Developing a Novel UAS Flight Planning and Reconstruction Software Package

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ABSTRACT

Images collected by an unmanned aerial system (UAS) provide a unique dataset that can be used to create realistic three-dimensional (3D) reconstructions through the process of photogrammetry. The accuracy of 3D photogrammetric reconstructions is strongly influenced by several factors including UAS image capture locations, 3D reconstruction method, and the overall terrain just to name a few. Current UAS flight planning software and reconstruction techniques can be limiting in regards to generating UAS flight paths that account for specific features such as flight boundaries, flight avoidance zones, the underlying terrain, reconstruction processing time, and reconstruction product quality.

This paper will present the current state of UAS flight planning and 3D photogrammetric reconstruction software along with a discussion of their main limitations and their impact on the resulting 3D reconstructions. This paper will also describe the challenges encountered with respect to flight path optimization when accounting for specific preferences in flight path parameters and 3D reconstruction quality. Newly developed capabilities and their impact on 3D reconstructions will also be discussed, including the ability to create UAS flight plans that adhere to user-supplied flight boundaries, account for interior avoidance zones within a survey area, and adapt to the underlying terrain in the area of interest. The resulting improvements lead to improved UAS flight paths and 3D photogrammetric reconstructions that target a variety of use cases from commercial to military applications.

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INTRODUCTION

The expanded utilization of three-dimensional (3D) reconstructions created from aerial imagery for both commercial and military use cases, from construction to reconnaissance, has led to the development of a myriad of unmanned aerial system (UAS) software platforms. These software platforms are designed to help users conduct UAS flight planning, acquire aerial imagery, and/or generate their own 3D reconstructions. The more this market continues to grow, the more sophisticated and accessible this software becomes for users in specific industries and those within the public at large. As with all software, there are certain strengths and limitations depending on the situation and needs of the user, so it is difficult to find a one-size-fits-all software that satisfies the needs of every industry. The limitations of the current UAS flight planning and 3D reconstruction software landscape provide the rationale for our research and highlight how these newly developed capabilities can benefit UAS flight planning to generate optimal 3D reconstructions in both commercial and military applications.

Current UAS Flight Planning Software

With recent advancements in UAS systems technologies and increased market accessibility of these systems, a multitude of flight planning and 3D photogrammetric reconstruction software have been developed for use in a range of industries. An exploration of the leading commercial and public software for conducting UAS flight planning highlights critical areas of improvement (Table 1). This is not an exhaustive list, but focuses on commonly used software. Some overarching limitations of both commercial and open-source software is the inability to offer strict adherence to defined survey areas, collision avoidance capabilities based on pre-existing data, and the optimization of flight parameters to improve 3D reconstructions with reduced flight times and/or optimally placed image captures.

Table 1. Comparison of Current UAS Flight Planning Software (DroneDeploy, n.d.; Oborne, 2024; Pix4D SA, n.d.; QGroundControl, 2020)

Categories	DroneDeploy-Aerial	Pix4Dcapture	Mission Planner	QGroundControl
Benefits	User-friendly interface, UAS terrain-following, customizable parameters	User-friendly interface, designed for mapping and photogrammetry	Open-source interface with extensive features and customizations	Modern and open-source interface, supports various survey types
Limitations	Geared towards construction projects, restricted to DJI drones, not open-source	Targeted toward DJI products, less customization, not open-source	No flight plan obstacle avoidance, flight path may not adhere to survey bounds	No flight plan obstacle avoidance, flight path may not adhere to survey bounds
Industry-Specific Solutions	Specialized tools for agriculture, construction, and inspection	Focused on mapping and photogrammetry, cell tower reconstruction	Highly customizable with extensive plugins and script support	Flexible and customizable for a range of applications

DroneDeploy is an effective example of a software-suite that includes both UAS flight planning and 3D photogrammetric reconstruction capabilities (Adjidjonu and Burgett, 2019). The software offers a wide set of flight planning features to easily create optimized flight plans, with options like terrain-following and vertical façade inspections, in addition to the normal gridded survey options available in most systems. Specifically, most of the analysis tools are geared towards construction projects or inspections. The main limitations of this software are the limitation of code alteration and the restricted application to DJI drones, all of which can be limiting factors based on the use case. Like DroneDeploy, Pix4D offers similar commercial flight planning and photogrammetry features with Pix4Dsurvey and Pix4Dmapper, respectively. The Pix4D suite supports various survey types beyond DroneDeploy capabilities and integrates well with other widely used Pix4D products, but it is generally targeted to DJI products with their flight planning. While Pix4D software components provide a strong competitor on the market, the inability to customize the software can limit the usefulness for some users.

As for free and open-source software, there are two common UAS flight planning software programs that are widely used, Mission Planner and QGroundControl (Ramirez-Atencia, C., & Camacho, 2018). Both of these programs offer various flight planning capabilities, UAS autopilot setting adjustments, and flight log analyzing tools. Compared to the commercial options, Mission Planner and QGroundControl may not have the breadth of flight planning features or ease of use needed for commercial or military applications. While they are both under continuous community development, their feature-set is generally geared towards more generic user cases, lacking specialization. In addition, these open-source software platforms can suffer from flights paths that do not adhere strictly to the designated flight bounds and also do not have methods of handling obstacle avoidance when building the flight plan.

The Effect of Software Memory Usage on 3D Reconstructions

Another significant limitation for current UAS operators utilizing data for 3D reconstructions is the potential computer memory limitations resulting from the number and resolution of UAS images collected and used for the 3D reconstruction, which could result in a failed reconstruction. Knowledge of this potential limitation demonstrates the need to advance current flight planning software to optimize image collections with the goal of minimizing the number of images processed if possible.

A study of the relationship between the number of images and memory requirements show that the amount of computational memory used and time taken to complete the 3D reconstruction scale linearly with the number of images used, as shown in Figure 1. This analysis was completed using OpenDroneMap (ODM) reconstruction software on a system with 64 GB of RAM and an Intel(R) Core(TM) i9-9900K CPU at 3.60 GHz (OpenDroneMap Authors, 2020). In regards to the ODM parameters, PC-Quality was set to “medium” using a resolution that is 12.5% of the original image size for the *openmvs* stage and Feature-Quality was set to “high” using a resolution that is 50% of the original size for the *opensfm* stage. While this analysis demonstrates the need to investigate flight area and parameter improvements, the results also suggest that the inclusion of a computational memory usage estimation would be useful to understand the potential difficulties reconstructing 3D data with the current flight plan selections.

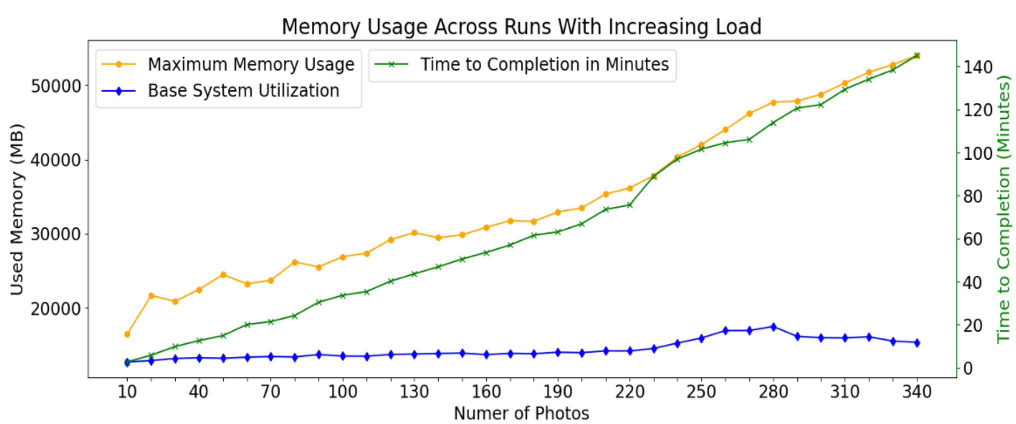

Figure 1. Relationship Between Number of Photos and Total Memory

TESTING ENVIRONMENTS

The following section discusses the testing environments used during this research to allow for the creation of UAS flight plans and analysis of the impact of those changes on the resulting 3D reconstructions.

UAS Flight Planning Testing Environment

To test UAS flight path algorithms, we use in-house code developed in Python that takes in a survey polygon and flight parameters (frontlap, sidelap, altitude, and camera parameters) and allows us to evaluate different flight path generation methods and compare them to other software. For UAS collections, we use our own Aurelia X6 hexacopter with a Sony Alpha a6000 24.3 MP camera (15.6 mm camera height, 23.5 mm camera width, and 16 mm focal length).

Synthetic Environment for Testing UAS Survey Parameters

In order to test new algorithms and procedures on a UAS, it is quite difficult and sometimes infeasible to conduct a UAS survey for each and every test due to the time, cost, weather, and wear-and-tear on the UAS. Additionally, it is necessary to consider the difficulty of testing in diverse terrain environments, some of which may be too difficult or hazardous to get to safely. As a result of this, it was a conscious decision to use synthetic environments to our advantage for the purpose of testing our hypotheses and algorithms in a quick and effective manner to evaluate the impact of altering UAS flight path parameters on the resulting 3D photogrammetric reconstructions. This synthetic testing environment utilizes the ODM 3D reconstruction software to process image captures taken either virtually over the synthetic environment or real-world images collected by a UAS for validation.

Before synthetic environments can be used to test new algorithms and evaluate the corresponding impact on 3D reconstructions, the efficacy of synthetic environments must be validated as a trustworthy means of testing. The synthetic environment is built using a “reference” dataset. For this research, we utilize a colored, geo-registered point cloud provided courtesy of the Campus Geospatial Assets group at The University of Texas at Austin. This point cloud was acquired with UAS imagery, reconstructed with Pix4D, and geo-registered with ground control points to within 10 cm accuracy. The point cloud elevation and Red-Green-Blue (RGB) values from this dataset are rasterized into associated digital surface model (DSM) and RGB GeoTIFF files, after which they are converted into a textured triangle mesh (OBJ format). Next, a “real” dataset is created from actual UAS imagery collected by our team over the same area as the reference dataset and processed through ODM to create a 3D reconstruction. Then, a “synthetic” dataset is created using the reference dataset by positioning virtual cameras in an open-source 3D data processing library, Open3D, at the same camera extrinsics (camera position and orientation), intrinsics (focal length and resolution) and altitudes as the real UAS data collection to mimic the original process as closely as possible. These virtual images are processed in ODM to create the synthetic 3D reconstruction. This full process is summarized in Figure 2.

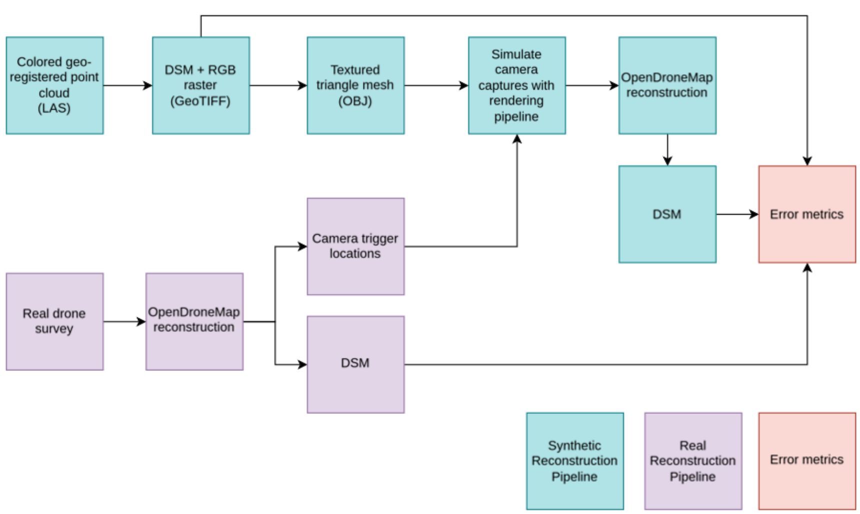

Figure 2. Flowchart of the Synthetic Data Generation and Validation Process

With our synthetic and real 3D reconstructions, we can now compare the two to each other and to the reference data, using a mix of qualitative and quantitative metrics. Figure 3 (upper) shows both the reference point cloud and synthetic reconstruction from the same point of view, showing a qualitatively close agreement between the two reconstructions. A comparison of a profile line calculated using both the reference and synthetic reconstructions is shown in Figure 3 (lower). The two models are similar in appearance, with all features of the profile line successfully reconstructed via the synthetic reconstruction method. The only difference is a slight overestimation of elevation values in the synthetic reconstruction for structures.

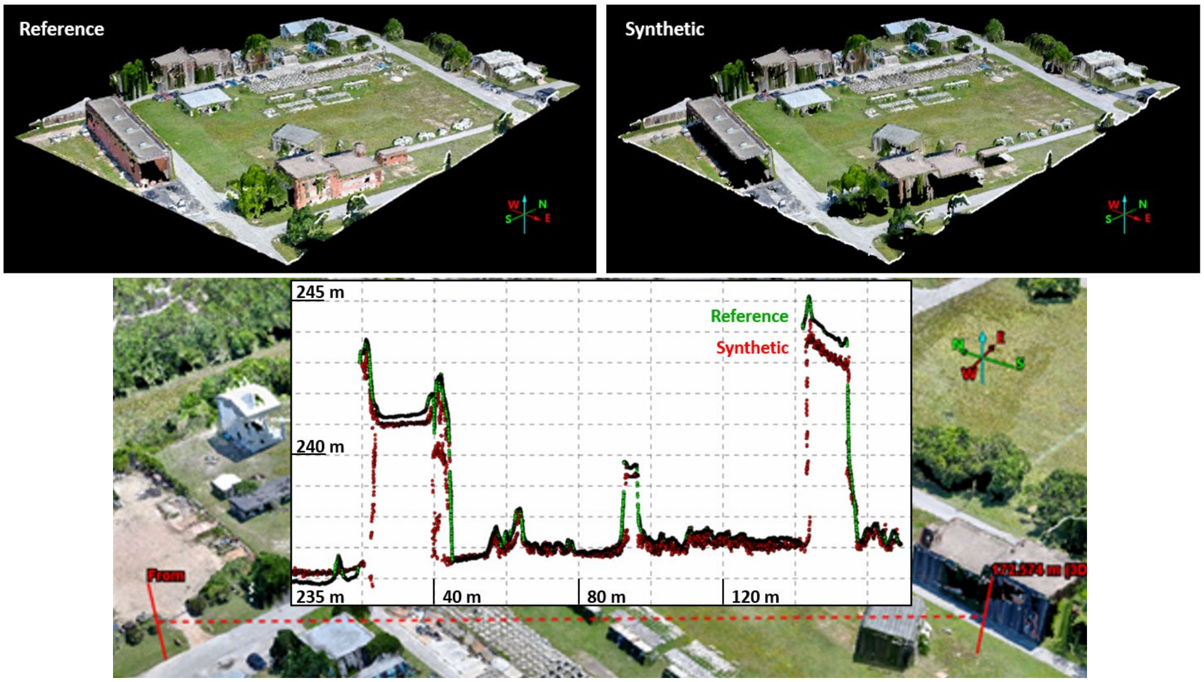

Figure 3. Comparison of Reference vs Synthetic Reconstructions

For quantitative metrics, we examine the elevation difference between the reference DSM and each of the real and synthetic reconstruction DSMs, as shown in Figure 4. Each of the models are within an acceptable range of differences, with the synthetic and real reconstructions having mean absolute error (MAE) values of 0.58 and 0.45 m, respectively. Using these qualitative and quantitative methods to validate our approach, we can have a higher level of confidence with our analysis in utilizing this synthetic reconstruction method to test different image capture strategies.

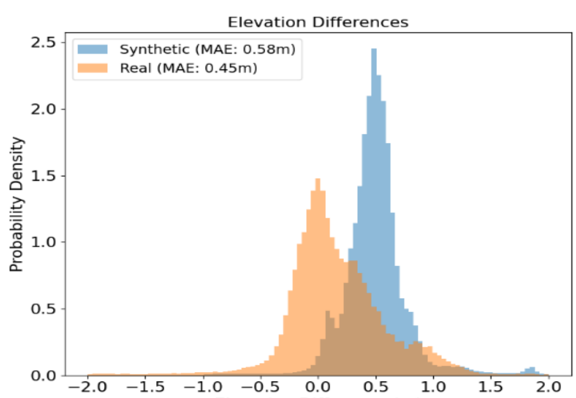

Figure 4. Synthetic vs Real Elevation Error Histograms

IMPROVING UAS FLIGHT PLANNING CAPABILITIES

Before generating a 3D photogrammetric reconstruction from aerial imagery, a UAS flight plan must first be created and executed. The research presented in this section focuses on improving UAS flight planning capabilities to design optimal flight parameters that help improve 3D reconstructions while accounting for user survey restrictions and computational processing capabilities.

Optimizing Flight Paths Through User-Defined Polygons

UAS flight planning software requires a user-supplied survey polygon, defining the area of operation, to help create a survey flight path. Current UAS flight planning software, referenced in the previous section, can accept most polygon shapes and ensure an optimal UAS flight path that adheres to the polygon boundaries. However, this research has uncovered instances where more complex survey polygons can lead to sub-optimal UAS flight paths and situations where the UAS flies through regions outside of the polygon boundary during operation, as shown in Figure 5 (black arrow). There are many reasons why this could be undesirable behavior and why a user may need to have more confidence that their UAS will fly an optimal path within the survey polygon regardless of the shape. For commercial UAS flights, there might be a need to avoid electrical utility equipment, trees, buildings, or other restricted areas within an aera of interest (AOI) which may necessitate the need for a particular survey polygon shape. Physical obstructions may not be the only reason for strictly adhering to the boundaries of a survey polygon during flight. For instance, users in a military setting may wish to create specific survey polygons that contain efficient flight paths due to mission critical needs such as conserving battery life, minimizing flight time, and providing concealment during operation.

Figure 5. Example of UAS Flight Plan Failure to Adhere to User-Supplied Polygon Boundary

In addition, most common UAS flight planning software tools do not provide an option for creating user-supplied avoidance regions within an AOI. Instead, a user would need to either break up a mission into multiple flight plans that, when aggregated, cover the desired AOI without entering the avoidance region or accept UAS movement through an avoidance region, which may not be an acceptable option. Both of these solutions can adversely affect the time taken to create and conduct UAS surveys safely and according to mission needs.

We have developed a method to create optimized flight paths through user-supplied polygons regardless of the shape and optionally containing interior avoidance zones by decomposing the original polygon into smaller, constituent trapezoids through a process known as polygon decomposition (Li et al., 2011) (Figure 6). In this process, adjacent trapezoids are repeatedly merged if the resulting merged polygon can be easily swept with straight lines. This condition guarantees that a line at a particular orientation does not cross the polygon's boundaries more than twice. In the context of coverage path planning, this means that the polygon can be entirely covered with a lawnmower pattern sweep without having to exit the boundary. Sweep segments are then created to cover each of these polygons, followed by a traversal simulation, where each segment must be visited exactly once. Additionally, the traversal simulation is extended to ensure that no violation of avoidance zones occurs by traversing a visibility graph that connects all segment endpoints, while avoiding the avoidance zones. The final waypoints and camera trigger locations generated by this process can then be exported as a flight plan that can be executed by a UAS.

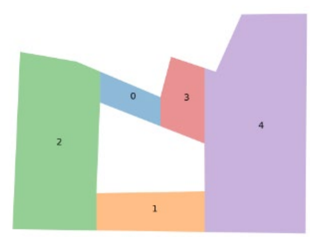

Figure 6. Example Flight Plan Using Polygon Decomposition

Testing this new method in our software shows a significant improvement over current software, not only in adhering to the user's boundaries, but also in improving flight time and image count, as shown in Figure 7. This capability can add benefit to both commercial and military UAS missions by providing confidence that a UAS will fly an optimized path within its defined survey polygon, thereby avoiding any potential hazards during flight as identified by the user while also reducing the flight time and aerial image count which can reduce the time taken to generate the 3D photogrammetric reconstruction

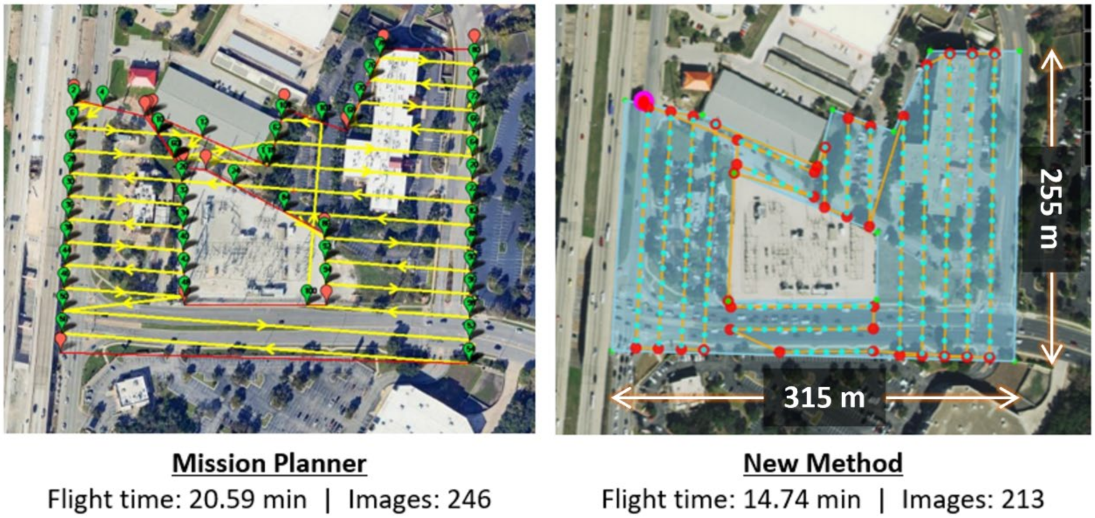

Figure 7. Comparison of Current and New Flight Planning Methods Using 70% Overlap at 40 m Altitude

Advancing UAS Collision Avoidance

A potential hazard during UAS flights is the presence of large obstacles which can result in a collision. Currently, the main responsibility of collision avoidance during a UAS mission falls on the UAS operator to identify these obstructions through visible line of sight (LOS) and adjustment of the flight plan to avoid the hazard. For commercial UAS flights, there might be a need to avoid specific obstacles within a survey polygon such as electrical utility equipment, communication towers, trees, tall structures, or other restricted areas within a subset of the larger AOI. Also, users in a military setting may wish to avoid potential obstacles within an AOI to allow for capabilities such as flying low to prevent detection or maintaining RF connectivity by avoiding communication towers which may cause signal interference.

To further extend the ability of using avoidance zones within a flight plan, we implemented an automated option that utilizes an object avoidance input file, currently defaulted to the Digital Obstacle File (DOF) from the Federal Aviation Administration (FAA) (Federal Aviation Administration, 2021). With this option, a user can see the locations of potential obstructions provided by the FAA file such as radio antenna, communication towers, and other hazards. Our algorithm uses the obstacle's height above ground level (HAGL) from the FAA file to aid in determining a safe altitude and flight path for the UAS during operation to avoid a potential collision with a known obstruction, as shown in Figure 8. However, there are two limitations with using this method. First, the FAA Digital Obstacle File is publicly sourced and, as a result, may contain potential inaccuracies for some obstacle locations and heights if used without first verifying the accuracy of the information. Second, this FAA file only has coverage for the United States and a few select areas outside of these bounds which may not be helpful in certain use cases.

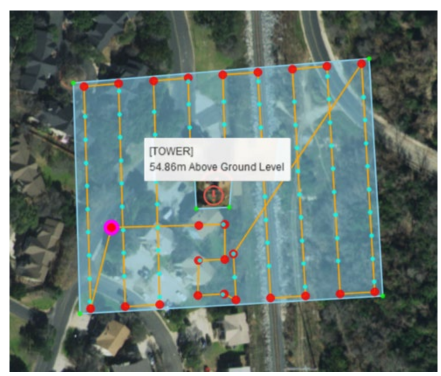

Figure 8. Example Communication Tower Obstacle from FAA File Within Flight Boundary

In situations where the FAA file does not have information about obstacles, we implemented another method to allow the UAS to avoid potential obstacles during flight by using a known DSM for the area. If the terrain for the AOI is already known from prior UAS collections, publicly sourced data, or other global terrain sources, then this terrain surface height information (tree tops, buildings, etc.) can be used to create a terrain surface-following flight plan for the UAS, as shown in Figure 9. This method will take into account any potential intersection with a known obstacle and the UAS flight path within a specified buffer and adjust the flight path accordingly to keep the UAS at a safely specified distance above the obstacle.

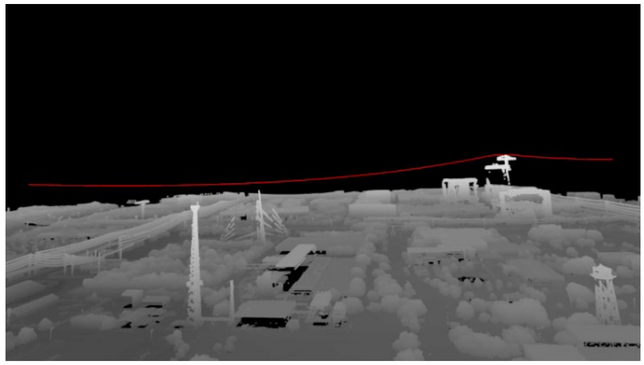

Figure 9. Example Flight Path Using Known DSM for Obstacle Avoidance

Modern UAS terrain-following approaches smoothly adjust flight altitude according to the underlying terrain (Gómez-López et al., 2020). This style of altitude adjustment uses a bare earth model and allows the UAS to fly over large terrain features. This approach, however, can leave the drone vulnerable to collisions with surface features such as trees and large buildings. When developing our terrain following technique, we wanted to achieve a higher level of safety by including the DSM into the terrain following. Our approach breaks the process up into two different stages with the bare earth model being used for terrain following and the DSM being used for collision detection and avoidance. The algorithm starts with naively increasing each waypoint's altitude to the desired flight altitude above the ground at that location. Next, each waypoint altitude is smoothed via a 1D sliding window convolution with a mean filtering kernel. After mean filtering, the flight waypoints are checked for intersections with the DSM plus a safety margin. This is done by interpolating waypoint-to-waypoint altitudes at the surface DSM resolution. These interpolated flight altitudes are then subtracted from the DSM surface height at those locations. If the result of that operation is less than the safety margin, the altitudes of the waypoints around the collision are increased by the safety margin. The entire path is then smoothed again and rechecked for collisions. This process continues until no further collisions are detected.

IMPROVING 3D RECONSTRUCTIONS FROM UAS IMAGERY

This section discusses modifications to the UAS flight parameters within a survey AOI which can have a direct impact on the resulting 3D reconstructions. These modifications include determining optimal amounts of image overlap needed for a reconstruction and a method for evaluating UAS image capture locations based on the underlying terrain.

Determining Optimal UAS Image Overlap Using Synthetic Environments

Image overlap is known to affect photogrammetry results, since the process relies on matching key points between overlapping images of the scene from varying viewpoints. This leads to a tradeoff between processing time and reconstruction quality, where higher overlap leads to more accurate 3D models at the expense of processing time due to an increased number of images. For UAS-based photogrammetry, frontlap (overlap in the along-track direction) and sidelap (overlap in the across-track direction) have varying effects. Both contribute to an increased number of images, with sidelap also increasing flight time as it determines lateral spacing between flight segments. Within most common UAS flight planning software, frontlap and sidelap are typically user-defined parameters that depend upon user judgement given the specific mission needs.

To make a recommendation for default frontlap and sidelap parameters, an analysis was conducted on the effect of overlap on 3D reconstructions using our synthetic environment as discussed in the Testing Environments section. In this process, surveys with varying frontlap and sidelap parameters were simulated using virtual cameras over the synthetic terrain, producing a different 3D model for each combination. Each 3D model could then be compared to the original reference 3D model. Results for mean absolute error along with their underlying distributions across varying combinations of frontlap and sidelap are shown in Figure 10. The results in Figure 10A indicate a decrease in error as a function of increasing overlap, which is consistent with other findings in this area of study (Seifert et al., 2019; AIRCAM Drone, 2024). We do note a slight increase in elevation error at the highest level of overlap tested, but overall, there is an exponential decrease in error with increasing overlap. This is represented when looking at frontlap and sidelap in one dimension (Figure 10B). In this figure, the line colors transition from lighter to darker red as the reconstruction processing times increase. What this indicates is that the optimal amount of frontlap and sidelap is best determined by a specific user and use case that can dictate the appropriate amount of trade-off between output 3D reconstruction quality versus processing time. In this decision, it is important to consider the impact of UAS survey flight time, which is increased by sidelap, and reconstruction processing time, which is increased by the number of images that must be processed. This approach, when executed more comprehensively over a variety of terrains, could be extended to predict elevation error based on the level of overlap used for a UAS collection.

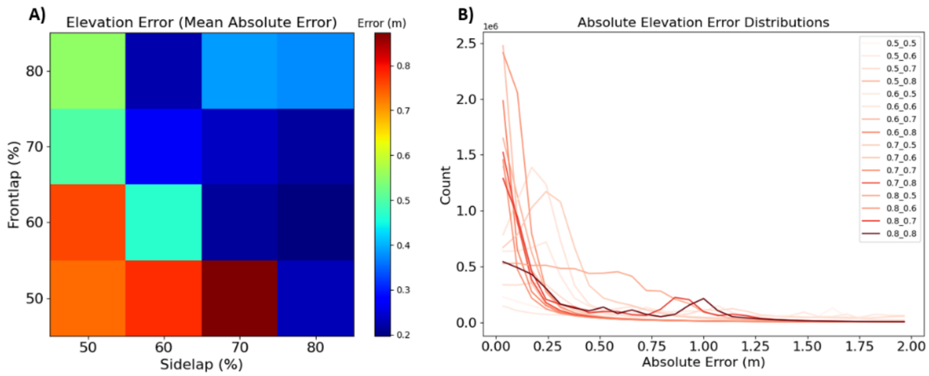

Figure 10. Elevation MAE Values (A) and Distributions(B) Across Frontlap and Sidelap

Analyzing Terrain-Based Image Capture Methods Using Synthetic Environments

Current UAS flight planners are useful for quickly designing a generic UAS flight path with image capture locations for a given AOI. One thing to note with this capability is that these UAS flight planners generate flight paths and image capture locations based solely on the shape of the survey polygon which is invariant to the underlying terrain. This means that for a given survey polygon with the same UAS flight parameters, the flight path and image capture locations would be the exact same if the UAS flew over a flat, empty field versus a sloping, feature-rich area. In this example, the responsibility would be on the user to vary the amount of image overlap needed for the mission based on the terrain itself or features in the terrain (presence of vegetation, buildings, etc.). This process requires experience and intuition on the part of the UAS operator. Our goal is to help automate this process so that UAS flight parameters, with a focus on image overlap for this research, can be dynamically set as a function of the underlying terrain, thus maximizing the amount of information gained while minimizing the amount aerial images requested to benefit the 3D photogrammetric reconstruction process.

Photogrammetry packages like ODM use a roughly standardized pipeline that typically involves feature detection, keypoint matching, structure-from-motion (SfM) point cloud generation, depth map estimation, meshing, and texturing. While specific implementation details in each step may vary, failure to successfully detect and match features between overlapping images can adversely impact downstream outcomes. For example, visually homogeneous areas like fields or paved roads, which have a high likelihood of mismatching due to a lack of distinctive visual features, can have poor reconstruction results. On the other hand, areas with a high density of distinctive features due to unique objects like human-made structures will tend to have more feature matches. Increasing image overlap is one way to deal with image homogeneity, since it decreases the likelihood of feature mismatch, however this leads to longer collection and reconstruction times since more images must be acquired and processed.

A method to account for this variable feature density across an area is analyzed by adaptively spacing image captures in a synthetic environment. For this process, the density of Scale Invariant Feature Transform (SIFT) features is computed over an area using satellite imagery for the specific AOI. Once a flight path is generated, the spacing of image captures in the along-track direction of the flight path is adjusted such that image capture density best matches the inverse of feature density for a fixed number of captures in the along-track direction (Figure 11). This process aims to automatically vary the number of images required based on the amount of features in different regions of the AOI. The effectiveness of this method is still being assessed, however preliminary results are promising.

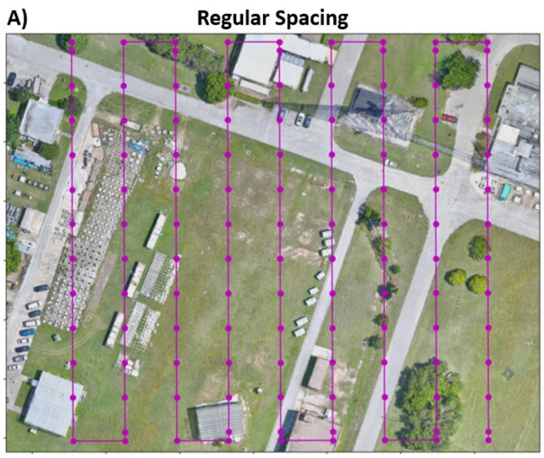

Figure 11. Regular (A) vs Inverse SIFT Density (B) UAS Image Location Spacing Using 70% Overlap

When tested against our reference 3D model, the synthetic captures using inverse SIFT density spacing show a reduction in elevation error in the output 3D reconstruction, while having the same number of images as the synthetic capture case with regular spacing, as shown in Figure 12 to the right. Although there is room for growth in this area of study, the current results point to the fact that varying the UAS image captures and their locations over a specified AOI based on the underlying terrain can benefit the quality of the output 3D reconstruction. More work is needed in this area to further confirm the strength of this hypothesis along with evaluating the effectiveness of our method of synthetic testing with respect to other terrains and adaptive image location methods. Another avenue to investigate is determining whether this method can be used to maintain a certain level of elevation error while reducing the number of images.

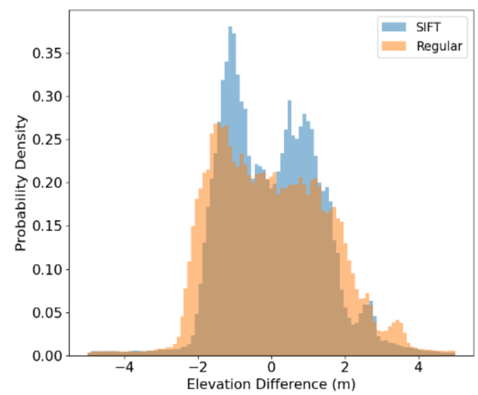

Figure 12. Elevation Error Histograms for Inverse SIFT vs Regular Spacing

CONCLUSION

Imagery from a UAS can provide a unique dataset that can be used to create realistic 3D reconstructions for a variety of use cases. While there are many UAS flight planning and 3D reconstruction software platforms currently available, some flight planners are limited when it comes to adhering to UAS survey boundaries and avoiding collisions during flight while some reconstruction software platforms are limited in allowing users to vary UAS image capture locations based on the underlying terrain to benefit 3D reconstructions.

We have made improvements to UAS flight planning to create optimal UAS flight plans that adhere to user-supplied polygons of varying complexities which may contain interior avoidance zones using polygon decomposition while also reducing the possibility of UAS collisions during flight by avoiding obstacles through the use of ancillary data such as the FAA Digital Obstacle File or an existing DSM. We have also done analysis to understand the tradeoffs between 3D reconstruction and UAS flight time versus elevation error when it comes to the amount of UAS image overlap needed during a mission, enabling the user to make a decision based on their own needs, along with understanding the impact of variable UAS image captures with respect to the underlying terrain and how utilizing the amount of features in an area can be used to toggle the amount of UAS images needed to improve the output 3D reconstruction. Both of these methods were tested in a synthetic environment in which the results trend with what can be expected in the real world, thus strengthening the effectiveness of using synthetic environments for testing methods employed on a UAS. The resulting improvements lead to an ability to generate improved UAS flight paths and 3D photogrammetric reconstructions that target a variety of use cases from both commercial to military applications.

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