Integrated Multi-Camera Photogrammetry: Toward the Simulation of Human and Faunal Access to the Pleistocene Cave Systems of Quintana Roo, Mexico

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Abstract

Caves are an inherently challenging environment for the collection of 3D data. Low-light, complex morphology, and often remote access contribute to the need for more integrated and portable systems for 3D documentation of archaeological and paleontological features. As part of the initial stages of the Human and Faunal Access Project, based in Quintana Roo, Mexico, our team completed documentation of cave entrances utilizing the Looq Integrated Multi-Camera Photogrammetry system for the purpose of providing accurate models of cave entrances. The now-submerged cave systems hold a myriad of evidence for Late Pleistocene and Early Holocene human and faunal interaction during a time when lower sea levels made the caves dry and accessible. The nearest entrances to known archaeological and paleontological features are important for understanding access, and the photogrammetric data will be combined with existing surface mobile LiDAR and traditional 2D cave mapping data as well as underwater photogrammetry and mapping data for the rest of the cave system. This paper serves to present the findings and methods used in incorporating the Looq system into our multi-modal data collection strategy alongside preliminary results for simulating both human and faunal access.

1. Introduction

The now-submerged cave systems of Quintana Roo contain abundant evidence of Pleistocene/Holocene human and faunal activity and human interaction. Current and previous studies in these cave systems have documented unique archaeological evidence including; skeletal remains, burn features associated with torch use, speleothem modification, evidence of ochre mining, and water collection activities (MacDonald et al., 2020, Chatters et al., 2017). Similarly, the wide variety of paleontological evidence showing Pleistocene megafauna from larger *gomphotheres* and giant ground sloths to smaller *smilodons,* in a relatively concentrated geographical region, has particular significance to the paleontological record. Due to the favorable preservation environment, these caves continue to reveal a nuanced picture of life not often preserved at other paleo sites around the world. Detailed documentation and mapping of cave entrances is necessary to understand how humans and fauna accessed, navigated, and exploited these caves as part of the larger landscape, and it is the first step in creating a more complete view of human and faunal access.

This analysis represents one component of the overall Human and Faunal Access Project, which aims to demonstrate how access and use of these systems changed over the course of their postglacial inundation. The highly collaborative nature of this project, which involves geologists, biologists, paleontologists, geochemists, archaeologists, and divers, requires the tools we use in the field to accommodate a large variety of research questions while avoiding duplication in data collection. Extensive documentation, employing both 2D and 3D techniques, has been completed in the submerged areas of these cave systems, centering around major archaeological and paleontological finds at the site of Hoyo Negro, Sagitario/La Mina, and numerous adjacent systems These studies have created a baseline for understanding what types of archaeological materials exist in the caves and their relative position to surface access points. The Hoyo Negro Project, specifically, has also provided an ongoing test case for digital reconstruction through multiresolution photogrammetry (Rissolo et al., 2015). Visualization and manipulation of these digital twins has allowed for an evaluation of missing data in relation to questions surrounding how and why humans and fauna entered the caves at a time when they were dry.

2. Integrated Multi-Camera Photogrammetry

2.1 Multi-Camera Photogrammetry System

The collection of multi-camera photogrammetry data in the complex cave entrances allows for a more visually comprehensive model that includes RGB metadata for each point as compared to the other 3D data collection modalities utilized during this project. Single camera photogrammetry can be difficult and time consuming in covering large swaths of inconsistent terrain, and the designs of larger multi-camera rigs, even ones designed for subterranean use as seen in Meyer et al. (2020), are not conducive to efficient movement through the jungle and the complex, often narrow, morphology of the cave entrances. The Looq Ai system is a fully integrated hand held multi-camera photogrammetry unit similar in concept to systems created by Perfetti et al., which were designed for narrow architectonic spaces (2022, 2023). The system can be carried by a single operator with ease wearing a small battery pack with no additional equipment required. The Looq's fully enclosed system allows for preservation of the internal geometry and synchronization of the camera sensors. Four cameras allow for 270 x 150-degree field of view and each camera has an integrated strobe, which can be set to constant or intermittent function, for low light conditions (Figures 1 & 2). The system also includes an integrated RTK GNSS receiver which allows for more seamless track recording, though the lack of direct sky access due to jungle canopy and subterranean environment made the geodetic data collected by the system largely irrelevant in this study.

A single phone interface is mounted on the housing and controls the cameras via a linked wireless signal. Like many 3D recording units, this system was designed primarily for the commercial applications of open-air engineering and utilities management, but the compact and enclosed nature of the Looq system made it a good candidate for use in the semi-dry cave systems.

Figure 1. (top) Looq Integrated Multi-camera Photogrammetry system (photo courtesy of Looq). (bottom) D.Rissolo employs the Looq system in recording a partially submerged cave entrance (photo by M. Broen).

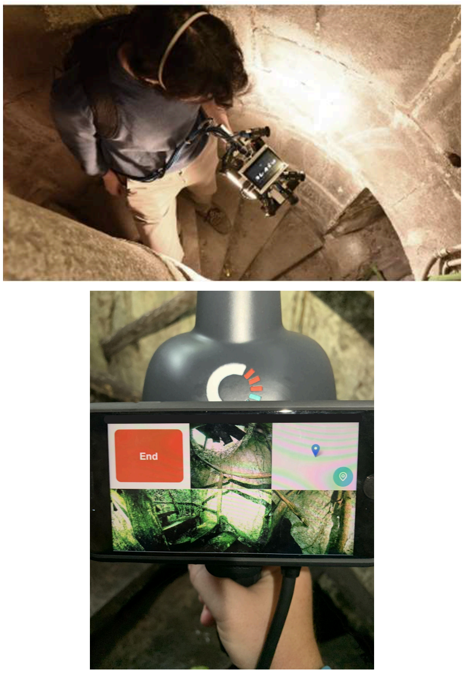

Figure 2. (top) Multi-camera photogrammetry system shown in Perfetti and Fassi (2022) in use on an indoor spiral staircase. (bottom) Looq system in use on similar spiral steps built in a vertical cave entrance (Photo by L. Clark)

2.2 Data Collection

During the first phases of field collection in February and August 2024, our team completed 38 total scans at 10 different cave entrances in both the Outland (Sac Actun) and Sagitario systems over the course of eight field days. These entrances represent the most proximal access points to large sections of archaeological and paleontological data recorded in the submerged sections of the cave systems. The relative ease of operating a hand-held mobile photogrammetry system allowed for the more scans to be completed in the short field season we were afforded in these crucial first stages of research.

The operation and data collection workflow using the Looq system is relatively straightforward with only one control unit (mounted phone), one corded battery pack, and one enclosed housing (cameras). Using maps and observations from the dive team, members on the Human and Faunal Access Project planned out clear photogrammetry routes with the intent of gathering surface and subterranean dry cave features at each entrance. As overlap is critical in photogrammetric modeling, the four cameras allowed for a more organic collection path than more traditional gridded methodologies. Due to this flexibility in photo overlap, the team was able to follow the natural morphology of the caves and the surrounding environment. The upward facing camera was also particularly useful in capturing overhang and ceiling data while not taxing the operator. The complex nature of many of the cave entrances also necessitated collecting a series of scans for each entrance. These individual scans would be stitched together using common marker points in each scan. The necessity of collecting multiple scans can also be linked to the 20min scan duration limit imposed by the Looq's collection interface. With the understanding that more than one scan was likely for most of the cave entrances in the study area, it was important for the team to place ground control points (GCPs), directional markers, and make note of key cave features that would assist in aligning separate scans after processing (Figure 3). A minimum of three ground control points were placed in each entrance complex.

Figure 3. Collection of placed ground control point, color correction, and North arrow by the integrated multi-camera photogrammetry system (photo by M. Broen)

The placement of GCPs also allowed for a more stable GNSS rover and base station system to be used for the eventual georeferencing of the finalized point clouds. Georeferencing the final point clouds was completed using dual-band RTK data collected using an Emlid Reach system at each ground control point. For those cave entrances highlighted in previous expeditions, ground controls were placed intentionally to link with visible features on the mobile LiDAR data collected using an Emesent Hovermap 100 in 2021. GCPs were also integral in checking the scaling of processed models, and in the case of this round of data collection, 10cm block, numbered black and white, GCPs were sufficient in accomplishing the aforementioned tasks. It is important to note that, unlike the Perfetti and Fassi (2022) study, these GCPs were not placed with the intent to assist in camera calibration or compensate for drift error, and their primary function was in alignment and georeferencing.

2.3 Lighting Considerations

Both the jungle canopy and interior of the overhang and cave passages offered an obstacle to properly lighting the scene for photogrammetry. Because this system was designed to be mobile, stationary lights would not be appropriate for illuminating the entrance features. As noted previously, the Looq system houses integrated strobes that encircle each camera lens which allows for some light assistance in some structural or shadowed contexts. The integrated lights alone, however, were not enough to allow for acceptable photo capture, especially within the caves themselves. Team members already incorporated lights onto their cave helmets for safety and visibility so adding additional lights was not a logistical problem. During this phase of the project, the operators attached one Zebralight Flood Headlamps to each side of their helmet to provide additional lights to the side view cameras while their primary forward light was set to a wider coverage angle. All lights were set with the widest angle and the brightness was adjusted based on the proximity of the features in each entrance complex.

Figure 4. Operator’s helmet showing additional flood lighting added. (Photo by M. Broen)

3. Processing and Visualization Workflow

3.1 Looq Processing Workflow

Upon collection in the field, each Looq scan was recorded internally, uploaded to a server, then run through an initial processing by the Looq team before being made available as a point cloud, or through a more in-depth workflow involving the decrypting and processing of individual images. These point clouds were brought into Cloud Compare and filtered for noise and oriented based on the waterline and the north arrow in each scan. For any entrances where multiple scans were collected, individual scans were aligned using the GCPs and distinct cave markers then exported as a single point cloud with distinct scalar fields (Figure 4). Point clouds were then georeferenced using the control points for each scan before exporting for mapping and visualization.

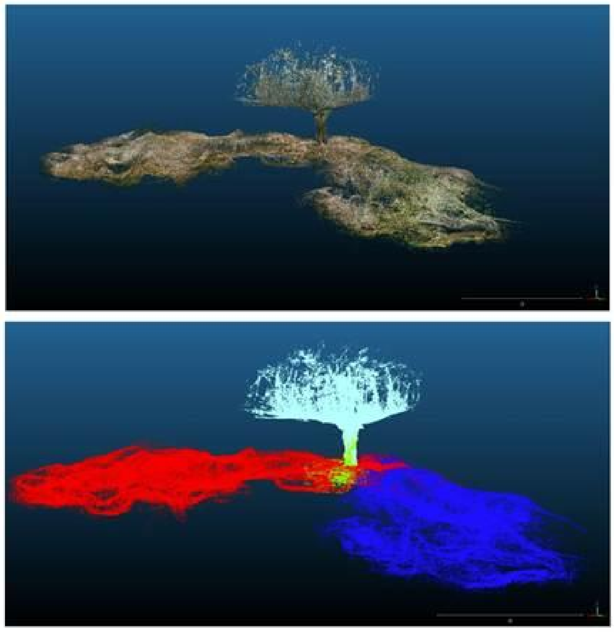

Figure 5. Aligned point clouds from four separate Looq scans in the same cave entrance showing the surface, vertical shaft, and sections of the underground cave. (top) RGB output of combined scans, (bottom) individual scalar fields of combined scans.

3.2 Multimodal Data Integration

The utility, and often necessity, of multimodal data collection in caves has been shown through studies of both dry and submerged caves in the region (Rissolo et al., 2024). The variable terrestrial and submerged environments inherent to this project necessitate the use of equally variable collection methods and instruments. To this end, another primary goal of the fieldwork was the integration of the Looq datasets with previously collected photogrammetric models, mobile LiDAR clouds, and physical cave markers surveyed into the submerged dive lines. Surviving cave markers reconstruct in the photogrammetric models and can be flagged, labeled, and cross-referenced with other survey data. This allowed for further combination and orientation of the 3D data with previous detailed 2D mapping efforts. The combination of these datasets, often collected decades apart, is a somewhat interpretive process with near constant consultation with everyone involved on the project to create cohesive baseline datums. This interpretive framework for combining 2D and 3D data allows for the overlap of what are now submerged features with dry cave morphology. Preliminary results are still being processed which involves combining diver observations, underwater photogrammetry, videography, and archival cave cartography with newly captured 3D datasets to create "heat maps" showing the relative accessibility of each cave passage and entrance (Figure 6).

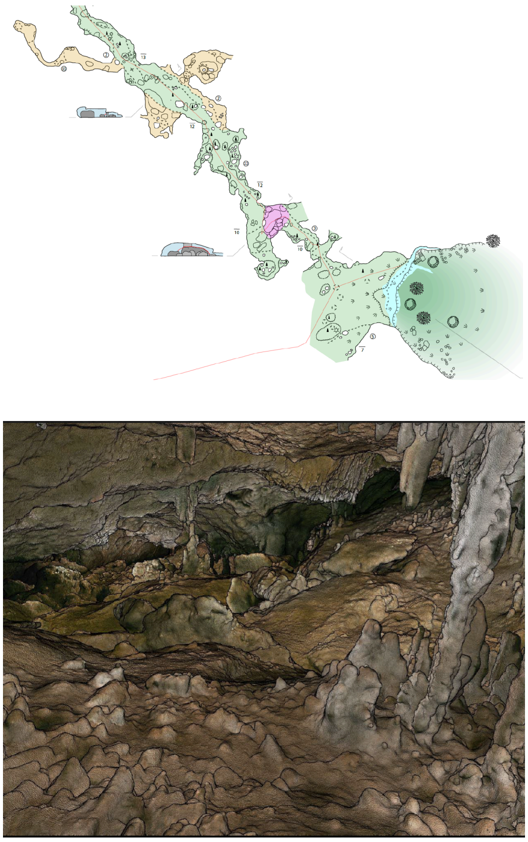

Figure 6. (top) Preliminary interpretive "heat map" where accessibility zones are shown as relatively less accessible (red), moderately accessible (yellow), and relatively more accessible (green) with room for additional refinement of parameters based on 3D data like the Looq (bottom) which shows more nuanced perspectives of the detailed cave morphology.

Additionally, none of these entrances had been recorded previously using photogrammetry above water, and only five had been previously documented using mobile LiDAR. While the photogrammetry data allows for a more visually comprehensive perspective of the cave entrance features, the LiDAR allows for more accurate long range data collection in low light environments. Alignment of these datasets holds unique challenges as the resolution of the point clouds and the metadata parameters for each instrument often create different surfaces in both point clouds and meshes (Figure 7). However, the combination of these various datasets is critical for analysis of these cave entrance complexes as well as the continued effort to stitch together the dry land and submerged datasets.

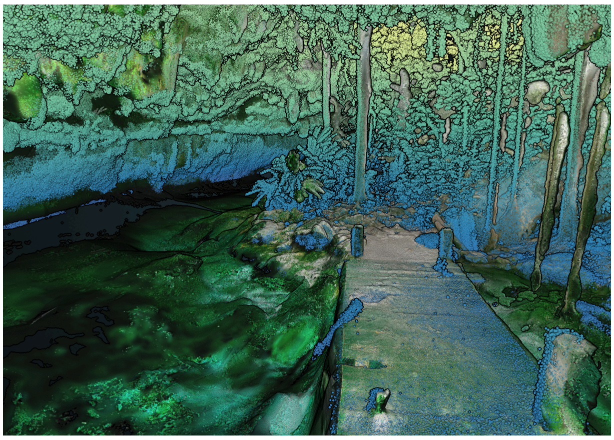

Figure 7. Example of Looq multi-camera photogrammetry interpretive mesh and the Hovermap mobile LiDAR point clouds aligned and simultaneously displayed.

3.3 Data Visualization

Our photogrammetric and LiDAR data outputs are dense point clouds (generally 1 to 3 cm resolution), noisy, and filled with occlusions. There are many features which can be parsed visually by humans, but cause errors in the final mesh reconstructions and simulation environments, as objects get stuck on invisible barriers, or inside of complex geometries. For this reason, we rely on point clouds to visualize and validate raw data throughout the process, quickly and easily referencing full resolution data through the Potree system (Schütz, 2016). We've found that meshes extracted from the Hovermap LiDAR are especially difficult to work with, as their fuzzy and noisy surfaces often result in floating disconnected objects and errors in face direction. Low light conditions in the caves and the presence of other equipment during scanning increases the possibility for disconnected points. Still, as the mobile LiDAR provides more data for distant objects that would be out of range for the Looq, we must consult it as we create our final data integration clouds and the eventual human and faunal access simulation environment (Figure 8).

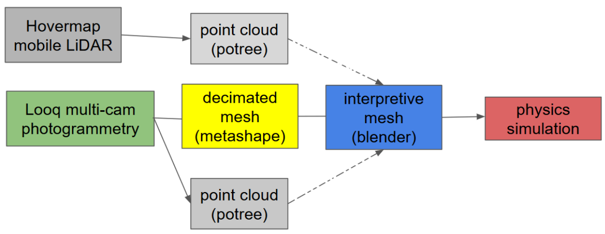

Figure 8. Data pipeline for simplified simulation environment

4. Results

4.1 Multi-Camera Photogrammetry

The successful collection of a large amount of data during short preliminary field seasons highlights the efficiency of using an integrated multi-camera photogrammetry system, especially considering that these caves are not easily accessible. Point clouds, once processed, were able to be analyzed and "flown through" using Potree to highlight and mark features of interest that were noted during the fieldwork, and, similarly, additional features could be identified that were not obvious while moving through the cave in person. The latter is particularly true in the fully dark cave sections where the photogrammetric models show a fully or partially lit scene where in-person visibility was restricted to helmet lights. The most common features identified in the Looq data were the dry cave markers left by previous cave mapping projects (Figure 9). These markers are often surveyed in and combined with submerged cave line data for ease of navigation and accurate reference. These markers are not as visible in some of the other modes of 3D data collection as their identification after processing often relies on RGB color differences to stand out against the cave walls and root systems. In the next phases of the project, the surviving cave markers in the 3D data will be compared to the extensive GIS database at CINDAQ to update the database and more accurately tie in the photogrammetry and LiDAR in the dry cave sections to the underwater photogrammetry and map data.

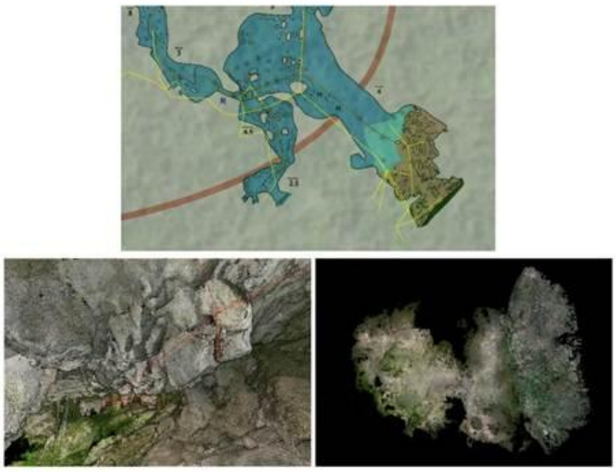

Figure 9. (top) GIS layer of a cave entrance showing recorded links from underwater cave navigation lines to dry cave markers (map courtesy of CINDAQ). (bottom) Internal oblique and top-down views of Looq scans of the same entrance with visible dry cave markers.

The photogrammetry data also allowed us to create a series of cross sections in order to determine passage heights at different areas of the dry caves (Figure 9). These cross sections, created in Potree, show a much more complex variation in the shape and height of some of these entrance complexes which would not have been apparent through traditional top down maps and plans. This is important in answering questions of access, especially for the larger Pleistocene megafauna. Viewing the data in cross section for the entrances and for the underwater data is also crucial for modeling and displaying sea level changes over the roughly 20k years this study encompasses. Rising sea levels pushed up the existing fresh water aquifer, potentially cutting off dry routes to certain passages while often making fresh water more accessible from different entrance complexes. Nuances in cave morphology, which can be detected in higher resolution 3D data, impact how the water would be distributed throughout the cave and when/where certain entrances and passages might be affected.

Figure 10. Cross Section of one of the vertical entrance complexes. Full model (top) shows the extent of the dry cave, from the entrance to the waterline. Partial subsections of the model (bottom) show the individual passages and the ability to take and display measurement data for later analysis.

5. Simulation of Human and Faunal Access

As stated previously, access and use of these caves, by humans and fauna, is dependent upon morphology. If a chamber is too small for a certain individual to access, it will probably not enter. If an individual is found within an area which seems inaccessible, it would be reasonable to conclude that either 1) the geomorphology of the cave has changed since the initial entrance, or 2) that the individual was brought into the space by a third party (perhaps a human or other predator). In creating a simulation from current 3D datasets, we intend to provide a more tangible framework on which we can map and evaluate all possible means of ingress and egress for each species over time. In order to reuse these models as environments within simulation environments, we must modify them significantly. Geometries must be simplified significantly to utilize common pathfinding simulation pipelines.

5.1 Protagonist Modelling

The giant ground sloth model presented in this paper represents the *paramylodon harlani*, modelled in Blender. At this time, the model is rigid, meaning that we lose the capacity to bend and compress the models as animals may naturally contort themselves to fit through strange spaces. Moving forward, we hope to add skeletal riggings to our faunal models which will

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lend a more realistic range of movement and animation.

5.2 Simulation Environment

The general collision based simulation environment follows a traditional video game development pipeline, requiring simplified meshes. We must transform our raw data for this purpose (Figure 6). Photogrammetric models are meshed in Agisoft, decimated and exported into the Blender 3D graphics system (Blender Development Team, 2022), where we manually reconstruct features of interest, while leaving out extraneous interpolated 'globs' and noise using a 3D tracing process common to the game development industry. During this manual reconstruction we refer back to the point clouds to see which features are true, and which are false. We had initially attempted to use Blender's pathfinding node to perform shortest path simulations between start and end points, but found that it performed suboptimally with collision physics features enabled. We decided to use theWebots robot simulation program (Michel, 1998) to perform an exhaustive pathfinding simulation, highlighting all potential regions of the cave where the sloth model could reasonably fit. While this methodology seems accessible and viable in the short term, we do lose the ability to account for animal contortion. We hope to find another way enabling a more elastic tolerance to account for these non-rigid environmental interactions. One promising option involves the full resolution physics pipeline in development within the Unreal Engine. The system features realistic muscle simulation, collision systems and incorporates complex high resolution meshes. Though the complex skeletal/musculature simulations are available for common game animals (humans, horses, some big cats) it may not be viable to create such complex assets for other Pleistocene megafauna.

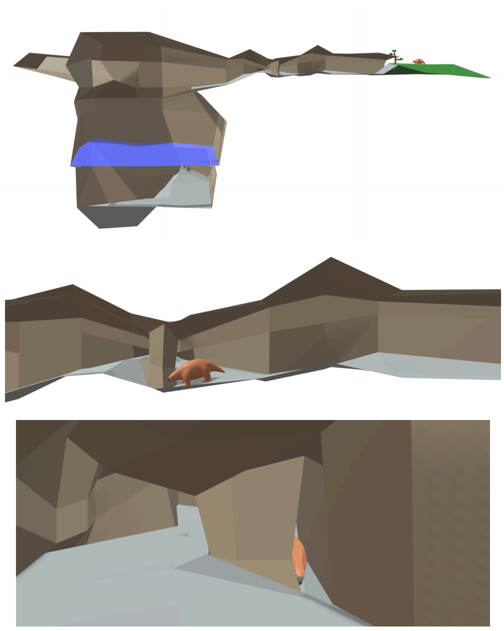

Figure 11. Geometrically simplified cave system with giant ground sloth (top), stuck at passageway profile view (middle) and interior view (bottom).

5.4 Visualization

Simulation results are published to sketchfab.com for easy sharing. Animated pathways can be easily inspected and verified. Like video, the 3d animations can be played, paused, and rewound. Cave floors are differentiated from walls by color, and all walls are rendered with "backface culling" enabled (Hultquist, 1990), enabling an inside-out visualization (Figure 11), always seeing the inside of the cave, the interior is never occluded by the outer walls.

6. Conclusions

The incorporation of a multi-camera photogrammetry system and simulation environments into the already extensive documentation effort undertaken by the members of the Human and Faunal Access Project has allowed for new analytical and interpretive pathways toward answering the wide variety of research questions born out of these amazing cave systems. From the perspective of heritage management, the incorporation of multiple data modalities allows for more engaging educational opportunities and access to local communities in Quintana Roo and researchers around the world. The results of this paper have shown the capabilities of this data collection methodology, which will be critical in continuing documentation efforts.

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