Curtin University

**Curtin HIVE (Hub for Immersive Visualisation and eResearch)
and the School of Earth and Planetary Sciences**

Creating 3D models of the Kyrenia shipwreck amphorae

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Abstract

One of the most interesting shipwrecks of the 3rd century BC was discovered on the north coast of Cyprus in 1967. During the excavation that took place for two consecutive years, Nikonos underwater cameras were used to record the excavation of the wooden ship and its cargo. Most of the cargo consisted of Rhodian amphorae with a few other amphorae of different types and styles. The records of the excavation consist of a series of black and white films that were photographed at different times from various angles. From these photographs, temporal 3D models were built of the amphora cargo using Metashape by Agisoft. Each temporal 3D model represents a certain phase of the excavation of the wreck and cargo. This step was very selective since a lot of images biased the model and presented distorted results. In order to improve the quality of the models, a histogram equalisation process was applied to all the images using OpenCV. This step provided better models and consequently improved the following processing steps. Common features in the temporal 3D models were exploited to link and align each of them via reference points in order to complete a 3D model for the whole cargo stack. The professional version of Metashape was used to produce the reference points and achieve the alignment between the series of temporal 3D models. The next stage was to match and overlay a 3D CAD model of the amphora to each of the amphorae that appear in the digital 3D models so that a complete CAD model for the whole cargo can be established.

The concept demonstrated in this work is revolutionary since it proved that it is possible to turn old black and white images into a rigorous 3D model that will significantly assist in studying the cargo and conclude a lot of informative details about the wrecked ship. This work also recommended a thorough criteria of building 3D models. For future work, this document presented a proposed methodology of how to evaluate the precision of the alignment of the temporal 3D models to each other and the amphorae to the models.

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1. Introduction

1.1 Kyrenia Shipwreck Discovery

The Kyrenia ship was a third century BC shipwreck (Figure 1A) that was discovered on the north coast of Cyprus in 1967. During the subsequent excavation, the cargo of amphorae and millstones, and the remaining wooden hull timbers were recovered. The hull timbers were conserved at Kyrenia Castle and the hull rebuilt. The ship's cargo (Figure 1C) consisted of different types of amphorae, with the majority being known as Rhodian. Also, a number of millstones (Figure 1B) were found on the ship. During the excavation works, divers used Nikonos film cameras to take around 10,000 images using 292 35 mm black and white films. These films were scanned and became available for processing in order to build a digital 3D model for the whole cargo of the ship by using Agisoft Metashape software, a photogrammetric 3D reconstruction program, to produce a digital 3D model that could then be exported into a CAD program for further analysis.

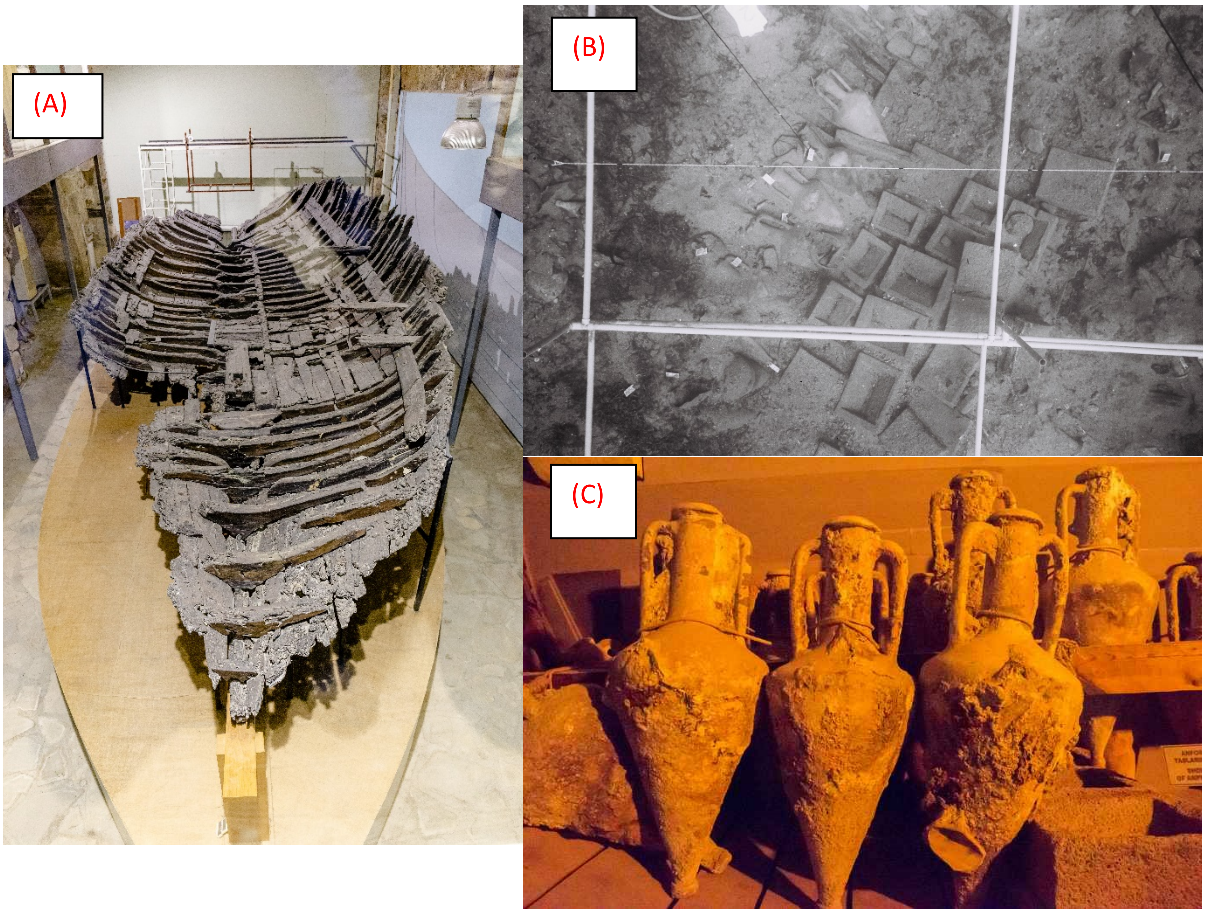

Figure 1:*(A) The remainder of the ship hull timbers, (B) The milestones and (C) The most dominant amphora in the cargo.*

1.2 Objectives

This project aimed to implement many objectives which are listed as follows:

- Transform 2D images of the excavation process into a digital 3D model.
- Build successive 3D models as required that represented the temporal propagation (layers) of the excavation works.
- Link the successive 3D models to cover the whole cargo.
- Establish a 3D CAD model for the whole ship cargo through matching a 3D CAD model of an example amphora to the intact amphorae shown in the built photogrammetric digital 3D models.

1.3 The HIVE internship program

This project was made possible by technical and financial support from the Curtin HIVE Summer Internship Program (2020-21). The Curtin HIVE Summer Internship Program allows a Curtin student to undertake a 10-week full-time internship to undertake a research project investigating the application of visualisation technologies to a particular discipline area. Interns had regular access to the Curtin HIVE, were supported by the HIVE staff, and were supervised by a discipline leader. The results of the HIVE Summer Intern projects were presented at the HIVE Summer Intern Showcase held at the Curtin HIVE on Friday, 19th of February 2021, and also presented in a written report (this report). This internship project was supported by a scholarship from the Faculty of Science and Engineering through the Dean of Research, Professor Kate Trinajstic.

2. Background

2.1 Why Kyrenia needs to be studied?

This old ship had lain at depth of 90 feet, with all its cargo of around 500 amphorae for over 2000 years. The wooden hull and most of the cargo lay under the sea floor - covered by sand and eel grass. A water jet was used to loosen the grass from the roots and then the usual suction tools were used to remove the sand. Amphorae were removed day by day and around ten different styles of amphorae were found which suggest that they had been collected from various locations, but the Rhodian style was the dominant style among them. Although there was no evidence about what was carried in these amphorae, some of them contained in-shell almonds. In addition, around 27 mill stones were discovered at the bottom of the ship alongside its axis. It is believed that they are made of volcanic stone supplied from the Cycladic islands, Thera or Melos. Many parts of lead were discovered in the excavation site which are believed to have been used as a shield from the marine life. This method of ship protection was known in Roman ages, however the Kyrenia ship represents the first example of this. Despite all of this information, many questions still need to be answered such as: what is the origin of this ship? What was the itinerary of the ship before sinking in Cyprus coasts? What is the main usage of the ship? Was it used for war supplies or commercial usage? Finally, what is the main reason that caused the ship to sink? [1]

2.2 Prior work

Seeking answers for the previous questions, the Curtin HIVE proposed a project in 2019 that used modern advancements to collect information from the previous archaeological records. For example, photogrammetry techniques were used to check the hand-drawn built diagrams for the Kyrenia wreck site. This was done through processing the images in Agisoft Metashape to generate a digital 3D model of select excavation layers of the site and then exporting an orthomosaic map of the layers to compare to the original hand-drawn diagrams. An error of in the order of several centimetres was determined in the position which was considered acceptable, and confirmed that photogrammetry can be used in this situation [2]. This project aimed to extend this work, by being more thorough with the generation of multiple digital 3D models of the separate stages of the excavation of the wreck site, and producing a CAD model of the cargo of the vessel as it lay under the sea floor.

3. Methodology

3.1 Pre-processing

In this work, there were two main processes. The first was building the digital 3D models of the temporal layers of the excavation site from the available legacy photography using Agisoft Metashape. Before the processing step, the images needed to be classified and categorized into separate groups. Each group of images represented a certain level of the excavation of the ship, so that new layers revealed new amphora as well as some of the previously remaining amphora. This categorising was done by Jeremy Green, and included consultation with Jeremy Green and scientists from other organisations who had a great experience with the data.

The outcome was classifying the data into three main levels which are designated level zero, one and two. Level zero was the original site of the amphorae sticking out of the sea floor before the site was excavated. Level one was the excavated site showing predominantly amphorae. Level two was the excavated site showing the mill stones. Also, level one was divided into 4 sub levels from A to D representing the temporal change of the amphorae stack during the excavation process. However, after the processing attempts, that will be discussed later, the data was re-arranged into level zero, one, two and three as shown in Figure 2A. Level 3 was mainly the bed of the ship as it contained few amphorae (about four of them) and many milestones. Level one was divided into only two sub levels which are A and C and this was done because the images in each sub level were found consistent and providing a good coverage for a particular temporal state of the amphorae. This means that if the images were divided into more sub levels or combined to only one level, poor models will be produced, or some changes will be missed respectively. Furthermore, data was filtered from all unclear images (Figure 2B) since they caused distortion to the 3D models and repeated photographs (Figure 2C) which would create identical features persisting across multiple images triggering many false positive matches and subsequently lead to an incorrect image alignment. The repeated images do not need to be identical, if they share many features and were taken from a very similar angle, there is a high probability that the produced 3D model will be distorted.

After that, a masking process was implemented to all the images that contain any unwanted features such as divers, excavation equipment, and sea debris (Figure 2D). The rationale behind this was that these features were not fixed and moved from an image to another and consequently caused a lot of confusion for the software (Metashape) in the process of building the 3D models. There will be no need to mask these issues, if the obstacles do not affect the view and there is a guarantee that their occlusions and overlaps are fixed through a combination of different images.

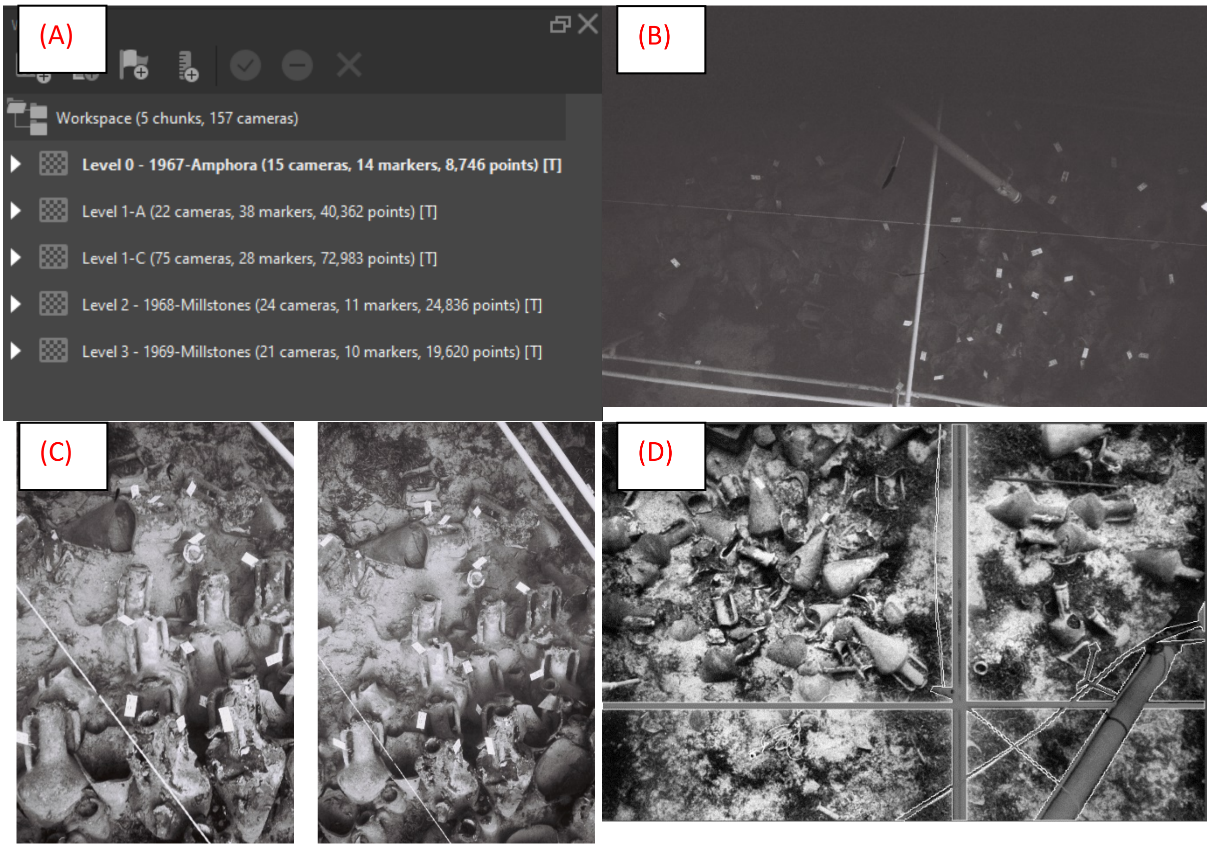

Figure 2: *The figure shows the different steps performed to purify the data and prepare it for processing as (A) represented the images grouping, (B) an example of unclear images, (C) an example of repeated images and (D) shows how masking was made for unwanted features.*

3.2 Histogram equalisation

The next step that was taken to improve the construction of the 3D model through the application of histogram equalisation for all images. This is an OpenCV function which can manipulate the properties of the image to make them clearer and to improve the contrast as shown in Figure 3 A and B. Simply and briefly, the histogram equalisation tends to change the narrow contrast range of the image pixels to contain a full range of contrast that produces better results. This can only be applied when the whole image is confined in a certain narrow range of contrast, but in some other cases, each group of pixels of the original image has a different range of contrast and applying histogram equalisation to the whole image will produce bad results. Therefore, a so-called adaptive histogram equalisation is applied. The concept of this technique is to divide the image into small parts called tiles and then apply the histogram equalisation to each tile for the contrast range. The only obstacle for this is noise since it will be amplified. To overcome the noise issue, a contrast limit is defined so that pixels can be redistributed among tiles – hence the full algorithm used is called Contrast Limited Adaptive Histogram Equalisation (CLAHE). Information about Histogram Equalisation and CLAHE can be found in references [3] and [4].

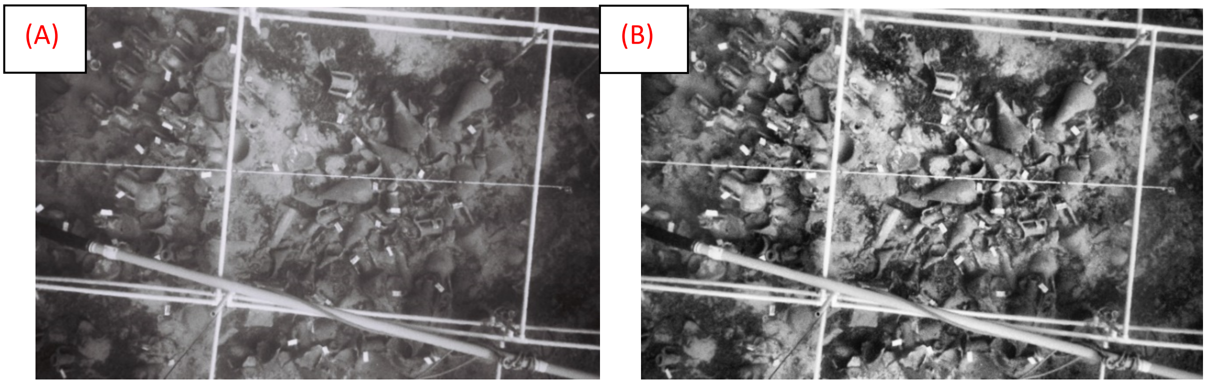

Figure 3**:** The effect of applying histogram equalisation as (A) represents an image before being histogram equalised, while (B) represents the same images after applying the histogram equalisation.

3.3 Building of the digital 3D models

Overall, CLAHE processing has assisted in improving the 3D model, in addition to some specific settings that were used during image processing in Metashape [5] to further improve the model. The first step in Metashape is image alignment. During this stage, the software searches for common features between different images, and consequently calculates the camera position for each image through the transformation parameters of the features between images. The parameters available in the setup of this processing step include the accuracy, pair preselection, reset current alignment, key point limit, tie point limit, apply mask to and adaptive camera model fitting. The interested reader can refer to [5] for more info about the function of each parameter and its effect on the image alignment process. By the end of this step, camera positions will be obtained, and a 3D point cloud generated through the dense reconstruction step.

The following table describes the used settings for images alignment in this work. The alignment settings are:

Accuracy	High
Generic Preselection	Off
Reference preselection	Source
Key point limit	240,000
Tie point limit	0
Apply masks to	Key points
Guided image matching	On
Adaptive camera model fitting	Off

The second step in Metashape is producing a dense point cloud. This feature depends on the estimated positions of the used cameras and it performs calculations to determine depth information. The following table shows the settings used for dense cloud building:

Settings of dense cloud build:

Quality	High
Depth filtering	Disabled
Calculate point colours	Off
Calculate point confidence	On

The dense point cloud can then be edited and filtered in order to get better results. For example, a point in the cloud can be derived from a single depth map (two overlapping images), or from multiple depth maps (multiple overlapping images). Points generated from a low number of depth maps (say for a single pair of overlapping images) can be deemed as weak or poor (there is not a lot of redundancy in their calculation). These can be removed through the "Filter by Confidence" feature and by setting the limits to:

Set min: 0

Set max: 1

The entire point cloud in that range (0-1 point confidence) was removed. Noting that the max value could be 2 in case that there is enough coverage and overlap in the aligned images. In addition, any other points that represented a noise or unwanted elements were manually removed by eye.

After dense point cloud generation and filtering, the software generates a mesh and/or DEM (digital elevation model). This is a 3D mesh model for the data based on the point cloud. This can be built by selecting between various kinds of projections. The following table shows the settings defined in that work:

Build Mesh settings:

Source Data	Dense Cloud
Surface Type	Arbitrary 3D
Face Count	High
Interpolation	Enabled
Calculate vertex colours	Off

The final stage is texturing the 3D surface and the following settings were used in that work:

Build Texture settings:

Texture type	diffuse map
Source data	images
Mapping mode	generic
Blending mode	Mosaic
Texture size/count	8192 x 1
Enable hole filling	On
Enable ghosting filter	On

The exported 3D models from the photogrammetric reconstructions feed directly into the following step which is the building of the 3D CAD model. But before proceeding with the next step, all the temporal 3D models needed to be linked, aligned, and connected to each other. For that purpose, Metashape Professional was used which offers a feature that allow the user to create reference points (markers) at any two or more levels. These common reference points were used to align the levels together. An example of these points linking the levels are shown in Figure 4 A and B. Through this feature, it was possible to connect each subsequent sequential level to each other and subsequently all levels were connected and linked. The process for this alignment process is as follows:

1- Define a point or more which is located at the two levels that are required to be connected.
2- Inside the chunk of the images of each level, a marker can be installed over the shared point(s) in one image of the chunk and the software will apply it to the same point(s) at all the remaining pictures that contain that point(s).
3- The marker can be added by a right click over the point(s) and selecting add marker. It is a good thing to double check the marker installation in the rest of the images that it has the same name and located at the same place.
4- The chucks can be aligned after that by choosing a marker based as the alignment method.

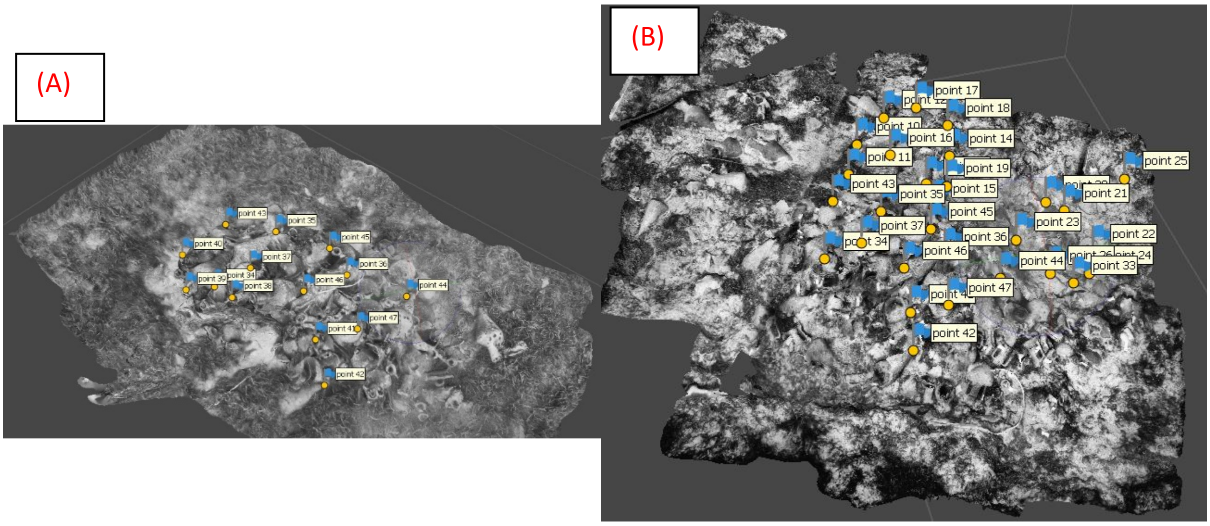

Figure 4: *Images (A) and (B) show how reference feature points can be used to connect different levels to each other.*

3.4 Building of the 3D CAD model for the ship cargo

The process of building the 3D CAD model was implemented using Rhino software. First, a 3D model was exported from Metashape as an OBJ file (which consists of a surface) and then opened by Rhino. Another OBJ file containing a 3D CAD model of the sample amphora was also imported. Using the features of Rhino, the amphora was controlled with six degrees of freedom until it was matched to its place with the individual surface models of the amphorae in the imported 3D model from Metashape. The main features that were used from this software were scale, move, copy, rotate and gumball option. The latter one was a key to effectively control and place the amphorae since it shows the six degrees of freedom of the selected object where the user can insert the value of the rotation or the transition to the desired direction. Also, the layers system in Rhino was exploited to build each level and its amphorae in a separate layer and sub layers. Care, precision and thoroughness were the key in matching the amphorae to a quality and accuracy. The number of amphorae and their distribution among different levels is discussed in the results section. It is imperative to mention that only intact amphorae were matched at each level. This decision was taken after discussions with specialised maritime archaeologists who advised this since any broken amphora would have a high probability of being moved from its original place due to currents. In such cases, the amphorae could provide some misleading conclusions as the settlement of the amphorae is the focal point of this work because it can lead to identifying information regarding the ship sinking events.

4. Results

The results of the project are very promising since they proved the main objective of the project and answered the question of: Is it possible to build a complete 3D CAD model of a series of underwater objects exploiting the temporal propagation of the excavation process? This concept was successfully proven, and a 3D CAD model was built for each temporal level (Figure 5) and then all levels were connected as explained in the previous section to form the complete 3D CAD model of the Kyrenia wreck cargo as shown in Figure 6.

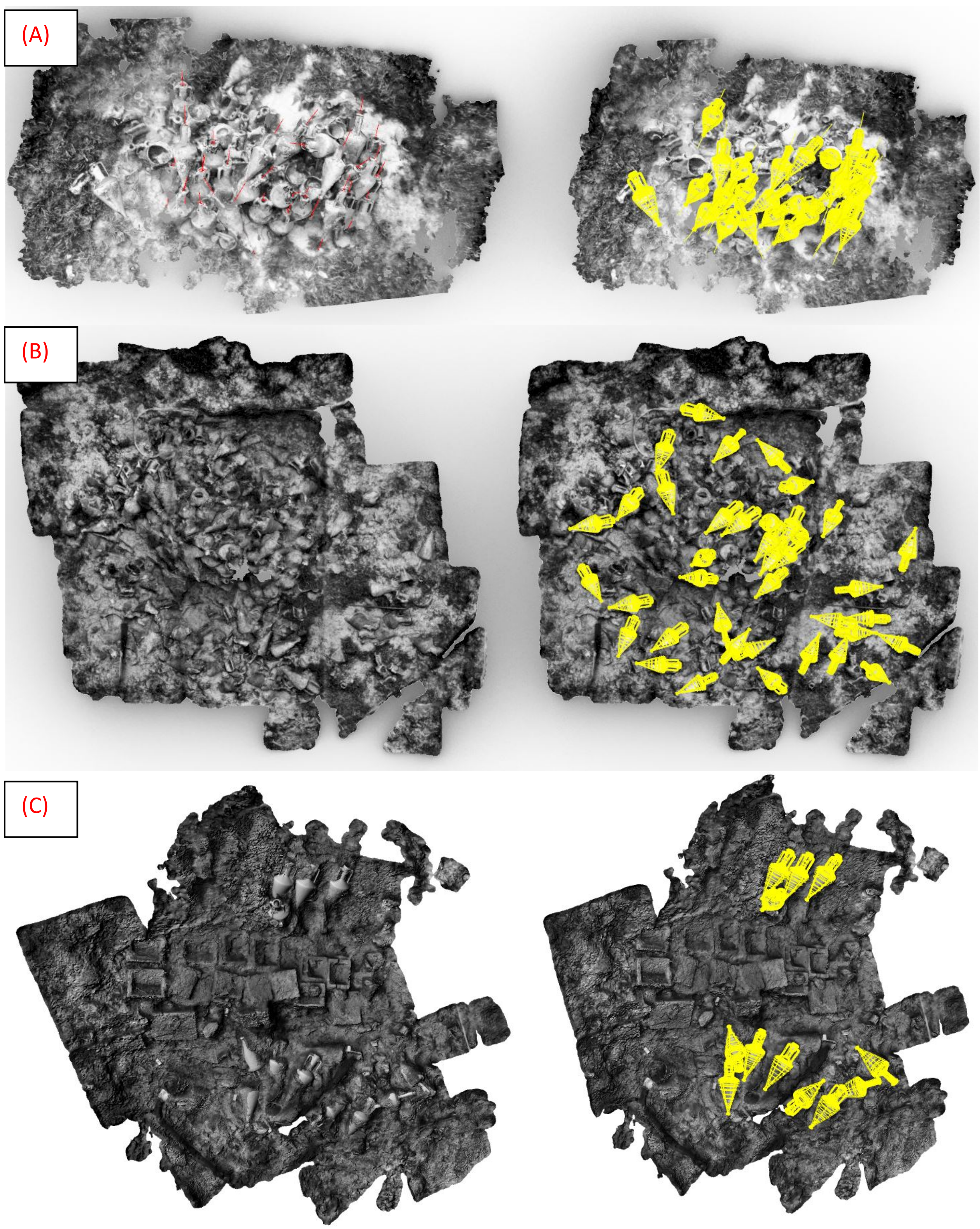

Figure 5: *The 3D CAD model of some of the levels is presented as (A) shows level zero, (B) represents level 1-A, and (C) depicts level 2. The left image is the generated digital 3D model for that level, and the right image of the pair shows the overlaid amphorae CAD models. Incidentally, the left and right pairs can be viewed as a cross-view stereo-pair.*

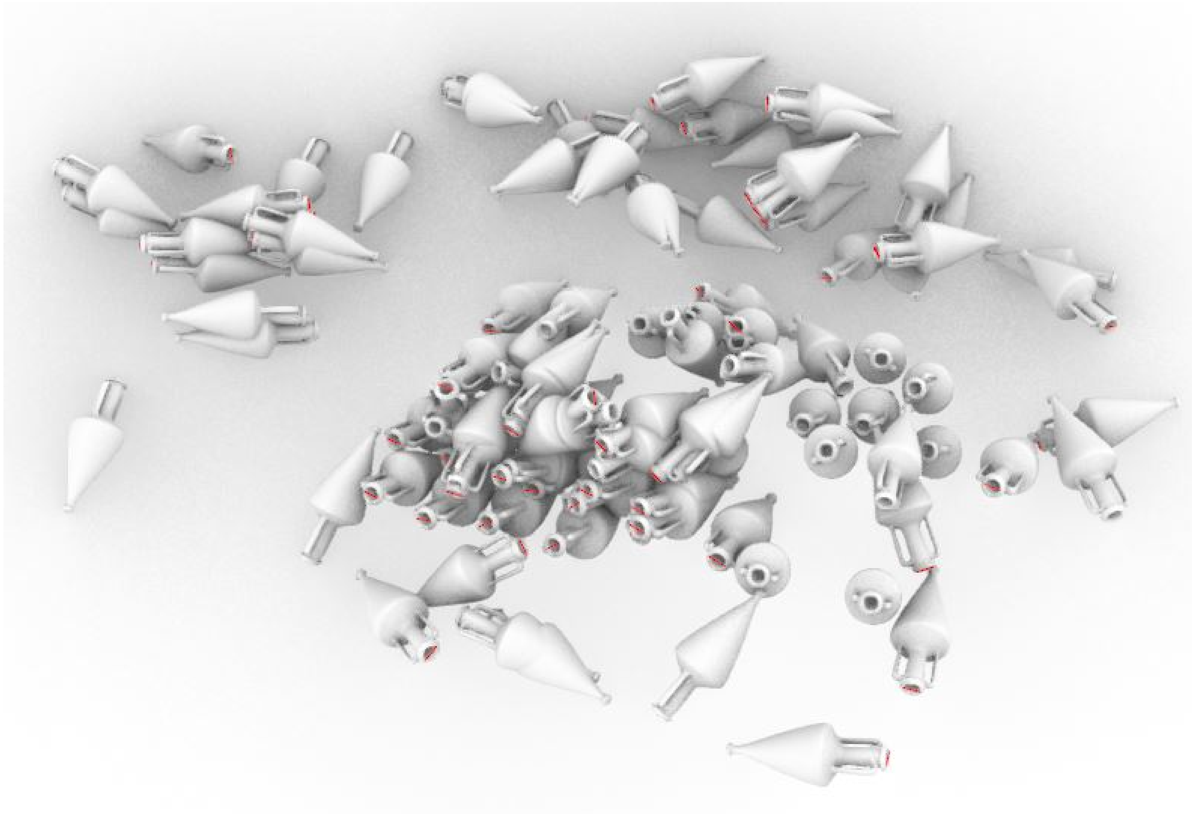

Figure 6: *Shows the complete 3D CAD model for the whole cargo. It could also be noticed that there is an overlap between some amphorae since they are located in different levels and this includes a shift because of the errors discussed in the following section.*

The work included matching 110 amphorae to the different levels. These amphorae are distributed as following: The first level which is called level zero contained 27 amphorae, while level 1-A included 40 amphorae which was the biggest number of amphorae assigned to a single level. Following that, 25 amphorae were aligned in level 1-C. Then 14 amphorae were matched to levels 2, and 4 amphorae were matched to level 3. Of course, there is an overlap between some amphorae from different levels. Therefore, the output of that work includes 3D models for the four main levels, level zero (Figure 5A), 1, 2 (Figure 5C) and 3, in addition to the two sub levels which are 1-A (Figure 5B) and 1-C. It also includes the 3D CAD model for each level.

The following list of links point to interactive 3D models of the output produced by this work loaded onto the Sketchfab website. As mentioned, these levels are level 0, level 1A, level 1C, level 2 and level 3. Also, the final link presents the combined 3D CAD model of the amphorae stack. These are illustrated in Figure 7.

The Sketchfab links are:

- (A) Level 0: https://sketchfab.com/3d-models/4a-1967-amphora-950f10682c4c4eab9fc4e15787f8f831
- (B) Level 1A: https://sketchfab.com/3d-models/level-1a-9eb41c1f79f54b0eb9395e5506a1867c
- (C) Level 1C: https://sketchfab.com/3d-models/level-1c-5ac6c3f8763d47dd9144ce9e98efaa7c

- (D) Level 2: https://sketchfab.com/3d-models/4a-1968-millstones-1df29d1a63c748feb5cee9704e3f1334
- (E) Level 3: https://sketchfab.com/3d-models/4a-1969-millstones-a1aea0f028474eaf865ecee129911b26
- (F) Amphora Stack: https://sketchfab.com/3d-models/amphora-stack-0fae3e72f8794d0c9152818b83cbfad2

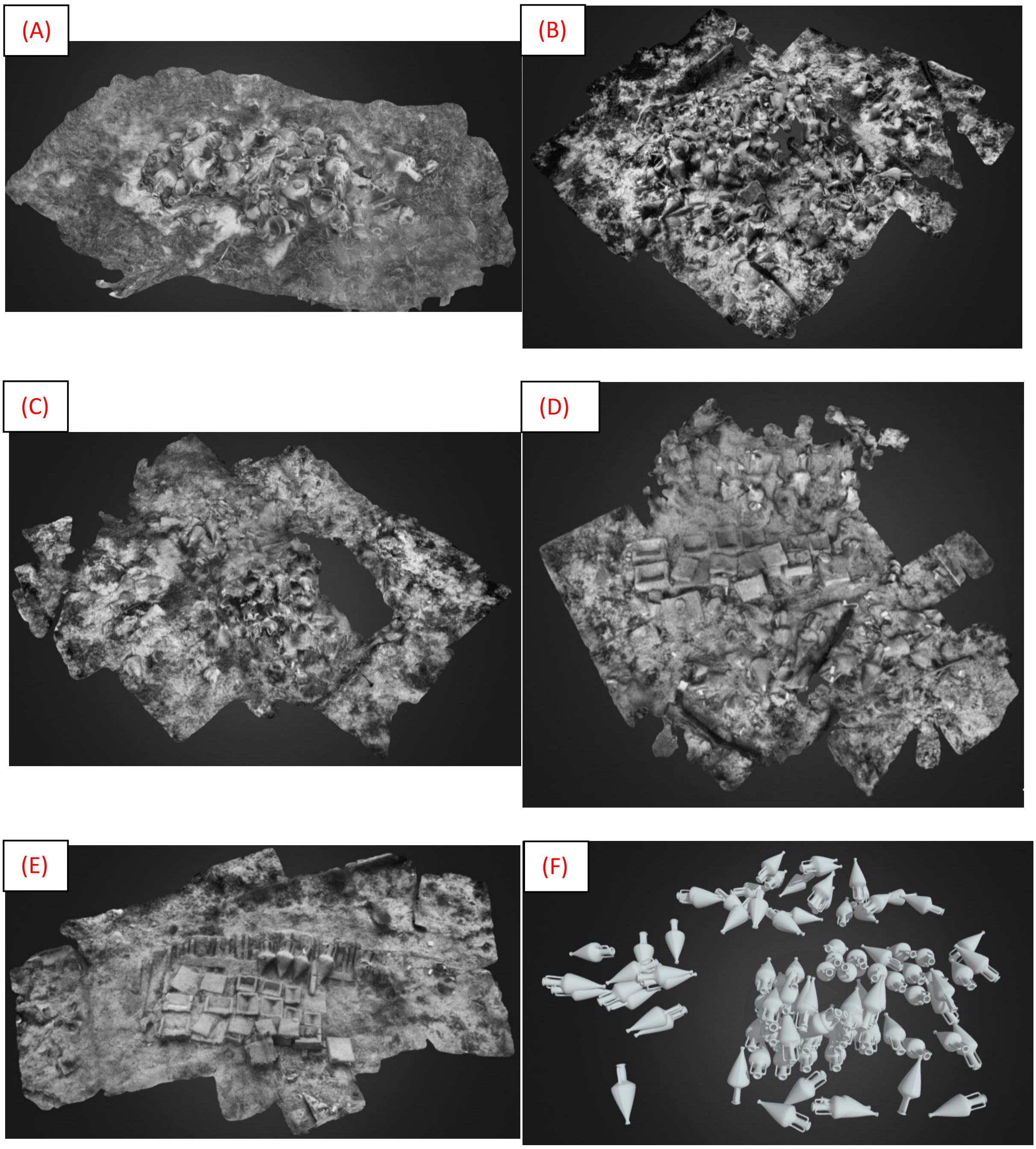

Figure 7: Pictures from A to F show the final 3D models for (A) level 0, (B) level 1a, (C) level 1c, (D) level 2 and (E) level 3 and (F) the final 3D CAD model, respectively as loaded on Sketchfab for interactive visualisation.

5. Discussion

5.1 Project achievement

The output of that work is exceedingly important. To illustrate more, when a discovered artifact is found in its actual place, it will tell a completely different story than if it is just discovered in the excavation site without knowing the circumstances about where and how it was found. Unfortunately, excavating a historical site destroys a lot of evidence, especially those related to the spatial information and distribution of the artifacts. Building a temporal 3D CAD model, a record of the historical site as it was excavated step by step and also to preserve the original status of any discovered item, is remarkably revolutionary. If this can be correctly achieved, archaeologists can reveal accurate information and important events that shape history. The notion of building 3D models for underwater discoveries was discussed in [6] using photogrammetric concepts where Metashape was used to produce such models. Furthermore, applying this concept to the Kyrenia shipwreck was not simple since that data is old and consists of black and white films whose composition affected the quality of the whole process and prevented any data discrimination based on colours. Also, the quality of the images themselves were not helpful, or at the very least are not compatible with the available technology used for capturing information nowadays. In addition, and from the perspective of the author, the available images were originally captured to record the excavation process, not to be used in building 3D CAD models, which is logical since the technology of 3D modelling did not exist at the time of the excavation. Therefore, it is very significant that the work was able to overcome all of these issues and a 3D CAD model was built, despite the possibility of further refinements which are stated in the next section.

5.2 Potential sources of error

Although the results reflected the status of the settlement of the amphorae at the bed of the sea which could be useful in concluding more information about what had happened to the ship, some errors still exist during the implementation of the above method. These errors determine to what extent this method is precise, and scientists who will work on these models will then need to determine whether such precision is practical. The main errors are concentrated in:

1. Amphora resizing error.
2. Amphora matching error.
3. Levels linking error.

To fully imagine the reason of the first error, it is worthwhile to mention that the 3D CAD model of the amphora was imported in the same file with the 3D surface of each level. Then, the amphora was resized as accurate as possible by matching it to one of the intact amphorae in the 3D model. Although this step was implemented with ultimate care, it is likely to still have an error in the final size of the amphora 3D CAD model in regard to the actual size of the amphora. This error could be eliminated through 3D laser scanning a real amphora, and then using this model in the following steps. Regarding the second kind of errors (matching error), the only way to decrease such error is to show much care and interest while matching the amphorae to their places, besides considering any improvements to the model construction will consequently increase the chance of matching the amphorae with better quality. This could be achieved through the first steps of data filtering, masking and histogram equalisation. Moreover, the third error could be significantly improved and minimized. This could be done by increasing the reference points as much as possible to assist the software in finding more common points to be linked. Also, in Rhino, each two connected levels can be visually inspected by looking for any gap between the levels at the linking points so that some refinements could be done. After matching the amphorae to each level, the shared ones between different levels can be inspected by measuring the distance vector between these amphorae. In an ideal situation, these vectors should be zero since they are between the same amphorae, however, this is not what actually happens since the linking between the levels is not perfect. So that, by studying this difference, it can be used to improve the levels' alignment with each other.

5.3 A proposed criteria for sites excavation

Based on the previous work, proposed guidelines for any upcoming excavation process is provided as follows:

1. All objects must be labelled and coded with an adequate labelling system.
2. Many reference features around the excavation location should be identified that will be fixed during the whole extraction process to be used in linking different levels later.
3. Taking as many photographs as possible from all available perspectives.
4. Avoiding close images that do not share many features with other images.
5. Avoiding any obstacles during capturing the images as possible.
6. The higher the quality of the images, the higher the quality of the 3D model and hence the better the precision of the 3D CAD model.
7. The extraction should be organized by taking photographs for the whole location from all perspectives, removing certain items, taking photographs for the whole location again from all perspectives and repeating the same steps once again till the whole site get excavated. This will make the building of the 3D model very precise and will not let any item to be lost from the model as well.

The fourth point in the previous proposed procedures needs more explanation. In general, close images are not preferred since they do not share many features with other images which makes the alignment process much harder. On the other hand, if there are small details that need to be represented and captures, close images will be required, but some precautions should be taken. One of the most important suggestions is to set a series of known fixed points in the view of the photographs. Also, taking many shots for that part from different perspectives with maintaining the same focal length for all shots as possible will be beneficial in images alignment process.

6. Conclusion

This work has provided a revolutionary outcome since it was able to process a 50-year-old dataset and build the temporal 3D models of the underwater cargo of a wreck site more than 2000 years old. The work also illustrated the possible issues that could happen during this process and how to overcome such problems. Moreover, recommendations regarding how to preserve any excavation process and properly record the steps were presented as well.

For future work, two main things could be done. The first is to number all the amphorae in the 3D CAD model based on the same numbering system, provided by the original data. The second is to investigate the precision of the applied method through measuring the difference between the same amphorae which are presented in different levels. If the difference in the six degrees of freedom is measured, an idea about how much this method is accurate will be concluded.

The following steps represent the summary of the processes that has been done in this project and can be done for any future projects with other similar data:

1. Dividing the images into different groups while each group of images represents a certain level of amphoraethe excavation that were taken from different perspectives.
2. Investigating the data of each group of images for any unclear or repeated images that will need to be removed.
3. If any image contains obstacles, particularly those ones which are movable from an image to another, these obstructions must be masked before processing.
4. All the images should be histogram equalised using CLAHE (Contrast Limited Adaptive Histogram Equalisation). It is worth mentioning that this step (#4) and the one before (#3) could be done after the processing step (#5) and the modified images (by masking or equalisation) can replace the original images and the 3D model will change accordingly.
5. Processing of the images to build the digital 3D model for the different levels using Agisoft Metashape software.
6. Defining the reference points between different levels in order to link all of them to each other into the same coordinate system using the professional version of Metashape.
7. Importing all the levels into Rhino as OBJ files and define each level in a separate layer.
8. Importing the amphora model to Rhino and start the scaling, moving, and copying steps in order to match all the amphorae in each model.

7. Acknowledgements

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