A Methodology for Accurate and Quick Photogrammetric Recording of Underwater Cultural Heritage

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Abstract

In the past seven years, photogrammetry has become one of the main recording methods in maritime and underwater archaeology. The application of photogrammetry allows archaeologists to re-create underwater cultural heritage sites in 3D digital formats, and extract from these 3D digital models data and information required for subsequent scholarly research. The author has been using photogrammetry since 2014 and has successfully created nearly 40 underwater cultural heritage models on more than 10 archaeological projects. The projects have ranged in size, accessibility, and water clarity, introducing a number of variables to the photogrammetry of the artifacts. The variety of experiences gained on these projects have enabled the author to construct his own methodology and workflow for photogrammetric recording. In this paper, the author shares examples of his methodology and workflow for photogrammetric recording of various projects in different countries.

Key words: UCH, photogrammetry, Photoscan

Introduction

Agisoft PhotoScan and other off-the-shelf photogrammetry software became available for archaeologists in 2010. By 2017, after only 7 years, photogrammetry has become a one of the most frequently used recording methods for UCH (underwater cultural heritage) sites. The author of this paper works as a professional maritime archaeologist and applied photogrammetric recording on more than 35 archaeological sites in more than 10 different countries. Because of its submerged circumstances of many shipwrecks, each site has different conditions: such as visibility and colors of waters, depth, topography, water current and so on. Those different conditions create problems that requires different ways to solve those difficulties. Additionally, each project has different mission statement, or project's goal. For that reason, each submerged site requires different types of methodologies for data-collection and data processing. Moreover, to use produced 3D digital models as archaeological data, it is important to create 1:1 scale-constrained georeferenced 3D models (Yamafune et al., 2016). Yet, to produce these accurate models, it is essential to takes a week to produce local coordinate system that gives scale and georeferenced on the model. To solve these lengthy problem, the author created a methodology that produces local coordinate system in short time (1 or 2 dives) yet provide fairly accurate results. In this paper, the author shall share his methodology of photogrammetric recording that he has developed and currently using.

Literature Review and Terminological Confusion of Photogrammetry

Before the author starts discussions regarding his photogrammetry methodology, there is an important point that must be noted. The point is a confusion related with the word 'photogrammetry;' 'photogrammetry' has been used repeatedly in history; probably the first time it appeared in/as a discipline of science was during the WWII. When airplane became widely available for military use, cameras were mounted on scouting airplanes; then photos taken from the mounted cameras where meticulously re-calibrated and composed to create a photomosaic, or a map, of enemy's territories. In other words, 'photogrammetry' that were used first during the WWII was a technique to create accurately composed photomosaic (Burtch, 2008; Van Damme, 2015; Konecny, 2003). And it was a well-known fact that Dr. George Bass and Dr. Frederick Van Doornick, well-known ‘first generation’ maritime archaeologists, used photogrammetry for their Yassiada underwater expeditions in 1960s; detailed site plans were produced based on photomosaic that were taken from a camera that was mounted on horizontally positioned rails on the seabed (Van Doorninck, 1967; Bass, 1972; Bass and Van Doorninck, 1982). In their publications, they used a word ‘photogrammetry;’ however, it must be noted that ‘photogrammetry’ in their article and ‘photogrammetry’ that produces 3D digital models today uses different systems and indicate different recording systems.

Another terminological confusion related to a word ‘photogrammetry occurred in 1990s. In 1990s, maritime archaeologists started practice DSM (Direct Survey Method); many cases this system is referred as trilateration. DSM provides a local coordinate system/network to help production of 2D site plans of submerged shipwreck site. DSM is a method to directly measure distances in between control points and detailed/reference points to create positional networks. Consequently, DSM provides XYZ coordinates of control points and detailed points, and maritime archaeologists use these XY coordinates to produce 2D site plans (Holt 2003: Green and Gainsford 2003). When DSM became a popular method among maritime archaeologists as a mapping method in 90s, another method was also often used to produce 2D site plans; and this another method is also called ‘photogrammetry.’ This photogrammetry is known with the software *Photomodeler*. *Photomodeler* is a photogrammetry software; and this photogrammetry mainly applied for underwater excavations in 1990s and 2000s uses a meticulously calibrated camera and its images that captures at least three reference points in one image. Thanks to meticulous calibration of the camera and its series of images, *Photomodeler* can calculate the XYZ coordinates of reference points; and these reference points are used to produce 2D site plans and 3D CAD drawings. Indeed, the data sets that DSM and this photogrammetry produced were very similar; both system provides XYZ coordinates of reference points on submerged sites. A few articles were published in 1990s and the early 2000s related to this photogrammetry that produce XYZ coordinates of reference points, or a local coordinate system (Green *et al*., 2002). However, photogrammetry that related *Photomoder* is different from photogrammetry that can produce 3D models. Confusingly, around 2010, when photogrammetry that can produce 3D models began to become popular recording methods, EOS system (the software company manufactures *Photomodeler*) released upgraded version of the software called *Photomodeler Scanner*. This *Photomodeler Scanner* can produce 3D models of subjects that uses similar system with ‘photogrammetry’ that the author will discuss in this paper. Nonetheless, it is important to be noted that *Photomodeler* that can provide XYZ coordinates of reference points and *Photomodeler Scanner* that can produce 3D models are different types of ‘photogrammetry.’ And a word ‘photogrammetry’ mainly referred in articles of maritime archaeology in 1990s and early 2000s were mainly focus on *Photomodeler* and its system that provides XYZ coordinates of reference points on archaeological sites.

In 2010, *Agisoft PhotoScan* was released. While *Autodesk 123D Catch*, *Photomodeler Scanner* and other photogrammetry software that produce 3D digital models were also released around the same time, thanks to its georeferencing systems and user-friendly workflows, *Agisoft Photoscan* immediately became popular photogrammetry software among maritime archaeologists are keen to apply quick and accurate recording methods on submerged sites. By 2017, many maritime archaeology projects enjoy this recording application. Nonetheless, another confusing terminological problem is happening. After 2010, almost all the time ‘photogrammetry’ indicates a system that produces 3D digital models; however, there are many different words were being used to indicate this one system. The author often hears SfM (Structure from Motion) in the United State and Japan, some articles including IJNA (International Journal of Nautical Archaeology) prefer Multi-image Photogrammetry, some Italian scholars sometimes use Close-range Photogrammetry, and scholars form northern European countries sometimes use Computer-Vision Photogrammetry. Yet all these words imply one system that produces 3D digital models based on digital images.

Concluding this section, the word ‘photogrammetry’ implies different systems when it was used for maritime archaeology. From 1960s and 1980s, ‘photogrammetry’ implies a system that produced a photomosaic of sites; from 90s and 00s, ‘photogrammetry”’ implies a system that used calibrated digital cameras and its photos to calculate XYZ coordinates of reference points located on the site to produce 2D site plans and 3D CAD drawing (by connecting reference points). After 2010, ‘photogrammetry’ implies a system that produces 3D digital models. Furthermore, this ‘photogrammetry’ after 2010 that produces 3D digital models is called in different names, such as SfM, Multi-image Photogrammetry, Close-range Photogrammetry, Computer-Vision photogrammetry, and so on, yet these all names indicate only one system. In this paper, the author shall use a word “photogrammetry” in his discussions, and this “photogrammetry” indicates a system that produces 3D digital models.

Importance of Local Coordinate Systems

Tying the site plan to a set of local coordinates is a key factor to create 1:1 scale-constrained georeferenced photogrammetric 3D digital models. There are two reasons that creating a local set of coordinates is important. The first reason is to correct scale and distortion of the photogrammetric models and to geographically reference the site plan. One of the advantages of photogrammetry is that it does not require precise calibration of the camera. Although calibration is recommended, the software primarily uses pixel information to reconstruct a site, which means that the construction of the point clouds does not require manual calibration. Moreover, the software reads metadata from the camera and lens and minimizes the errors. Distortions are inevitable, however, and this possible error can be minimized by applying known distances and specific photo capturing sequences, or “flight path.” The second reason to establish local coordinate system is that unless tied to a system of coordinates, models float in unspecified tridimensional fields. To fix the models in the correct position, local coordinates must be included on the models. Without this, it is impossible to export the computer graphics files to mapping software with the correct position. Georeferenced information facilitates a straightforward workflow when models and orthophotos (high resolution photomosaic) are exported.

Also, the processing and rendering capacity of the *Agisoft PhotoScan* software is limited by both software and hardware configurations. This constrains the maximum polygon count for the mesh (which makes up the surface of the model), and the maximum number and resolution of UV mapped textures (‘UV’ is a XY coordinates for texture), which are composed photomosaic on surfaces of mesh. Large data sets can be divided into smaller Chunks (*PhotoScan*’s term), which are separately processed. These Chunks can be imported into a single *PhotoScan* file afterward without merging (Tool > Append) and other modelling and mapping software applications and merged without decimation (the reducing of the polygon count). When models and orthophotos are georeferenced, the merging process is automatic, and exported files are opened in their correct positions in other software. A set of local coordinates is paramount to ensure an accurate manipulation of models or orthophotos.

Scale-bar Methods and DSM

While local coordinates system that is produced by DSM can be used to scale-constrain photogrammetric model, *Agisoft PhotoScan* also allows the input of measurements in a different way. *PhotoScan* uses scale bars, or known distance, instead of importing local coordinates collected using DSM. At actual archaeological sites, establishing control points and local coordinates may take a week. This may not be suitable for a short-term survey project. The author had tested the both methods to fix distortions and scale of photogrammetric models. Measuring methods that will be discussed and compared are: trilateration (DSM) using *3H Site Recorder*, and scale bars that are placed on the site. To compare and examine the accuracy both methods, local coordinates and known distances of both methods were applied to a photogrammetric model, and each different method was compared to control measurements. The control measurements were taken directly from the wooden model. For this test, the author used a 1:10 scale wooden model of a saveiro, a 20th-century Brazilian coastal sailing boat. In order to simulate an archaeological shipwreck site, the wooden model was laid down on its starboard side, and its floor timbers were pulled slightly out so that its starboard futtocks lay on the bottom (See also Fig. 2 and 3).

Direct Survey Method (Trilateration)

The first method to discuss is trilateration, also known as Direct Survey Method (DSM). Trilateration (DSM) has been repeatedly used in underwater archaeological recordings. For this DSM, the author used *3H Site Recorder* (Demo Version). In order to acquire coordinates of reference points, a control network first had to be established. The author placed eight control points around the wooden model, set all the control points to a congruent height (40 cm from the ground), and set this height as the surface of the water, or depth of 0 cm. To establish the positions of the control points, or a control network, 19 measurements were taken. The tolerance established for errors was set at 0.3 cm; therefore, all distance errors bigger than 0.3 cm were shown in red (shorter) and blue (longer). Only one distance (CP5 – CP7) showed a + 0.39 cm statistical error after the adjustment of the control points. After the control network, or positions of datum points, was established, 11 reference points were placed on the model. A total of 44 measurements were taken from the control points; each reference point was measured from the nearest four control points (Fig. 1). Two measurements indicated over 0.3 cm error; however, both errors were less 0.5 cm, which is within an acceptable range of error.

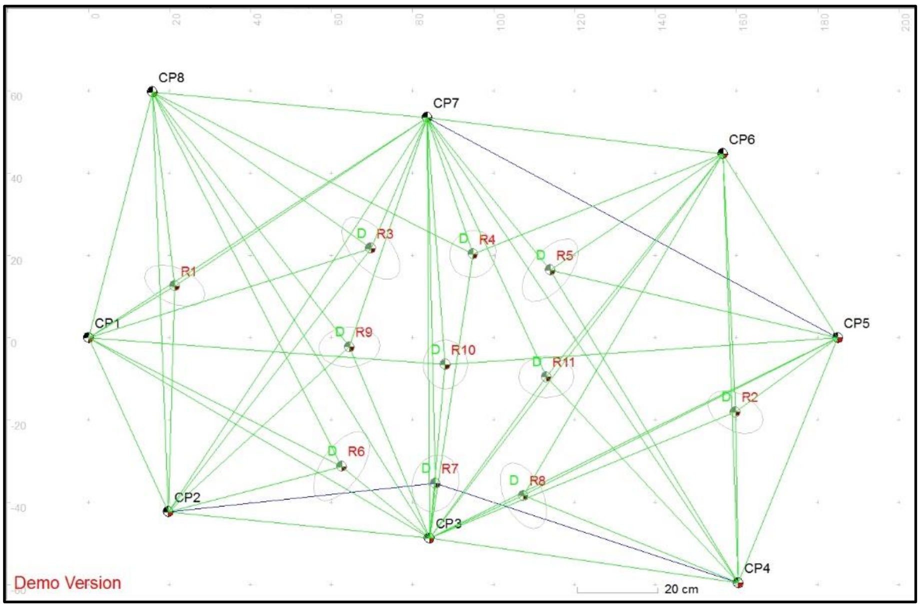

Fig. 1: The Local Coordinate Network of reference points and control points around the Saveiro Wooden Model (Top View: Horizontal Plane).

Scale-bars Method

Scale bars are often used when pictures of archaeological sites are taken. These scale bars can be extremely useful in photogrammetry. Scale bars give accurate scale information in archaeological photography, and when a site is being mapped using photogrammetry, they can be used to check measurements after other methods, such as DSM, were used to correct distortion and scale of a created photogrammetric model. However, distortions and dimensions can be fixed by using only scale bars, a feature that allows archaeologists to skip the time-consuming DSM system. To test the accuracy of this method, four scale bars were placed on the four sides of the saveiro model. In this particular case, considering the size of the model the four scale bars available were unnecessarily long. Therefore, seven 10 cm scale bars with markers were created on the existing scale bars. These smaller 10 cm bars were entered as fixed distances in the photogrammetric model (Fig. 2).

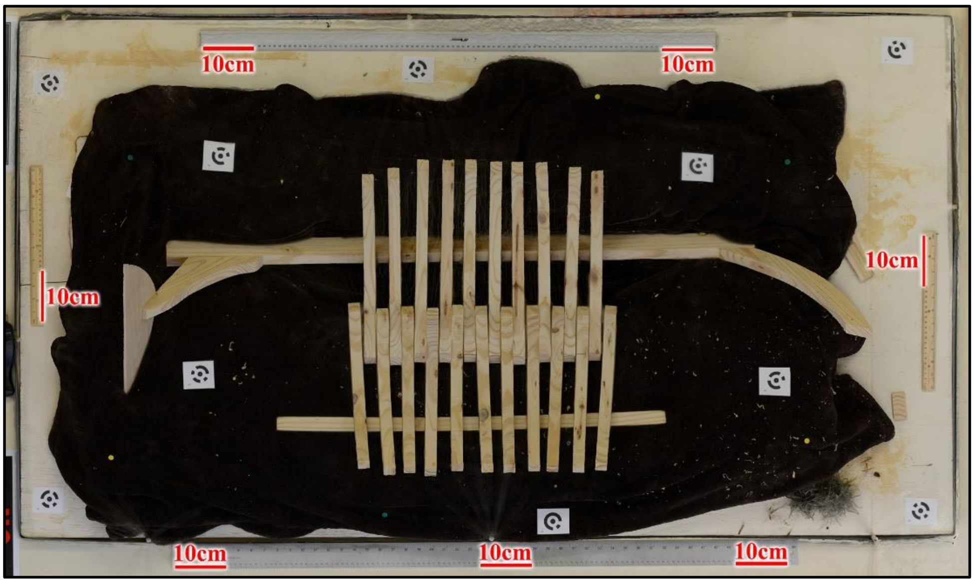

Fig. 2: Seven 10cm scale bars created on the Saveiro Photogrammetric Model for the Scale Bar Method.

Comparison of DSM and Scale-bars Methods

To test the accuracy of these two survey methods mentioned above, the measurements from all photogrammetric models of the saveiro were compared within a single set of control measurements. The control measurements were taken directly from the wooden model; 21 selected distances between reference points were taken for this purpose (Fig. 3). The control measurements were compared to the measurements obtained by the other methods (Table 1).

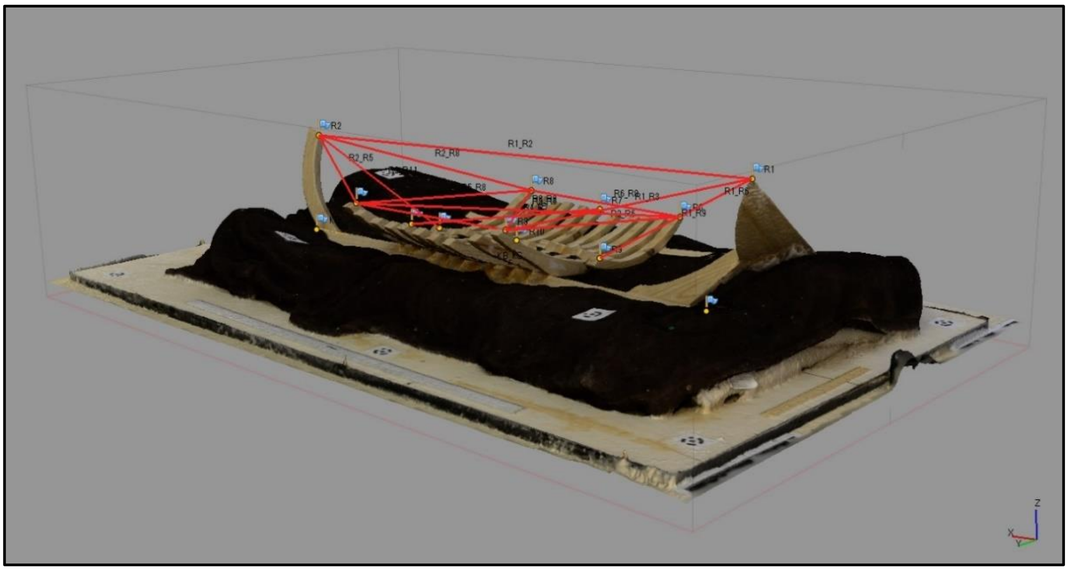

Fig. 3: The photogrammetric model of the Saveiro Wooden Ship Model and the measured distances between reference points for the comparison.

Table 1. Distances between reference points to compare different surveying methods to fix distortions and scales of the Saveiro Wooden Ship Model's photogrammetric mModel

	Control (cm)	**Trilateration (DSM) (cm)**	**Scale Bars (cm)**
R1 – R2	**142.5**	142.0	142.2
R1 – R3	**51.2**	51.3	51.0
R1 – R9	**51.1**	51.8	50.9
R1 – R6	**63.4**	63.9	63.2
R2 – R5	**57.6**	57.8	57.4
R2 – R11	**50.4**	50.5	50.3
R2 – R8	**57.0**	57.7	57.4
R3 – R5	**44.9**	44.6	45.1
R6 – R8	**46.6**	45.4	46.6
R3 – R6	**54.2**	53.9	54.3
R5 – R8	**55.3**	55.6	55.3
R4 – R7	**57.0**	57.0	57.1
R3 – R8	**71.3**	71.2	71.2
R6 – R5	**71.0**	70.4	71.7
Length of Keel	**115.2**	115.0	115.2
Average Error		0.39	0.19

The results suggest that scale-bar can be a more accurate scale-constrain method in a photogrammetric model. The measurements taken from the photogrammetric model with trilateration (DSM) coordinates display an average error of 0.39 cm. The more accurate results obtained were through the use of scale bars; the scale bars allowed an average error of 0.19 cm.

The results of the experiments with two scale-constrain methods discussed show that the scale bars method provided better results in fixing scales from photogrammetry surveys. The main disadvantage of trilateration (DSM) is that it requires many measurements. For instance, the saveiro model required 19 measurements to establish the control point network and 44 measurements to calculate the coordinates of reference points. On the other hand, the scale-bars method does not require any measurements. However, it is important to note that the scale-bars methods cannot establish a local coordinates system. This is a disadvantage when compared to the traditional trilateration (DSM) method; scale bars can fix distortion and scale of photogrammetric models, but they need a complementary method to establish local coordinates.

The Recommended Method to Produce 1:1 Scale-constrained Georeferenced 3D Models

Following is an experimental methodology that author composed and applied on several underwater shipwreck sites, and these photogrammetric models shows successful results.

Testing Scale-bar Method on Larger Underwater Sites

The author tested scale-bars method on various underwater shipwreck sites; including Operation Forager directed by Dr. Jennifer McKinnon and Dr. Toni Carrell (Saipan 2017: 8 wrecks), Fourni Underwater Survey Project directed by Dr. George Koutsouflakis and Dr. Peter Campbell (Greece 2017: 9 wrecks), and Converging the World Project directed by Nicholas Budsberg and Charles Bendig (the Bahamas 2017: 1 sites). While recording those submerged archaeological sites, the author positioned 4 – 8 scale bars on each site for photogrammetric recording. To test possible distortions in a larger submerged site (for instances around 30m x 30m), the author intentionally scale-constrained only one corner with a 1m scale bar using the Scale-bars method, and check calculated distance using a 1m scale bar on the opposite site. The result showed that the distance error of the 1m scale bar on the opposite side is 2.5mm. And this result stay same with other photogrammetric models of other sites (errors varies in 0.5mm – 3mm). In other words, if a 3D digital model is scaled by one side of the 30m x 30m coverage area, distance error (or distortion) can be less than 2.5mm anywhere if an archaeologist tries to measure 1m-long areas; and it also means that possible maximum positional errors from one end to the other end of the 30m-long site (if this distortion occurs in linier manner) is 7.5cm. Again, the biggest advantage of the scale-bars methods is its simplicity and speed. It doesn't require any tape measurements; scale-bars can be simply positioned around the sites. More importantly, once 'Scale Bars' are created in *Agisoft Photoscan*, camera locations and scale of the created model can be fixed based on known distances by 'Optimize Cameras' command (open 'reference tab' > input known distances on 'Scale bar' > 'Update' > 'Optimize Cameras'). Using this 'Optimize Cameras' command, distance errors on the 1m can be 0.5mm or less. This means possible distance error of 30m-long site is 1.5cm.

Importance of the 'Flight Path'

To obtain good/accurate results with minimum distortions on created photogrammetric models discussed above, the author strong believes that his distinctive "flight path" is the key factor. The author originally developed his flight path to ensure successful rate in "Align Photos" process. Photo alignment is the most important phase in photogrammetric modeling. To maximize the probability of creating successful photo alignment, the author developed a flight path for sequences of photo shooting. The best results have been achieved by capturing surrounding area first to lock the site. Then, photographs are taken perpendicularly to capture a top view of the site with appropriate overlap. After complete photo shooting in both transversal and longitudinal paths, additional photographs must be taken with the camera tilted to capture vertical surfaces of rich tridimensional structures (Fig. 4). Actual ‘flight path’ of archaeological sites can vary depending on multiple factors; therefore, meticulous planning of a flight path is an important part of successful photogrammetric recording. Most important factor of flight path is its interwoven manner; sometimes the diver who use photogrammetry only apply transversal path without the longitudinal path and the locking paths. In other words, if only one direction of flight path is applied, directional distance/length of from one point on one side to another point on the opposite side shall be long, and distortions on images will be accumulated. However, if three paths (Locking path, transversal path, and longitudinal path) are properly operated, distance from one side to the opposite side will be shorter hence the distortion can be minimized. For that reason, the author strongly recommends that photo-shooting sequences, or ‘flight path,’ for photogrammetry have to be practiced with interwoven manners.

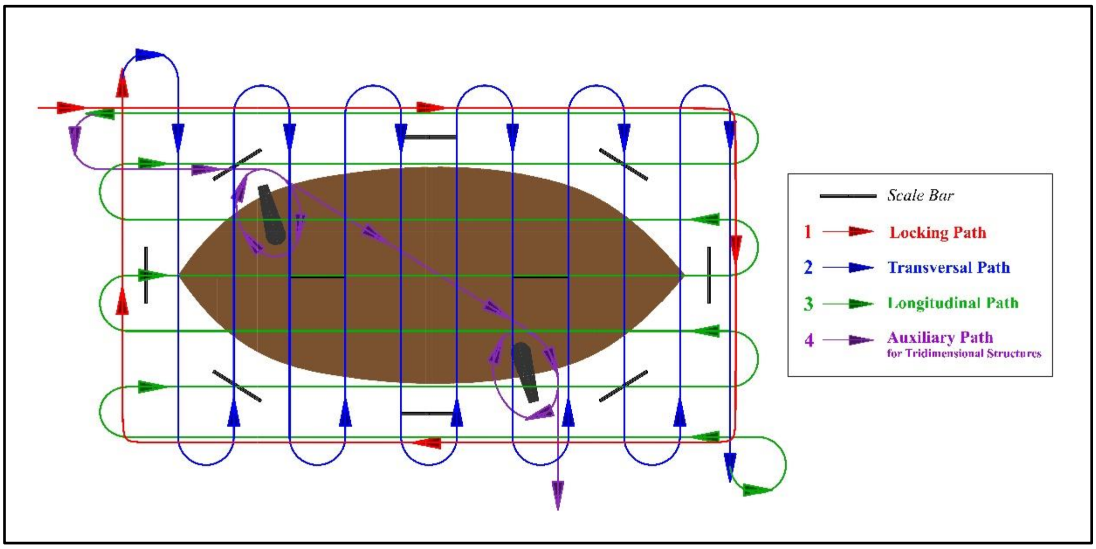

Fig. 4: Recommended flight path for photogrammetric recording.

Applying Local Coordinate System on Scale-bars Method

Next step to create a 1:1 scale-constrained georeferenced 3D models is to apply a local coordinate system on a created 3D digital model. As it was discussed earlier, scale-bars methods can produce fairly accurate scale-constrained 1:1 models; however, these models cannot carry georeferenced/positional information. Having a georeferenced/spatial information is essential for archaeologists to use 3D photogrammetric models as scientific data for their analysis. In order to apply/generate a georeferenced data on a created 3D model, it only requires XYZ coordinates of three control points within a site. The author uses distances between three control points placed on the archaeological site to establish a temporal XY coordinates on the three points. A triangle can be created if distances between three points are known. To obtain these distances from a created scale-constrained 3D model, control point must be created/placed on the model. Control point can be created easily in *Agisoft PhotoScan* as markers by double clicking on the respective position on the mode (these markers can be created on the photos by right clicking and choose 'create markers' in *Agisoft PhotoScan*). Then scale-bars were created between these three points to extract calculated distances between the points (choose two respective markers on reference pane > right click on selected markers > create ‘scale bars’ > click ‘view estimated’). Using these distances between three points, a triangle can be created using 3D CAD software such as Rhino 3D. Then orientation of the triangle must be adjusted based on depth-measurements of these control points collected by diver’s dive computer (Fig. 5). This adjusted triangle and positions of its three corners give new/adjusted XYZ coordinates of the three points; the author uses these coordinates to adjust angle of these three control points on the 3D model in *Agisoft PhotoScan* (open reference tab > input XYZ coordinates of the corner of the adjusted triangles > ‘update’). Once these adjusted coordinates were applied, the 3D photogrammetric model shall contain georeferenced information.

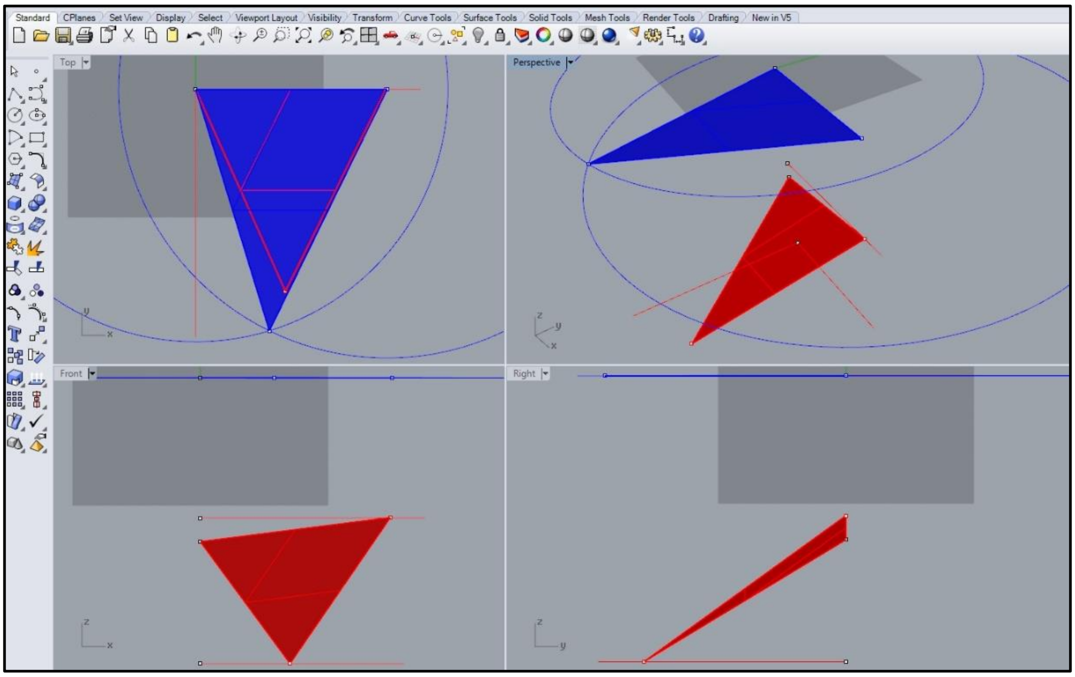

Fig. 5: Adjustment of the coordinate triangle (The blue triangle is a temporal triangle that was created based on distances between control points. And the red one is the adjusted triangle; its orientation was adjusted based on depth-measurements of the three control points. Then new coordinates were collected from corners of the red triangle).

Using a 1:1 scale constrained photogrammetric model as new local Coordinate System

On the Conversing the World Project, the team of maritime archaeologists excavated an early sixteenth century Spanish shipwreck in the Bahamas during the summer 2017; this shipwreck is also known as the Highbourne Cay Shipwreck. The author is in charge of photogrammetric recording of the shipwreck site, and he applied the combination of scale-bars and triangle geo-referencing methodology explained above to create 1:1 scale-constrained georeferenced 3D digital models. Furthermore, once a 1:1 scale-constrained georeferenced 3D model of the site was created in *Agisoft PhotoScan*, it is easy to extract coordinates of any possible points on the 3D model by creating markers (right click on the model or a photo > 'create makers' > 'view estimated'). This means that when 3D models are created on the same area or smaller areas within the site in following day, coordinates of reference points/markers can be collected from the first 1:1 scale-constrained georeferenced model, and apply these coordinates on newly created 3D models. This means once a local coordinate system is generated within the first model, archaeologists can use this coordinate system to both scale-constrain and geo-reference following photogrammetric models. The author prefers to call this first 1;1 scale constrained georeferenced 3D model as 'Mother Model', and following 3D models that receive coordinates from Mother Model as Child Models. In other words, the Mother Models itself works as a local coordinate system of the site, and archaeologists can extract XYZ coordinates of any reference points form the Mother models to create another 1:1 scale constrained georeferenced 3D digital models.

Conclusion

Past 7 years, photogrammetry became one of the most frequently used recording applications on UCH (Underwater Cultural Heritage). However, if archaeologists use these 3D digital models as scientific data, it is vital to create 1:1 scale-constrained georeferenced 3D digital models. Once a 3D digital model carries/contains correct/real scale and georeferenced information, archaeologists are able to extract dimensional information, section profiles, DEM (Digital Elevation Models) and contour maps, orthomosaics (high resolution photomosaic), 2D siteplans, and other scientific data. The author's methodology uses simple scale bars placed on site and a triangle created in 3D CAD software based on distances in between three control points. This methodology provide accurate results in a short-term (for instances, if a site is 30m x 30m in size and 20m deep, it will be 0.5mm possible error in 1m, or 1.5cm possible error in 30m, with the optimization, and it takes only 3 - 4 dives with one diver). Once the first model, or Mother Model, is created, following photogrammetric models from the campaign can take advantage of a local coordinate system of Mother Model. In other words, photogrammetric recording processes can be much faster, so that archaeologists are able to create series of 3D digital models during the same excavation campaign. Consequently, maritime archaeologists can obtain enough dataset to study a shipwreck site with layers of information and study stratigraphy of shipwrecks.

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Biography

Kotaro Yamafune received his Bachelor of Arts degree in history from Hosei University in Tokyo in 2006. He entered the Nautical Archaeology Program in the Anthropology Department at Texas A&M University in September 2009 and received his Master of Arts degree in August 2012. He continued his studies in the Texas A&M University Nautical Archaeology Program and earned his doctorate in May 2016. His research interests include shipbuilding in Medieval Europe and the European Age of Discovery, and ship reconstruction. He also focuses on photogrammetric recording of submerged cultural heritage, including ship