz, and the lidar distance information is provided at 20 Hz. These messages are output asynchronously, so to ensure the data is aligned, the lidar data is interpolated to the GPS data timestamps. This creates a synchronized time series of latitude, longitude, altitude, and the distance measured by the lidar.

The next step is to convert this raw data into useful information for a survey mission. Surveyors are usually interested in horizontal distance units rather than raw GPS coordinates, so the raw data must be converted to meet the mission's needs. On a spherical Earth, the distance between each degree of latitude is constant (approximately 111 km per degree [12]), and the distance between each degree of longitude decreases with the cosine of the latitude as the lines of longitude converge near the poles.

An improved model of the Earth accounts for the Earth's ellipsoidal cross-section. In this model, the length per degree of latitude changes slightly across different latitudes, and longitude no longer scales perfectly with the cosine of latitude. Calculating distances between two points becomes more complicated, but can be achieved with iterative methods such as Vincenty's formula [13]. If the distances across the Earth's surface are sufficiently small, the calculation can be simplified by fitting a spherical model of the Earth to the local radius of curvature at the point of interest. The radii of curvature along lines of latitude and longitude are calculated using Eq. (1) and (2) below, where R_m, the meridian radius of curvature, is the approximate spherical radius of curvature along north/south lines of longitude, and $R_{p,}$ the prime radius of curvature, is the best fit circle to the equator at latitude ϕ. Furthermore, a is the semi-major axis of the Earth ellipsoid (a = 6378137 m), b is the semi-minor axis (b = 6356752.3142 m), and e is the eccentricity as defined by Eq. (3) [14].

$$R_m = \frac{a(1-e^2)}{(1-e^2\sin^2(\phi))^{3/2}} \tag{1}$$

$$R_p = \frac{a}{(1-e^2\sin^2(\phi))^{1/2}} \tag{2}$$

$$e = \sqrt{1 - \frac{b^2}{a^2}} \tag{3}$$

Utilizing this model accounts for the Earth's oblateness, but since the UAV covers a relatively small distances across the Earth's surface, it is assumed that all measurements are taken at the same radius of curvature. To evaluate this assumption, consider that a change of 100 km in the north-south direction results in a change of approximately 0.015% in the value for Rm and a change of 0.005% in the Value for R_p. Since a typical UAV mission area covers distances significantly less than 100 km, a constant radius of curvature over the local survey area is a good assumption. With this fact, the spherical Earth approximation can be applied separately to the changes in latitude and longitude as shown in Eq. (4) and (5), where is the ϕ latitude and is the λ longitude. Δx represents a relative distance in the east-west direction, and Δy represents a relative distance in the north-south direction.

$$\Delta x = \Delta\lambda \, R_p \cos(\phi) \, \frac{\pi}{180} \tag{4}$$

$$\Delta y = \Delta\phi \, R_m \frac{\pi}{180} \tag{5}$$

These relative distances can be referenced back an absolute position if necessary. The raw GPS coordinates from the UAV data logs are provided with respect to WGS-84.

Experimental Results

The hardware system was evaluated in a series of experiments. To start off, the accuracy of the old LiDARLite v2 sensor was assessed independently from the UAV. Two copies of the same v2 sensor were available for this test. Accuracy was assessed by recording the sensor reading against a large flat indoor wall and comparing it to the true distance. The experimental accuracy results of each sensor, referred to as Sensor 1 and Sensor 2, are shown below in Figures 4 and 5. Sometimes, the sensor reading fluctuates between a lower and upper bound while sitting at a fixed distance from the wall, so both the upper and lower limits for the error are plotted for each point.

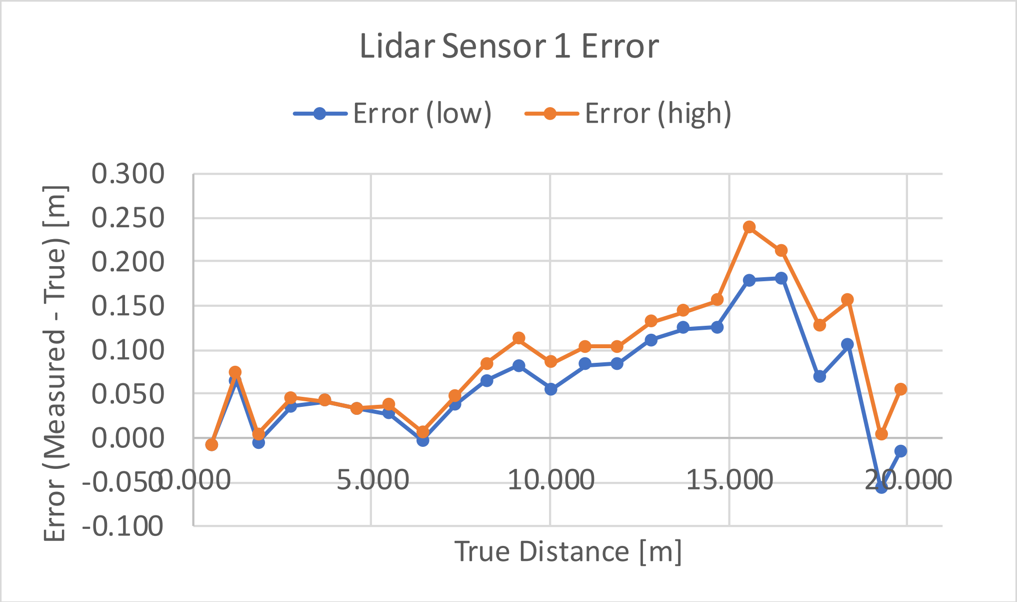

Figure 4. LiDARLite Sensor 1 Experimental Measurement Error

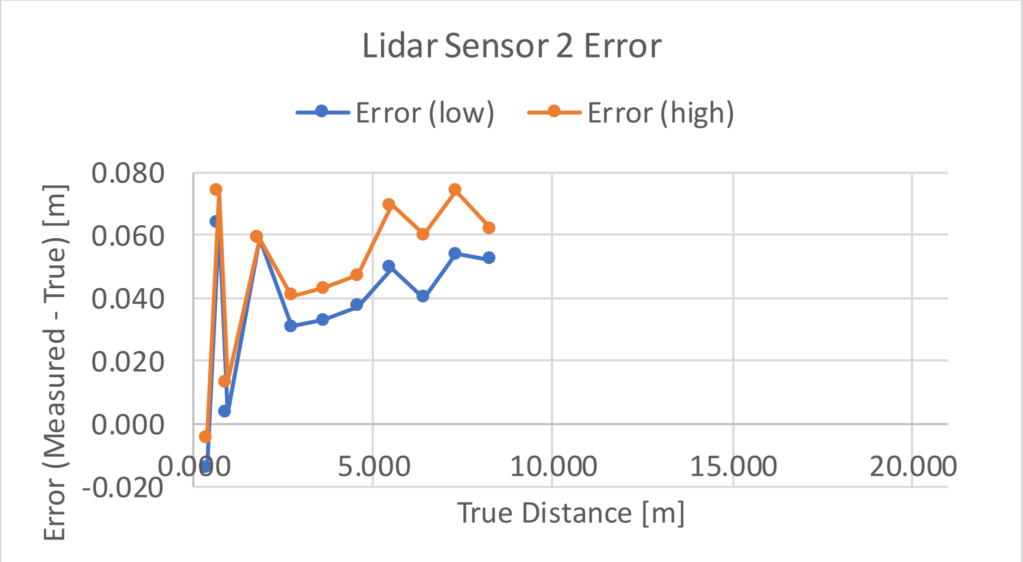

Figure 5. LiDARLite Sensor 2 Experimental Measurement Error

Both sensors had comparable performance at distances less of than 8 meters, maintaining a reading within 10 cm of the truth. However, Sensor 2 returned significant errors (greater than 6 meters) at higher distances. These have been removed from the plot to emphasize detail at the lower distances. Sensor 1 had more stable performance across a wider range of distances, so it is used for the rest of the analysis.

Next, the combined GPS and lidar accuracy was evaluated on the integrated UAV. To do this, the UAV system was tested over a relatively flat outdoor sidewalk area, in full view of GPS satellites. There were nine to eleven satellites in view throughout the duration of this exercise, and sufficient time was allowed for the GPS solution to converge. The UAV was situated over the sidewalk at low altitude, and the altitude was varied from about 0.5 to 2 meters above the surface as it traveled to the north up one side of the sidewalk, and then back down to the south on the other side of the sidewalk, which was about 5 meters wide. A plot of the two-dimensional path over the ground is shown in Figure 6. In this figure, the raw latitude and longitude values from the GPS data were converted to meters using the process described in Eq. (1) through Eq. (5). The distances are all referenced back to the minimum x and y to produce positive Δx and Δy values. The horizontal GPS data performs well, closely reproducing the real path traced over the ground.

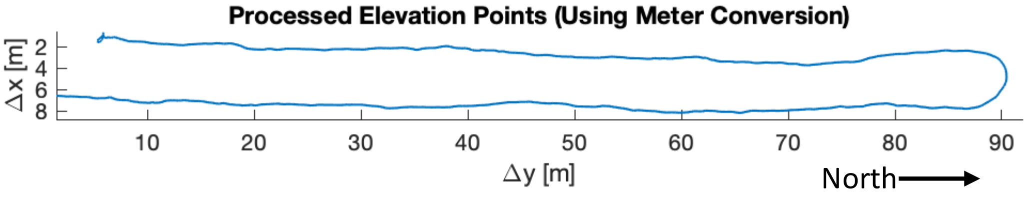

Figure 6. 2D Path Over Ground

The raw lidar distance reading and GPS altitude are plotted with respect to time, over the same time span as the data shown in Figure 6. These plots are shown in Figures 7 and 8.

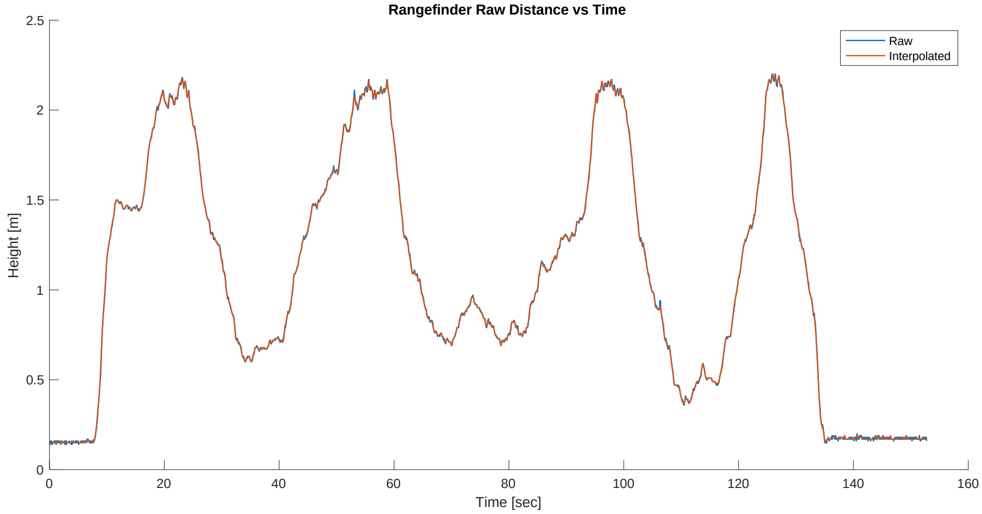

Figure 7. Lidar Sensor Raw Distance vs Time

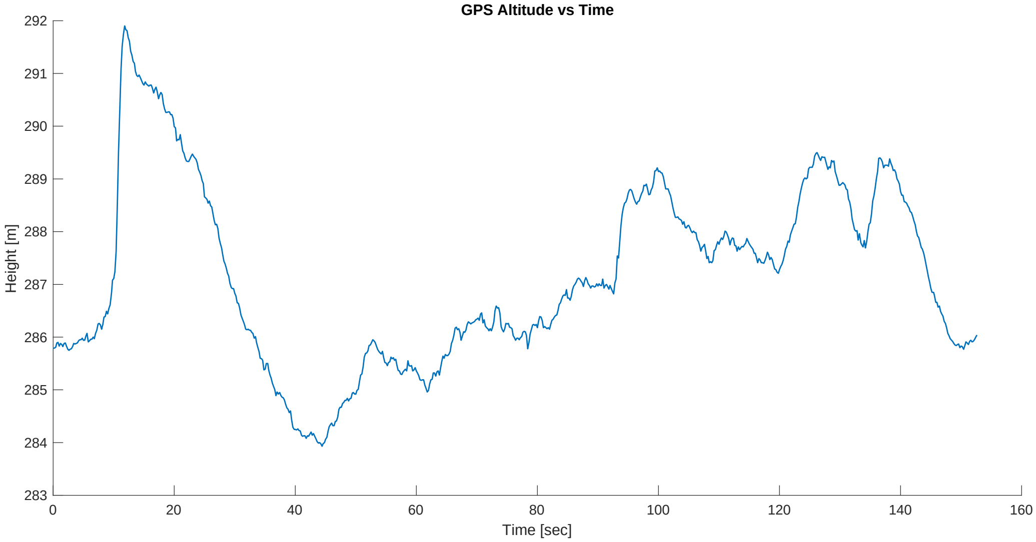

Figure 8. GPS Altitude vs Time

The GPS altitudes in Figure 8 are referenced to the WGS-84 ellipsoid, but they can be converted to the user's datum of choice. Since the test was performed over a relatively flat surface, it is expected that the GPS altitude data should closely mirror the behavior seen in the lidar data. As the UAV's height above the ground varies, the change in GPS altitude should approximately match the change in lidar height, so when the measurements are combined, the level terrain surface is recreated. However, while the lidar measurements showed expected behavior in this experiment, the vertical accuracy of the GPS was not stable or accurate enough to resolve the UAV's vertical movements. Instead, the GPS altitude varied over a range of about 8 meters, and none of the fluctuations appear to correlate with the motion of the UAV.

Next, these lidar and GPS datasets were processed and combed together. Since the lidar sensor is stabilized to continuously point straight down from the UAV, the lidar distance is subtracted from the GPS altitude measurement at each synchronized data point. A small adjustment is also included to account for the difference in height of the lidar sensor and GPS antenna on the UAV. The result of this calculation gives an estimation of the elevation of the terrain below the UAV at each GPS position. The elevation estimates can be seen in Figure 9, which shows the time series of the estimated elevation at each point, and Figures 10 and 11, which show a 3D representation of the elevation estimation. Figure 11 shows the same plot as Figure 10, but looks at the 2D cross-section of the elevation estimate from a side view.

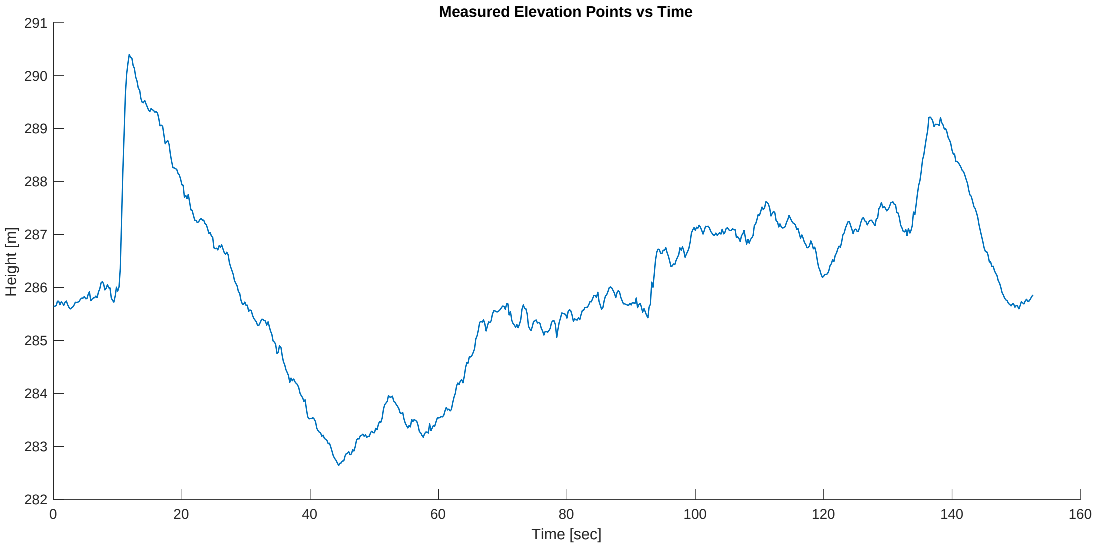

Figure 9. Terrain Elevation Estimate vs Time

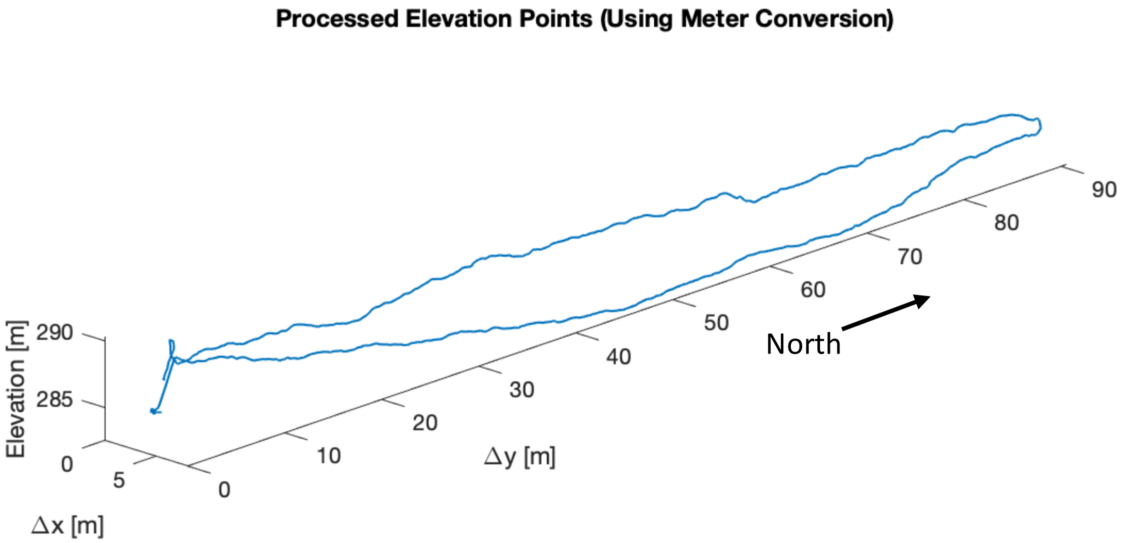

Figure 10. 3D Terrain Elevation Estimate

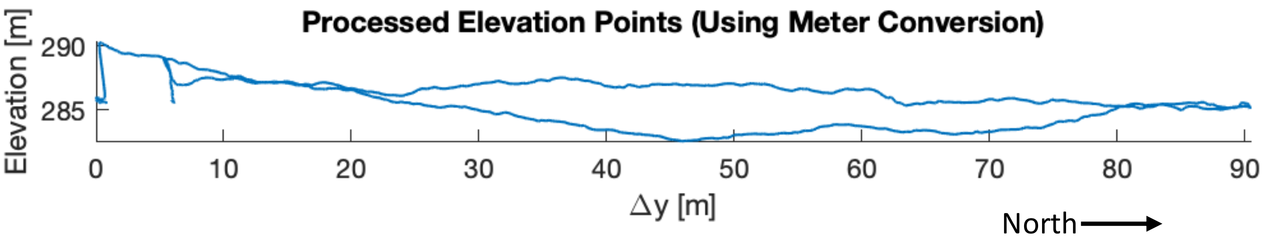

Figure 11. Side View of 3D Terrain Elevation Estimate

While the horizontal GPS data closely approximates the true 2D horizontal path across the ground, the elevation estimate fluctuates by more than 7 meters throughout the test. Recall that the test was performed on a flat sidewalk, so the true elevation would be shown in Figure 11 as a straight and level line across the plot. If the GPS altitude and lidar errors were sufficiently small, the elevation estimate should closely approximate a straight and level line. For this trial, the range of the estimated elevation points is 7.76 meters, and the standard deviation is 1.65 meters. If the sidewalk is assumed to be perfectly flat, these values help characterize the accuracy of the experimental UAV surveying system.

Recall this system uses an old GPS sensor and does not take advantage of RTK GPS, which has become the industry standard for most surveying missions. RTK GPS utilizes carrier-based measurements in conjunction with real-time corrections from a portable base station, and can provide centimeter-level position accuracy under the right conditions [7, 15]. To benefit from RTK, the UAV's GPS receiver must remain within range of the base station (usually within a few kilometers [15]), and as the UAV gets further from the station, the position accuracy starts to degrade towards standard GPS accuracy. This system lends itself well to survey applications because the survey area is usually constrained to a relatively small region that's defined in advance of the mission.

Given the significant accuracy improvement offered by RTK GPS, this raises the question, how would this UAV system perform using a modern RTK GPS receiver instead? To answer this question, a simulation of improved GPS altitude data was performed. This project did not have access to a real RTK GPS receiver, but performing a simulation of the improved GPS altitude within the same experimental setup provides insight into how a real system could perform.

To perform the simulation, a vertical RTK GPS accuracy of 10 cm was assumed. This value was chosen because it is higher than the published 3D RTK fix accuracy of 2.5 cm, and is within expectations when the RTK base station is allowed to survey itself in the field for a few hours [7]. The United States government defines accuracy as the maximum expected error with 95% probability [16]. If the GPS measurements are assumed to be a normally distributed random variable, the reported accuracy therefore corresponds to the 2σ value.

All of the data from the previous experiment is used, except the GPS altitude is replaced with a simulated measurement. The simulated GPS altitude is generated by adding normally distributed noise to the true altitude, with $2\sigma = 10$ cm. The true altitude is calculated from the raw lidar sensor measurement, where the raw distance measurement above the ground is corrected to the true altitude by assuming the error behavior in Figure 4 applies to all raw measurements. An estimate of the true height is approximated by performing linear interpolation on the observed errors at each distance in Figure 7. Errors at distances below the lower bound of Figure 4 are assumed to be negligible. It is worth noting the RTK GPS system would also improve the horizontal GPS accuracy, but this was not simulated because the GPS altitude is the primary source of error in this experiment. The results of the simulation are shown in Figures 12 and 13.

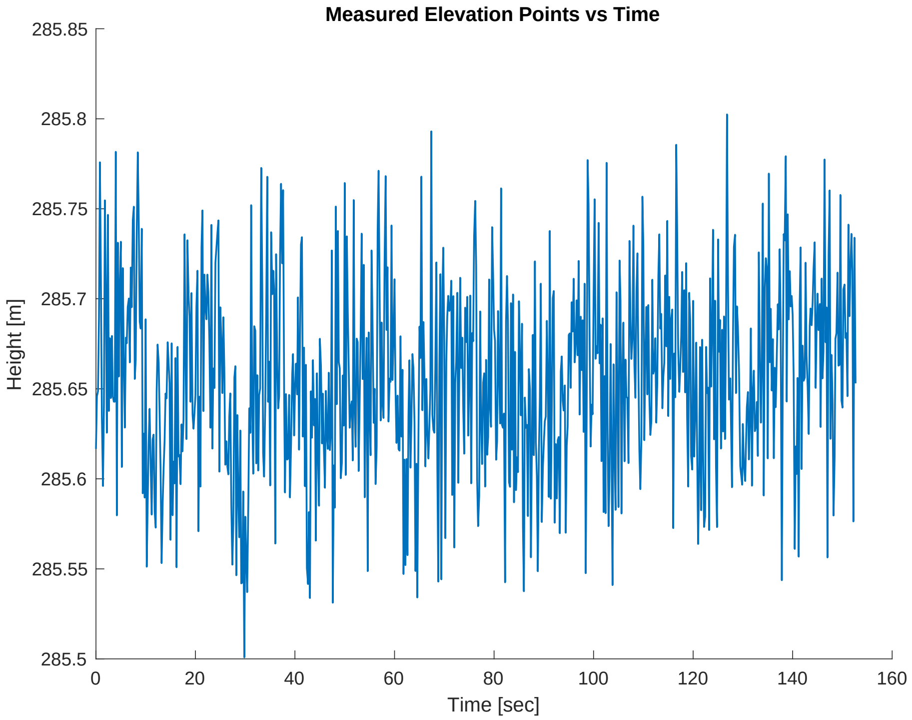

Figure 12. Terrain Elevation Estimate vs Time

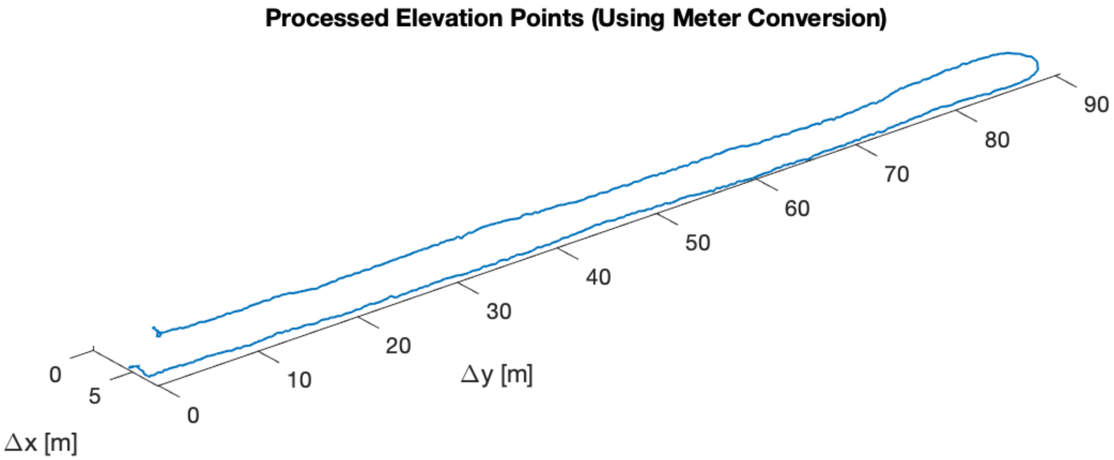

Figure 13. 3D Terrain Elevation Estimate

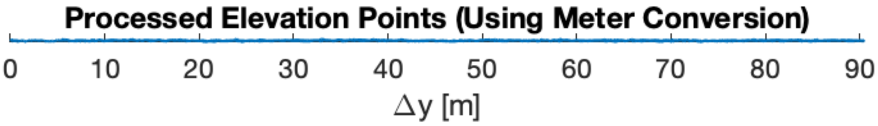

Figure 14. Side View of 3D Terrain Elevation Estimate

The results using simulated RTK GPS are significantly improved over the results using just basic GPS. The terrain elevation estimate closely mirrors the flat sidewalk surface where the system was tested. In Figure 12, the majority of the error is noise associated with the GPS measurement. However, looking closely at this plot, there is also a more subtle periodic movement in the estimate, which is due to the lidar measurement error associated with the UAV's vertical movement throughout the experiment. According to Figure 4, the lidar error varies with the distance it is measuring, so as the UAV changes altitude, it introduces changes in the lidar error which now appear in Figure 12.

Analysis, Future Work, and Improvements

The question of how much error is too much error can be subjective and application dependent. However, errors of 7 meters are generally not competitive for any surveying mission. It is clear that improvements need to be made to achieve any level of practicality with this UAV surveying platform. These improvements would require an upgrade for the GPS receiver, but are not limited to that alone. Suggested improvements, as well a number of other practical considerations, are discussed in the following sections.

RTK GPS

The first trial shows that in the current hardware configuration (with the old GPS receiver), the largest source of error is the GPS receiver's altitude estimate. Additionally, the simulated GPS improvement shows that upgrading this component would provide the greatest improvement in overall accuracy for this system. The best replacement for the GPS receiver is probably the Here3 GPS, which is a popular and relatively inexpensive RTK GPS system that's compatible with the Pixhawk 2.1 Cube autopilot [7]. This system advertises an accuracy of 2 cm when the UAV is within 1 km of the base station [15]. The GPS receiver is currently available for $125, and the Here+ base station costs an additional $300 [17, 18]. Since most of the errors in the current UAV setup are from the GPS altitude measurement, replacing the GPS will provide the greatest overall improvement in accuracy. RTK GPS is a good choice because it provides the opportunity to achieve centimeter-level accuracy.

This significant accuracy improvement offered by RTK GPS does come with some tradeoffs, and it is important to note that centimeter-level accuracy is not guaranteed. To take full advantage of RTK GPS, the receiver must maintain contact with a base station on the ground, which transmits real-time corrections to the UAV to improve the quality of its estimate. To achieve high absolute position accuracy on the UAV, the position of the base station must be known to high accuracy as well. The Here+ Base station has the ability to survey itself in the field, but there is a tradeoff of diminishing returns with regards to how much time it takes to achieve certain levels of accuracy. For example, the user manual for the Here+ base station states that it takes "a few minutes" to achieve an absolute accuracy of 2 m, "around an hour" to achieve an accuracy of less than 30 cm, and "a few hours" to achieve an accuracy of 10 cm [7]. Depending on the logistics of the mission, it may be difficult for the UAV to achieve 2 cm of position accuracy, which is advertised in the top-line performance numbers of the RTK GPS receiver.

An accurate base station position is only required if the UAV needs absolute position information. When the UAV is communicating with a base station, the relative position between the base station and UAV is always known to high accuracy, regardless of the knowledge of the base station's position. Therefore, if the survey mission is only concerned with relative distances and altitudes at the target, then the user does not need to wait for the base station to initialize itself.

RTK GPS is more sensitive to interference than standard GPS, so it is important to place the base station correctly. The base station needs to have a clear view of a wide area of the sky. Specifically, the Here3 user manual states that the base station should have a completely unobstructed view of the sky at least 30° above the horizon [7]. Mounting the base station on a stand may help with this requirement, as long as there are no large objects such as buildings, trees, or terrain blocking it from a distance. In addition, RTK GPS can be very sensitive to electromagnetic interference. To limit these adverse effects, sources of electromagnetic interference such as electronic devices, cell phones, high voltage power lines, transformers, etc. should be kept away from the base station. Taken together, these requirements can pose challenges when using RTK GPS, especially in urban environments.

Another thing to keep in mind is how error corrections start to degrade as the UAV gets further away from the base station. For example, the Here3 base station advertises an accuracy of 2 cm when the UAV is within 1 km of the base station, and 20 cm within 10 km of the base station. This is usually not a huge problem because most surveying missions are conducted over relatively small and well-defined areas. In general, RTK GPS lends itself well to UAV-based survey applications for this reason, in addition to the high accuracy it can provide. It does have some drawbacks and limitations, but these tradeoffs can be managed for most missions.

Lastly, it is worth noting that the Pixhawk 2.1 autopilot and ArduPilot firmware can support GPS blending for any compatible RTK or non-RTK GPS receiver. This functionality combines the estimates from two UAV-mounted GPS sensors [19]. GPS blending was not tested in this project, but it may provide some benefit in the form of improved accuracy and redundancy. It is common to see multiple redundant GPS receivers on many commercial-grade surveying UAVs [4].

Lidar Sensor

The survey accuracy could likely be improved by also updating the lidar sensor. The current sensor is a PulsedLight LiDAR-Lite v2 manufactured in 2015. It is challenging to find published accuracy specs for this old sensor, but the experimental errors are shown above in Figures 4 and 5. Since the purchase of the v2, Garmin has released the LiDAR-Lite v3, which costs $130 and advertises an accuracy of 2.5 cm [6]. It is difficult to know how much the real-world accuracy will deviate from the published accuracy, but it is reasonable to expect some improvement over the current sensor. Upgrading to the LiDAR-Lite v3 would have the advantage of using the same interface to the autopilot as the v2 version, so the integration would be a relatively simple plug-and-play into the current system. There is also the option to upgrade to another brand of sensor. Liteware brand lidars are commonly recommended in the UAV community. They have a number of models to choose from, and there are a few, such as the SF11/C, that are comparable to the LiDAR-Lite. Choosing Liteware sensor as a replacement would require a different integration into the UAV autopilot.

Aside from the accuracy of the survey itself, this experiment highlights some other limitations of the current setup. Firstly, the lidar sensor returns a one-dimensional distance measurement, and continuously points straight down from the UAV. This severely limits the coverage area of the system. Depending on the mission's requirements, this may be acceptable, or it may not. The UAV can fly a defined grid pattern and construct a profile of the terrain based on the one-dimensional lidar scan. However, in many surveying missions, it would be beneficial for the UAV to cover a swath of terrain underneath its flight path and provide data for off-track elevation estimates.

To expand the coverage area of the lidar survey, it could be valuable to implement a gimbal sweep angle, where the sensor was systematically pointed left and right in a stabilized fashion. Although the sensor can only point in one direction at a time, this functionality would increase the average swath of the survey area as the sensor swept back and forth. This could increase the coverage area of the overall mission and provide higher resolution estimates of the terrain elevation. The heading and instantaneous sweep angle of the sensor would need to be known at every time step to determine the pointing vector for off-track lidar measurements. Heading information is contained in the ArduPilot DataFlash logs, but its accuracy would need to be assessed. If the heading accuracy was found to be insufficient, it might be possible to improve it with the use of two RTK GPS receivers placed sufficiently far away from each other on the body of the UAV, and infer the heading from the relative orientation of two sensors. Determining the instantaneous gimbal sweep angle could be more challenging, because ArduPilot does not automatically record this information for the servo gimbal.

Other Improvements to the UAV

There are other changes to the UAV, beyond the sensing system itself, that could be made to improve overall utility and practicality for real-world missions. For example, to use this system in a cold and snowy climate, it would be important to protect sensitive electronics from the elements. The Pixhawk Orange Cube has heating elements in the IMUs to mitigate errors due to thermal effects, and that is very helpful in cold environments. However, water damage from snow, ice, and rain could still pose a big threat to any mission. Designing the UAV frame to shelter the autopilot from contaminants would be a valuable improvement for real field work.

Another issue is the mission endurance and range of the UAV. The utility of a survey vehicle depends on how much land area it can cover before recharging. This can be improved with investment in high quality LiPo batteries. The capacity rating, usually given in milliamp-hours (mAh), determines how long a battery will last on one charge. However, even for batteries with the same mAh rating, the quality of the cells themselves can have a significant impact on the flight time. Gens Ace or Tattu brand LiPo batteries are often recommended in the UAV community as high-quality options. Another concern is that in cold environments, the flight time of a LiPo battery pack shrinks significantly. Some of this may be mitigated with protection from the elements, but overall, it is difficult to overcome in harsh environments.

The current Y6B multicopter setup has a typical endurance of 15-20 minutes. In a real mission, this places a significant limitation on the area that can be surveyed. Aside from improved batteries, there are some other ideas that can be investigated to try and increase the endurance. Firstly, it is worth investigating if a hexacopter is truly necessary for the mission in question. If the only payload is a lightweight lidar sensor and gimbal, then it may be possible to get away with three motors instead of six, thereby reducing the power consumption. It wouldn't necessarily double the flight time, because each motor in the tricopter would need to work harder to make up for the loss, but it may provide some savings. Also, depending on the size and location of the desired survey area, it would be worth assessing whether a multirotor UAV was the right tool for the job in the first place. Fixed wing platforms can be much more efficient, achieving longer range and endurance with the same payload and battery capacity. The current autopilot is capable of flying a fixed wing as well, but the lidar and GPS systems would need to be re-integrated to the new form factor. Additionally, a fixed wing platform is harder to test in an urban, suburban, or university environment because it requires a larger area for safe operation.

Comparison to Commercial Grade Lidar System

Although significant improvements could be made to this UAV system, there are some fundamental limitations with using this particular type of lidar sensor. The biggest limitation is the type and granularity of detail it is able to capture. The LiDARLite and other one-dimensional UAV sensors are designed to return range estimates to relatively close objects. These sensors are commonly used on UAVs for object avoidance and to improve the UAV's estimate of height above the ground (for features such as auto-landing, hovering, etc). They are not designed to capture small and intricate details of the sensing target, and in fact, they are not really designed for surveying applications in general. As a result, the sensor has trouble resolving small objects, sharp corners and edges, and other fine-grain features. During indoor experiments, the LiDARLite sensor's reading would fluctuate widely and become unstable if the sensing target was not large and well defined. This problem becomes worse at greater distances.

This is where the advantage of a full commercial grade lidar system starts to become apparent. In contrast to the simple and low-cost surveying platform analyzed in this project, many COTS lidar systems can provide very high-resolution point clouds in three dimensions, and do so with high accuracy. The resolution provided by such a system is significantly better than what can be provided by a 1D sensor such as a LiDAR-Lite, and high accuracy is achieved in three dimensions instead of just one. In addition, COTS systems have the ability to resolve a very fine level of detail from a distance. To illustrate these capabilities, a sample point cloud from a LidarUSA ScanLook Revolution is shown below in Figure 15.

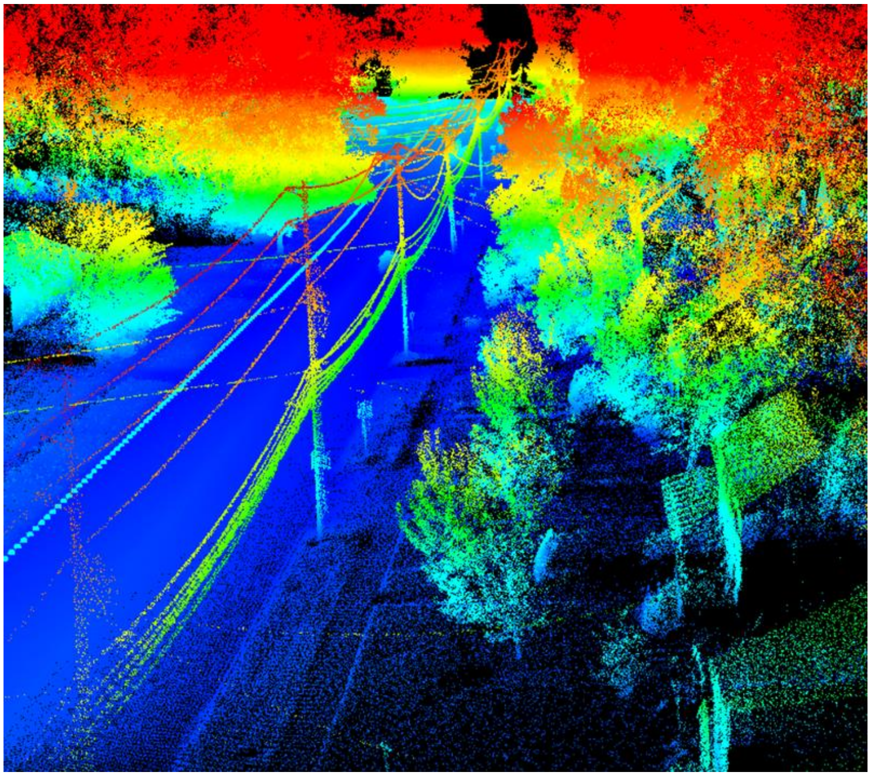

Figure 15. Example Point Cloud from LidarUSA ScanLook Revolution. Image obtained from [4].

This point cloud can resolve detail on a much finer scale than the LiDAR-Lite sensor. While the LiDAR-Lite may provide an accurate estimation of the street and sidewalk elevation, the ScanLook has the ability to resolve individual power lines on the telephone pole and branches on the trees. This may be exactly what is needed for some missions. For example, if the objective is to capture intricate, high-resolution 3D models of physical features, such as a buildings, trees, rock outcroppings, or telephone poles, then the mission would be better suited to a commercial grade lidar system. On the other hand, if the mission is looking to characterize an elevation profile over wider region, such as a glacier or costal area, and is not concerned with resolution of small features, then a commercial lidar may provide significantly more detail than is required. In this case, the simplicity and cost savings of the UAV system considered in this project may fill a specific niche, and allow the user to bypass the more complex and expensive systems. This would provide a real advantage to users with the right application in mind.

UAV Regulatory Issues

It is often the case that a UAV mission is constrained more heavily by regulations than by technology. In the United States, UAVs are rapidly changing the aviation industry, and the Federal Aviation Administration (FAA) is working to safely integrate them into the National Airspace System (NAS). As a result, there is considerable uncertainty surrounding the current regulatory environment for UAVs. In addition to federal regulations, which apply everywhere in the United States, it is important to keep in mind there may be additional rules, ordinances, and requirements imposed by local municipalities and organizations. In addition, the federal regulations are quickly evolving, so it is imperative that UAV operators familiarize themselves with all federal and local requirements well in advance of any mission.

If operators are interested in flying in other countries, there may be additional complexity. Aside from following all national and local rules in the destination country, there may be issues around which frequency bands are permitted for use. For example, in the United States, UAV telemetry systems use 915 MHz, but in Europe, they use 433 MHz [20]. This is not a comprehensive list of regulatory differences, but rather a reminder to scrutinize every rule closely, especially if traveling internationally.

In the last few years, the United States government has also raised cybersecurity concerns around UAV technology manufactured in China. Although most of the recent focus has been on DJI [21], the dominant UAV manufacturer in the US market, this concern could have implications for all UAV components manufactured in China. Executive Order 13981, which was signed on January 18, 2021, ordered a review of the Federal Government's "Authority to Limit Government Procurement of Covered UAS", with the goal to "prevent the use of taxpayer dollars to procure UAS that present unacceptable risks and are manufactured by, or contain software or critical electronic components from, foreign adversaries" [22]. A Covered UAS includes any UAV that is "manufactured, in whole or in part, by an entity domiciled in an adversary country", or "uses critical electronic components installed in flight controllers, ground control system processors, radios, digital transmission devices, cameras, or gimbals manufactured, in whole or in part, in an adversary country" [22]. The UAV in this project falls into the category of a Covered UAS because its Pixhawk 2.1 autopilot is manufactured in China. Although Chinese-made UAV technology is not currently banned outright, there is significant uncertainty about how the United States will proceed from here, and there is a non-zero risk that a targeted ban or a restriction on the use on federal research dollars for such UAVs may be imposed in the future. The rules in this area will need to be watched carefully, especially when building a UAV platform has the potential to be used on federally funded research projects.

Conclusions

In this project, a simple and low cost UAV surveying platform is assembled, integrated, and tested, with the goal of assessing its strengths and weaknesses against expensive commercial-grade lidar UAV surveying systems. The platform developed in this project collects data using a gimbal-stabilized LiDAR-Lite rangefinder sensor in conjunction with a standard GPS receiver to provide an estimate of the terrain elevation below. A fully integrated hardware experiment was performed to assess the quality of the results it can deliver in the field. In the current hardware configuration, which uses a standard (non-RTK) GPS receiver from 2015, the UAV does not provide data with sufficient accuracy to serve most surveying needs. An analysis of the raw data shows the largest source of error is in the GPS altitude estimate, and since an accurate UAV altitude is required to compare to the lidar measurement, this throws off the rest of the survey data points. To overcome this limitation, an upgrade to RTK GPS is suggested. A simulation of measurements from a more accurate RTK GPS receiver shows this upgrade would significantly improve the accuracy of survey data collected by the UAV.

A variety of other improvements to the UAV are also discussed, including upgrades to the LiDAR-Lite sensor itself, as well as changes to how this sensor is utilized. The survey coverage area of the UAV could be expanded by implementing a sensor sweep angle to collect data points to the left and right of the UAV in addition to directly underneath. This would improve the resolution and efficiency of each mission. In addition to sensor improvements, there are a number of practical considerations to consider for a real-world mission, including regulatory issues, protection from harsh environments, UAV endurance, and coverage area capabilities. It is worth considering whether a fixed-wing platform fitted with the same sensor payload would be better suited to a mission's needs. Fixed wings are generally more aerodynamically efficient than rotorcraft, so this has the potential to increase the endurance and survey coverage area for each flight.

Finally, although there are opportunities to significantly improve this platform, it does have some fundamental limitations. The inexpensive LiDAR-Lite sensor only returns a distance measurement along one dimension, and this limits the resolution of data it can collect. In addition, due to the original intended use of this sensor, it has a difficult time resolving small and irregularly shaped features, especially from longer distances. This is in contrast with many commercially available lidar surveying systems, which are capable of producing dense high resolution point clouds that are significantly more refined from what the experimental platform can provide. With this in mind, each mission needs to be assessed to determine the level of detail that is required. In cases where the mission requires intricate 3D detail on a fine scale, it will probably be necessary to use a commercially available lidar system. However, this low-cost experimental platform could provide a real advantage to users who want to conduct an accurate survey of a region, but don't require the full detail and fidelity offered by a commercial system. With the right improvements, this UAV surveying platform has the potential to fill a niche that would allow some users to avoid more costly lidar systems.

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