8-2019

Comparing Structure from Motion Photogrammetry and Computer Vision for Low-Cost 3D Cave Mapping: Tipton-Haynes Cave, Tennessee

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Recommended Citation

Elmore, Clinton, "Comparing Structure from Motion Photogrammetry and Computer Vision for Low-Cost 3D Cave Mapping: Tipton-Haynes Cave, Tennessee" (2019). *Electronic Theses and Dissertations.* Paper 3608. https://dc.etsu.edu/etd/3608

Comparing Structure from Motion Photogrammetry and Computer Vision for Low-Cost 3D Cave Mapping: Tipton-Haynes Cave, Tennessee

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A thesis

presented to

the faculty of the Department of Geosciences

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Master of Science in Geosciences

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by

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August 2019

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Keywords: Speleology, Caves, Cave Mapping, 3D Mapping, Google Tango, RGB-D, Photogrammetry, Structure from Motion, Paleontology, DistoX, Cave Survey

ABSTRACT

Comparing Structure from Motion Photogrammetry and Computer Vision for Low-Cost 3D Cave Mapping: Tipton-Haynes Cave, Tennessee

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Natural caves represent one of the most difficult environments to map with modern 3D technologies. In this study I tested two relatively new methods for 3D mapping in Tipton-Haynes Cave near Johnson City, Tennessee: Structure from Motion Photogrammetry and Computer Vision using Tango, an RGB-D (Red Green Blue and Depth) technology. Many different aspects of these two methods were analyzed with respect to the needs of average cave explorers. Major considerations were cost, time, accuracy, durability, simplicity, lighting setup, and drift. The 3D maps were compared to a conventional cave map drafted with measurements from a modern digital survey instrument called the DistoX2, a clinometer, and a measuring tape. Both 3D mapping methods worked, but photogrammetry proved to be too time consuming and laborious for capturing more than a few meters of passage. RGB-D was faster, more accurate, and showed promise for the future of low-cost 3D cave mapping.

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CHAPTER 1

INTRODUCTION

Caves represent one of the last largely unexplored environments found in the world. For many, these dark cold worlds represent the home of demons, dragons, and the ever-elusive “Civil War gold,” as referred to in folklore told across the cave-forming regions of the Southeastern United States. Kids grow up hearing about the mystery, danger, and adventure waiting in these dark openings, visible from the back deck of the old family farmhouse. As time progressed, the important role these fragile underground environments has played to the health of the local people, and to the natural environment above ground, has become more understood. For many of the small rural communities established on the carbonate-rich lands of the Nashville Basin and Highland Rim, and the Valley and Ridge provinces of Tennessee, Alabama, and Georgia, well water and springs have represented two of the most widely used sources of drinking water for generations. The quality of this water is often highly dependent on both the condition of the cave passages carrying these subsurface streams, and the locations that surface streams sink down into the extensive underworld below. Beyond the scope of water quality, caves impact many different aspects of the societies living above them—from ground stability to significant scientific discoveries. This makes mapping these cave systems an important, yet widely ignored concern for many of the people who call these regions home.

Much of the terrestrial world can now be mapped using Global Positioning Systems (GPS) or Global Navigation Satellite Systems (GNSS), but these technologies are limited underground. The signals used by satellite-based positioning systems do not penetrate the dense layers of earth that make up the ever-present ceiling that is central to the definition of a cave (Redovniković et al. 2014; Zlot and Bosse 2014). This huge limitation, along with the harsh environment of caves, has led to a slow progression of cave mapping technology and methodology.

In the United States, nearly all cave exploration, science, and survey is carried out by the otherwise everyday people who have taken up cave exploration as a lifestyle-defining hobby. Scientific studies account for a small fraction of the total time spent studying these natural underground environments; the few scientists that do study caves typically started out as hobby cavers (Marbach and Tourte 2002; Palmer 2007). This revelation, often unknown by those who make their career in science, is why it is important to focus on affordable tools and techniques that are within reach of the huge community of low-budget cave explorers. These “unofficial” hobby cave explorers are the unsung heroes that build the massive foundation of knowledge that all academic cave science relies upon. That is why this project focuses on two modern mapping techniques: Structure from Motion (SfM) photogrammetry and a new RGB-D mapping device called Tango. Tango is an augmented reality computing platform developed by Google that uses computer to enable smartphones and tablets to detect their position in 3D space without GPS. Either could bring about the availability and feasibility of 3D mapping to the average cave explorer in the United States. The main goal of this study is to test the practicality of these two modern 3D modeling methods to replace standard cave mapping methods widely used today.

CHAPTER 2

BACKGROUND

Mapping/Survey

Important Concepts for Cave Mapping

Several important issues in cave survey must be addressed when considering the goal of the survey and the eventual map: accuracy, speed, detail, and usability of the map. These are important when managing a survey since cave mapping is typically a voluntary service done by cavers in their spare time. This places the attribute of speed as a very important, yet often ignored, goal for the survey. If the survey is exceedingly slow, the cavers typically lose steam and interest in continuing the project. This is a far greater problem in places like the Southeastern United States. where there is a massive number of accessible caves that need to be explored and mapped. In Tennessee alone, there are well over 10,000 documented caves, and this number grows at a rate of about fifty new caves per year (TCS 2018). Two counties in Middle Tennessee, White County and Van Buren County, have two of the highest cave densities in the world (TCS 2018). White County has 1,266 documented caves for an area of 982 square kilometers, or about 1.29 caves per square kilometer. Van Buren County has 873 caves in an area of 712 square kilometers, or about 1.23 caves per square kilometer.

Depending on the size of the cave system, usability and accuracy of the map is typically less important than the speed of survey. Most maps of larger cave systems will be used for guidance through the cave. In this role, it is important to include changes in passage shapes and obvious features that are clearly visible in the cave. Too much detail can clutter a map for a larger cave system, and some of it often has to be removed for the final product to be usable in this role. It is also important to include any scientifically important details that can be identified on the map for future research and studies. One example of this is how paleontologists and biologists rely heavily on avocational cavers for discovering locations of interest and creating the cave maps they use in their studies.

Cave Survey Technique

For decades, cave mapping has been a long and tedious process involving a small team of dedicated cave explorers (Marbach and Tourte 2002). The procedure relies on human interpretation of the environment with many artistic liberties mixed in. The quality of each cave map is determined by in-cave sketches done by the cavers and the ultimate goal of the cartographer drafting the map (Grimes 2000).

The entire concept of surveying a cave rests on the simple process of building a single 3D wireframe that extends down the cave passage, called a “line plot,” by measuring line-of-sight survey shots between two arbitrary points, often easily identifiable natural features known as “survey stations.” These survey shots are used to determine the location of each new survey station in reference to the location of the previous one. This progression of mapping each new survey station by measuring the azimuth (the compass reading), vertical angle, and distance of the line-of-sight linking it to the previous station (Figure 1) creates a line plot extending through the cave beginning at the cave entrance (Figure 2).

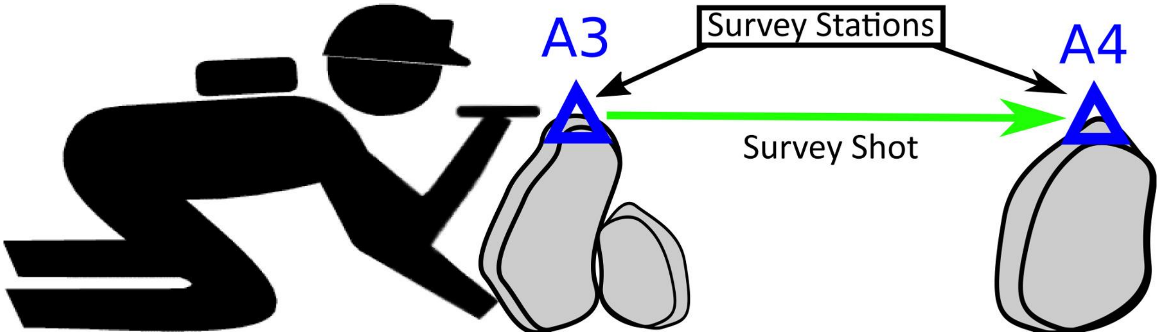

Figure 1. *A caver measures the azimuth and vertical angle of the vector line linking survey station A3 to survey station A4.*

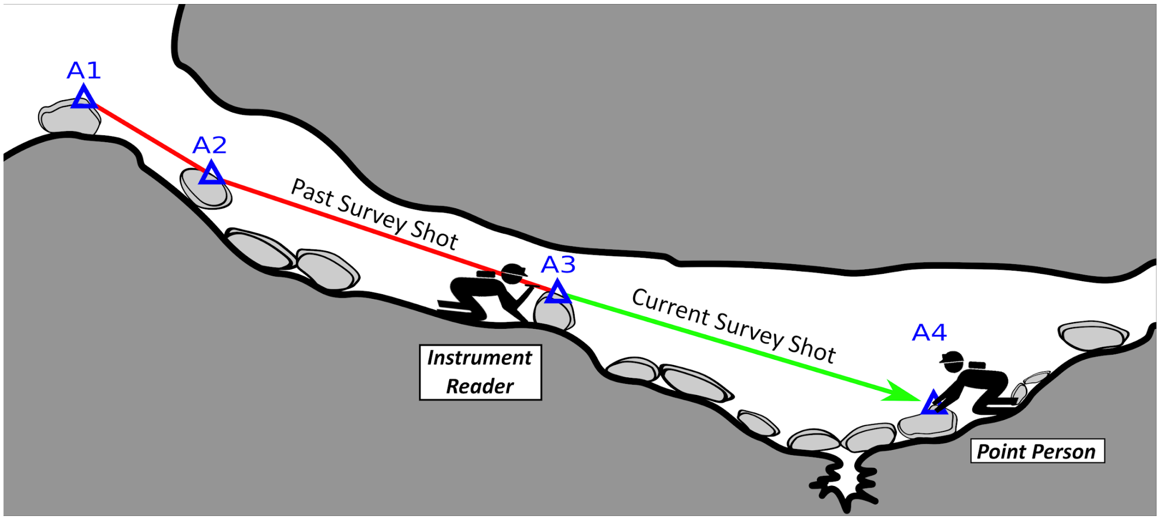

Figure 2. *The process of cave survey with the cave entrance located at survey station A1. One caver reads survey instruments at survey station A3 while another caver indicates the location of survey station A4.*

A typical cave survey team requires a minimum of three cave explorers to be efficient: one who is on “point,” one who operates survey instruments, and one who is the sketcher/book keeper (Figure 3). The caver on point, also called the "point person," scouts ahead down the cave passage while placing survey stations in locations that are within line of sight.

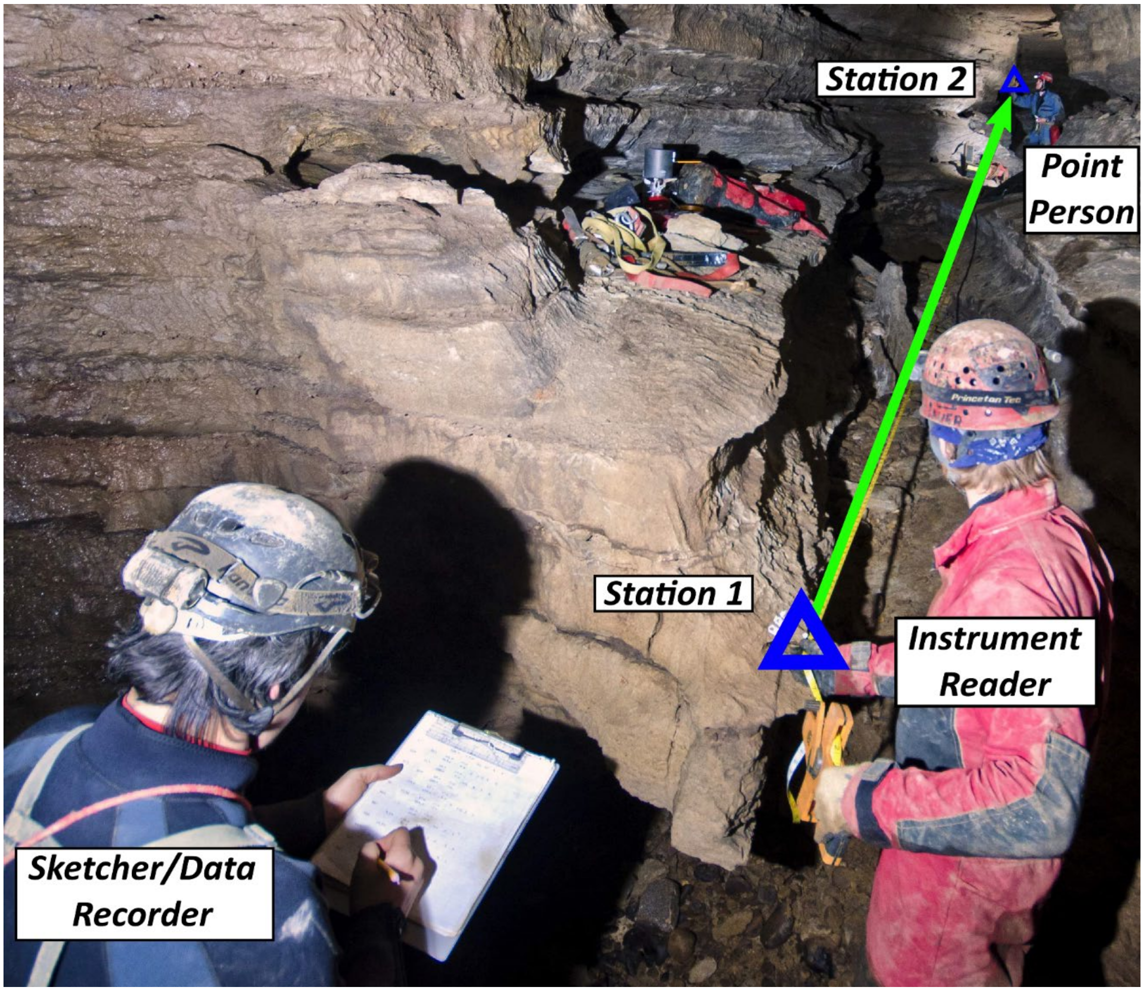

Figure 3. *A caver records data as two other cavers measure the distance between survey stations using a surveyor's measuring tape. Photo taken by Chris Higgins and used with his permission.*

Survey designations typically follow an alphanumeric naming scheme, such as having the first survey in the cave named "A," with a number following the letter designator to represent each individual station in the “A” survey. When using this typical scheme, side passages are given new letters or a second letter after the letter “A” depending on the size of the cave system and the significance of the side passage. This common naming scheme is used in this study.

The job of the third caver, the sketcher, is the most important. The sketcher plots the line using a protractor, drawing what is essentially a rough map of the cave passage surveyed during the trip. This rough sketch map (Figure 4) typically includes the dimensions of the cave passage, features observed, the date of the survey trip, the survey team member names, and any other important notes about the survey trip. Cavers capable of sketching detailed and accurate passages, while keeping up with the cavers measuring the survey shots between survey stations, are a rare commodity; the sketcher has to record survey shot data as it is called out, be aware of cave hazards, and draft a rough cave map all at once.

The sketcher also writes down all the values obtained by the instrument while the point person or the instrument reader estimates or measures the “LRUDs.” LRUDs are the distances between the survey station, typically the forward station, and the passage walls around that station. The LRUDs are the measurements of the distances between the station and the Left wall, Right wall, the ceiling (Up), and the floor (Down). These values help the sketcher draw a more accurate representation of the passage dimensions while in the cave, and provide details for drafting the final map.

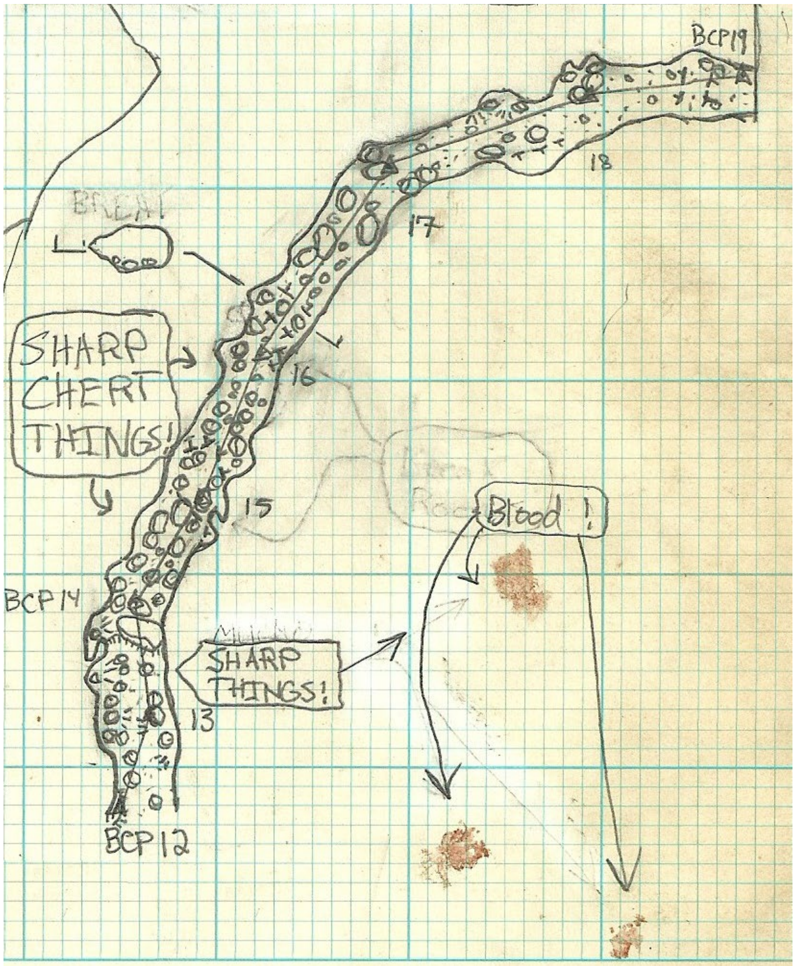

Figure 4. *An example of high-quality sketch created during a survey trip into Blue Spring Cave in middle Tennessee. This sketch includes the survey shots between survey station BCP12 and survey station BCP19. Blue Spring Cave is a very extensive cave system, and passages with three to four letters designating the survey of a passage, like the BCP survey, are not uncommon.*

All survey data and sketches are used to draft the cave map, accomplished by many different methods depending on the desired quality of the cave map and how complex or extensive it is. In the past, the survey data line plot was plotted out by hand on a piece of graph paper sized to accommodate the entire cave survey. Finally, the individual passage sketches are plotted out on the same graph paper together to create a final cave map. Thanks to the availability of computers and cave survey software, the drafting process is both simplified and far more accurate. Using a computer, the survey data is entered into one of the many cave survey programs available, and that program plots out the survey data for the cartographer. Next, each of the sketches from the cave survey are scanned and saved on the computer. These sketches are then “transformed” to fit the plotted survey shots represented by the sketch. The process of morphing is where the sketch is stretched to fit the data; this can be a painless process or a major difficulty depending on the quality and accuracy of the sketches. The morphing process allows the cartographer to connect all the sketches in a coherent manner and use those sketches to draft the passage details (Marbach and Tourte 2002; Palmer 2007). The line plot is then exported to a program that allows the sketches to be displayed as a layer behind the line plot and digitized with a line drawing feature in the program. The program used to digitize the cave map sketches in this study is the open source vector drawing program Inkscape; however, many different programs have been used to fill this role.

Many difficulties can be encountered when drafting cave maps of more complex cave systems, such as multiple overlapping levels and low-quality in-cave sketches. The cartographer must use skill and artistry to overcome these hardships and produce a usable cave map. The time it takes to map a cave using traditional methods varies a great deal; it is mostly dependent on how much detail, accuracy, and precision is desired or required. Typically, in larger cave systems, speed is the most important aspect of mapping. With a large complex cave system, producing any usable cave map for other cavers and/or scientists is a monumental task that can take generations of cavers to complete. Many of these massive mapping projects start with great momentum while the cave is new and exciting, before ultimately slowing to a crawl as cavers lose interest and leave them for other new and exciting discoveries. The persistent problem of keeping momentum in cave mapping projects means that many cave maps never get finished and, sometimes, the survey data eventually becomes lost. The method of surveying cave passages described above is the main method used by nearly every cave explorer in every cave around the world (Palmer 2007).

Analogue Survey Equipment

Cave survey requires a specialized adaptation of common land survey and construction survey techniques used widely throughout history. Most modern land and construction survey methods and tools can be directly traced back the invention of the theodolite. The theodolite is a specialized telescope-like device that is used to measure the vertical angle and/or the azimuth (horizontal angle) of the line of sight between it and a target. The very first description of what could be considered a theodolite is found in the book, Margarita Philosophica, written by Gregorius Reisch in 1512. The word "theodolite" was first used in the surveying textbook, A geometric practice named Pantometria, written by Leonard Digges in 1571 (Avram et al. 2016). The theodolite has been upgraded through the years, with the largest improvement coming in the form of a digital device named a "total station theodolite," or just "total station."

The total station is a ubiquitous sight in modern land and construction survey. Total stations are theodolites with an electronic distance measuring device built in. This combination allows the total station to accurately record all three dimensions of line-of-sight shots between the total station and the target. Total stations are large, expensive devices created to calculate extremely high precision measurements. While this level of precision is important in construction and land survey, trading some of the extreme precision in favor of smaller, more practical and cheaper devices is favorable when it comes to cave survey.

Typical cave survey methods of the past few decades utilize three different devices that, when used together, collect the same data as a total station: the azimuth, vertical angle, and distance of a survey shot. The most commonly available analogue instruments used to fill this role of a theodolite in cave survey are the Suunto sighting compasses/clinometers and the Brunton Pocket Transit, with the commonly available surveyor's measuring tape used to measure distances (Palmer 2007; Redovniković et al. 2014).

The All-in-one Survey Instrument

A goal for the current generation of cavers has been to combine all of the analogue cave survey instruments into one digital survey unit (Heeb 2008). Many attempts at building, modifying, or adapting existing all-in-one survey devices for use in cave survey have been successful. The most successful all-in-one survey instrument at this time is arguably the "DistoX" and its successor, the "DistoX2." Development of the DistoX devices started in 2007 by Beat Heeb (Heeb 2009). The DistoX is built by modifying a Leica Disto A3, while the DistoX2 is created by modifying the Leica Disto X310 or the Leica Disto E7400x, the latter being a specific model for the United States (Heeb 2014). The DistoX and DistoX2 both combine a 3-axis compass and clinometer with the preexisting Leica laser range finder. The use of the 3-axis compass allows the user to achieve rapid and accurate measurements regardless of the device's orientation. With the first DistoX, the inclination is measured by an SCA3000-D02 accelerometer, while the azimuth is measured by three magneto-inductive sensors (Heeb 2014). The DistoX2 uses the same 3-axis compass of the original DistoX. For inclination, the DistoX2 uses a combination of the preexisting acceleration sensor on the X310/E7400x and another 3-axis sensor mounted horizontally. The original DistoX used off-the-shelf AA batteries, presenting a major issue: calibration was needed after every battery change due to the change in the magnetic fields of the batteries (Heeb 2009). This issue was resolved with the DistoX2 with the addition of a built-in rechargeable lithium polymer battery pack that never changes magnetic orientation (Heeb 2014). Both devices transmit data via Bluetooth to a handheld device, such as a tablet or Personal Digital Assistant (PDA) device. This allows the sketcher to digitally construct the line plot and sketch the passage details at the exact moment measurements are recorded.

Typically, either a Windows Pocket PC or an Android tablet is used in conjunction with a DistoX. Several programs have been created or modified to work with the DistoX devices. The DistoX family of devices can be used as a direct replacement for the analogue survey instruments even when the sketching is done on graph paper. The use of a tablet or PDA in conjunction with the DistoX is entirely optional.

The DistoX and DistoX2 are both well-suited for cave survey; they are generally robust and have been shown to be very accurate, even in the most extreme environments. The DistoX devices are nearly as accurate as a digital total station when corrected for magnetic declination (Ballesteros et al. 2013; Redovnikoviü 2014). Both the digital total station and the DistoX far exceed the accuracy of the commonly used analogue survey instruments the DistoX set out to replace (Redovnikoviü 2014**).**

3D Cave Mapping

LiDAR (Light Detection and Ranging)

LiDAR refers to the process of collecting spatial location data on the surface of an object or area of land by measuring the time it takes for a pulsed laser to bounce back to the LiDAR device. These location data are compiled into a large database known as a point cloud, used to reconstruct the surface of the target object or area of land. In the world of three-dimensional cave mapping, several methods using LiDAR have shown moderate success. The main goal has been to shorten the time it takes to survey while increasing the amount of data collected and therefore increasing detail. Cavers dream of “scanning” the entire cave passage in 3D at a walking pace (Zlot and Bosse 2014). This dream has remained elusive with several attempts coming close.

The main issue encountered when it comes to the practicality of the former methods attempted is the reliance on expensive LiDAR units and the costly gear required to use those LiDAR units. Caves can be a very harsh environment and the typical cave explorer doesn't have the funds or technical knowledge to buy and use a LiDAR unit. Despite this, some cavers and cave scientists, with access to large amounts of funding, have utilized LiDAR for cave mapping and produced some spectacular results– most notably the 3D scan of the monstrously big Miao Room, Titan Chamber, and Hong Meigui Chamber in China, showcased in the July, 2014 issue of National Geographic Magazine. The main limiting factor to using LiDAR for cave mapping remains the cost of the LiDAR unit. Currently this issue is apparent, however, the cost is rapidly declining as technology advances. As the accessibility of LiDAR increases, the prevalence of LiDAR cave mapping will likely increase.

Photogrammetry

Photogrammetry is the science of using multiple photographs to make measurements and/or create a 3D model or image of the chosen subject. The process involves using overlapping photographs of a subject taken from multiple directions under similar lighting conditions to determine the spatial location of each feature of the subject. This spatial location can be determined by everything from humans using stereo image viewers to advance computer algorithms implemented by modern photogrammetry software utilizing a concept known as Structure from Motion (SfM). In modern geoscience, photogrammetry is typically used to measure or document the terrain or some feature on the surface of Earth using aerial photography. Due to this historical focus, the adaptation of photogrammetry techniques to non-aerial photographs of subjects that are less than 300 meters (1,000 feet) away is often referred to as “Close-Range Photogrammetry” (Matthews 2008).

Structure from Motion represents a modern approach to photogrammetry that does not require ground control points (GCPs) because computer algorithms automatically align photos based on features that are identifiable in multiple overlapping photographs. The advantage of using SfM is that most of the work is done by computers after taking photos out in the field. Photogrammetry using georeferenced targets often involves additional time in the field collecting the location data of each target. This process consumes far more time and requires expensive GPS units or the use of costly land survey equipment and preexisting georeferenced features. SfM effectively eliminates these major requirements and makes photogrammetry available to essentially anyone who owns a camera and computer (Westoby et al. 2012). The program used in this study, Agisoft PhotoScan, utilizes SfM to create 3D models from photographs. For the sake of efficiency, any time the word “photogrammetry” is used in this paper without additional descriptive adjectives, it refers to the practice of Close-Range Photogrammetry utilizing SfM.

With the advent of 3D viewing software and 3D printing, photogrammetry has exploded in popularity, and a large number of people—with little prior 3D mapping knowledge—are learning and perfecting many aspects. The explosion in interest has largely been limited to modeling objects and environments on the surface; however, there are occasional attempts to model an indoor and/or underground environment.

The difficulty of cave photography and the massive logistics of taking a large number of photos in caves have largely limited the practice of photogrammetry to modeling smaller objects in caves, such as cave formations or petroglyphs. Many difficulties must be overcome when using photogrammetry in a cave: consistent and adequate lighting in a completely dark environment; robust gear able to withstand the harsh cave environment; the ability of the participants to travel to places that are often very inaccessible to all but the hardiest explorers; the ability to reach vantage points that have complete vision of the passage without adversely impacting to the cave environment; carrying all your own battery power in the cave; finding a method of identifying tie-point features or GCPs for the photogrammetry program to recognize when calculating the location that the photographs were taken. And these difficulties only grow with larger and more complex cave passages. There are also occasional massive cave passages or rooms that still require the venerable old magnesium/zirconium-filled flash bulbs to light up vast areas where modern electric flashes are incapable of producing enough light. Currently, the logistics required to take more than a few photos of these massive underground voids renders photogrammetry, as a universal solution to cave mapping, nearly impossible; hundreds of large flash bulbs would be required to map just one room.

Despite these shortcomings, photogrammetry is a particularly appealing process of low-cost 3D mapping that will be heavily utilized in certain cave related applications.

One of the most important aspects of photogrammetry is that most cavers already have the necessary gear, which is affordable and useful for general cave exploration. The standard set of caving photography gear typically consists of a camera, a wide angle lens, a set of three remote flash units, AA batteries for the remote flash units, remote flash triggers, and a waterproof and shockproof case to carry the flash units, camera, and lens (Figure 5). Another very important aspect is that the skill level required for photogrammetry is not dissimilar from general cave photography. Accessibility to the average person is very important because so much of cave science is carried out by the average cave explorer while on vacation from his or her standard non-cave related job.

Figure 5. *The standard setup for cave photography. This same setup is used to create photogrammetry model/maps of cave features/passages.*

The process of taking photographs for photogrammetry can become very difficult in a cave. The goal is to take photos that largely lack depth, shadows, and high dynamic lighting. All of these characteristics are often very important when it comes to the artistic nature of cave photography; however, they are either unimportant or unwanted in photos that have to be spatially aligned by a photogrammetry program. To take good cave photographs, setting up remote flash units at different angles to the camera is very important, particularly backlighting a subject with a flash somewhat facing the camera behind the subject. This setup using off-camera flashes creates nice shadows that lead to a more pronounced display of distances and depths in the desired photo. However, when it comes to photogrammetry, flat photos with minimal shadows are desired. The lack of shadows helps the photogrammetry program orient the photos correctly and create 3D textures to cover the model. In short, photogrammetry uses the standard cave photography toolkit, but in a very different way.

Computer Vision (RGB-D)

In contrast to the more mature methods of LiDAR modeling and photogrammetry, Computer Vision is a relatively new concept in geosciences. Computer Vision devices typically use a RGB-D sensor to create a model of the environments or an item. RGB-D sensors, or cameras, have grown out of their use in the robotics field and as virtual reality devices. In geosciences– and many other scientific fields– the first introduction of RGB-D sensors for 3D mapping occurred on a large scale with the release of the video game device, called the Xbox Kinect (later renamed: the Microsoft Kinect). The term “RGB-D” refers to the integration of two different types of cameras in the same device. RGB refers to a camera that records light on the visible part of the electromagnetic spectrum. This is a standard camera sensor that people have been using to record videos and take pictures since the introduction of digital photography. The “-D” in RGB-D refers to a depth sensor. The typical depth sensor, including the one found in the Kinect and Tango, is a combination of two devices that operate along the infrared (IR) range of the electromagnetic spectrum: a projector and camera. The IR projector and IR camera are set at a predetermined distance apart; this offset distance is a critical element in the final calculation of the depth by the sensor. The IR projector projects a predetermined pattern of laser dots onto the object or scene being scanned, and the IR camera records the dot pattern as it appears on the object or scene in front of the depth sensor. The deformation of the recorded dot pattern, in contrast to the projected dot pattern, is used to triangulate the distance between the dot and the sensor when it was reflected back to the camera, which determines the distance of the surface the dot was projected onto. In the case of Tango, this process occurs at a rate of 90 frames per second. Tango combines the depth camera and RGB camera into a single unit (Figure 6), with a quarter of the pixels collecting the IR data (Aijaz and Sharma 2016). Tango can use this combined RGB-D sensor to map subjects that are 0.5-4 meters (approximately 1.5-13 feet) away from the tablet (Google Developers 2017).

Figure 6. *Features of the Lenovo Phab 2 Pro mobile device, which runs Tango.*

In addition to the RGB-D sensor, Tango is unique in that it uses multiple other methods to keep track of the spatial location of the device while it is being used for 3D mapping. Google has adapted the robotics concept of SLAM (Simultaneous Localization and Mapping) to help keep an accurate location without aid from GPS. For this, Tango uses a wide-angle motion tracking camera and inertial sensors to aid in the spatial tracking of the device (Aijaz and Sharma 2016).

Tango is marketed as a virtual reality device focused on recreating virtual worlds or imposing virtual objects that fit, or react with, the room or place the operator is located. The device relies on having ambient lighting to record the surface texture of the model and helps correct for drift. The Tango tablet is most often used in a well-lighted area for a limited amount of time, while being able to fit inside a pocket; the build of the tablet reflects these considerations.

The first consideration to be dealt with is the poor ergonomics of using the tablet to map for a long period of time, particularly the unfortunate location of the power button where it is often pushed by mistake while holding the tablet for 3D modeling use. One other important aspect of using any imaging device in a cave is the complete lack of light; all lighting equipment must be brought in by the caver. As stated before, the Tango tablet is typically used in a well-lighted (or poorly lit) environment; the device does not fully function in an environment where no light exists. Another consideration is that Tango's battery is inadequate for the long periods of time required for mapping larger environments, such as a cave. Another consideration that must be addressed is the limited protection the tablet has against the harsh environment of a cave.

Most of these issues were solved by using and modifying a standard camera stabilizing “caddie” that the tablet was attached to via a purpose-built tablet holder that had a standard tripod mount (Figure 7). A standard 18-volt LED car fog light was attached to the bottom of the caddie and used for lighting. The type of lighting required was diffused soft light, so a folded piece of cooking wax paper was attached to the front of the car fog light with rubber bands. The 18-volt LED was attached to the bottom of the camera cradle with the fog light mount, washers and nuts, and several zip ties. A switch and wiring for the light was connected to the upper part of the caddie with zip ties and vinyl electrical tape. The chosen wiring was standard US "NEMA" grounded cord connector. A standard 12-volt motorcycle battery was used to power the LED fog light—specifically the smallest one found at a standard box store; this battery was set up with a long cord that had a grounded NEMA connector to complement the NEMA connector used for the caddie light. A small cave survey bag was used to carry the motorcycle battery while the NEMA cord linked the battery to the switch and LED light. A standard light switch was mounted to the top handle of the caddie; this switch was used to switch the LED light on and off as needed. To address the inadequate (for this task) battery life of the Tango tablet, a store-bought large-capacity USB battery bank was strapped to the base of the caddie with zip ties. And a USB-to-Micro USB cable was routed through the handle and held in place with vinyl electrical tape. The USB cable was used to link the tablet to the battery bank, allowing the tablet to be used far longer than the built-in battery, which only lasted for around an hour while mapping. To help protect the tablet, a purpose-built rubberized case was used to cover the bare tablet. The entire caddie setup made mapping with the tablet far easier and more effective at mapping Tipton-Haynes Cave.

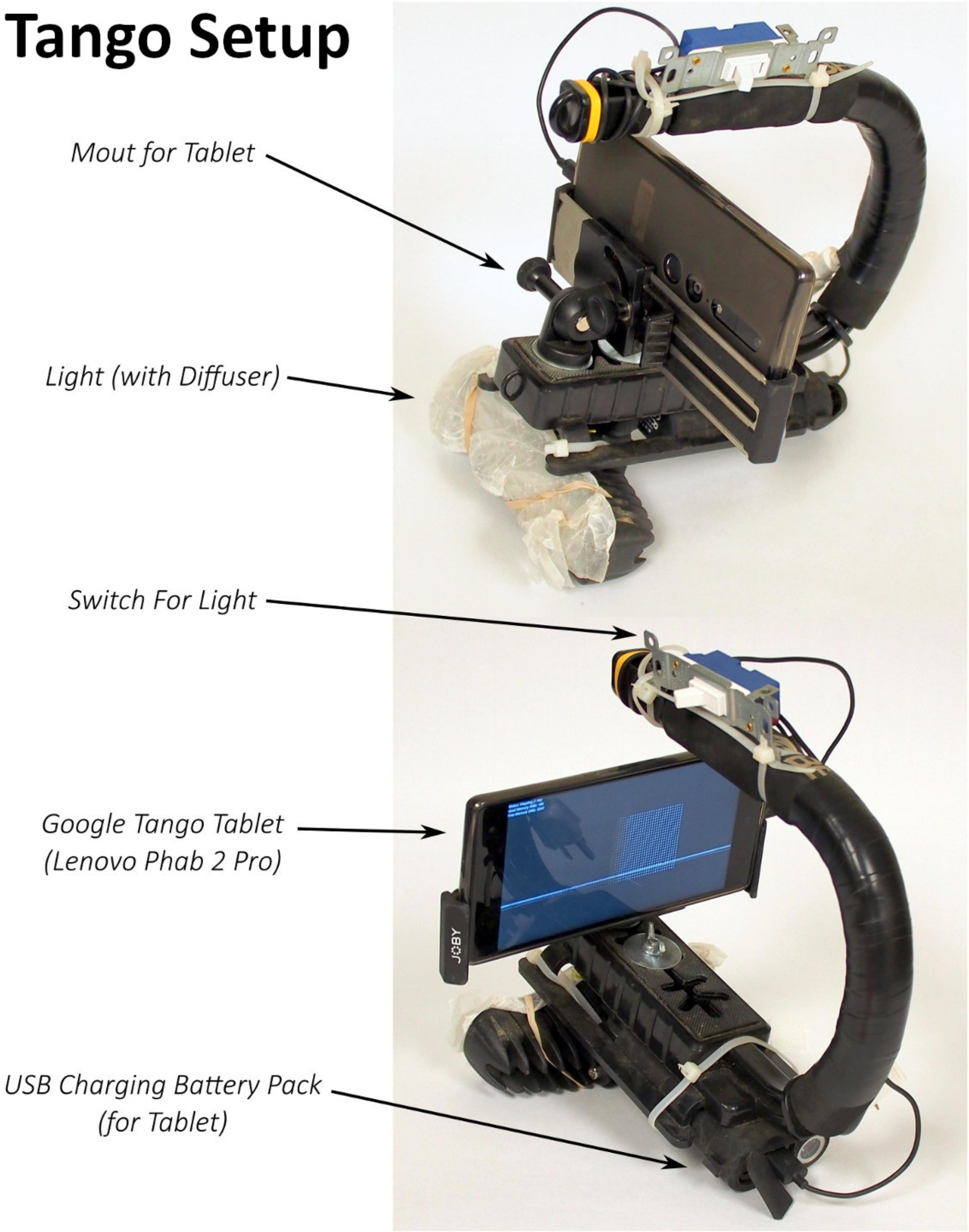

Figure 7. *Tango setup used in this study. The lighting, extra battery, and cradle allow for a more efficient use of the Tango tablet when it comes to mapping a large dark environment such as a cave.*

Other Methods

Several other methods of remote sensing have been investigated for 3D cave mapping, including: ultrasonic mapping (Sellers et al. 1998), ground penetrating radar (Chamberlain 2000; Kasprzak 2015), and survey with a total station (Paul 2013). Of these listed methods, two require access to the cave passage: ultrasonic mapping and survey with a total station. The third method, using ground penetrating radar, provides the ability to map underground voids from the surface above. These methods have been shown to work, however, they typically produce lower resolution models, require more time/effort, and cost more than other methods.

Location

Geography, Hydrology, and Geology

Tipton-Haynes Cave is 175 meters long, with 8.5 meters of vertical extent. It is located in the Tipton-Haynes Historic Site, 760 meters northeast of the northernmost flank of Buffalo Mountain along the southeastern bank of Catbird Creek. The cave is a truncated section of an old, mostly phreatic cave system formed in the steeply dipping carbonate beds of the massively thick Ordovician- Cambrian-aged Knox Group—the main cave-producing rock unit found in the Valley and Ridge Province of Tennessee (Palmer AN and Palmer MV 2009). Buffalo Mountain is located on one of the many thrust sheets found in the easternmost extent of the Valley and Ridge Province; the thrust sheet the mountain sits upon is called the Buffalo Mountain Thrust Sheet. On this thrust sheet, the Knox Group is locally a mostly limestone rock unit that is around 900 meters thick with intermittent sandy dolomite layers and cherty limestone. Cambrian-age sandstones of the Chilhowee Group, along with some small pieces of the Cambrian-age Shady Dolomite, have been thrust over top of the younger Ordovician- Cambrian-aged Knox Group, forming a large volume of the erosion-resistant Buffalo Mountain. The Knox Group remains exposed along the flanks of Buffalo Mountain, particularly along the northern and western sides (Ordway 1959). It is difficult to determine which part of the Knox Group Tipton-Haynes Cave is formed in without a detailed geological study, which is beyond the scope of this paper. The cave is formed mostly in limestone, with some narrow intermixed sandy dolomite beds along with the occasional chert bed. In this area, the Knox Group is harshly dipping to the northwest.

As stated, Tipton-Haynes Cave is a truncated section of an old, mostly phreatic cave system that formed as a conduit carrying (typically) slow-moving water under the water table. The stream that currently flows through portions of the cave uses the cave passage as a route of convenience and is unlikely to be related to the former drainage that created the cave passage in Tipton-Haynes Cave. It is entirely likely that several inaccessible phreatic conduits, currently located well below the water table, drain the northern end of Buffalo Mountain along a similar route and trend to Tipton-Haynes Cave today. In short, Tipton-Haynes Cave is a small piece of a very old cave system that is isolated in a more weather resistant section of the Knox Group that remains intact, forming a low rocky ridge at the edge of a grassy field. The grassy field signifies either a less weather resistant section of the Knox Group or a portion of the rock unit that was subjected to more powerful erosive forces (Figure 8).

Figure 8. *A map of Tipton-Haynes Cave (in red) is overlaid on top of a blend of satellite photos and a hillshade made from the LiDAR terrain data for Washington County, Tennessee. This overlay also shows the spring-fed pond in the valley northwest of the small hill in which Tipton-Haynes Cave is formed.*

Eleven entrances are formed where cave passages in Tipton-Haynes Cave have been truncated by the hillside of the low ridge the cave is in. These numerous large entrances have created a cave that animals can easily use as a shelter or den. This use by animals through the ages has made the cave an important site for the study of local Pleistocene fauna. Many of the chemical deposits of travertine throughout the cave contain fragments of bones that have yet to be fully studied (2016 conversation with B Schubert). Many of the chemical deposits of travertine throughout the cave contain fragments of bones that have yet to be fully studied. These calcite travertine deposits form a matrix that glues together everything contained in the cave passage around the time the travertine is being deposited, forming a natural time capsule. The resulting matrix of travertine, rock fragments, and bone-fragments is often called “bone breccia” by paleontologists (Schubert and Mead 2012).

Tipton-Haynes Cave was formally mapped by members of the Holston Valley Chapter of the National Speleological Society in 1981 (TCS 2016). The 1981 map (Figure 9) is above average for the time, however, a more modern map is desired by the managers of Tipton-Haynes Cave, Dr. Schubert (paleontologist), and the author.

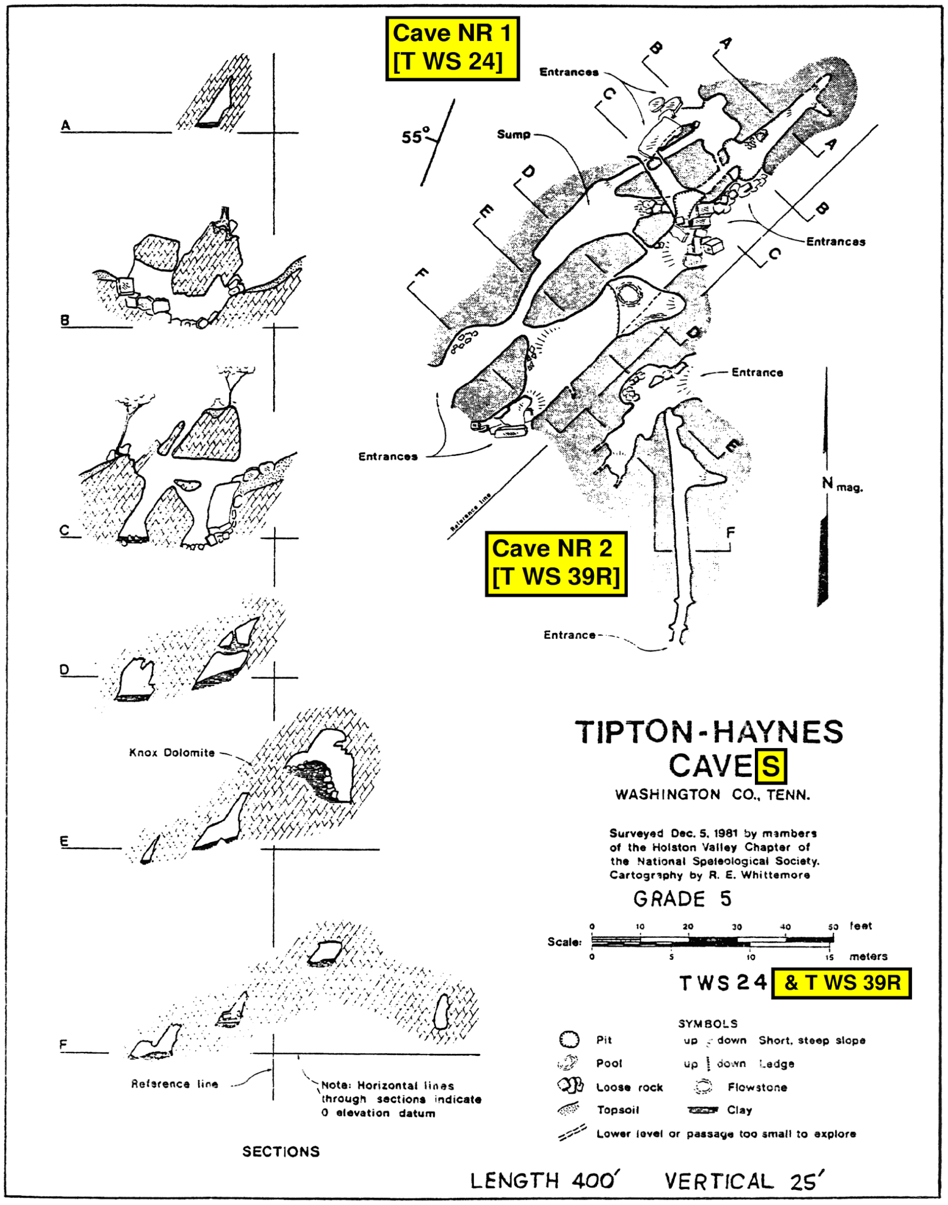

***Figure 9.** The original map of Tipton-Haynes Cave created in 1981 by members of the Holston Valley Chapter of the National Speleological Society. The cartographer of the map was Robert E. Whittemore. Yellow indicates any corrections and/or additions made by the TSC map director. At the time of the edits, Tipton-Haynes Cave Nr1 and Tipton-Haynes Cave Nr2 were not physically connected.*

Brief History of the Greater Tipton-Haynes Site

Tipton-Haynes Cave is located on Tipton-Haynes Historic Site, which consists of a farmhouse, outbuildings, a spring-fed pond, a spring house, and a modern museum. The historic site covers 17 acres of mostly farmland along the banks of Catbird Creek, located 1.75 miles southeast of the current city center of Johnson City, Tennessee. The name "Tipton-Haynes" comes from the last names of the two families who historically lived on this plot of land: Tipton and Haynes. The first documented claim to the property was the purchase of a 524-acre tract, including the property of the site, by Jonathan Tipton of Virginia in 1775. In 1782, and not long after the 1775 property claim was declared null and void, the land was sold to Samuel Henry, a cousin of the famous Revolutionary War hero Patrick Henry. In 1784, Samuel Henry sold the land (on a 100-acre tract) to Colonel John Tipton, Jonathan Tipton's brother. The farm remained in the Tipton family until 1837 when it was sold to a local land speculator, David Haynes, who gave it as a wedding gift to his son Landon Carter Haynes. The land switched hands several times until 1945 when the Simmerlys, relatives of the Haynes family, sold it to the Tennessee Historical Commission. The Tipton-Haynes farm was placed on the National Register of Historic Places in 1970 and is open to the public as a museum and educational site under the stewardship of the Tipton-Haynes Historical Association (Brock and Whitaker 2012).

CHAPTER 3

METHODS

Use of the DistoX2 to Make a Traditional Map

A new map was created for this project in a style that is more detailed than the typical modern digital cave map, allowing for a proper comparison of how well a high-detail cave map stacks up to the newer 3D mapping methods tested in this study. The job of the survey measuring tape, compass, and clinometer was carried out by a DistoX2, giving the new map much more accuracy and precision when compared to analogue survey instruments.

The LRUDs were measured using the DistoX2, via shooting a shot from the station to the walls and ceiling. Typically, this method is done by surveyors who strive for more precision at the large expense of speed; however, Tipton-Haynes Cave is a shorter cave, and a more detailed map was desired, so speed was sacrificed. The passage was sketched at a 1:120 scale on 8.5 x11-inch weatherproof, 1/10-inch grid paper. Measurements were recorded on 4 5/8 x 7-inch weatherproof paper specifically set up for recording survey notes. Using the much larger 8.5 x11-inch grid paper for sketching allowed for a much greater level of detail, accuracy, and precision while also speeding up the entire survey in the process. Survey stations were temporarily marked using either flagging tape or zip ties. Some important stations were described in greater detail in the survey notes for potential future use.

Mapping took place over the course of three days, with five hours spent in the cave each day. This is excessively long for a cave of this size, however, accuracy and detail were important for making comparisons. The focus on accuracy and detail leads to much more time spent sketching the passage. The survey started out with an obvious point on a large slab located just outside the main entrance to the cave (entrance E1); this station is the first station of the newly designated “A Survey,” or “Station A1.” The survey then extended into the cave, passing by a “hand-and-knees” crawl along the left wall in between stations A2 and A3. Past the side passage crawl, the A Survey extended up a slope to the southeast, leading into what is considered the “main passage” of the cave; this main passage is the largest known passage in Tipton-Haynes Cave. The main passage extended as a mostly walking, canyon-shaped passage formed along a northeastern-southwestern trend, following the strike of the harshly dipping beds of the Knox Group. In the floor of the main passage, a prominent point of a buried rock was chosen as the “tie-in” survey station, Station A4, to survey down both directions of the passage. The A Survey continued to the northeast towards of entrances E6, E7, and E8. Survey Station A5 was located on a large boulder that, along with many others, has fallen into the cave passage due to the intersection of the outside hillside (which created the three aforementioned entrances). The A Survey then skirted the northern edge of the boulder pile at the base of entrances E6, E7, and E8 while extending into an upper level tube-shaped passage trending northwest (perpendicular to the strike of the bedding). The next survey shot extended down the length of this upper level tube-shaped passage, ending at Station A7 on the floor at a climbable balcony overlooking a lower-level passage. The eleventh entrance to the cave was located mere feet to the northwest of this station and was clearly visible. The A Survey then extended down a short climb-down and into a larger passage below.

This lower-level passage is damp and contains far more organic debris then the rest of the cave; the floor is covered in tracks from small animals that utilize this passage as a shelter or den. Another tie-in station, Station A8, was placed on a large rock at the base of the aforementioned balcony descent. From Station A8, the A Survey extended back to the southwest to Station A9. Station A9 is located at a junction between a lower level passage extending to the east, roughly underlying the upper-level tube-shaped passage described earlier. The next survey station, Station A10, is located on a pointy rock partially embedded in the hard, moist dirt floor. At this point, the passage connected back into the entrance passage via the "hands-and-knees" crawl located between survey stations A2 and A3. The rest of the surveys, B Survey, C Survey, D Survey, and E Survey, signify side passages and lower levels found in the main portion of the cave.

A second part of the cave, formally known as the separate unconnected cave "Tipton-Haynes Cave Nr2," was surveyed next. The entire portion of this cave is surveyed as the AA Survey, AB Survey, AC Survey, AD Survey, and the AE Survey. This portion of the cave started at an entrance passage formed along the strike of the rock with a lower, southbound canyon passage that contained a small flowing stream in the floor. Along the lower part of the northern wall in the entrance room, a lower crawl passage extended in the direction of the main passage in the "Tipton-Haynes Cave Nr1" (the A Survey). The two traditionally independent caves were connected via a very tight tube-shaped crawl between stations A4 and A5, along the southeastern wall at floor level.

The data collected while mapping consisted of sketches and survey vector data recorded on paper while in the cave. These data were scanned to make digital images that were then cropped and post-processed in GIMP, an open source image editing software. The survey vector data were entered into the cave survey software called Compass. Compass produced the line plot of the cave from the vector data. This line plot was converted to a Scalable Vector Graphics (SVG) file using the Compass SVG exporter. The SVG file created in Compass was then opened in Inkscape, an open source vector drawing program, along with the scanned and cropped sketches. Typically, sketches are transformed to fit the vector data using the Compass Sketch Editor, however, the sketches created during this study were accurate enough to directly upload into Inkscape without needing any transforming. The sketches were then digitized and compiled into a single map using Inkscape. Passage cross sections were digitized and placed next to the passage they represent. A title, key, and other relevant information were then modified and/or added to complete the draft of the map.

Photogrammetry for 3D Cave Mapping

Photogrammetry was carried out in a non-technical and fast way to represent the most practical usage in standard cave mapping. No control points were used; the proper alignment of the photographs is entirely reliant on the algorithms of modern photogrammetry software. This is to limit the required time spent in the cave and expedite the survey process in attempt to obtain the speed and efficiency of traditional mapping techniques.

The photos were taken with attention given to maintaining consistent lighting, color, and depth of field. This consistency allowed the photogrammetry program to georeference the photos and stitch them together into a 3D model. The easiest way to keep the lighting aligned in the same direction for each photo, with respect to the camera, is to mount the flashes onto a bracket with the camera. This makes the camera bulky to carry; however, that is far more preferable than having to keep off-camera flashes aligned while not venturing in between those remote flashes and the subject, which creates a large human shadow in the image.

Mapping Tipton-Haynes Cave with Photogrammetry

For mapping Tipton-Haynes Cave, the author opted for a lightweight Micro Four Thirds (M4/3) camera system over a traditional digital single-lens reflex (DSLR) camera. This is due to the difficulty of shooting hundreds of photos over the course of several hours, all while holding the camera and two large flashes steady for the photos. A 12mm wide-angle pancake lens was chosen due to its low barrel distortion, light weight, and availability. An ultra-wide lens, while better at capturing more of the passage, would need post processing to correct for the typical barrel distortion and vignetting that even the best ultra-wide rectilinear lens typically has.

Ninety-seven photos were taken of the main entrance and the narrow, odd-shaped, entrance passage extending into the cave. A total of 987 photos were taken past the entrance passage and throughout the main part of the cave (the strike-oriented passages and rooms). Most of these photos were shot with the camera lens perpendicular and facing the passage walls when possible. Due to the irregular character of the cave passage, taking photos from the most desirable angle was often not possible. This led to a more random approach to taking pictures with hope that the photogrammetry software could automatically sort out the photos during post-processing.

A challenge with the lighting occurred where narrow bedding plane shelves or slots extended out of, or retreated into, the cave wall. These narrow features were not properly lit due to the location of the flashes just slightly above the level of the camera lens. This could be mostly resolved by turning the entire camera setup and shooting the slots or shelves with the camera at a different angle.

The number of AA batteries required for shooting all 987 photos was not excessive; the flashes could be used at a very low setting due to the size of the cave. Each flash used only two sets of four AA batteries, for a total of 32 AA batteries. This would be a concern if the subject location was deep in the bowels of a large and difficult cave system. Photogrammetry requires a massive number of photos compared to how many are taken on a typical cave photography trip.

The photographs of Tipton-Haynes Cave were taken back to the East Tennessee State University Geosciences computer lab and sorted according to how usable they were and how even the lighting was. Several overexposed and underexposed photos were tossed out. No editing was done to the individual photographs before they were imported into Agisoft PhotoScan Pro. All 987 photographs were included in the first run and at least 250 of those photos could not be properly aligned. This could be due to many reasons; however, the misalignment for one area was apparent: the sunlight around the entrance caused conflicting sources of light. Beyond the entrance, additional photos could not be aligned through many of the tighter passages in the cave due to the difficulty of shooting pictures in confined spaces.

Tango for 3D Cave Mapping

The mapping program chosen for this study is called Real-Time Appearance-Based Mapping, or RTAB-Map. This type of program is referred to as a "Simultaneous Planning, Localization And Mapping" program, or SLAM. The goal of SLAM programs is to make it possible for an autonomous robot to map the surrounding environment in real time and compile the collected data into a continuously updating map that the robot uses for terrain navigation and obstacle avoidance (Labbé and Michaud 2011). RTAB-Map contains algorithms used for "loop closure." Loop closure is where a previously mapped passage is intersected by a later survey, where the later survey is tied into the former survey to correct any error and provide a more accurate location. The ability to correct for drift via loop closure is extremely important in both traditional cave survey and SLAM, and RTAB-Map does this on the fly when an area previously mapped is detected. One limitation that cannot be remedied, only worked around, is a RAM memory limit built into the Android operating system of the device (Google Developers 2017). The work-around involved saving the current scan and starting a new scan every time the program was close to reaching its RAM limit. Most 3D mapping/modeling programs for Tango have been built to accommodate this hard RAM limit; RTAB-Map is no different.

Mapping Tipton-Haynes Cave with Tango

Many trial runs were done with the Tango device as it is new technology, and different methods and software had to be explored. This led to many days out in the field with little return. An efficient method of using the tablet to map cave passage was eventually found and used.

The area outside the main entrance was mapped first, followed by the narrow walking passage leading into the cave. This passage has an odd shape that was 1.5 meters wide at the floor level up until around 0.5 meters off the floor. At that point, the passage narrowed to a width of about 0.5 meters all the way to the cave's ceiling. This odd-shaped passage proved difficult to map with the Tango due to its narrow nature. Beyond this, the narrow odd-shaped entrance passage increased in size after three meters of traverse, extending into the main room of the cave.

Scanning continued through the main room to the southwest until the small rocky crawl extending out the second entrance was encountered. This crawl proved to be a very difficult area to properly scan due to the small size and irregular shape of its passage. After the author was satisfied with the results displayed on the tablet, the large, mostly walkable passage extending northeast was navigated. The small but decorated upper level area in the ceiling overlooking the main chamber of the cave was ignored; mapping it would require a difficult free climb while strapped down with relatively fragile gear. The lower passage extending to the northeast was scanned up until the pile of boulders extending down from E6, E7, and E8—where the passage is cut off by a break to the surface. That entrance area was scanned, followed by the cave passage below leading around the northern end of the boulder pile. The cave passage bifurcates into an upper-level tube crawl and a lower-level dirt-floored crawl a few meters down its passage. The lower route was taken to simplify the mapping process and the final model. Also, including the upper-level passage would make the final product more difficult to understand by stacking passages on top of each other, creating a blob of passages. The passage extending into a more complex portion of the cave to the northeast was scanned next with no issues. Next, entrance number nine was scanned to aid in the process of georeferencing the cave map.

After scanning the ninth entrance, mapping continued to the southwest in the direction of the main entrance. No difficulty presented itself in this passage until the crawl connecting this portion of the cave to the main entrance passage was reached. This crawl, once again, proved difficult to capture due to the tight dimensions and the minimum range of the device. Once through the connection crawl, a section of the entrance passage containing memorable features was rescanned, which allowed RTAB-Map to close the loop made by the main two passages of the cave. After mapping the main part of the cave, the scan was saved onto the tablet's hard drive.

Next, the southbound section of the cave was mapped. The entrance was scanned in by the device, followed closely by the entrance room/passage. After this passage was scanned, the focus was set on the southbound passage containing the small stream. The area linking these two passages, once again, caused the same issue with the minimum range, though, like the other tight areas, the passage was adequately mapped despite these issues. The passage extending south proved easy to scan, just like the other walking passage present in the cave; however, at the time of the scan, no water or stream was present which aided in the endeavor. After scanning in twelve meters of walking-canyon passage, and two very short side alcoves, the breakdown climb-up and crawl signified the end of the passage at the third entrance to the cave. This area was yet another tight passage that proved difficult to map. The third entrance of the cave was not exited and scanned due to the presence of large spiders and mud.

Comparing cave maps is a difficult task as nearly all mapping methods create inaccuracies. This leads to the conflict of what basemap to use as a control. Due to the proven accuracy of the DistoX2, the hand-drawn map (created with the DistoX2) was chosen as the base map. Several identifiable features on each map were chosen as "control points" for use in the comparison. The chosen control point features were points where a sudden change in passage shape occurred, which helped when trying to locate these features in the 3D models. The 3D models were stitched together (where necessary) and exported as a plan view slice of the passage to be compared to the traditional plan view map.

Due to the limitation of the photogrammetry model (the limited number of photos that were able to be stitched together by the photogrammetry software), the main comparison was done using the original "Tipton-Haynes Cave Nr1" (Figure 10) portion of the cave. This portion contains six easily identifiable points where the passage drastically changes. The points were identifiable on all three maps: the traditional map, the photogrammetry map, and the Tango map. Six additional control points were added to the "Tipton-Haynes Cave Nr2" (Figure 10) part of the cave for additional comparison between the Tango model and the traditional map. All 3D models were treated as 2D plan view maps in this comparison, which allowed for the inclusion of the hand-drawn plan view map. The Z values for the 3D models were zeroed, which collapsed the point clouds down to what are essentially plan view cave models.

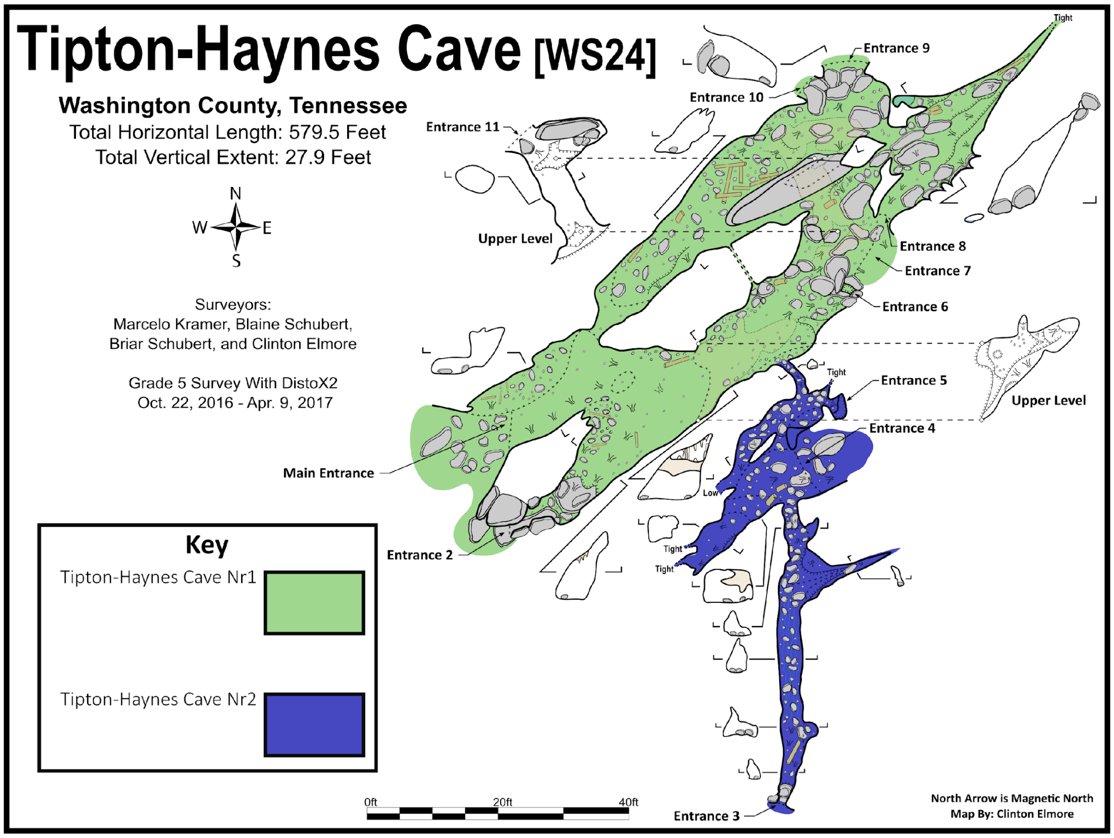

Figure 10. *The cave passage labeled according to the formally unconnected areas of passage in Tipton-Haynes Cave. The labels "Nr1" and "Nr2", which stand for "Name reuse 1" and "Name reuse 2", indicate that both caves were formerly named "Tipton-Haynes Cave." The two caves were connected through the extremely tight crawl shown on the map just inside the entrance E5.*

CHAPTER 4

RESULTS

Traditional Cave Map

The traditional cave map produced during this study (Figure 11) includes both portions of the cave, formally Tipton-Haynes Nr1 Cave and Tipton-Haynes Nr2 Cave. The caves were connected during the mapping process via the tight crawl located between E5 and E6. The survey lines were excluded from the final map as they are not needed for the map comparison to show everything happening in the cave. Both the total vertical extent and total length are included on the map. Due to the location of the cave, and possible future uses of the map by local people, standard American units were used. The standard US 8.5×11-inch dimensions are used for the plot of the cave. This allows the map to be printed out by a standard US printer for future use. Color was sparingly used on the map to allow the use of the map in either color or black and white.

3D Cave Map/Models Created Using Photogrammetry

While the maps and model produced with photogrammetry is limited to the Nr1 portion of the cave, the model includes most of the large main room and second room (Figure 12). The 3D model was flattened by collapsing the Z axis based on a portion of the cave floor that was measured as a level plane using the DistoX2.

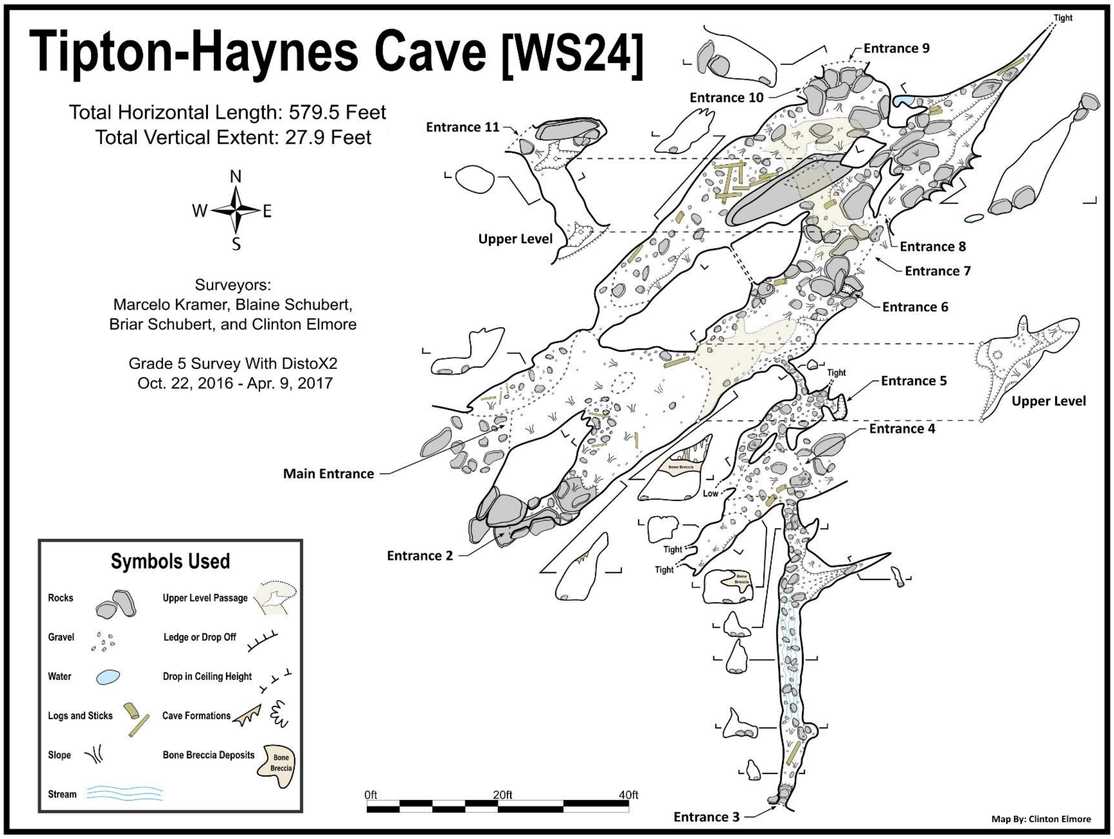

Figure 11. *The new map of Tipton-Haynes Cave created during this study. Surveyors included cave paleontologist Dr. Blaine Schubert and his son Briar Schubert, Brazilian caver Marcelo Kramer, and Tennessee caver/geologist Clinton Elmore. The cartography was done by Clinton Elmore.*

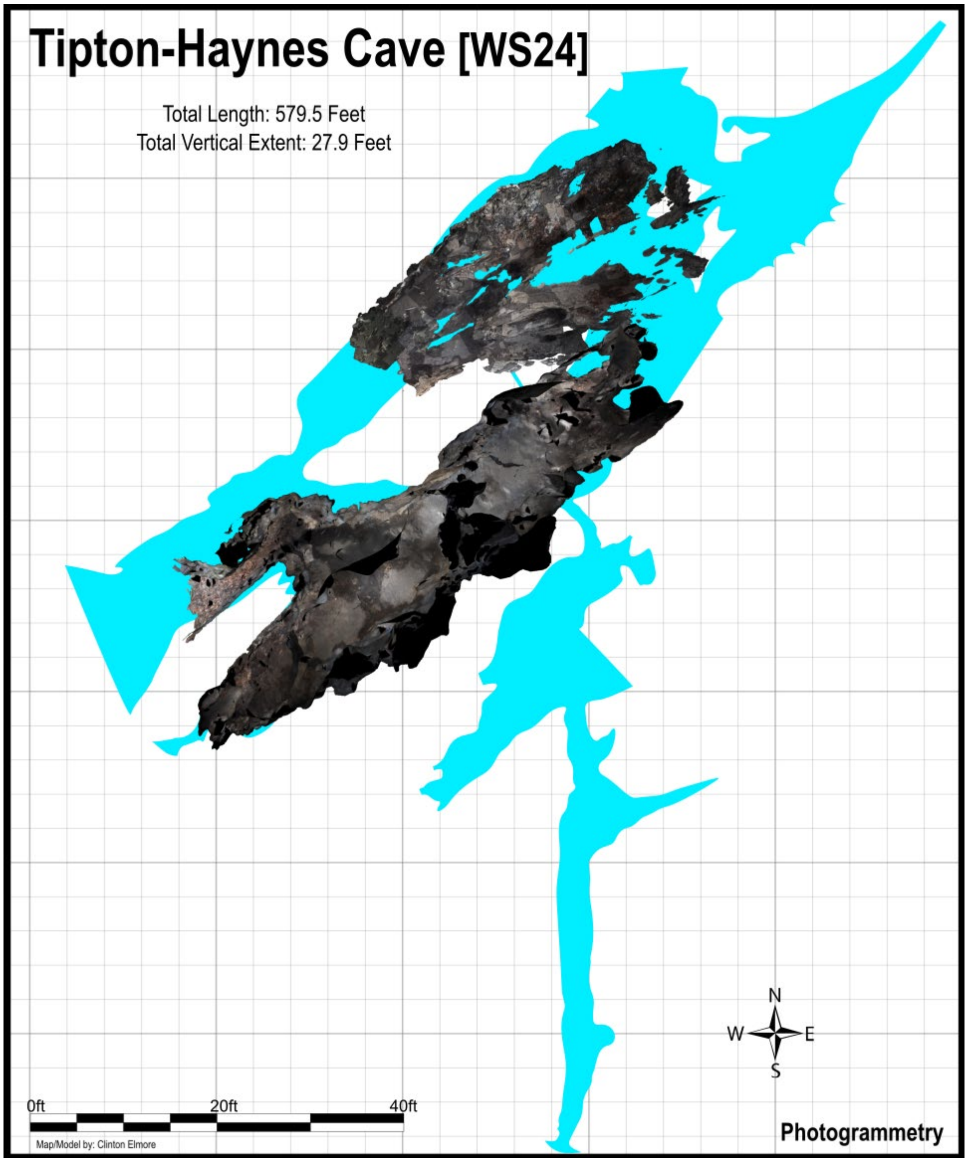

Figure 12. *The extent of the 3D model created using photogrammetry by overlaying it over top of an outline of the traditional map (in blue).*

3D Cave Maps/Models Created Using Tango

Tango correctly located and aligned passage while recording data which produced a more complete 3D model of the cave compared to photogrammetry. Both the Nr1 and Nr2 parts of the cave were modeled. The model was then flattened on the same Z axis that the photogrammetry model was flattened along. This process created a plan view map of passage based on the 3D model created by Tango. A textured mesh model (Figure 13) was produced and compared to the DistoX2 basemap (Figure 14).

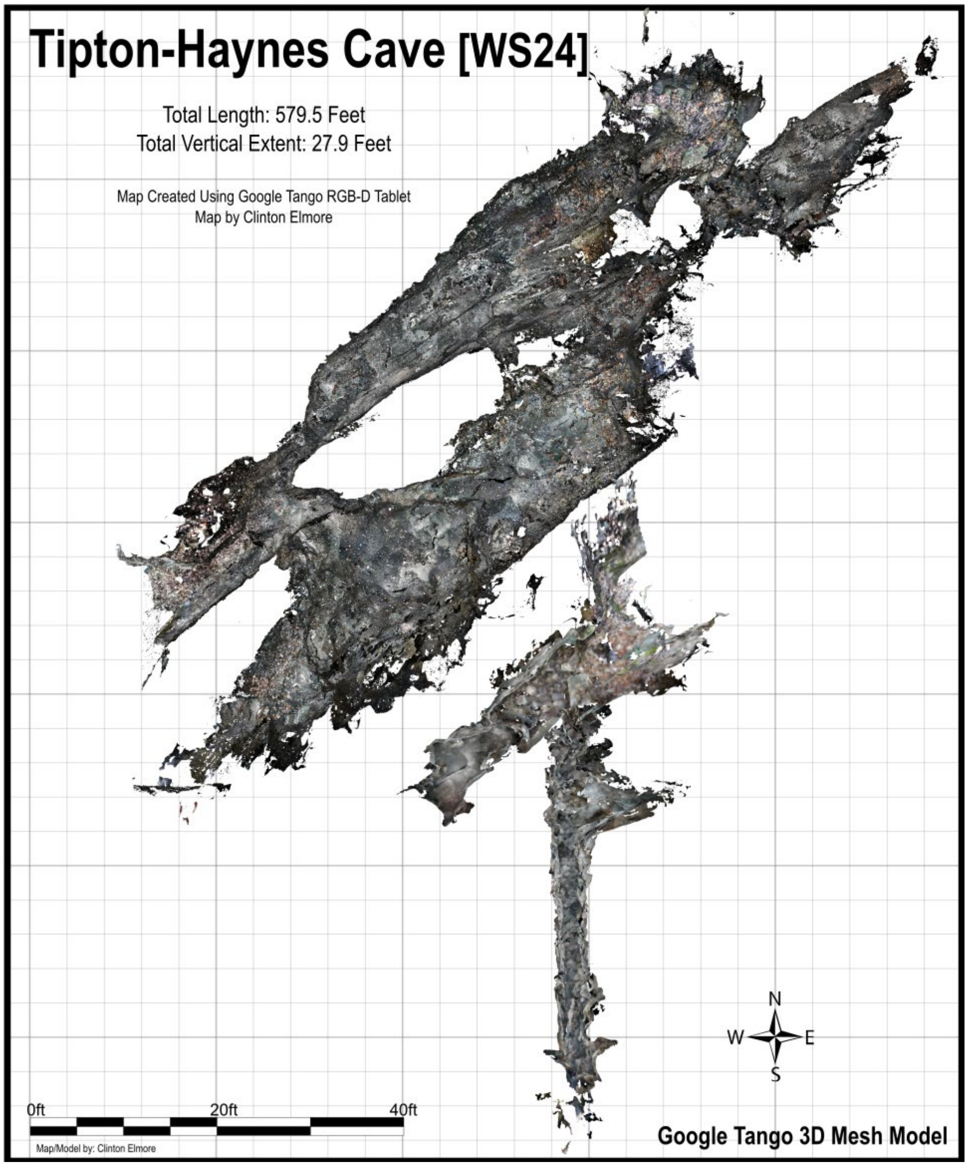

Figure 13. *The 3D texture map created using Tango. Much more of the cave could be captured due to the ability of the Tango device to tack the location of the user using multiple different types of algorithms and sensors.*

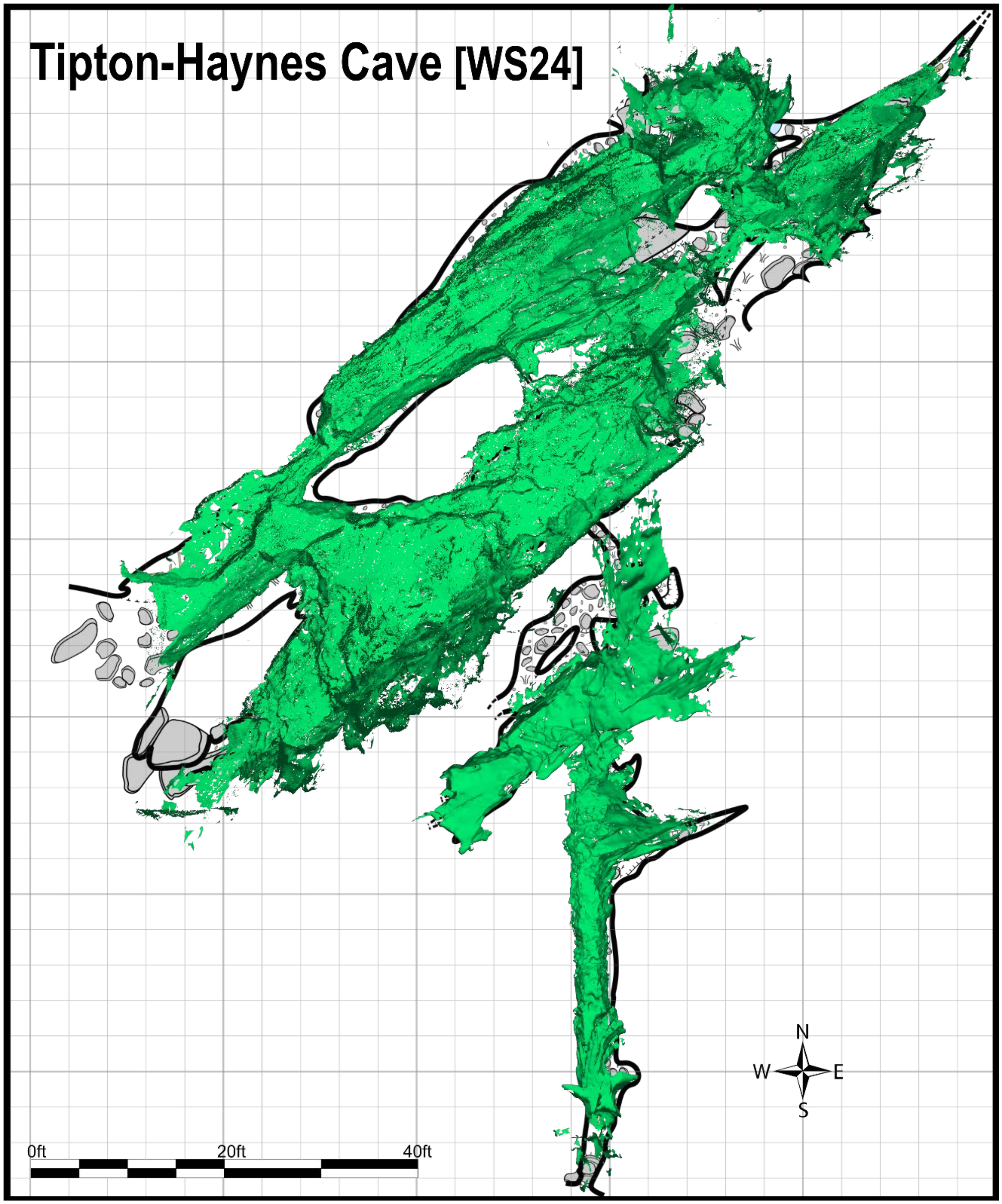

Figure 14. *The 3D mesh created using Tango (green) georeferenced over top of the DistoX2 base map.*

CHAPTER 5

DISCUSSION

Photogrammetry

In larger cave passages where the flashes would have to be at a higher setting, many more batteries would be required for the flashes. The size and scope of a project may justify buying rechargeable flash battery packs if the flashes you are using have the option. Another consideration with the flashes is the time spent adjusting the power of the flashes. The most effective method to do this is to buy flashes with the option for radio control from the camera or from a sender unit in the hot shoe of the camera. Adjusting flashes becomes less of a problem if the flashes are mounted on a flash bar attached to the camera—like the unit used in this study. The zoom feature present on most modern flashes would greatly help illuminate places that are unreachable via walking for any reason. These could be areas distant from the main trail or areas far off the floor. This, however, is not a huge issue in a small spaces like Tipton-Haynes Cave.

The model produced with photogrammetry only included part of the area where photos were taken. This failure to map some areas may have to do with lighting near the entrances or the lack of easily recognizable features. No objects that could be used as control points were placed in the cave during the study. The results in this study show that control points are likely required for doing photogrammetry in caves.

Tango

Though not as convenient to carry as most modern camera gear setups, the overall setup used with the Tango device is not unwieldy. The device itself is carried in a plastic waterproof case that is built to carry the generic 7-inch tablet. The cradle, on the other hand, proved much more difficult to safely transport in a harsh cave environment; the cradle used in this study is entirely made out of plastic. To map more inaccessible cave systems in the future, either a more robust metal cradle, or a protective case for the cradle, is needed as the plastic cradle would not last long after being dragged through a cave in a pack while unprotected. The motorcycle battery is far more convenient to carry, but with one major caveat: lead-acid batteries, like the motorcycle battery in this study, must be avoided in any cave that has any type of rope work due to the extreme vulnerability that nylon has to acid. Many other concerns arise for this setup if it is to be used in a wet cave, though this new list of concerns is beyond the scope of this study.

RTAB-Map conveniently reminds the user when the passage wall is extremely close, as Tango does not work as well when capturing data about objects that are roughly 0-0.5 meters away from the tablet. A similar problem occurred with photogrammetry while trying to take photos of cave walls in snug cave passages. A very convenient aspect of using Tango to map is that, unlike photogrammetry, the passage walls are showcased instantly on the tablet screen as scanning occurs. This allows the mapper to rescan any areas that show holes or errors. With photogrammetry, these holes or errors would not show up until after processing the photos and producing the 3D model on a computer away from the cave.

The ceiling height showcases one of the major limitations of Tango: the 4-meter maximum range of the RGB-D sensor (Froehlich et al. 2017). This short range would not be a concern if all caves resembled Tipton-Haynes Cave; however, many caves contain far more spacious passages. To use this device in larger passages, the operator would be required to trample over most of the passage floor, and this is a major issue that conflicts with the idea of keeping a low human impact on the cave environment. In some caves that have been regularly visited for years, this isn't a problem, however, in the more pristine cave passages that only have a narrow path extending through the center, this device would not be able to capture the entire passage without stepping on and destroying the delicate terrain that flanks each side of the foot path. The issue of range in the taller areas in Tipton-Haynes Cave was offset by the ability to hold the cradle in one hand while extending the arm out. This was possible only because the ceiling was only just out of range while using the device normally.

Time Spent Mapping

With Tango, it took just four hours to map 543.4 feet of the 579.5 total feet of cave passage in Tipton-Haynes Cave. This comes out to a rate of 135.85 feet of small-to-medium cave passage per hour. This is spectacularly fast compared to the other methods of mapping performed in this study. A one-man team mapping with the DistoX was able to map 94.55 feet of passage per hour; however, surpassing the 135.85 feet per hour rate of the Tango could easily be done with a survey team and less detailed sketches.

Photogrammetry took the longest time with 225.7 feet of cave passage photographed in four hours, which comes out to 56.43 feet mapped per hour. The time it takes to set up and take a massive number of photos adds up quickly, however, photogrammetry results in far higher resolution textures. This slow pace could be greatly increased with practice and improved technique, as photogrammetry relies a lot on the skills of the photographer.

With post-processing, both Tango and photogrammetry require the use of more complicated 3D modeling software that requires skill and practice to use effectively, which greatly limits the number of cavers who can easily adapt to these new techniques. Most 3D modeling programs are specifically focused on mapping items from the outside, rather than having the perspective of being on the inside of the model looking out, which makes post-processing cave passage models very difficult for the untrained caver.

Drafting a traditional cave map is a tedious process that is entirely dependent on the quality of the sketches and the quality of the survey notes. The major benefit to drafting traditional cave maps, however, is the abundance of programs and information available for this specific process. Compared to survey done with analogue sighting compasses and clinometers, the DistoX2 greatly increased the speed of the survey as it allowed far easier survey station placement and reduced instrument reading errors.

Comparing the Accuracy of the Cave Maps

The comparison was carried out using the common GIS software, ArcGIS Pro. Obvious observable features that could be accurately tagged on all maps were chosen as "control points," or exact points used to georeference each model to the hand-drawn basemap. Each of the chosen points were easily identifiable features—sharp corners in the passage and abrupt changes in passage direction at junctions—visible on the 3D maps and the base map. Five control points were chosen to compare each 3D map to the base map created using the DistoX. These control points are labeled 1-5 in Figure 15. Two additional points, A and B, were used to initially line the maps up in Figure 15. All of these control points are located in the Nr1 part of the cave.

The total amount of error between the control points on the two models being compared at the given time is given as the Root Mean Square error, or RMS error. The RMS errors for each control point indicates the physical distance between the control points on the base map and the control points on the map that is being compared to the base map—the higher the value, the more error. The value used to compare each map in this study is the total RMS error. The total RMS error value is the sum of the individual RMS errors for all five control points (Figure 15.) After the total RMS errors were recorded for the non-transformed maps, each map was transformed to better fit the shape of the DistoX base map. For both 3D maps, a similarity transformation produced the most visually accurate final results. A similarity transformation is a first order transformation which tries to preserve the shape of the original raster (Esri 2018). The total RMS error from each transformed map is shown in Figure 16.

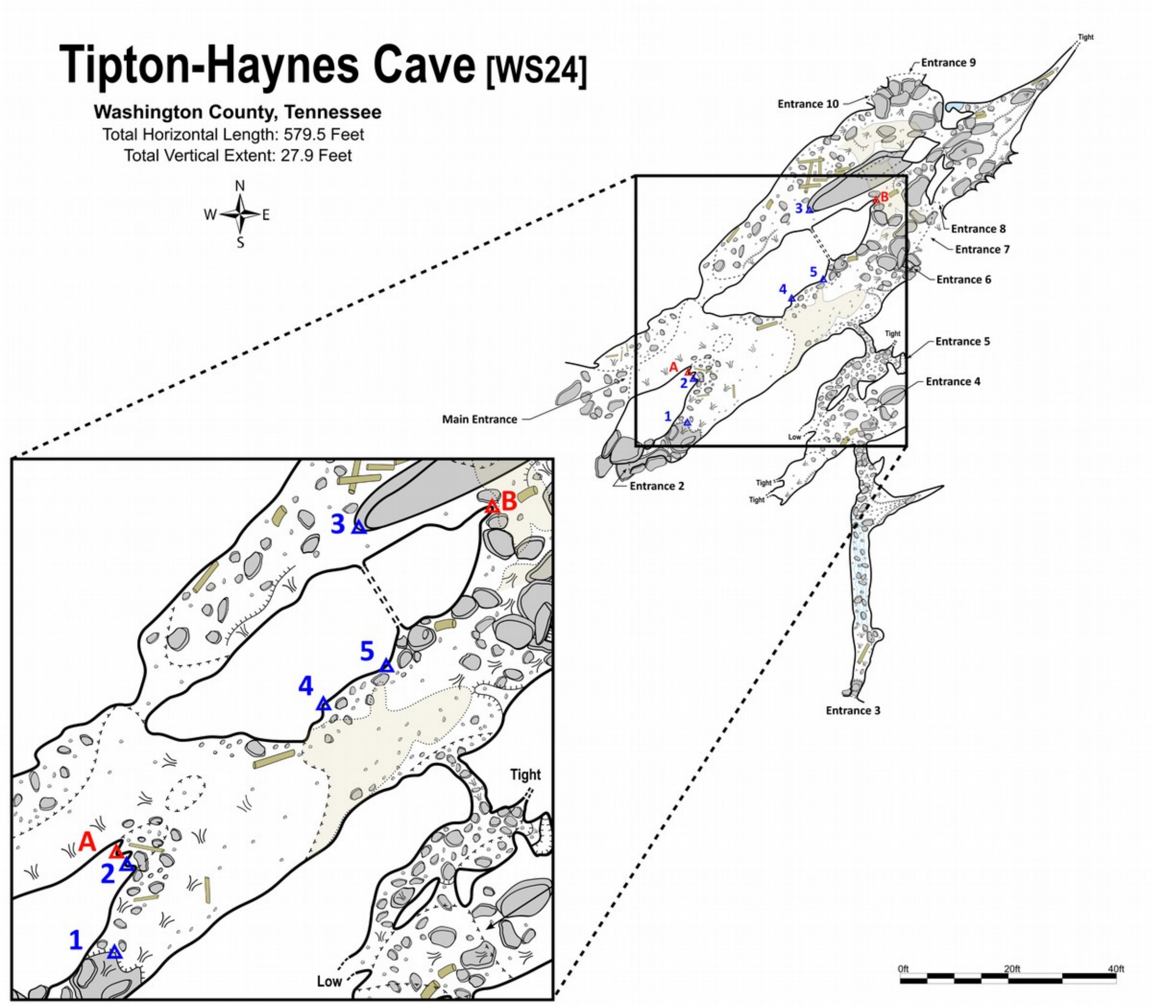

Figure 15. This map shows the chosen control point features in blue. The two points used to initially line up the maps are shown in red. Control points are essential for a quantitative comparison of the mapping and modeling investigated in this study.

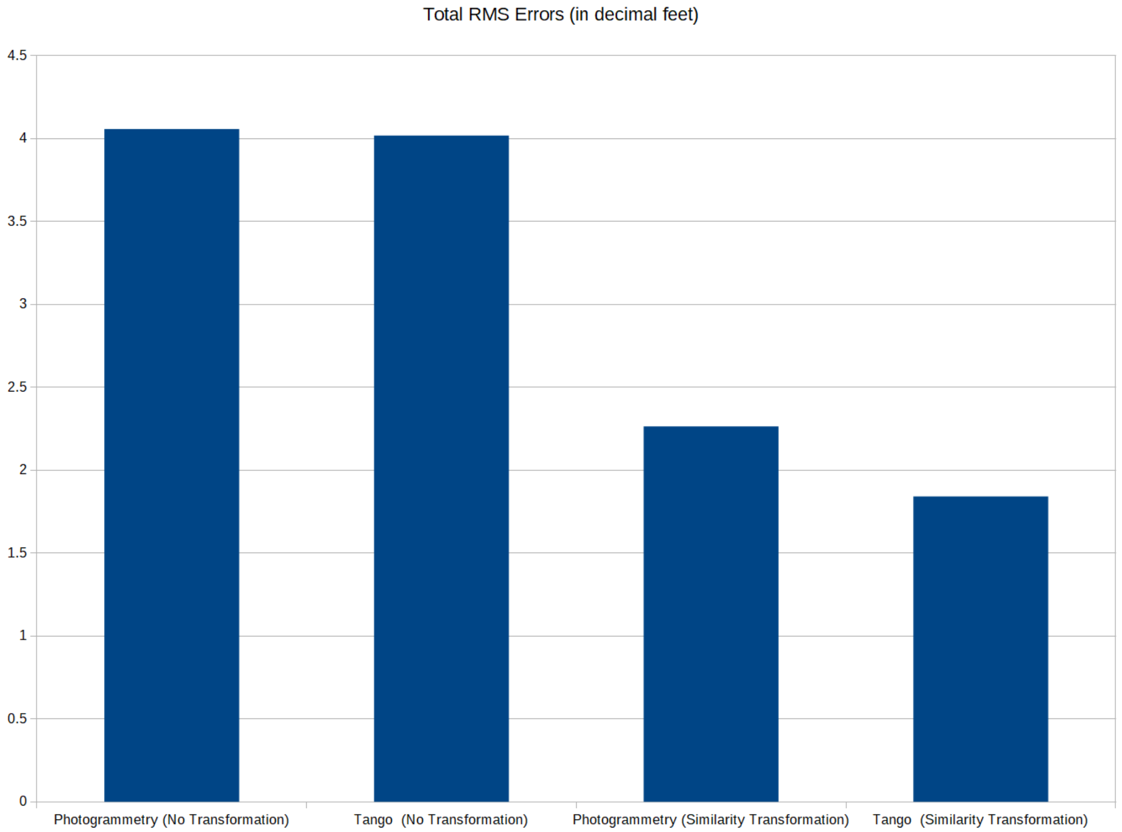

Figure 16. *The total RMS error values for each comparison and the final RMS value after a similarity transformation was applied. The values are in decimal feet. Similarity transformation was chosen for both of the maps because it produced the most visually accurate end results.*

CHAPTER 6

CONCLUSION

Are Photogrammetry and Google Tango Viable Mapping Techniques?

The number of different ways to map a cave in 3D has increased greatly with new technologies. The two methods tested in this paper represent two techniques that contain a lot of promise for future use in cave mapping and cave science. Photogrammetry provides the ability to take standard camera gear and produce models showcasing extreme accuracy and detail; however, current limitations relegate its use to features and sections of cave passage rather than entire cave systems. That is not to say that photogrammetry cannot be used to model an entire cave system; the process required would just be very difficult and time consuming. The most exciting part of this study was using the Tango tablet. This tablet performed exceptionally well mapping the cave passage to a usable standard of quality. Small objects weren't as detailed or accurate, but the overall cave passage was surprisingly accurate, especially considering that no control points were used. The entire process of mapping was generally very fast and easy with Tango. The only place where Tango stumbled a little was in tight crawls. The biggest problem with Tango is the RAM limit, which has more to do with the Android operating system then Tango itself. This problem was solved by dividing the cave into sections and providing control points to link them in 3D editing software. For this particular study, the two main sections of Tipton-Haynes Cave could be georeferenced using the multiple entrances and the traditional survey data, so control points were not needed. In the future, the decision to use control points must be considered when mapping larger cave systems; connecting each segment of passage without obvious control points is extremely difficult.

One thing to consider with the two 3D mapping techniques tested in this study is that neither of them works well in passages with pools of water. This is due to the reliance that each of these methods has on visible light, ultraviolet light, or infrared light. Perhaps with help from a polarizing filter, photogrammetry can penetrate some water, while Tango seems to somewhat work when the tablet is held very close and perpendicular to the water's surface. Above ground, some LiDAR units have been used to map near-shore areas of the ocean floor; however, it remains a very expensive process. (Irish and White 1998).

For Average Cavers

Both 3D techniques used in this paper have attractive qualities when it comes to empowering cavers to utilize them during a weekend cave trip. As stated before, photogrammetry only requires standard cave photography gear and photogrammetry software, which make it an attractive method for cavers without large funding. Tango also has some attractive aspects: it’s relatively cost effective, almost the entire mapping process is automated and done in real, it is fast, and it is accurate enough for mapping cave passages. This paper barely scratched the surface of the use of photogrammetry to produce 3D models, as the main focus was on the use of RGB-D methods, particularly

Tango. With a lot of user experience and the use of control points and/or scales, photogrammetry is capable of producing extremely accurate and detailed 3D models and maps. This ability makes photogrammetry an extremely important asset for cavers, albeit not a quick and efficient way to create a normal cave map; SLAM mapping with devices, like Tango, excel at this process. Perhaps the differences between the two methods will slowly become less and less over time; combining the extremely high-resolution models produced by photogrammetry with the practical usability and speed of a SLAM setup like Tango.

For Scientists

Scientists operating in many different fields of study have started to incorporate 3D mapping by both RGB-D devices and photogrammetry, along with other more expensive methods like LiDAR. This trend will continue as universities continue to acquire more instruments and teach future scientists how to use these exciting new technologies as practical tools. Photogrammetry has been a staple of scientists for years now; however, with new computer programs and the creation of a huge base of hobbyist photogrammetry users, the entire concept of photogrammetry will become more advanced and more accessible in time. This and the extreme level of detail that photogrammetry can achieve, with relatively little effort, will keep it as a mainstay far into the future for scientists and hobbyists alike. Tango is a little more specialized when it comes to its use in science. Perhaps due to the speed at which it can scan an environment, it will likely find niche uses outside of the robotics field. One possibility is in extreme environments where humans are incapable of residing for the time it takes to do photogrammetry.

Final Conclusion

Mapping and modeling technology is rapidly becoming more advanced and available for both the modern consumer and professional. This massive shift away from large expensive devices, and techniques that require very skilled and experienced experts, paints a very exciting future for those seeking the ability to rapidly 3D map previously inaccessible environments, such as caves. As the community of average consumers using these techniques and technologies to produce 3D models and maps continues to explode in size, the methods and devices used will continue to improve with time.

Photogrammetry will continue to find large-scale use with this bustling new market of consumers and hobbyists wishing to capture as much of the world around them in 3D, as well as professionals who require extreme accuracy and detail. The ability to use regular photography gear is an attractive feature for any potential user. This being said, devices like Tango, and SLAM mapping in general, will continue to march into the future for completely different reasons—such as providing exciting new consumer virtual reality technology and creating drones with area mapping and collision sensors. In the realm of science, mapping will likely be the main use of SLAM devices. This study showcased the exciting capability of a SLAM device, like Tango, for rapidly mapping areas previously not able to be mapped without expensive and large equipment. Even LiDAR itself is starting to become used on a large scale in the field of robotics as part of different SLAM systems; this usage will bleed over into the consumer market just as SLAM devices using RGB-D cameras have.

The future of modeling caves in full 3D is especially bright; however, the extreme practicality of maps produced using traditional survey methods will live on into the future as well. The readability of well-produced cave maps may remain impossible to surpass in the foreseeable future. The availability of devices like the DistoX bring traditional cave mapping a much-needed boost in accuracy and efficiency as well. Perhaps the ability to produce a traditional cave map directly from a scanned 3D model of cave passage may be the ideal use of these technologies. Future cavers may choose to combine the ever-increasing speed and accuracy of 3D scanning via SLAM, with the usability of traditional hand-drawn maps.

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