Unmanned Aerial Vehicle (UAV) Remote Sensing for Hyperspatial Terrain Mapping of Antarctic Moss Beds based on Structure from Motion (SfM) point clouds

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Abstract- This study is the first to use an Unmanned Aerial Vehicle (UAV) for mapping moss beds in Antarctica. Mosses can be used as indicators for the regional effects of climate change. Mapping and monitoring their extent and health is therefore important. UAV aerial photography provides ultra-high resolution spatial data for this purpose. The aim of this study is to use Structure from Motion (SfM) techniques to generate a detailed 3D point cloud of the terrain from overlapping UAV photography.

Keywords: Unmanned Aerial Vehicle (UAV), Antarctica, moss beds, Structure from Motion (SfM) point cloud, terrain mapping

1. INTRODUCTION

Polar regions are experiencing rapid and severe climatic shifts with major changes in temperature, wind speed and UV-B radiation already observed in Antarctica (Convey et al. 2009; Turner et al. 2005). Since vegetation is isolated to the coastal fringe and climatic records only extend back 50 years, with limited spatial resolution, we urgently need new proxies to determine if coastal climate has changed over the past century. In a manner similar to trees, old growth mosses also preserve a climate record along their shoots. Our ability to accurately date these mosses and map their extent in sufficient spatial detail means that, for the first time, mosses can be used as sentinels to provide crucial information on how the Antarctic coastal climate has changed over past centuries and how biota has responded to these changes (Lovelock & Robinson 2002; Robinson, Wasley, & Tobin 2003; Wasley et al. 2006).

The spatial scale of the moss beds (tens of m^2) makes satellite imagery (even recent very high resolution imagery of 0.5 m) unsuitable for mapping their extent in sufficient detail. Due to logistical constraints aerial photography is impractical and also does not provide the required spatial resolution. Recent developments in the use of unmanned aerial vehicles (UAVs) for remote sensing applications provide exciting new opportunities for ultra-high resolution mapping and monitoring of the environment. A recent special issue on UAVs highlights that this field has an increasing potential for remote sensing applications (Zhou et al. 2009). Rango et al. (2006) and Hardin & Jackson (2005) developed and used a UAV based on a remote controlled helicopter and a plane capturing <1 cm resolution colour photography for rangeland mapping and monitoring. Several recent studies have highlighted the benefit of UAVs for crop mapping and monitoring (Berni et al. 2009; Hunt Jr et al. 2010; Lelong et al. 2008; Zarco-Tejada 2008). Laliberte & Rango (2009) and Dunford et al. (2009) demonstrated how UAV imagery can be used for mapping natural vegetation using geographic object-based image analysis (GEOBIA) techniques. Finally, Nagai et al. (2009) showed how multiple sensors (visible, near-infrared, and LiDAR) can collect very high resolution data simultaneously from a large UAV. The key advantages of UAVs platform are their ability to fill a niche with respect to spatial and temporal resolution. The imagery acquired from a UAV is at sub-decimetre or even centimetre resolution (i.e. *hyperspatial*) and UAV imagery can be flown on-demand making it possible to capture imagery frequently allowing for efficient monitoring (i.e. *hypertemporal*) .

In this study, we developed a small UAV based on a remote controlled helicopter carrying three different cameras: visible colour, near-infrared, and thermal infrared for cost-effective, efficient, and ultra-high resolution mapping of moss beds within an Antarctic Special Protected Area (ASPA) near Casey, Windmill Islands, Antarctica. This paper focuses on a new technique, Structure from Motion (SfM), for deriving very dense 3D point clouds from overlapping UAV photography.

2. STUDY AREA

The Windmill Islands region near Casey has the most extensive and well-developed vegetation in Eastern Antarctica (Figure 1). The vegetation communities in Antarctica and the sub-Antarctic are undergoing rapid change. Climate change is now recognised as occurring in the high latitudes rendering Antarctica one of the most significant baseline environments for the study of global climate change. Temperature, UVB and changes in water availability have been identified as the three key factors that will change in the Antarctic regions with climate change. Despite this, there have been few long-term studies of the response of Antarctic vegetation to climate (Convey et al. 2009; Robinson, Wasley, & Tobin 2003).

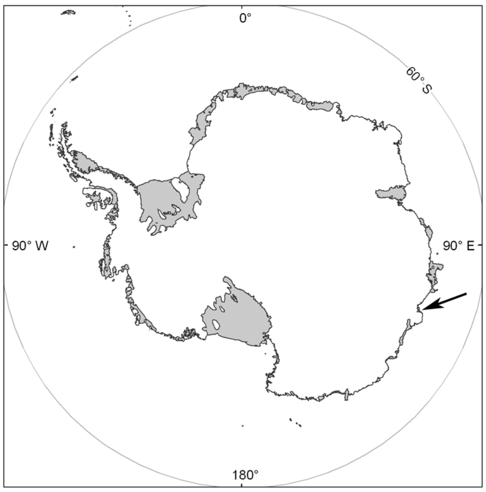

Figure 1. Study area: the continent of Antarctica with an arrow in Eastern Antarctica indicating the location of the Windmill Islands (source: Australian Antarctic Data Centre).

Most focus of change in the Antarctic region has been on the Antarctic Peninsula where dramatic shifts in temperature of up to 5 degrees Celsius have been recorded (Turner et al. 2005) with subsequent expansion of local plant communities. However, the first documented major change in a terrestrial community in Continental Antarctica has now been reported (King 2009). Preliminary analysis of January 2008 data compared with 2003 data shows a decrease in live moss and a concomitant increase in moribund moss in Antarctic Specially Protected Area (ASPA) 135, Bailey Peninsula (King 2009). Changes in colouration of moss turfs from green to red-brown have also been observed. This change in colouration is probably a stress response reflecting a transitional stage between live and moribund moss.

Our study site is the Antarctic Special Protected Area (ASPA) 135 near Casey (Figure 2). The site is approximately 200 m by 100 m with several tens of m^2 occupied by bryophytes. The location of bryophyte communities is largely driven by water availability and it is restricted to wet environments that receive water during the summer snow melt. Topographic factors, such as micro-topography (e.g. boulders and rocks), water drainage, upstream catchment, slope, and solar irradiance, play a key role in bryophyte occurrence and health.

Figure 2. Photo of a moss bed in the Antarctic Special Protected Area (ASPA) 135 near Casey.

3. METHODS

UAV and sensors

We developed a new UAV consisting of a small electric remote controlled (RC) helicopter capable of carrying three different sensors (Figure 3). The RC helicopter is an electric hobby model helicopter, Align Trex 500, capable of lifting 1.5 kg with a flight time between 6 and 10 minutes (Figure 3). The UAV is manually flown, however, the flight is stabilised by a Helicommand 3A attitude stabilisation system. The UAV flight path is recorded by a small SkyTraq USB GPS dongle (18 grams) logging at 1Hz. The aluminium camera mount was custom-built to hold three separate cameras. The UAV can carry one camera at a time. We tested a variety of vibration isolation devices to reduce motion blur in the photographs. Bungy cord was found to give a satisfactory and efficient result.

The camera system consists of a Canon Powershot G10 camera, capturing 15 megapixel photographs every ~3 seconds. The G10 is a high-end compact camera weighing 355 grams. Photos were triggered with an URBI USB controller connected to the G10 and the receiver on the UAV. A switch on the transmitter allowed for remote and continuous shutter release. The advantage of the G10 is that it provides high quality photographs with low noise (compared to other compact cameras) and it has many options for manual adjustments. We set the camera to aperture priority using the widest aperture and an ISO value between 200 and 800 to capture photographs at a shutter speed of 1/1000 or faster in order to reduce motion blur. At a flying height of 50 m the 28 mm focal length lens captured aerial photographs with a spatial extent of 64 m by 33 m at 1.5 cm resolution. The time on the camera was synchronised with GPS time so that each photo could be geotagged afterwards. In addition, small orange markers were used as ground control point (GCPs) for accurate georegistration of the UAV photographs.

Figure 3. Our micro-UAV at the study site mounted with a camera, GPS receiver, and flight stabiliser.

Two Leica GPS1200 receivers were used in dual frequency real-time kinematic mode, providing centimetre positional and height accuracies. Static GPS points were recorded for small aluminium markers that were installed during previous field seasons. These markers indicate the location of 20x20 cm moss quadrats that have been photographed in the past and are used for photo monitoring and change detection. Accurately locating these moss quadrats will allow us to compare their locations to terrain layers and UAV photography in the future. In addition, 24 bright orange aluminium disks with a diameter of 10 cm were spread out over the study area. These disks act as ground control points (GCPs) with which the UAV aerial photographs were georeferenced. The influence of terrain (slope, solar radiation, hydrological conditions) on bryophyte health is very important. Differences in these terrain characteristics might explain the variability between the moss samples within a site and between sites. To determine these local environmental terrain characteristics a very high resolution digital elevation model (DEM) is required. The following section discusses how extremely dense point clouds (~1 cm point spacing) can be derived from overlapping UAV photography.

Structure from Motion (SfM) point clouds

Recently, a new computing vision technique, Structure from Motion (SfM), was introduced that allows the extraction of 3D structure of an object by analysing motion signals over time (Dellaert et al. 2000). The SfM technique can be applied to large collections of overlapping photographs to obtain sparse point clouds for a wide range of objects, such as buildings and sculptures (Snavely, Seitz, & Szeliski 2007; 2006). The power of this technique was demonstrated by (Snavely, Seitz, & Szeliski 2007) who developed the Bundler software and used it to construct 3D models of well-known world sites, such as the Notre Dame, based on hundreds of overlapping photographs available from community websites. The technique is based on identifying matching features in images that are taken from different viewpoints. Image features are identified by the scale invariant feature transform (SIFT) algorithm (Lowe 2004), which is robust in terms of its feature descriptors for image features at different viewing angles. The SfM algorithm also accommodates different cameras, lenses, focal points, and image resolutions. No prior knowledge is required on the position and orientation of the camera or lens distortion parameters. Once the SIFT features have been identified in each individual image, the features are matched against each other, using an approximate nearest neighbour (ANN) *kd*-tree approach, and poor matches are filtered out using RANSAC (Snavely, Seitz, & Szeliski 2007; 2006). Based on these SIFT matches, the camera positions, orientations, radial lens distortion, and finally the 3D coordinates of each SIFT feature are calculated using a bundle block adjustment. The 3D positions of the SIFT features essentially form a 3D point cloud that captures the structure of an object.

The point cloud is known as a sparse point cloud that can be densified with a more recent technique called multi-view stereopsis (Furukawa & Ponce 2009). The stereopsis algorithm takes the output from the Bundler algorithm, camera positions, orientations, and radial undistorted images, and applies a match, expand, and filter procedure. It starts with the sparse set of matched keypoints, and repeatedly expands these points to neighbouring pixel correspondences, and finally applies visibility constraints to filter out false matches (Furukawa & Ponce 2009). The algorithm is implemented in the Patch View Multi-Stereo (PMVS2) software tool. SIFT, Bundler, and PMVS2 work in sequence to generate an extremely dense 3D point cloud just from overlapping photographs. The PMVS2 point cloud contains the following information for each point: XYZ coordinates, point normals (i.e. direction of the slope through the point), and point RGB colour values (i.e. derived from the photographs). Even though these computing vision algorithms were designed for building and object reconstruction, this study is the first to show that the algorithms work very well on UAV aerial photography. Movement of the UAV platform at low altitudes (e.g. 50 – 100 m) ensures that terrain features are captured from a wide range of angles. Our UAV camera setup allows frequent capture of aerial photographs, resulting in 100+ photographs for a typical 5 min. flight covering ~1 ha, which ensures that there is sufficient overlap for SfM algorithms to work efficiently and accurately.

One of the problems of using SfM point clouds in geographical applications is that the point cloud's coordinates are in an arbitrary coordinate system. In order for the point cloud to be compatible with other spatial datasets it needs to be transformed to a real-world coordinate system. In this study, we used bright orange markers as ground control. The PMVS2 point cloud has an approximate point spacing of 1 – 2 cm. This incredible point density allows each orange marker disc to be covered in multiple points. The marker points were filtered out of the point cloud based on their colour values and a user-defined RGB threshold. The marker points were then matched to the corresponding DGPS coordinates. A 7-parameter Helmert transformation was calculated based on the coordinate pairs (PMVS2 XYZ – GPS Easting, Northing, Height) and the transformation was applied to all points in the point cloud, resulting in a georeferenced point cloud. Finally, the point cloud coordinates with their RGB values were exported to the LAS 1.2 format, commonly used for LiDAR datasets. LiDAR visualisation and interpolation tools can then be used to explore and analyse the point cloud. A triangulation and rasterisation resulted in a 1 cm resolution DEM of the moss bed area. Several terrain derivatives, such as slope, topographic wetness index, and solar radiation were derived from the DEM. In future research, these terrain derivatives will be related to health and moisture information derived for each moss quadrat in order to explore the relationship between drying trends and environmental terrain parameters.

4. RESULTS

Figure 4 shows a georeferenced image of the core ASPA135 moss bed area captured by UAV. Moss quadrat sampling locations are labelled in the image (in yellow). The image has a resolution of 1 cm on the ground.

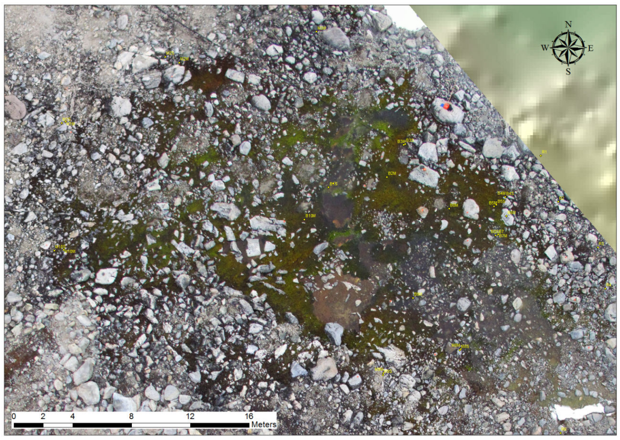

Figure 4. Georeferenced UAV image of the ASPA135 moss bed.

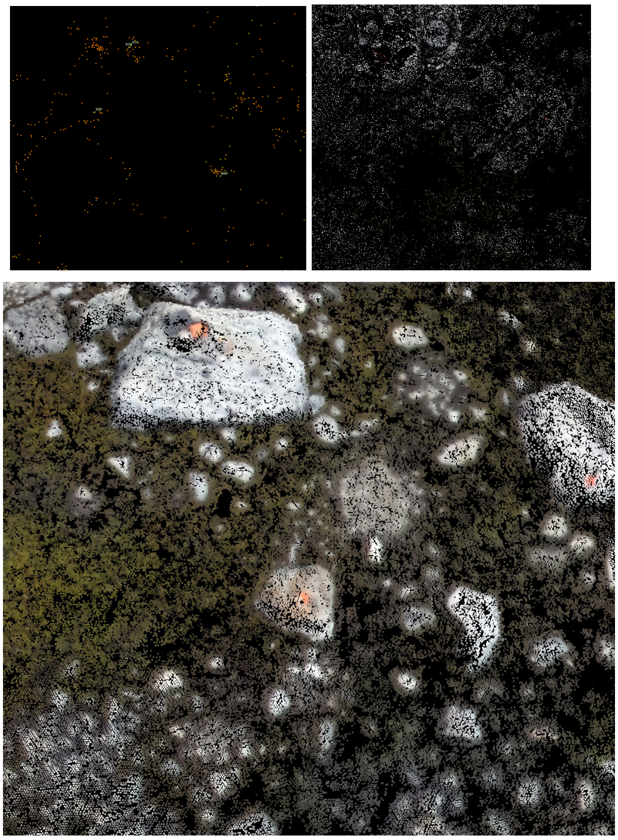

Figure 5. Comparison of a GPS transect (top-left), Bundler point cloud (top-right), and the final PMVS2 point cloud (centre) of a ~5x5 m moss bed area interspersed with rocks.

Figure 5 shows a comparison of three different point clouds. The top-left figure shows a point transect captured by GPS for a small moss area interspersed with rocks and boulders (~5x5 m). We collected ~10,000 GPS points by walking transects logging points at 1Hz. The point density on the transects was 0.5 m and between transects 1 – 5 m. The top-right figure shows a 'sparse' point cloud derived from the Bundler SfM algorithm. The main figure in Figure 5 shows the densest point cloud derived with the PMVS2 algorithm, resulting in a point spacing of ~1 cm and six million points in total for the study area (50 by 60 m). The overall RMS error of the coordinate transformation was 3 cm, resulting in a very accurate and detailed representation of the terrain. Preliminary analysis of the point cloud has resulted in a 1 cm DEM, a slope layer, a wetness index layer, and a solar radiation layer of the ASPA135 moss bed.

5. CONCLUSION

This study has demonstrated the application of an exciting new technique for 3D point cloud generation from overlapping UAV photography. Structure from Motion (SfM) algorithms designed for object reconstruction from overlapping photography were successfully applied to UAV photographs of an Antarctic moss bed, deriving extremely detailed 3D point clouds of the terrain. The point cloud was transformed to a real-world coordinate system based on ground control points with an accuracy of 3 cm. The resulting point cloud had a point spacing of ~1 cm covering the study area in six million points. Subsequent interpolation produced a 1 cm resolution DEM, capturing very fine details in the moss bed topography. These detailed terrain features will be used in future research to explore the relationship between moss die-back, caused by to water stress, and terrain characteristics.

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