Optimizing UAV Systems for Rapid Survey and Reconstruction of Large Scale Cultural Heritage Sites

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Abstract— Recording geometrically and aesthetically accurate models of cultural heritage sites is important for both their conservation and understanding of historical importance. Rapid imaging systems are required to capture models efficiently so that large sites can be documented with sufficient resolution. Increasing availability of consumer-level drones has fostered digital data collection to replace traditional surveying methods. While such systems allow photogrammetric data to be gathered, they often prove inadequate for large scale rapid imaging. We propose an aerial system infrastructure based on: adapted aerial platforms; optimizations for flight path generation and UAV operations; high-bandwidth LTE transmission; methods of efficient point cloud generation, to rapidly document large scale heritage sites.

Index Terms—UAV; Photogrammetry; LTE; Structure-from-Motion

I. INTRODUCTION

The development of airframes, control systems and communication networks has allowed low-cost drones to become more useful to collect data. Improvements of payload capacity, flight time, user operation and reduced costs has made it possible for a diverse population to use UAVs to carry sensors to image objects. While the improvements have made it easier for people to create videos and aesthetic photographs, few systems have demonstrated improvements for creating 3D models from a variety of sensors on large scale. Large scale fixed wing UAVs such as the Penguin B are able to carry the necessary payload over a large range. Such platforms however require a large take-off area and are hard to transport. Our scaling method is to have lower cost-fixed wings which operate in swarms over a long range. This allows us for easier field deployment and repair. Each aircraft would be carrying a high-resolution mirror-less camera to obtain high resolution imagery.

It can take multiple weeks before data gets to locations where it can be processed. Smaller survey areas can be computed on field compatible supercomputers, whereas large datasets require an infrastructure of SFM dedicated machines, or distribution over cloud processing. We suggest using a software-defined radio system to upload data in close to real-time to the ground where field computers are located or a high bandwidth access point to upload to the cloud for processing. Integrating IMU information from the platform together with GPS makes it optimal for rapid processing as the software can estimate a camera position for the reconstruction. It is possible to integrate a live preview of merged images however it will take hours of cloud processing time to render high resolution point clouds.

II. MOTIVATION

Applying remote sensing technologies to survey and reconstruct heritage sites is important for a multitude of reasons. A majority of sites need to be documented to preserve their information as they risk to physically change. Due to a destruction from war, conflict, weather and urbanization, a significant number of sites are at risk of disappearance or degradation. While site preservation programs attempt to protect sites, it is often the case that less visible parts of the site are left out, or not known of. With the aid of aerial imaging it is possible to find and document all parts of heritage sites. It is often physically impossible to map areas between sites using total stations or traditional equipment, therefore one must rely on correct geo-referencing of sites or satellite imagery to merge datasets. Being able to image over multiple sites simultaneously will have an incredible impact on the understanding of the interaction between sites or societies.

Three- dimensional reconstructions are often imported into CAD software to do structural analysis of structures, as well as creating support structures. Rapidly generating 3D models of historic sites is crucial to the rapid restoration of buildings and artifacts.

Natural disasters can often devastate heritage sites in a very short time. Post-disaster analysis of sites can lead to effective damage analysis as well rapid reconstruction plans to be created.

III. OPTIMIZATION OF AERIAL PLATFORMS AND SENSOR INTEGRATION

Surveying of remote areas present a unique challenge when tackling data acquisition for rapid imaging of geographical sites. Target areas can often be remote or inaccessible due to geographical constraints. The use of UAVs for rapid aerial data acquisition make them a crucial novel technology. UAVs have the ability to take off and land in rugged terrain, carry high resolution imaging sensors, withstand weather condition, and remain portable enough to transport them around the world. Figure 1 shows a map of a case study in Mexico, where 400 km^2 documented in a total of 5 flying days. This area is of interest to understand the interaction between old Mayan

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cities, in the north eastern part of Quintana Roo, Mexico, and will be further discussed throughout this paper. A total of 800 km was flown in that time period.

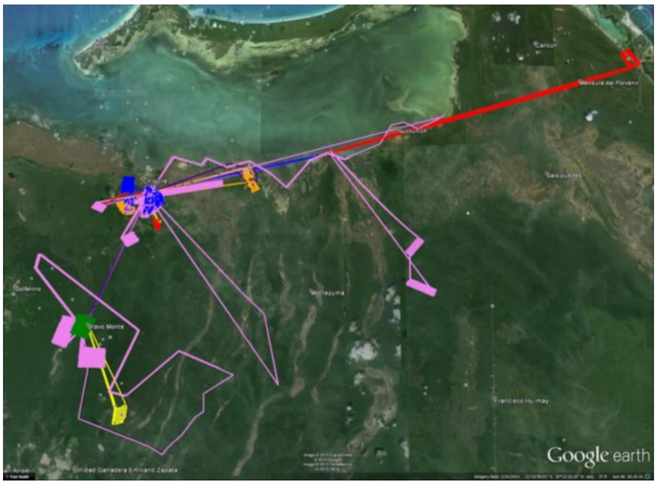

Fig. 1. Large Scale Mappign in Quintana Roo

In general, most UAV platforms are well diverse and can be combined to satisfy most survey applications. The goal is to meet the eight requirements for 3D reconstruction of large-scale heritage sites: high geometric accuracy, capture of all details, photorealism, high automation level, low cost, portability, application flexibility, and model efficiency.[3] Since one specific system is not known to satisfy all specified criteria of 3D reconstruction, the criteria can be used as a base to select Unmanned Aerial Vehicle. In order to select an aerial platform for rapid survey and 3D reconstruction we also need to: identify the size of the area of interest, obtain weather conditions for the region, assess take-off and landing logistics, and determine the aircraft's flexibility and portability.

Based on the above criteria, we selected three main types of platforms that can be used for rapid large scale mapping: fixed/rotary wing aircraft, foldable wing aircraft, and multi-rotor helicopters. Each platform characteristics and flight parameters are shown in Figure 2.

Platform	Payload (kg)	Flight Time (min)	Horizontal Airspeed (m/s)	Vertical Speed (m/s)	Max Wind Speed (m/s)	Take off space (m)
Multi-rotor	1-2	<30	5	3	12	5
Fixed Wing	<1	80	16	3	10	100
Paraglider	1-2	60-120	9	1	6	50
Helicopter	1	60-120	8	3	10	10
Baloon	0.5	Unlimited	0.5	1	5	10

All numbers are estimates for average platforms

Fig. 2. Aircraft Specification for Rapid and Large Scale Surveying

Fixed/rotary aircraft are most common in the UAV development for long range mapping. In a case study deployment done in Quintana Roo, Mexico two fixed/rotary aircrafts were tested for the use of rapid long range 3D mapping. The first airplane used was the ready-to-fly 3DR Aero aircraft produced by 3D Robotics Inc. and the second airplane used was the Ranger EX 757-3. Both aircraft were, previously tested for autonomy stability and safety before surveying the Quintana Roo jungles. A total of 19 survey flights were done with the Aero covering a distance of 350 km. Similarly, a total of 12 survey flights were done with the Ranger, flying 450km. Together the platforms reached 800km automated flight distance

Both platforms were equipped with a Pixhawk autopilot system, 3DR GPS and Compass, and a digital airspeed sensors that enable full autonomy. Detail specification of the platforms can be seen in Figure 2. Figure 3 shows us launching the 3DR Aero.

Fig. 3. Launching 3DRobotics Aero Fixed Wing in Mexico

Multicopters have the potential to maintain level flight and close range to structures. They are able to obtain high geometry accuracy, capture rugged details, obtain photorealism photography, while maintaining high automation level, low cost, and portability. Although, multicopters have a limited flight time of less than 30 minutes depending on the payload weight, multicopters are the closest platform that can meet the eight requirements for 3D reconstruction. As battery technology advances and the problem of flight endurance is overcome, multicopters will meet the eight requirements for creating long range 3D mapping models. Detail specification of the multirotors can be seen in Figure1.

The optimization of UAV sensors for rapid survey and reconstruction of large scale cultural heritage sites is highly dependent on the cost and size of the sensors. Many approaches to create 3D models are often done by combining multiple techniques: image-based modelling, range-based modelling, and image-based rendering. Many of these techniques require expensive imaging sensors that can be costly and large to equip on portable UAVs. For this reason we are forced to explore the alternative and equip our aerial platforms with relatively low cost and compact sensors. A representation of our data acquisition can be seen in Figure 1. The data shows the parameters obtained from our visual survey of (Conil, Q. Roo) taken with a (Sony QX1). The flight was performed at an altitude of 203.24 meters covering a total area of 2.3 square km, with a ground resolution of .0384 m/pix. A 3D photo-mosaic panorama was stitched together using structure from motion (SFM) techniques, allowing us to create a rapid large scale map of the region to search for cultural heritage sites.

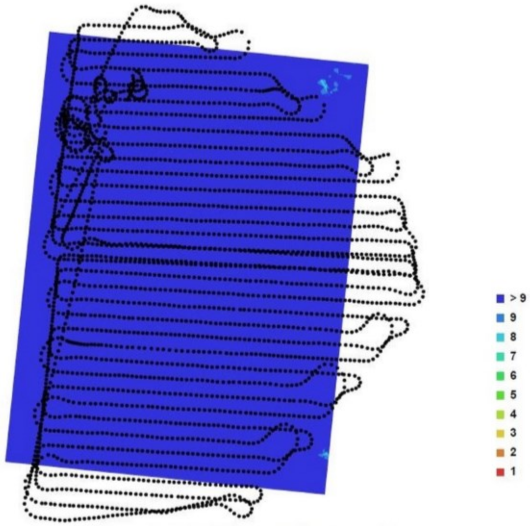

Fig. 4. Coverage of Conil in Quintana Roo, Mexico

Some of the other sensors used in the Quintana Roo deployment as well as other deployments include IR (infra-red), thermal, and high resolution cameras along with laser range sensors.

IV. Generation of Flight Paths for Sensors

The use of flight paths for large-scale mapping and autonomous data gathering is of high importance. Before any survey platform is deployed, the site of interest is usually surveyed using satellite images to identify key points of interest. Preparation of a survey deployment for large-scale mapping consists of a preliminary digital survey, selection of the target mapping area, and a pre-planned flight path based on weather conditions. All sensors used required overlap between the images or samples. This is so that they can optimally be merged. For visible light cameras, we use a standard overlap of 60% to 70%. This is so that if there is one anomalous image or data point, that it can be ignored, and data from nearby images can substitute it. The distance between flight lines is calculated between a spreadsheet which combines Field of View from the sensors, their resolution and the desired model resolution. Figure 8 links the data resolution to flight altitude for the Sony Qx1 Camera.

Height (m)	Resolution (cm/px)
50	1
100	2
200	4
400	8

Fig. 5. Table of resolutions at flight altitudes for Sony QX1

V. LTE Communication and Telemetry

Communications are a key component to the rapid survey and large scale mapping of cultural sites of interest. In the case for rapid survey and real time image processing, we propose the use of LTE communications as a solution that would consist of a workflow for the streaming of data back to a base station. A mobile phone would be used onboard the UAV to capture imagery at regular intervals using a self-designed app, and paired with GPS and IMU data from the flight controller. This device is connected to the ground station via an LTE network on 400 MHz. The phone uploads JPEG images through this connection to a LTE ground station.

The mobile phone will either be flown on a long-endurance UAV (Fixed/rotor aircraft, foldable aircraft, or multi-rotor helicopter) as mentioned in the optimization of aerial platforms section. In the case of a fixed/rotor wing aircraft, we will pre-program a commercial autopilot with a mapping mission characterized by flying in an optimized lawn-mower pattern, with automatic triggering of any arbitrary camera at distance intervals designed such that the images overlap by 50-70% for a given flight altitude. Further work will focus on achieving stereo imagery using 2 smartphones located in each wingtip of a fixed wing, to enhance orthorectification of the imagery and create better height profile maps. By closing the feedback loop of visualization and path planning without needing to land, we can reconfigure the flight path in real time to further examine particular areas of interest in higher resolution.

A second communication system on board is required for telemetry to provide real-time health and status dates of all the UAV avionic systems. Each aerial platform transmits important information to the ground station. The telemetry data allows the flight team to monitor all aspects of the flight including altitude, mission duration, battery life, flight plan, etc. Real-time health and status dates enable us to determine the stability of our platform. Without such sensors rapid survey and large scale mapping would not feasible. Loss of communication and platform health can result in the loss of aircraft and jeopardize data acquisition.

VI. Visualization and Analysis of Data

For this project, we used existing computing resources of CISA3 at Calit2, University of California San Diego for the image stitching and visualization. A multitude of dedicated computers will continue to complete feature recognition, image alignment, and blending algorithms already generated by other researchers. The images would be saved to the processing machines directly, and the output streamed to a visualization display. The visualization room of Calit2 offers unique capabilities to view high resolution imagery in 2D or 3D across a tile display array. We wish to further use the visualization room with real-time imagery as it is being collected with overlaid GIS satellite data to help viewers to rapidly contextualize the imagery. Any pictures taken by the UAV will directly appear on the display, merged into the data which is already visible. The workflow can be summarized in the flowchart in Figure 9:

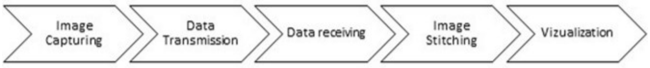

Fig. 6. Workflow for imaging.

VII. Rapid Processing of Large Datasets

We use Agisoft Photoscan Professional to create structure from motion reconstructions from our aerial imagery. Photoscan processing has multiple stages: sparse point cloud generation, dense point cloud reconstruction, meshing, and texturing. For geometrically accurate visualization, we use the dense point cloud, visualized with a custom point cloud renderer. To condense the data into a more easily digestible format, we mesh the point cloud, enabling generation of a digital elevation model (DEM) or a textured photorealistic orthophoto.

We have observed that each stage of processing has different computational requirements. The feature detection and matching in the sparse point cloud generation parallelize well across CPU cores, making it advantageous to use a dual CPU system with high clock rate, such as the Intel Xeon E5-2690, which has 8 cores and a base clock frequency of 2.9GHz. Dense cloud generation has more stages which appear serially bound, making CPU clock rate more critical than number of cores. In addition, the overhead on having 2 CPUs interact with GPUs over PCIe slows down processing significantly compared to the same processing with 1 CPU. As Photoscan does not use double precision floating point calculations on the GPU, the more expensive compute processors, such as Nvidia's Tesla line, are disadvantaged compared to the higher clocked consumer GeForce line. Regardless of the processing stage, a large amount of memory is required to process large datasets. Our workstations are equipped with 128GB or 256GB of RAM to meet these needs.

To prepare imagery of a large area for processing, it must first be divided into individual chunks which can be run efficiently. With the previously described Xeon workstations, we have found that chunks of around 1000 images work well. Each chunk should include all the images of one region, but also have images that overlap with neighbouring regions, to ensure that chunks can align well. Having geotagged images of a survey area can help in determining how to chunk the image set.

Amazon AWS presents an attractive alternative to purchasing multiple expensive dual CPU systems for processing a large amount of data for short period of time. By creating a number of EC2 instances with virtualized dual Xeon setups, such as the c3.8xlarge instances, multiple chunks can be run efficiently to generate sparse point clouds in less than a day. The EC2 instances can then be terminated, and the individual chunks combined on local hardware.

Conclusion

With the availability of consumer-level drones we are able to foster digital data collection to replace traditional survey methods. While meeting the requirements of high geometric accuracy and photorealism we are achieving large scale surveys. Adapting an infrastructure around the optimization of large-scale imaging, we are able to rapidly image large heritage sites for their conservation. Our research has shown that we are able to obtain a 1-8 centimetre per pixel resolution from a flight altitude range of 50-400 meter. We hope to provide accessible, cost effective solutions that will enable archaeologists to explore and record historical sites with unprecedented accuracy and reproducibility.

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