A Technique-Based Approach to Structure-from-Motion: Applications to Human-Coastal Environments

Robert Van Alphen

University of South Florida

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A Technique-Based Approach to Structure-from-Motion: Applications to Human-Coastal Environments

by

Robert Van Alphen

A Thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science School of Geosciences College of Arts and Sciences University of South Florida

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Keywords: Photogrammetry, Lidar, Geomorphology, Computer Vision

Copyright © 2021, Robert Van Alphen
Dedication

This work is dedicated to my family and their endless support of my interests in whatever I found fascinating. Who knew where a rock collection could take you?
Acknowledgements

I would like to thank my committee who has helped me not only with this thesis but on my journey as a scientist. I would not be here without the invitation by Dr. Mel Rodgers and Dr. Tim Dixon into the geodesy lab after my undergraduate graduation. It was my summer in the lab which sparked my interest in the work I have done here. Dr. Rocco Malservisi has been a constant support and mentor in both the research and teaching duties that comes with Graduate school. Lastly, I cannot forget the hours of help, encouragement, and company of my fellow graduate students, specifically, Mitch Hastings and Troy Berkey.
Table of Contents

List of Tables iii
List of Figures iv
Abstract v

1 Introduction 1
   1.1 Photogrammetry 1
      1.1.1 Analog Photogrammetry 1
      1.1.2 Digital Photogrammetry 2
   1.2 Structure-from-Motion Photogrammetry 4
      1.2.1 Introduction 4
         1.2.1.1 Algorithmic Workflow 4
         1.2.1.2 Survey Design 5
         1.2.1.3 Applications 6

2 Ground-Based SfM – Egmont Key Battery 9
   2.1 Introduction 9
   2.2 Ground Survey 9
   2.3 Structure-from-Motion and Mesh Creation 11
   2.4 Results/Discussion 12

3 Merging ground-based SfM with airborne Lidar – College of Marine Science 16
   3.1 Introduction 16
   3.2 Ground Survey 16
   3.3 Structure-from-Motion 18
   3.4 Point Cloud Merging with Lidar and Mesh Creation 20
   3.5 Results/Discussion 22

4 UAV-Based Photogrammetry with 4-dimensional data – Indian Rocks Beach 26
   4.1 Introduction 26
      4.1.1 Sand Key 27
         4.1.1.1 Beach Nourishment 27
      4.1.2 Hurricane Michael 29
         4.1.2.1 Forecasted Coastal Change 29
   4.2 UAV Survey 31
   4.3 Data Processing 32
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3.1 SfM</td>
<td>32</td>
</tr>
<tr>
<td>4.3.2 Cloud to Cloud Differencing</td>
<td>32</td>
</tr>
<tr>
<td>4.3.2.1 Cloud Registration</td>
<td>32</td>
</tr>
<tr>
<td>4.3.2.2 Elevation and Volume Change</td>
<td>33</td>
</tr>
<tr>
<td>4.4 Results</td>
<td>35</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>39</td>
</tr>
<tr>
<td>5 Conclusions</td>
<td>42</td>
</tr>
<tr>
<td>5.1 Limitations</td>
<td>42</td>
</tr>
<tr>
<td>5.2 Future Work</td>
<td>44</td>
</tr>
<tr>
<td>References</td>
<td>45</td>
</tr>
<tr>
<td>Appendices</td>
<td>55</td>
</tr>
<tr>
<td>Appendix A: Indian Rocks Beach Preprocessing</td>
<td>56</td>
</tr>
<tr>
<td>Appendix B: Mesh Models</td>
<td>59</td>
</tr>
</tbody>
</table>
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1</td>
<td>The camera models used for image acquisition and their respective parameters</td>
<td>18</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>A comparison of the two work spaces to create the SfM USF-CMS models.</td>
<td>19</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Volume change based on rasterization of pre and post Michael point clouds.</td>
<td>35</td>
</tr>
</tbody>
</table>
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Traditional aerial photograph used for photogrammetry.</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Generalized SfM-MVS workflow modified from Rodgers et al. (2022).</td>
<td>7</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>McIntosh Battery near the northwestern coast of Egmont Key</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Overlapping Images.</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Various stages of model creation.</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Interior transition images.</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>USF College of Marine Science and the surrounding area.</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>The three-point clouds used and their respective meshes.</td>
<td>21</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>These images illustrate some of the obstacles encountered in this survey.</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Multiple views of the final mesh.</td>
<td>25</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Indian Rocks Beach, Pinellas County, Florida.</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Left: Track of Hurricane Michael through the Gulf of Mexico.</td>
<td>30</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Point clouds for each survey section.</td>
<td>34</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Point cloud details.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Storm surge run-up.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Significant change for each survey</td>
<td>37</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Middle Section Digital Elevation Models</td>
<td>38</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>R monument transects extracted from pre, post, and difference point clouds.</td>
<td>40</td>
</tr>
<tr>
<td>Figure A1</td>
<td>Initial M3C2 difference cloud.</td>
<td>57</td>
</tr>
<tr>
<td>Figure A2</td>
<td>Registration Histograms.</td>
<td>58</td>
</tr>
</tbody>
</table>
Abstract

Photogrammetry is a method by which physical information can be extracted from the correspondence of 2-dimensional images. In the geosciences, Structure-from-Motion (SfM) photogrammetry is a technique that has seen considerable interest in the past decade of research. Here I present three case studies of various scope and methodologies which can inform the use of SfM in the geosciences. First, I discuss the theoretical and algorithmic basis of SfM photogrammetry and its uses thus far in the geosciences. Chapters two through four show specific studies which highlight several approaches to SfM and the data which can be produced. Chapter five then concludes by detailing the limits of this method as well as techniques that can be used to mitigate them.
1 Introduction

1.1 Photogrammetry

1.1.1 Analog Photogrammetry

The fundamental principles of all photogrammetry rely on the understanding and manipulation of human binocular vision. Human depth perception relies on the fact that the distance between any two viewing points (left and right eyes) forms an angle between those two points which becomes more acute at greater distances from the viewpoints. In other words, the farther an object is from your eyes the smaller the angle formed between each eyes’ line of sight. Photogrammetry through analog and digital manipulation allows us to see in hyper-stereo perceiving 3D depth over much greater distances (Jensen, 2007). Photogrammetry as defined by the American Society for Photogrammetry and Remote Sensing “is the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording measuring and interpreting images and patterns of electromagnetic radiant energy and other phenomena” (WhatIs ASPRS? – ASPRS, n.d.). The following discussion of early photogrammetric techniques is summarized from Chapter 6 of Remote Sensing of the Environment: An Earth Resource Perspective published by Pearson Education Inc.

Analog photogrammetry is traditionally practiced using vertical aerial photography and its accompanying fiduciary marks to extract quantitative information. The sets of these images (Figure 1.1) are taken along the flight lines with overlap and sidelap. Geographic information can be extracted from single photos based on the geometric relationships between the image space and real-world object space. Information such as scale, object height, and
ground altitude can be achieved through one single image. To extract more information for a larger area the parallax effect must be used. The overlapping images are key to this. The fiduciary markers on an image are at each corner, the center of each side, and the image center (Figure 1.1). These marks allow alignment along the flight path by matching their centers, or Principle Points, with the corresponding point (Conjugate Principal Point) on its overlapping pair. Here, the aid of a lens stereoscope is used to train one eye on each image of the pair. This causes hyper-stereo to be achieved and the viewer perceives the overlapping areas in 3D. When images are viewed in this superposition, objects look to be shifted from one image to another; this is called x-parallax. This special form of parallax establishes geometric relationships between the same object in different scenes that are exploited for various quantitative calculations. From here, ground elevation and object height calculations can be performed for any object in the overlapping part of the image.

1.1.2 Digital Photogrammetry

Performing manual measurements across a large series of photos would be time-consuming as well as physically demanding for the operator’s eyes. Since the 1980s, these manual techniques have been transferred into a soft copy of digital methods allowing for computer aid. The computational power of digital photogrammetry allows these quantitative calculations to be performed on entire sets of aerial photography. Utilizing these methods, however, comes with its challenges. Before calculations can be performed images must be manually oriented in space so the software can perform proper measurements. This orientation includes camera orientation, image location, and aero-triangulation. Aero-triangulation matches an images’ pixels to ground control points (GCPs) whose real-world coordinates are known. Assuming these corrections are done properly, computing algorithms can then be utilized to perform several tasks across all or a subset of pixels in the image. These pixel-by-pixel calculations can create Digital Elevation Models (DEMs) by performing height calculations. Calculating relief displacement across images can be corrected by forming orthophotos which allow for accurate real-world measurements to be performed in the
Figure 1.1: Traditional aerial photograph used for photogrammetry. Markings at the four corners and center of each side are the fiduciary marks used to find the image center and flight path between photos. The image itself shows part of the USF Tampa campus and its surroundings. Courtesy of USGS EarthExplorer. Image captured on May 13, 2002.
image space. Choosing subsets of pixels based on a given parameter can calculate the area of a given feature or provide a bounding polygon around a feature for use in a geographic information system software.

1.2 Structure-from-Motion Photogrammetry

1.2.1 Introduction

Modern photogrammetry again utilizes the high powered computing that originally took the process from analog to digital. Now, however, new algorithms based in computer vision are used in a processes called Structure-from-Motion (SfM). This new process advances digital photogrammetry by solving for the geometry, positioning, and relative motion of objects within a camera scene as well as the position of the camera at the same time (Ullman, 1979). This is performed iteratively computing the relative positions of cameras to one another without the need for prior georeferencing information (Westoby et al., 2012). These algorithms allow for a much more simple survey method without the need for specialized cameras or equipment beyond a computer. Ultimately, this SfM processing results in a densified point cloud with, in most cases, greater than one hundred thousand points.

1.2.1.1 Algorithmic Workflow

There are many commercial as well as free and open-source software that provide the tools necessary for computer-based photogrammetry. Each software solution, however, follows a standard workflow: feature detection and bundle adjustment, sparse point cloud generation, point cloud densification, and geolocation. Additional data product generation (Digital Elevation Models, Orthophoto, etc.) can also be bundled in these software packages or created elsewhere (Figure 1.2) (Agarwal et al., 2011; Rodgers et al., 2022; Westoby et al., 2012).

The first two steps of the generalized workflow use various Structure from Motion algorithms. These algorithms aim to identify static features and key points in patches of an image which are then tracked through images based on unique descriptors. These key points,
which are assumed to be rigid, minimize the viable solutions for camera orientations which are constructed from the matching of multiple key points in each scene. The key points can then become a sparse point cloud oriented in an arbitrary coordinate system based on the computed camera orientations. This means that no a priori information is needed in the reconstruction (Brown & Lowe, 2005; Ullman, 1979).

Point cloud densification then utilizes Multiview Stereo algorithms. These algorithms take image pairs where there is overlap and extract depth information like manual photogrammetry or human stereo vision. The scene geometry is further refined and filled out, creating a multi-fold increase in the point density of the model (Seitz et al., 2006). Finally, the densified model can be brought into the real world using Ground Control Points (GCPs). These are points that have been measured in some way at the survey site and represent the real-world location of a series of points throughout the field site. This gives the model an accurate scale and orientation in the chosen coordinate system (Westoby et al., 2012). Direct georeferencing can also be performed through geotag metadata assigned to each image as they are taken (Chiang et al., 2012; Turner et al., 2014).

Once a sufficient model is created additional processing can be performed to create other data products. Commercial software such as Agisoft Metashape or Pix4Dmapper can be used for DEMs, orthophotos, textured triangular meshes, and more. Free Software MeshLab and CloudCompare also perform similar functions.

1.2.1.2 Survey Design

Whichever software one chooses, the images themselves and their relationships to each other and the subject are the determining factors in achieving satisfactory results. As described above, both the Structure-from-Motion and Multiview Stereo Algorithms used for reconstruction need images of the subject from multiple scene geometries. In practice, this is done through conducting a survey that prioritizes the image’s side-lap and overlap, as in traditional aerial photogrammetry surveys (Jensen, 2007). To solve this problem, the proper platform for image acquisition should be chosen based on the field site location, dimensions,
and project budget. Both ground-based and aerial imaging platforms have been used with success. Ground platforms are usually traditional handheld photography which can also be performed from a moving platform at various angles and elevations. Aerial platforms come in a variety of forms from airplanes, balloons, Unoccupied Aerial Vehicles (UAVs), and kites (Chidburee et al., 2016; Conlin et al., 2018; Passalacqua et al., 2015).

If GCPs are to be used they should be visible throughout the images. The stations chosen do not need to be taken the same day as the initial survey as long as the station locations will not change over time and can be easily identified in the imagery. It can, however, help to create GCP stations through high contrast markers to aid in visual identification and ease of marking in images when data processing.

A final consideration in the SfM survey design is avoiding images where occluding or moving objects are present. When there are occluding objects, sections of uniformity (smooth or reflective surfaces), or moving objects (waves, branches), it can lower the ability to resolve image matches. These sections of noise in images can ultimately result in more point cloud cleaning if they are not avoided.

1.2.1.3 Applications

SfM-MVS methods have been an ever-growing field as computing power has grown and the technological barrier to entry has lowered with high-performance hardware and software becoming widely available (Fawcett et al., 2019). Data availability has also grown with large collections of public images being hosted online. These public and crowd-sourced image repositories have allowed researchers to rely on already available data for scientific study (Michez et al., 2020; Warrick et al., 2016; Sherwood et al., 2018). Reconstruction is possible through these crowd-sourced images shown by Agarwal et al. (2011), Strecha et al. (2010), and Snavely et al. (2008).

The use of photogrammetry in the geosciences has been growing along with the technology (Anderson et al., 2019; James & Robson, 2012; Rodgers et al., 2022; Tannant, 2015). Initial efforts in the geosciences focused on the comparability of this method to traditional
Figure 1.2: Generalized SfM-MVS workflow modified from Rodgers et al. (2022).
survey methods such as TLS, and airborne LiDAR (Lague et al., 2013; Passalacqua et al., 2015; Prosdocimi et al., 2015; Westoby et al., 2012; Mancini et al., 2013). Since its adoption, this technology has been able to expand the way morphological and temporal change is assessed (Andaru & Rau, 2019; Biass et al., 2019; Brunier et al., 2016; Cucchiaro et al., 2018). Beyond RGB imaging, photogrammetry has found its uses in difference mapping. Thermal imaging allows greater monitoring capabilities where thermal data may be more useful or when RGB data is not available (Biass et al., 2019; Patrick et al., 2016; Thiele et al., 2017). Multispectral and hyperspectral instrumentation has expanded the role of SfM photogrammetry in ecology and agriculture where these methods can be combined with previously developed classification techniques and ecological monitoring (Jeziorska, 2019; Li et al., 2017; Suo et al., 2019; Van Alphen et al., 2021). UAVs with their lower relative cost and quick deploy time have become a primary method of image collection for many of these applications (Brunier et al., 2016; James & Robson, 2014; James et al., 2017, 2020; Van Alphen III et al., 2020). SfM has found a niche as a standard, rapid, and reliable geodetic surveying tool.
2 Ground-Based SfM – Egmont Key Battery

2.1 Introduction

Egmont Key is a small island located at the mouth of Tampa Bay with both historical and cultural significance. The island was used in the 1850s during the third Seminole War as an interment site of the Seminole by the U.S. government. Since 2013 it has been a site identified by the Seminole Tribe of Florida and the U.S. Army Corps of Engineers as a historic site worth preserving (Billie et al., n.d.). The island is also populated by several military constructions of historical significance which are being preserved. One such site is a set of gun batteries constructed during the Spanish-American War (History and Culture - Egmont Key - U.S. Fish and Wildlife Service, n.d.). These batteries are located at the north end of the island adjacent to its western coast. The McIntosh Battery (Figure 2.1) is the southernmost of these two structures. The site is approximately 2,100m² and is being actively eroded from the western coast. To digitally preserve this section of the island we chose this site for a photogrammetric survey.

2.2 Ground Survey

The survey for this field site took place over two days, May 08, 2019, and May 16, 2019, with each survey collecting 676 and 730 images, respectively. Two point-and-shoot-style cameras were used in data collection. One camera was handheld, and the other was mounted to a 4m tall PVC pole and placed off nadir for larger image footprint. Images were captured in various patterns around the battery. Some were captured along lengthwise tracks (approx N-S) at varying distances from the front of the battery (Figure 2.2). While on top of the structure images were taken following the perimeter of the upper floor and along each
Figure 2.1: McIntosh Battery near the northwestern coast of Egmont Key. Imagery courtesy of Google Maps.

set of stairs. The battery interior was imaged taking photos along corridors, interior room perimeters, and at entryways. Some random points were also chosen to allow for any bias in
the choice of locations to shoot from. Pole-mounted image capture was completed similarly
to the handheld. Additionally, stations of 360° image capture was done with the pole, while
not an ideal method it compensated for the difficulty in carrying the pole. Ground control
points were collected primarily along the perimeter of the second floor of the battery as well
as several points in front of the building with RTK survey GPS equipment.

Figure 2.2: Overlapping Images. Each image shows a different view of a section of the
battery with each image overlapping the view of another. This is used in bundle adjustment
and feature detection and point cloud densification.

2.3 Structure-from-Motion and Mesh Creation

Image processing followed steps aligned with the workflow visualized in (Figure 1.2.
Once loaded into Metashape the initial photos were processed through the bundle adjustment
and feature detection. This aligned 806 of the 1402 total cameras to be aligned. Part of
the images was then masked to remove sky and other unwanted parts of the images such
as people, and the background vegetation. This process along with removing images of low
quality allowed for an additional 584 cameras to be aligned. Once the initial survey’s model
showed reliable results the images from the second survey were added as well as the GCPs.
The bundle adjustment was run on the setting “highest”, which upscale each image by a
factor of 4 for more precise tie points, and the resultant sparse point cloud was cleaned for
noise. This SPC then was used to produce a dense point cloud (DPC) which was then again
cleaned.
Using the inbuilt features of Agisoft Metashape the DPC was subsequently used for the creation of both the Digital Elevation Model as well as an orthophoto. The DEM was created using the default workflow in Metashape which uses interpolation to fill the missing sections of the model creating coherent rasterization. The orthophoto itself is built upon the DEM. Default settings were used except for the ghost filtering option which filters for sections of images that may have been cropped from the final cloud.

Using the DPC as a base, a 3D mesh was also constructed using MeshLab (Cignoni et al., 2008). The DPC was exported as a .ply file and imported into MeshLab. Using the inbuilt “Screened Poisson Reconstruction” tool a mesh was created with a reconstruction depth of 10 as well as a minimum number of samples of 10 with the rest of the parameters being the default. The model was then smoothed using the “Laplacian smoothing (surface preserving)” tool with 20 iterations to better reconstruct the flat walls and stairs of the battery. After successfully meshing the DPC the model was reimported into Agisoft Metashape for texture creation (Figure 2.3). This was performed using the default settings.

2.4 Results/Discussion

The models all have an accuracy of approximately 9cm calculated by Agisoft Metashape for the GCPs taken at the field site. Ground control points form the basis of the georeferencing of any SfM based model and are vital to an accurately scaled model.

The data products show a wide range of what can be produced using SfM-MVS. After following the initial steps in data processing 1326 or ∼94% of the total 1403 images were aligned. The cleaned DPC contains 79,279,977 points, which reconstructs the entire outside of the battery and partially reconstructs the interior. Where noise is present it is in sections of high vegetation concentrations, such as the far-left (South) side of the model. This high point density and accuracy results in the reconstruction of a sub-centimeter resolution DEM and Orthophoto, 6.18mm/pixel and 1.54mm/pixel, respectively. Focusing on a single building, as we did here, with off-nadir images and from elevation combined with variable
distance horizontal photos allows the reconstruction software more opportunities to find tie points and fill out the bundle adjustment.

One challenge of this survey was to model not only the outside of the battery but the inside as well; with this, there was partial success. For this aspect, we see the best reconstruction of the interior of the model in portions of the battery which were most lit by the sun, while the other openings have been sealed off by black points representative of the shadows cast into the interior (Figure 2.4). As described in the previous section images were acquired from within the battery but most of them did not align, possibly due to not enough transitional scenes to correlate the entrances with their interiors.

The DEM itself highlights the tiered nature of the battery and where the point density of the DPC is low. Interestingly, where these two features converge the DEM is still able to accurately show the floor of an inner chamber at its proper ground level height.

The final product of interest, the 3D mesh, was also easily produced after the final additional cleaning to reduce unnecessary features such as trees, sky points, and a thin pole structure. The final mesh is constructed of 1,385,172 faces and 703,735 vertices. The subsequent texturing of the mesh in Metashape utilizes the default setting to extract color and texture information from the survey images onto the faces of the mesh. This textured mesh resulted in a more detailed 3D view of the battery (Figure 2.3, Appendix B). This highlights both well-resolved sections, walls of peeling and cracked paint, as well as less well-resolved, non-cylindrical columns and incomplete metal grates. The Mesh itself, along with the other data products, will be an important aspect for further site monitoring and preservation for state park officials as the island faces further erosion.
Figure 2.3: Various stages of model creation. A-C: North section of the Dense Point Cloud, Mesh, and Textured Mesh.
Figure 2.4: Interior transition images. Left: An image that was used in model reconstruction where sunlight allows for a view of the interior to be aligned with the whole model. Right: An image that was aligned in model reconstruction but whose shadows did not allow for the interior to be reconstructed.
3 Merging ground-based SfM with airborne Lidar – College of Marine Science

3.1 Introduction

University of South Florida College of Marine Science (USF-CMS) is in Pinellas County, Fl on the interior coastline of Tampa Bay. The campus is adjacent to the University of South Florida St. Petersburg campus and Albert Whitted Airport which restricts the use of UAVs in its vicinity. (Figure 3.1). The campus itself houses the USF College of Marine Science as well as various offices and facilities operated by the United States Geological Survey, National Oceanic and Atmospheric Administration, Florida Fish and Wildlife Conservation Commission, US Coast Guard, and more. This dynamic location is an example of a critical site where accurate environmental and hydrologic modeling would be of interest. Here we set out to create a full three-dimensional model of the campus combining both ground-based SfM and airborne lidar. Utilizing these two methods allowed us to fully capture both the horizontal and vertical surfaces of this large field site. Ground-based SfM was leveraged to model the smaller scale complex nature of the site as well as the vertical walls and corridors between campus buildings. Airborne lidar on the other-hand is capable of imaging the large scale horizontal roads and roof tops of the site culminating in a full 3D model combing the strengths of each technique.

3.2 Ground Survey

Data was collected through an on-the-ground survey using two point-and-shoot cameras, a Panasonic Lumix DMC-TS6, and a Panasonic Lumix DMC-GF1, and a GoPro HERO5 Black (Table 3.1). Most images were captured with the two Panasonic cameras with images taken at eye level from the ground and on rooftops, utilized a pole-mounted
camera as in Chapter 2, and while aboard a Florida Institute of Oceanography (FIO) skiff piloted in Bayboro Harbor that surrounds USF-CMS. This wider view of USF-CMS allowed for some images to have a greater overall view of the campus and tie together the intra-campus images.

Two total surveys were conducted at various times of the day on November 15, 2017, and October 25, 2018. All surveys ended before sundown to avoid glare from the sun. The
first survey focused on getting a wide base of coverage through the entire campus as well as its perimeter. Photography locations were chosen to maximize coverage and overlap.

The second survey was used to fill in major gaps after the first survey’s data was processed. This led to the use of the skiff method described above to complete the perimeter sea wall as well as the outward-facing walls of the various buildings. One factor that could not be controlled in this survey was the general dynamic nature of the campus. This includes the various movements of equipment, people, and vehicles in and around the campus. The primary areas affected were the two parking locations. These issues are addressed in the sections to follow.

Table 3.1: The camera models used for image acquisition and their respective parameters.

<table>
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<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
<th>Precalibration</th>
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<td>1.31 x 1.31 µm</td>
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<td>DMC-GF1</td>
<td>4000 x 3000</td>
<td>14mm</td>
<td>4.33 x 4.33 µm</td>
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<tr>
<td>DMC-GF1</td>
<td>2816 x 3000</td>
<td>16mm</td>
<td>6.2 x 6.2 µm</td>
<td>no</td>
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<tr>
<td>HERO5 Black</td>
<td>4000 x 3000</td>
<td>3mm</td>
<td>1.53 x 1.53 µm</td>
<td>no</td>
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</tbody>
</table>

3.3 Structure-from-Motion

Image processing was handled using Agisoft Metashape Pro using a standardized workflow. In total 2339 photos were captured with 794 images from survey one with the rest from survey 2 (Table 3.2). Survey one images were first processed through feature detection and bundle adjustment. SPC alignment was run on the accuracy setting “highest”, as in Chapter 2, creating the greatest number of points. The SPC was then decimated through the gradual selection tool filtering poorly aligned points. A dense point cloud (DPC) was then created using the ”Medium” setting and aggressive filtering mode which downscales the images by a factor of 4 and filters out most outlier points during cloud densification.

Manual cleaning of the DPC was performed to remove erroneous and unneeded areas such as cloud and water/wave points and background buildings. This preliminary
model was examined for areas of least and most point cloud coverage as well as the amount of image alignment. These parameters allowed for the planning of the second survey which would fill in these gaps. After conducting the second survey a new blank workspace was used for the uploading of images and the same steps as survey one were conducted on these new images. After a satisfactory result was achieved with each survey, the two surveys were merged. This was accomplished by the append feature in Metashape Pro. This allows for two separate workspaces to be appended and merged into a single workspace with single point clouds and all images.

Table 3.2: A comparison of the two workspaces to create the SfM USF-CMS models. Approximately 58% of the images from day 1 were aligned compared to ~78% image alignment after the addition of more images. Number of total points for each model type are given post final cleaning but before 10cm point space filtering of the final model.

<table>
<thead>
<tr>
<th></th>
<th>Total Photos</th>
<th>Aligned Photos</th>
<th>SPC Total Points</th>
<th>DPC Total Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey 1</td>
<td>794</td>
<td>462</td>
<td>276,534</td>
<td>19,580,347</td>
</tr>
<tr>
<td>Survey 1 and 2</td>
<td>2339</td>
<td>1831</td>
<td>601,572</td>
<td>27,494,231</td>
</tr>
</tbody>
</table>

The new combined workspace had a total of 2339 images across both surveys (Table 3.2). A new bundle adjustment and SPC were created following the same parameters as previously. After completion ground control points (GCPs) were gathered through google earth. GCPs were not collected during the surveys do to the predominance of vertical surfaces as the image focus. GCPs would have needed to have been collected on horizontal surfaces which were lacking as the focus. GCP locations were selected where images had significant overlap between the two survey photo sets. These GCPs would allow for better image alignment and feature detection. A complication that has been noticed in the reconstruction of buildings with similar geometries and patterns at multiple angles is the production of duplicate or overlapping structures which was seen in initial reconstructions of the field site (Heinly et al., 2014). Correcting this and to allow for greater scene correlation, additional checkpoints were created in images that had low or no alignment in the model. These checkpoints were
used to tie non-aligned images with aligned images that shared overlap with the checkpoint feature. These points along with the GCPs were used for recalculation of the bundle adjustment and the manual alignment of images after SPC creation. The image locations were then optimized by the location of the GCPs and a new DPC was created.

Cleaning of the final DPC was done through a combination of manual point deletion and masking. Masking was used to block areas of docked boats, water, and sky. Some areas where objects had changed from different days were masked. Carrying out this process created a cleaner DPC. Before the final export of the DPC, it was filtered to a 10cm point spacing to create a more uniform cloud.

3.4 Point Cloud Merging with Lidar and Mesh Creation

Our ground-based SfM survey excelled at imaging surfaces and objects which were parallel to the field of view (FOV), such as walls, pillars, cars, and miscellaneous equipment. Problematic surfaces were those which horizontal to the cameras’ FOV such as flat rooftops, and the ground. This is from the fact that both rooftops and the ground are at the edges of most images with objects of most focus, the walls, being a larger percentage of each image. Airborne Lidar scans collect data parallel to the flight vehicle (i.e. horizontal surfaces) which compensate for the ground-based SfM shortcoming (Lidar Download, n.d.). An airborne lidar point cloud was then chosen to combine with the SfM point cloud to create the full 3D model. Lidar data processed using open-source software CloudCompare (CloudCompare v2.11.1, 2020). The Lidar point cloud was cut to the approximate field site and classes filtered to leave only those that represented the ground surface, vegetation, and rooftops. Both the lidar and SfM point clouds were transformed into the same coordinate system. To maximize the ease of merging these two data sets the SfM DPC was heavily decimated using tools and plugins available in the Cloud Compare software (Qian et al., 2005). The goal of the decimation was to primarily isolate the building walls and the walls of smaller structures, all other points were cut out of the model. The process of this isolation started with the cleaning of the major areas of noise such as trees, misaligned roofing, and boats. A
filter was then applied to keep only points whose normals were oriented between 45 and 90 degrees (Figure 3.2A1). In sections where the noise had previously resulted in the reversing of the point normal that should be in that section (wall point normal facing inward instead of outward), these points were isolated and reversed using the Cloud Compare invert normal tool. This resulted in a model that did not have noise caused by the dynamic nature of the field site discussed previously.

Figure 3.2: The three-point clouds used and their respective meshes. A: 1. The SfM constructed point cloud after initial model cleaning, 2. Mesh was created from the SfM cloud using parameters based on those chosen for the final model shown in C2. B: 1. The Lidar point cloud after initial model cleaning, 2. Mesh was created from the Lidar cloud using parameters based on those chosen for the final model shown in C2. C: 1. The final merged point cloud after all model cleaning, 2. Final mesh using the merged point cloud model.

The lidar model required far less cleaning than that of the SfM as presumably data processing had been done before they released the Lidar product. Vegetation and noise were the primary targets of the cleaning of these points and a final filter was applied to keep those normals that were oriented less than 25 degrees (Figure 3.2B1). This was done to provide the SfM model with suitable points that represent the ground and rooftops. Previous research has shown the ability to programmatically take advantage of building symmetry and scale to merge building segments (Cohen et al., 2015); here instead we chose to use tools available
within the Cloud Compare software. This decision was predicated on the result of both cleaned point clouds. Both final models showed easily identifiable features that one can match up with the naked eye such as building and roof corners. To accomplish this, both models were roughly aligned in Cloud Compare with the final alignment created using the fine registration tool. Models were then merged into a final coherent model (Figure 3.2C1).

The merged cloud model for USF-CMS was then imported into MeshLab. Using MeshLab’s Screened Poisson tool (Kazhdan & Hoppe, 2013), several mesh models were created each time changing the values for the reconstruction depth or the minimum number of sample parameters. Through these iterations, sections of low point density were identified which caused misconstruction. These sections were cropped out to produce the final model. These parameters control the final mesh’s level of detail in the reconstruction and the number of points that must be in a single triangle. The final model that was chosen was constructed with a reconstruction depth of nine and a minimum number of samples of 10 (Figure 3.2C2). This allows the mesh to accurately construct both small and large structures without allowing areas of low point density to cause large areas of misconstruction. The singular SfM and lidar clouds that make up the final cloud model were then individually meshed using the same parameters to allow for a visual comparison of the products that would result without merging (Figure 3.2 A2 and B2).

3.5 Results/Discussion

The model that resulted from the SfM processing demonstrates both the advantages and pitfalls of this technique. In about a week of work, the near-complete modeling of a 24,400m² area can be accomplished. The SfM model best reconstructs the largest buildings first which is due to their presence in many images. Other smaller features that were stationary between days, (radar station, smaller buildings, signposts, and tree trunks) were also well defined in model reconstruction. Image overlap throughout the field area is greater than nine images with GCP’s total error of 3m calculated by Agisoft Metashape. GCP errors could be reduced in the future by high-precision GPS stations. This accuracy, however, was
compensated for in the merging of the SfM model with the lidar model. Each building alone
could be used as an individual product for high-resolution mesh modeling if an intercon-
connected model was not needed. The camera position shows a high level of accuracy for the
level expected in a consumer-grade product. Where the accuracy shows the greatest error
was under a thick tree canopy.

Where the SfM model had its failures in reconstruction there are several attributable
sources. Vegetation and trees within the model caused the greatest amount of low or no point
density throughout the field site. The swaying of branches and the density of leaves created a constant barrier. This can be best noticed on the eastern side of the campus where a line of trees blocks nearly the entire side of a building. Other moving non-stationary objects such as parked cars were the next major factor in the creation of data gaps (Figure 3.3). Another minor contributing factor was the similar architecture of several of the major buildings with sections of low variation. The corrugation-like surfaces of these areas confused the matching of model tie points. Overall, the resulting DPC served as a competent basis with which to form the final mesh keeping only the areas of best reconstruction. The lidar cloud model which collected data over a single day in our field area allows for compensation for the limitations of the SfM method. This results in a final combined cloud that gives the best results for a clean base model that could be further populated if more fine-grained result were needed (Figure 3.4).

The final model (Figure 3.4, Appendix B) created here shows the extent to which photogrammetry and SfM can be combined to utilise the strengths of both methods. Using simple consumer-grade cameras aided by low-cost equipment (PVC pole and skiff) a relatively large and complex site can be surveyed and modeled. The technique deployed here in future projects would allow for better survey design and more efficient image capture. The use of lidar data from the outset can determine what sections of a site need to be filled in as well as areas that have changed significantly from the date of collection. Along with sectioning off the field area into individual surveys to be merged after the fact, this would reduce overall
Figure 3.3: These images illustrate some of the obstacles encountered in this survey. The top left and right panels show approximately the same location on different days of the survey. The bottom left and right panels show various sections of the buildings of interest being blocked by sizable portions of vegetation.

noise and increase the ability of tie points to be properly detected without confusion. The employing of these techniques is also not limited to areas where areal-based photogrammetry surveys are prohibited but also for sites where more vertical views are needed. The vertical image capture displayed here would not only be a hazard if done via UAV at this field site, given the proximity of an airport, but it would also be a far more complex survey to build for an automatic flight. The data coverage and density which is shown here is a unique product of the combination of ground based and aerial survey methods. Both aerial lidar or SfM are able to provide coverage of the field from the horizontal perspective, while ground-based SfM
produces all vertical points that would otherwise be hidden by aerial surveys. This creates a single point cloud which takes advantage of the best of both methods. The human element in the technique here allows the survey to have an on-the-fly nature to optimize where the focus should be.

Figure 3.4: Multiple views of the final mesh.
4 UAV-Based Photogrammetry with 4-dimensional data – Indian Rocks Beach

4.1 Introduction

Hurricanes are a constant hazard to coastal and low-lying areas in the Gulf of Mexico region of the United States. High winds and storm surges threaten both the structures built on and nearshore as well as human efforts to effectively preserve natural beaches and barrier islands. High erosion events, and the environmental response to these events, such as erosion transport, vegetation health, and dune structure are key areas of interest (Claudino-Sales et al., 2010; Wang et al., 2020; Wang & Briggs, 2015; Wang et al., 2006). These events have also led to the development of metrics by which these events can be qualitatively and quantitatively categorized (Janssen et al., 2019; Plant & Stockdon, 2012; Sallenger, 2000; Stockdon et al., 2012). In fair weather conditions, beaches and coastal environments are still monitored to track natural changes in the nearshore (Benedet et al., 2007; Cheng et al., 2016; Cheng & Wang, 2020), allowing governments to update current and existing laws and plans around coastal improvement and protection (Hanson et al., 2002; Strategic Beach Management Plan: Southwest Gulf Coast Region, 2018). Structure-from-Motion techniques have shown their usefulness in coastal environments of various types (Brunier et al., 2016; Jeziorska, 2019; Mancini et al., 2013; Rodgers et al., 2019; Suo et al., 2019; Warrick et al., 2016). There are a variety of acquisition and processing techniques that can be utilized in the event of both planned and opportunistic data acquisition (Chiang et al., 2012; Cook & Dietze, 2019; Sherwood et al., 2018; Turner et al., 2014). Here we use SfM photogrammetry to assess the accuracy of erosion forecasts, quantify the impact of Hurricane Michael on a
freshly nourished barrier island, and highlight the role UAV SfM can play in future coastal management.

### 4.1.1 Sand Key

Sand Key is one of the longest barrier islands in west-central Florida at approximately 18km in length. The island experiences wind-generated waves with a neap tide of \( \sim 0.4m \) and spring tides of about 1m. The beach experiences primarily longshore sediment (Cheng et al., 2016; Cheng & Wang, 2020; Wang & Briggs, 2015) with the entirety of Sand Key being designated an erosion hotspot by the Florida Department of Environmental Protection (*Critically Eroded Beaches in Florida*, 2021). Sand Key is traditionally divided into sections based on local municipalities. Here we focus on the Indian Rocks Beach section of Sand Key, highlighting three approximately 250m sections, which were chosen as Representative of Indian Rocks Beach as a whole and for ease of data processing. (Figure 4.1).

#### 4.1.1.1 Beach Nourishment

Various sections of Sand Key have been nourished since the mid-1980s and are currently part of the Pinellas County Shore Protection Project. Nourishment is designed to dredge infill from various locations offshore and add fill to beaches every 5 years with consistent monitoring in between nourishment. The most recent nourishment had been in progress when this survey was conducted with sections presented here having been completed before surveying. In total since 1988, approximately 7.1 million m\(^3\) has been placed onto Sand Key (*Strategic Beach Management Plan: Southwest Gulf Coast Region*, 2018). Past nourishment monitoring from the 2018 and 2006 nourishments showed overall retention of infill with 70% retention from 2006 to 2010. Both surveys identified a major erosion hotspot in north Sand Key, which results from divergent longshore transport (Cheng & Wang, 2020; Wang et al., 2006). Both the 2006 and 2018 nourishments compensated for this hotspot by creating a wider beach in north Sand Key than in other sections; 76m in 2006 and 60m in width in 2018 (Cheng & Wang, 2020; Wang et al., 2006).
Figure 4.1: Indian Rocks Beach, Pinellas County, Florida. Black boxes are the extent of each survey which are labeled by relative location.
4.1.2 Hurricane Michael

Hurricane Michael is the fourth largest Hurricane to impact the US in the last century with damages of approximately $25 billion in the US alone. The storm was monitored even before its true formation with a Potential Cyclone advisory being given to the weather system it formed out of. Storm development began on October 7th, 2018 as a tropical depression in the Gulf of Mexico. The storm grew rapidly, becoming a category one, on the Saffir-Simpson Hurricane Wind Scale, by the next day. Hurricane Michael made landfall near Tyndall Air Force Base, Fl on October 10th, 2018 (Figure 4.2). Before landfall, the storm was upgraded to a category five with maximum sustained winds of approximately 225km/h. As the storm came close to landfall, the national weather service issued storm surge warnings for the panhandle region and storm surge watches for Tampa Bay. Storm surges were at their highest where Michael made its landfall with maximum estimates of $\sim 4.3m$ (14 ft) above ground level (AGL). Surges surrounding Tampa Bay range between 0.6 - 1.2m (2 - 4 ft) AGL (Beven et al., 2019). Erosional regimes of both overwash and inundation were seen in the area around Tyndall Air Force Base. Foredunes were heavily eroded with overwash extending at least 100m into the barrier interiors (Wang et al., 2020).

4.1.2.1 Forecasted Coastal Change

Details of forecasted coastal change can be found from Hurricane Michael NHC Advisory 15, 0400 AM CDT WED OCT 10, 2018, informed by modeling provided by the USGS (Doran et al., 2019). This dataset forecasts the probability of dune erosion utilizing techniques derived by Plant & Stockdon (2012) and Stockdon et al. (2012). The Wednesday advisory uses advanced modeling techniques to define the probability of coastal erosion due to hurricanes in the Gulf of Mexico. The models use two wave height metrics, extreme high water level and mean water level, to define four erosion regimes: swash, collision, overwash, and inundation. These four regimes were originally described in Sallenger (2000) as simple morphometric descriptions of beach response to storm-induced erosion.
Figure 4.2: Left: Track of Hurricane Michael through the Gulf of Mexico. Point color records wind speed in km/h. Points are labeled to show category change and date/time (UTC). Michael track from NHC Tropical Cyclone Report AL142018. Right: (A) Indian Rocks Beach is overlaid with the calculated probability of extreme water level collision with dune toes. (B) Probability of wave overwash of the dune crest. (C) Probability of the mean water level inundation of the dune crests. Erosion forecast data courtesy of USGS Storm-Induced Coastal Change Forecasts: Archive of Individual Storm Events doi.org/10.5066/P9Z362BC
The swash regime is defined by low energy conditions where erosion is confined to the beach below the dune toe. Collision is erosion occurring at the toe (base) of dunes eroding sand seaward. Overwash erodes dunes at their crest (top) emplaceing that sand landward behind the dune. These first three regimes are defined against the extreme high water level while the final regime, inundation, is defined by the mean water level. Inundation occurs when the dune is fully submerged underwater causing the most intense erosion regime, depositing sand behind the beach. (Stockdon et al., 2012).

For a more detailed view of storm surges in the Tampa Bay area, the USGS provides an animated time-series view named ”Total Water Level and Coastal Change Forecast Viewer” where sectional or regional views of predicted model outputs can be searched through and seen for specific periods. Using these forecasts allows a point of comparison to the post-hurricane beach morphology. Forecasts along Sand Key show probabilities of 76% to 94% for a collision regime (Figure 4.2A). Overwash and inundation probability minimums of 28% to 65% (Figure 4.2B), and 0% - 14% respectively are shown for the same geographic extent (Figure 4.2C). In summary, from this forecast we expected to see an elevated level of erosion up to at least the dune toes with some indication of primary dune crest reduction.

4.2 UAV Survey

The pre-Hurricane Michael survey was conducted on Oct 8th, 2018, along Sand Key, a ~20km section of the Pinellas County coast. The beaches included here are North Sand Key, Belleair Beach, Belleair Shore, Indian Rocks Beach, Indian Shores, Redington Shores, Redington Beach, and Madeira Beach. The survey was conducted using a DJI Phantom 4 UAV. Flight path was a point-to-point single line with images taken following the line of the beach. This method allows for the quick acquisition of image data over the long-distance needed to be covered. GCPs were placed on the beach backshore at intervals during stops for battery changes. GCPs were collected with RTK survey GPS equipment.

The post-hurricane survey was performed following a similar extent on Oct 10th, 2018. Similar procedures were conducted with the same UAV during this survey. The
greatest change in methodology was that in some areas images were acquired in several lines along the beach. This changed owing to the passing of the storm which presented more favorable weather conditions allowing greater survey time. GCPs were collected in the same manner as the first survey, but with additional GCPs placed where obvious erosional effects were observed.

4.3 Data Processing

4.3.1 SfM

Images for SfM were processed using Agisoft Metashape and each survey was processed using similar steps. Images were first imported into Metashape and filtered. The filtering process was based on a quality assessment algorithm, as well as the exclusion of takeoff and landings. Both image coordinates and subsequent point cloud coordinates were then internally converted to NAD83 (2011) + NAVD 88 height to match GCPs.

Bundle adjustment and Sparse point creation were run on the “High” setting, which does not upscale or downscale the image but uses its native resolution, for the full extent of Sand Key. Before dense cloud construction, sparse point clouds were cleaned, aligned to GCPs, and images were masked to lessen the effect of wave movement between images. Only the Indian Rocks Beach section of the SPC was used for dense point cloud creation as the focus for this study was the Indian Rocks Beach area only. The dense point cloud was then created on the ”Medium” setting with aggressive filtering mode as in Chapter Three.

4.3.2 Cloud to Cloud Differencing

4.3.2.1 Cloud Registration

The Indian Rocks Beach dense point cloud georeferencing was unsuccessful due to inadequate ground control points (Appendix A). As a consequence the Indian Rocks Beach model had an approximate 2km wavelength distortion. To compensate for this three approximately 250m length sections were selected. This method was chosen to minimize any effect of the distortion, owing to its much smaller length than that of the distortion. These
sections are labeled by North, Middle, and South based on their location relative to the full model to represent the overall change from end to end.

To compensate for the lack of GCPs for geolocation, an iterative closest point approach was chosen. Each pre-hurricane model was aligned using iterative closest points to airborne lidar ((Lidar Download, n.d.)) choosing only locations which would not have changed such as the sea wall, board walk, and patios. Post-hurricane models were then matched using the same logic as the pre-hurricane model with the addition of points selected at the edge of the stable beach to compensate for the difference in model widths.

4.3.2.2 Elevation and Volume Change

One of the biggest challenges in calculating changes in elevation and volume between the Pre- and Post- models is determining how much of the change is due to model error (georeferencing and distortion), and how much of the change is real storm induced difference. To account for this error between each model the Multiscale Model to Model Cloud Comparison (M3C2) method was used (Lague et al., 2013). This method uses registration error between clouds and surface roughness to calculate a confidence interval at each point. The M3C2 algorithm calculates this confidence level on each point as it finds the difference between each location (Figure 4.3). This method of cloud differentiation lets us identify areas of significant change while considering the registration error.

Given the large extent of the survey locations, profiles were drawn and extracted using CloudCompare along several locations. These include along the range or R monuments, which are Florida Department of Environmental Protection coastal survey markers, local to the beach section. These profiles were then compared to transects collected by USF’s Coastal Research Laboratory 4 days after the post-hurricane UAV survey. Minor offsets, likely due to limited georeferencing of the UAV survey, were seen in the North and South models in comparison to the Coastal Research Lab transects. Using these transects as ground truth the North model was offset by -1m and the South by +1.5m. After offset, each model transect matched well with the ground truth allowing for better comparison.
Figure 4.3: Point clouds for each survey section. The left column is pre-hurricane, the middle column is post-hurricane, and the right column is the difference between the two models.
change was also calculated using tools built into CloudCompare. Volume change estimates are reported in Table 4.1 for each section gridded at 0.1m resolution.

<table>
<thead>
<tr>
<th>Model</th>
<th>Added Volume (m$^3$)</th>
<th>Subtracted Volume (m$^3$)</th>
<th>Total Change (m$^3$)</th>
<th>% Shared Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>88.018</td>
<td>6,228.772</td>
<td>-6,140.754</td>
<td>75</td>
</tr>
<tr>
<td>Middle</td>
<td>35.193</td>
<td>5,997.402</td>
<td>-5,962.209</td>
<td>70</td>
</tr>
<tr>
<td>South</td>
<td>120.055</td>
<td>6,192.506</td>
<td>-6,072.450</td>
<td>66</td>
</tr>
</tbody>
</table>

Net Total Change (m$^3$) -18,175.413 % Volume Change Since Nourishment* -4.8

* Total Indian Rocks Beach nourishment based on value from Cheng & Wang (2020).

4.4 Results

Using the SfM method of point cloud generation we can extract both qualitative and quantitative data from our models. A significant qualitative dataset is in the RGB color that is inherent to the survey images. These images allow us to see several different effects of the tides and storm surges (Figure 4.4). The recording of these events in the saturated sand itself can show us where the storm surges reached. In the middle and south sections, the storm surge only reached the sand in a few places and flowed along the shore with the dune toe. In the north, the storm surge did not reach the dune toes where the nourishment was at its full extent (Figure 4.5).

Each section, north, middle, and south, shows two areas of significant change (Figure 4.6). The eastern section of change is explained by the differences in the pre and post models which have different amounts of vegetation and housing captured. This leaves the western section showing the true meaningful change. All significant topographic and volume changes are seaward (westward) of the post-hurricane scarp (Figure 4.7). Topographic changes are consistent in both the along-shore and cross-shore directions for all three sections. Both the North and South sections show significant erosion from -0.5 to -1.5m of vertical elevation change, while the middle section shows less erosion from -0.5 to -1m of vertical elevation change.
Figure 4.4: Point cloud details. A portion of the middle survey section annotated to show details in point cloud models.

Figure 4.5: Storm surge run-up. A: north section shoreward extent of storm surge run-up. B: middle section of shoreward storm surge run-up. C: south section of shoreward storm surge run-up. The Middle and south sections have at least one other portion which shows dune toe storm.
Figure 4.6: Significant change for each survey. Red sections of point clouds represent areas of significant change based on the M3C2 method. Grey sections are areas of non-significant change.

The total volume change across the three sections is approximately -18,000m$^3$ or approximately 5% of the total nourishment volume for the Indian Rocks Beach section of nourishment from Cheng & Wang (2020). The average volume loss from the three sections here is 6058 m$^3$. If this average is assumed to have been loss per 250m section of IRB then the total loss from Hurricane Michael is approximately 72,696 m$^3$, or 19% of the total nourishment (Cheng & Wang, 2020).

The shoreline defined as the 0m NAVD88 contour and dry beach, 1m NAVD88 contour, showed retreat from before and after Hurricane Michael (Figure 4.8). The north section model only captured the dry beach contour, due to the progressive start of nourishment along the beach. To measure beach retreat, the distance from the seaward end of each pre-hurricane model to the post-hurricane scarp was measured. This was done in two places for the North section due to the progressive start to the nourishment as described above. The North model dry beach change, in the initial section is 2-4m, while a retreat 30-35m is measured in the
Figure 4.7: Middle Section Digital Elevation Models. Left: Pre-Hurricane Michael DEM. Right: Post-Hurricane Michael DEM
middle and south section of the model. This pattern of a 30-35m beach retreat was also measured between the pre and post-hurricane Middle and South models.

4.5 Discussion

Initial use of our Indian Rocks Beach models was met with complications tied to the placement of ground control points as well as the geometry of the barrier island. The initial model showed significant distortion (Appendix A) due to the clustered nature of the ground control points. To remedy this, the steps followed above were taken to account for this. The overall small spatial extent of unmoving structures at the field site should be taken into consideration when doing studies for beaches and barrier islands. The relative size of the field area of interest compared to the size of the sandy beach itself should also go into the planning of future surveys. The overall abundance of the sandy beach compared to unmoving structures biases tie point recognition to those non-beach sections of the images captured. These are two major considerations if further surveys were to be conducted in Indian Rocks Beach or any place of similar geography. Studies have looked at both the ability of SfM in coastal environments as well as storm impacts (Conlin et al., 2018; Sherwood et al., 2018). Here we are showing the ability of these techniques to be integrated into already existing monitoring systems with long-term and short-term needs. These techniques as demonstrated lend themselves to a wide array of data products (point clouds, DEMs, orthophotos, GIS integration, linear transects, etc.) allowing even greater flexibility. The initial beach change forecast release by the NHC shows a 70% confidence of a collision regime along Indian Rocks Beach. The storm surge profiles shown above reveal only a minimal amount of collision. This regime is not widespread in each survey but only in geographically small sections of the beach. The overall character of the forecast however indicates a much stronger level of collision with up to a 65% and 14% chance of overwash and inundation regimes, respectively. Both qualitatively and quantitatively there is no indication from our models of either of these more extreme regimes being present in Indian Rocks Beach. The prevailing regime shown here is that of the swash regime (Sallenger, 2000; Wang & Briggs, 2015). This regime
Figure 4.8: R monument transects extracted from pre, post, and difference point clouds. Each line was extracted to match profiles from Cheng and Wang 2020 labeled Coastal Research Lab Transect. Top: R72 Transect from the north survey section and the M3C2 difference between the Pre- and Post-model transects. Middle: R77 from the middle survey section and the M3C2 difference between the Pre- and Post-model transects. Bottom: R83 from the south survey section and the M3C2 difference between the Pre- and Post-model transects.
is characterized by erosion confined to the seaward beach below the foredune. As noted by Wang et al. (2020), the erosional intensity at the site of landfall was controlled primarily by beach width and wave height. Our findings echo this; the nourished beach provided a much larger area of resistance than what was forecasted. USGS erosion modeling utilizes lidar data from 2010 to 2016 for these modeling forecasts which did not account for the recent nourishment. (Doran et al., 2019). This shows the necessity of up-to-date elevation models for making accurate and actionable predictions of erosion-inducing events. UAV-based SfM elevation models uniquely fill this gap between scheduled Lidar missions where time-sensitive data could be collected and utilized. This rapid data acquisition can then be fed into computer modeling for precise and accurate forecasts. Beyond storm impact assessment, UAV-based SfM can enhance traditional transect monitoring techniques, by focusing on the qualitative value of these data products as well as the allowance of DEM and point cloud-based techniques to capture more area.
5 Conclusions

Structure-from-Motion Photogrammetry allows for the accurate and precise reconstruction of the real world and the objects that occupy it. These models can then be used in the extraction and manipulation of data about these scenes. Chapter One focuses on the emergence of these techniques from analog methods. In the geosciences, the creation of representations of the real world is an invaluable tool. SfM photogrammetry allows for the forecasting of hazards, quantifying, and modeling of change, and in the education of young geoscientists.

Here I have displayed three techniques and their results. These methods allow the creation of models which can be taken and utilized for the investigation of further scientific questions. Chapters Two and Three looks at ground-based surveying methods, their benefits, faults, and how they can be augmented and modified by other data.

Chapter Three provides a case study of 4-dimensional photogrammetry as well as UAV-based surveying. The methods entailed allowing for precise modeling of change between two datasets that have experienced a great amount of change. The ability of these techniques to simplify the quantification of such large datasets is a valuable tool in the geosciences as technology allows for greater data processing.

5.1 Limitations

SfM photogrammetry is not without its limitations. Many of these limitations however can be compensated for with proper planning and/or equipment. SfM photogrammetry finds its niche in the mesoscale below large dataset acquisition like lidar but above what can
be done by a single person in the field. When reaching the spatial limits of SfM, partitioning of a field site, or limiting the field to only the most essential segments will be required.

Image acquisition can also be limited by environmental factors. When capturing images, changes in lighting over one or several days can be detrimental to the feature matching algorithms and in the bundle adjustment. This is where UAV-based surveying can be utilized in its quick and efficient workflow covering an area of interest. Most commercial UAV software allows the user to plan their flight path which the software then reports the total flight time and battery changes that will be required for completion.

The technological limits of SfM are also something that can provide a challenge in both model processing and model accuracy. Image quantity is a primary driver of processing time for the SfM technique. Even with advancing computational technology, the more images to be matched the longer processing time is needed. Software-based solutions primarily rely on the use of the computational power of both the CPU and GPU. Ground control points are a major component in the accuracy of any given photogrammetric model. GCPs should be placed throughout the field site to give coverage of the entire space. Their placement must also consider that they will not move throughout a single survey and that replacement of the points in the same spots will be possible in future surveys. Again, there are different technique-based and technological solutions to accurate georeferencing of photogrammetric models. If high positional accuracy is not a need for a project, then the results of the feature detection and bundle adjustment are all that are needed. Otherwise, GPS-enabled cameras or RTK-GNSS equipped UAVs will allow for image metadata to be used in model referencing. RTK-GNSS is the more accurate of the two. Finally, as discussed in Chapter One the primary assumption of the SfM-MVS algorithms is that the scene to be reconstructed is rigid. If objects within a scene move throughout images or if they are highly reflective, the construction of artifacts can be a result. The primary remedy is in the masking of problematic images or sections of images before processing takes place.
5.2 Future Work

Taking from the techniques discussed here future work in the geosciences should focus on the application of these techniques to answering scientific inquiry. The technology and methods have been proven here and by others to be at least comparable to traditional methods and have highlighted the benefits of SfM photogrammetry. These data products, DEMs, and point clouds especially have begun to find their use in the augmentation of existing scientific research methods and models.
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Appendices
Appendix A: Indian Rocks Beach Preprocessing

Processing of Indian Rocks Beach data was originally done with comparisons of the full beach itself. After the M3C2 differencing of the full model, a distortion with about a 2km wavelength was seen (Figure A1).
Figure A1: Initial M3C2 difference cloud. Based on registration of the Pre-Michael point cloud to a airborne lidar dataset and Post-Michael Hurricane to the Pre-Michael point cloud. The colorscale is from -5 to 5 m difference. An obvious distortion with approximately a 2km wavelength. End and middle points of the wavelength match well with the locations of collected ground control points.

Several different trials of each of the three 250m beach sections were performed to determine the variation in iterative closest point registration. Except for the North section all trials were similar. Trial T4 was the final model used for each section (Figure A2).
Figure A2: Registration Histograms. Histograms of various trials of pre and post point cloud iterative closest point registration. T4 plots are the final plots used in Chapter 4. The most significant variation is seen in the North survey.
Appendix B: Mesh Models

The links below show the full models produced for chapters one and two.

- Egmont Key McIntosh Battery Untextured Mesh https://skfb.ly/osAsD
- Egmont Key McIntosh Battery Textured Mesh: https://skfb.ly/osA8V
- USF College of Marine Science Mesh Model: https://skfb.ly/o7JWp