Thesis Dissertation

Virtual Butterfly Exhibition

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3D Butterfly Exhibition

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ABSTRACT

Nowadays, technology is progressing at an alarming rate, and the natural environment is constantly put under pressure due to the urbanization of the cities and climate change. Therefore people, especially younger generations, are becoming increasingly disconnected from nature. This growing gap threatens not only our understanding and appreciation of the natural world but also the survival of many species, including butterflies. This thesis explores a new way to reconnect people with nature by creating an interactive online exhibition that showcases every butterfly species that inhabits Cyprus and Greece. We created high quality 3D models of each preserved butterfly specimen by using a 3D scanner, along with photogrammetry. These models, along with the metadata for each specimen, are displayed on a website that serves as an online exhibition where visitors can explore and learn in a visually engaging way. The goal of this project is to spark curiosity, raise awareness about the importance of biodiversity, and encourage people to care more about their conservation. This project also opens the door for future developments like recognition apps or even animated virtual environments where these butterflies could "come to life" again.

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Chapter 1

Introduction

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1.1. Introduction to the topic

As technology keeps evolving and societies have become increasingly urbanized, there is a growing concern that future generations will be alienated from the natural world. The distance that is generated from nature, reduces the understanding and the appreciation that is required for life on this planet. Ecosystems are already dangerously fragile, and they are now further threatened by climate change. In addition, wildlife invasion is increasing destructively due to human activity. The rise in temperatures and changing weather patterns along with pollution, deforestation, and the widespread destruction of natural habitats are putting immense pressure on the ecosystems. In addition to threatening numerous species, these disruptions are also hindering the natural balance on which the earth is depending on.

Recognizing the urgent need to bridge this growing gap between humans and nature, this exhibition is set up to focus on displaying every member of the butterfly species that is found in Cyprus and Greece. Therefore, it is important to highlight the beauty, diversity, and ecological importance of these species, in order to foster a deeper connection between people and the natural world and promote awareness of the need for conservation efforts to protect both local and global biodiversity.

1.2. Project’s development motive

Insects, including butterflies, are increasingly threatened by urbanization, massive climate changes and the widespread use of pesticides. Up until now, researchers used to document the species by either photographing or just mummifying them. However, our project introduces a more modern approach to exhibiting endangered species. By taking the mummified butterflies, we create detailed 3D models using an advanced 3D scanner for an online exhibition. While the colours may slightly differ due to the natural changes after death, these models are highly accurate and closely resemble how the species looked when alive. The goal of this project is to preserve and document every butterfly species in Cyprus, providing educational resources for the public and the newer generations to learn about these species and the importance of their conservation.

1.3. What is the problem and why did no one do anything about it

The challenge of effectively digitizing butterflies in such high detail involves several steps. The primary challenge, which is a main source of errors, lies in the hair that each butterfly has, and since it is extremely small, it is a very hard feature to capture with detail. Therefore, we require a high-resolution camera or a micro camera to capture the details of each species. Moreover, the significant variations in color intensity of each butterfly's wings also pose a challenge, since it is difficult to perform accurate white balancing, often leading to inconsistent color representation across samples. Also, it is important that each butterfly remains stable in a fixed position throughout the process, making sure that the images will be precise. Additionally, in order to ensure that the results of making a 3D model are accurate and consistent, the butterflies must be photographed from multiple angles, with an overlap of approximately 60%, capturing every aspect of their structure. Diffuse lighting is also essential to illuminate all the details without casting harsh shadows and thus having a clearer representation of the species. After capturing the images, it is necessary to use photogrammetry to convert these pictures into a precise 3D digital representation. This procedure has never been performed before due to the unavailability of all the tools necessary to conduct all the processes with the required level of accuracy. In order to photograph the butterfly specimen precisely as well as from various perspectives, highly specialized equipment is needed such as 3D scanners with high resolution cameras and improved lighting. Additionally, the technologies that were used to transform these images to 3D models, as well as the software, may have not been available in the past. Given the absence of these critical resources, it has been nearly impossible to implement the entire procedure with the level of detail and accuracy required for the preservation of the species and the design of such online exhibitions.

1.4 Usefulness of the project

The project will be able to educate both locals and naturalists worldwide about the rich diversity of butterfly species found on the island. In addition, the project will create e-learning materials, providing accessible and engaging resources for individuals to learn about the island's butterflies and make other projects with them. Moreover, the project also aspires to adding high-quality 3D models to the exhibition, and therefore allowing the user to observe the details of the butterflies as if they were real. Furthermore, this project will be an alternative way to get the younger population involved in nature through the new technology. As a result, they will be more connected to the natural world and become appreciative of the environment. Another basic component of the project is to make the people conscious of the criticality of conserving wildlife and the need to protect it, as well as their natural habitats. There is a critical need for society to come together and pay attention to these threatened ecosystems and critically endangered species. Lastly, by creating such a database that contains each species along with details and information about them, more paths can be opened for new projects. This database can serve as a foundation for developing recognition applications, enabling users to identify butterfly species.

1.5 Brief description of implementation

The implementation of the project involves several key steps. The first step involves the collection of comprehensive data, ensuring that the information is both correct and accurate. This data is literally the cornerstone of the project, as through this information the users will be educated about the butterflies and develop a deeper understanding about them. Then, the development and design of a website as an online exhibition is the next step. The project's goal is to construct a website that will serve as an online exhibition that is both interactive and visually appealing. The exhibition will showcase the various butterfly species from Cyprus and Greece for users to be able to explore and to be able to learn about. The utilization of specialized 3D scanning equipment is essential for the purpose of scanning each species. This process will result in the generation of high-quality 3D models and thus raising the bar higher by providing such an immersive way of learning. Finally, we will upload the 3D models on the website along with the organized information about each species. By following these steps, the exhibition website is turned into an immersive educational resource, by combining technology and the knowledge about the species to promote the learning and appreciation for them.

1.6 Contribution to the project

The entire team was able to collect the required metadata for each butterfly species relevant to this project. This metadata enables the rest of the work to be accomplished. My work in this project consists of creating a website that functions as an international online exhibition for butterflies. As I mentioned above, the website exhibition displays the 3D models, as well as the information about the actual species and the project itself. To create these models, we utilize ScAnt, which is an advanced scanning system, to scan every butterfly species. The scanner requires fixing the species in place so that images can be taken of them from different angles to create 3D imaging. Additionally, I will make use of Photogrammetry in order to create a quality representation of the butterflies‘ 3D digital models. In an effort to increase accessibility and interactivity, the 3D models produced are uploaded on Sketchfab, which is a website that enables viewing in both VR and AR. Since Sketchfab allows its users to create links of the models, I will utilize this functionality by embedding the link to the website exhibition -where the appropriate metadata for each species will be placed- and display the 3D model there as well. By combining detailed 3D visualizations and rich informational content, we are able to create a more complete resource that users can explore and learn from.

Looking towards the future, one of the possible additions to this project can be the creation of a realistic and dynamic 3D environment by attaching animations to each model, with the animations mimicking the motions of the actual species, which will allow viewers to become even more immersed in the experience.

Chapter 2

Theoretical Background

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2.1 Virtual Museums

The term "museum" originates from ancient Greece, where the word "*mouseion*" is referred to a place dedicated to the Muses, symbolizing a space for philosophy and reflection [1]. In general, a museum is a place dedicated to preserving and showcasing important objects that represent human history (paintings, sculptures, art objects, and archaeological artifacts), as well as the environment [3]. Unlike libraries, which are often compared to museums, the items in museums are not only unique, but also form as the raw material for study and research. These items are often taken out of their original context of time, location or purpose, enabling them to have a direct engagement with the viewers in their own unparalleled way. Nowadays, with the rapid advancements in technology, the use of virtual museums has been essential in preserving collections. Thus, the digitized collections not only preserve the cultural heritage, but also present the information to a broader audience in a more engaging way. Augmented Reality(AR), Virtual Reality, and Web 3D technologies are utilized to develop computer-generated exhibits for museums that can be viewed on the web and at kiosks inside the museum [2]. In addition, virtual museums are built with a great deal of thought about how their audience will experience the museum, as users can navigate through it in any way that suits them best: when using a computer, there is a keyboard and a mouse, and in some cases there is a VR headset or inverse touch screen on a smartphone. Also, virtual museums allow users to zoom in and rotate objects to provide more details for further research. Two great examples of virtual museums in Cyprus include the Virtual Dance Museum, which showcases traditional dances from all across the world, and the 3D Reptiles exhibition which - similarly to our project- preserves Cypriot reptile species through the creation of detailed 3D models, as well as capturing and animating their movements.

2.2 Butterfly Species Documentation

Up until now, high-resolution photography and digital imaging have been significant for biologists, as those techniques aided them in documenting butterfly morphology and coloration, and thus assisting them in identifying species [4]. Such approach proves to be still definitely effective, since it can successfully capture the butterflies with their true-to-life colours, as well as key identification markers about them, such as wing patterns and vibrant hues. Nonetheless, the method itself lacks a realistic and immersive representation of the animal, as it only provides static images of the species and thus fails to capture the animal in high detail. Consequently, the images hold significantly less information than the original specimen, since they are confined to a single image plane [7]. However, given the fast-paced evolution of technology, 3D Scanning technologies have emerged as a powerful tool for creating detailed 3D models. By capturing objects with exceptional precision, it brings a museum-like experience to life, making collections accessible in stunning detail through virtual museums. In our case, our goal involves the use of 3D Scanning technologies to present a detailed 3D model of each butterfly species that inhabit Cyprus, along with their documentation and thus give a more modern and realistic experience to the audience.

Our team has every butterfly species in Cyprus preserved in excellent condition, hence enhancing the prospects of assembling a realistic experience to a greater extent. That being said, one shortcoming of this procedure is that each butterfly that is used for scanning is lifeless which comes at the cost of the butterflies' true natural color. Consequently, the 3D models do not possess the same robust coloration as their living counterparts. Therefore, our intention is to utilize both methods in order to provide the complete and correct picture, as well as provide the public with an enriched and informative experience.

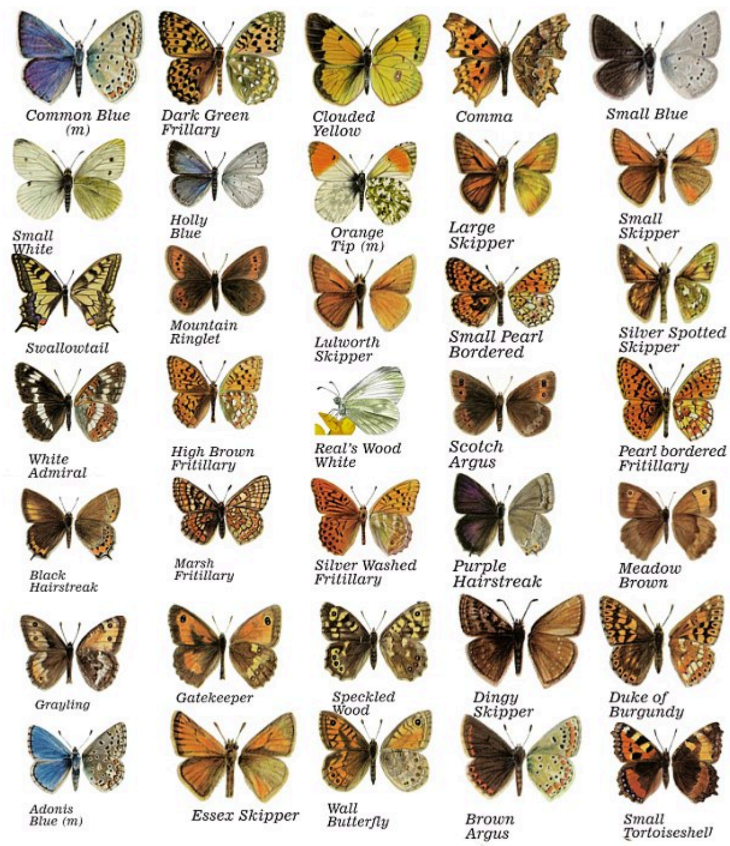

Figure 1: British Butterflies identification chart

2.3 ScAnt 3D Scanner

For our project, we will be using the ScAnt 3D scanner for the digitization of the species. ScAnt is an open-source macro 3D scanner for the creation of 3D models of small objects and arthropods. It is composed of a scanner and a Graphical User Interface and is designed to automate the creation of Extended Depth of Field images from different perspectives.

These images are subsequently masked using an automatic routine that integrates random forest-based edge detection, adaptive thresholding, and connected component labelling. The resulting masked images can be further processed using photogrammetry to produce detailed, textured 3D models and those 3D models can even be rigged for realistic digital specimen posing [5].

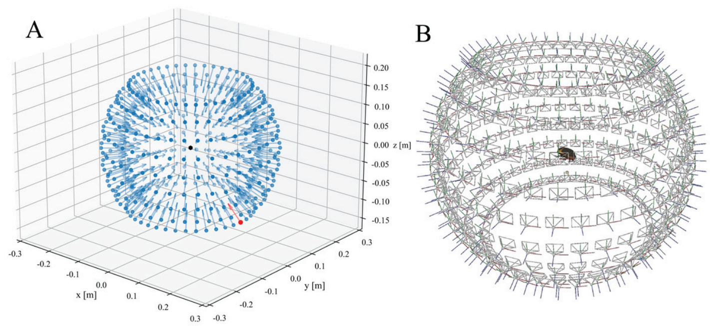

Figure 2: Representation of all the camera angles used for one scan

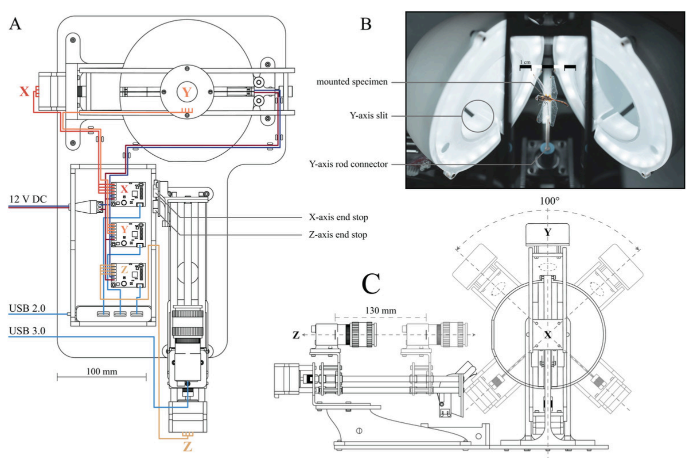

Figure 3: Photograph of the assembled 3D scanner.

2.4 Photogrammetry

Photogrammetry is a technique for determining the dimensions, shape, and position of objects in space through the use of photographs. This technique is used to collect information regarding the properties of an object or a surface, without any direct contact with the object or the surface itself. The term "photogrammetry" comes from three Greek words: "*phos*", meaning light; "*gramma*", referring to something written or drawn; and "*metrein*", which relates to measuring [6]. While photography has long been, and will continue to be, an integral part of archaeological and biological documentation, conventional photography alone cannot serve as a completely reliable means of extracting spatial data, even when scales or other reference points for dimensions are present. Photogrammetry, when combined with other techniques traditionally used in the field, can help overcome such limitations. Emerging in the late 19th century, photogrammetry offers a powerful method to enhance spatial accuracy and documentation capabilities, particularly when treating photography as another aspect of the materiality of excavation.

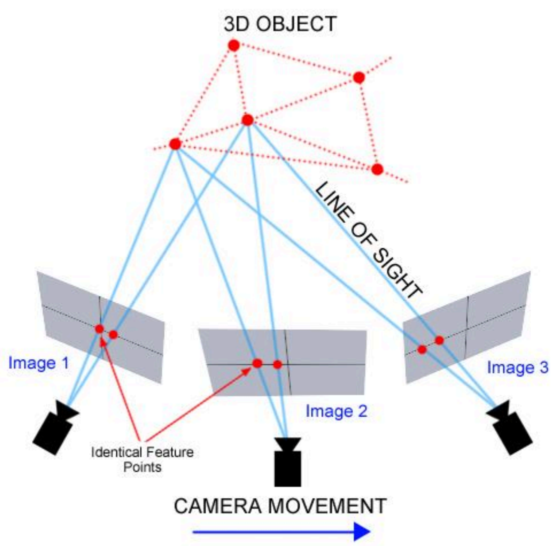

Figure 4:Representation of how photogrammetry works

2.5 Previous Work

A notable attempt to digitize butterfly specimens in 3D was made by Yale University, showcasing their work through a series of photogrammetry-based models. However, unlike our project, their focus was not on creating a structured virtual museum or interactive exhibition. Instead, they uploaded a general collection of models from the Yale Peabody Museum onto Sketchfab, primarily for visualization purposes. While their effort contributes to the preservation and accessibility of entomological data, it lacks the curated, thematic presentation and user experience design that our virtual museum aims to provide.[14]

Figure 5: 3D Model of Vanessa Atalanta, from the Yale Peabody Museum

Figure 6: Another specimen from the Yale Peabody Museum

Chapter 3

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3.1 Data Processing

Regarding the data collection, we were able to gather all the metadata of every butterfly, including its name and a photo, along with its individual traits, with the help of Dr. Elli Tzirkalli, Dr. Savvas Zotos, Christos Zoumides, Hasan Baglar, Christodoulos Makris, where she organised them in a folder that contains the pictures of each specimen and an Excel document. To be more exact, the document contains the unique traits of each butterfly, such as the geographical location of the species, as well as the region that the butterfly can be found in. Additionally, the document indicates whether a butterfly is endemic or not, and their wingspan measurements. It also provides insights to each species' flight periods and their generation numbers. Furthermore, the document presents the host plants that are crucial for each butterfly's survival as they grow up, as well as the nectaring plants they rely on for nourishment at later phases of their life. Finally, it includes valuable information regarding the altitudinal range that they fly in, if they migrate or not, the degree of which the species is common, their conservation status in Cyprus and the references that all the information was taken from.

All of this information proves to be crucial for the education of the users, since -aside of the 3D models- they are thoroughly giving a more complete picture of each species, highlighting their behavior, the places that they thrive in and the food they need to sustain themselves and grow. However, all of this information is also important because it can inform the audience about the vulnerability of these species and the protection requirements in order to conserve them before they go extinct.

Since this informational sheet was really well organised, we modified slightly the information before we converted the excel sheet to a comma delimited file (.csv) so that the table can be inserted into the simple database. We created a simple query and by using bulk insert, we managed to put the table with every species along with their unique personal traits into MSSql and thus created a small database that can be dynamically used in the website exhibition, to showcast each species trait in a more modern and immersive fashion.

Aside from the information regarding each species, Dr. Elli Tzirkalli has provided us with her collection of every butterfly specimen that inhabits Cyprus, mummified and preserved in excellent condition. Each specimen was put on a small pin and was used for the 3D scanning process, with the purpose to digitize them and make them 3D models.

Figure 1: Two of the specimens on pin from the collection

3.2 ScAnt Setup

3.2.1 Software Setup

Since the 3D scanner was already assembled at CYENS Centre of Excellence, by Dr. Andreas Aristeidou, the next step was to set things up. To set up the scAnt system we followed a step-by-step guide that consisted of installing requisite software, camera and motor setup, and the preparation of the environment for scanning. Firstly, we installed the Git and conda/mamba package manager, then cloned the scAnt repository from GitHub. Following the transition into the developmental branch for the latest settings, we established a conda environment with all the necessary dependencies. We made sure the installation was successful by testing the drivers and Python bindings with the execution of test scripts in order to confirm the functionality of the camera and the scanner in general. With the installation of the software being completed, the next step was to attach the first subject with the use of a pin. Therefore with the scanner software setup being completed, it was time to create a new project for our first specimen.

3.2.2 Camera Settings

As I mentioned above, with the setup being completed, we created a project for our first specimen, Vanessa Atalanta. We made sure the project files for all the specimens would be on a disk with enough space, since a full scan for one specimen can take up 150GB+ with all the RAW images. When the project was created, the next step was to configure the camera settings. In our case, we used a FLIR camera, so under "Add Camera & Lens Info" we configured our camera, by populating the field "Make" with "FLIR" and by selecting the model of our camera in the drop down menu. The last mandatory field that needed to be populated in order to be able to perform a scan was the "Focal length". Our camera had a 35mm focal length, so by writing down 35 in the field, the software automatically populated the "focal length in 35mm format". The rest of the fields are optional for logging purposes.

3.3 3D Scanning Process

3.3.1 Camera Parameters

Furthermore, with our FLIR camera configured, we were able to control these settings:

- **Exposure Auto:** This automatically determines the appropriate exposure duration, which is useful for setting the initial values.
- **Exposure Time [us]:** This setting controls the total scan duration, as the scan time increases linearly with the exposure time. A longer exposure allows for using lower gain settings, which can reduce noise—so there's a trade-off between image quality and scanning speed.
- **Gain Auto:** Functions similarly to Exposure Auto by helping with the initial setup.
- **Gain Level:** Adjusts the sensor's sensitivity to light, thereby influencing the brightness of the image. Using a lower gain can help minimize image noise.
- **Gamma:** Applies a contrast correction that mainly enhances the mid-tone range of the image.
- **Balance Ratio (Red/Blue):** Adjusts the balance between red and blue tones in order to adjust the white balance of the image.
- **Highlight Exposure:** Identifies areas in the live view that are overexposed by highlighting them in red, and it also shows normalized color curves in the bottom right of the display.
- **Start / Stop Live View:** Toggles the live video feed from the connected camera, allowing you to see a real-time preview.

With these settings, we had to change each parameters' values each time with the purpose to capture each specimen in the best way we could. Since each specimen has different colors and size, these settings had to be tested every time since brighter colors would require lower exposure time and gain, whereas darker specimens would require higher exposure time and gain.

3.3.2 Flash Settings

In the flash settings, we are able to control the flash length, as well as the flash delay. For the flash length. We made sure the flash length to be set at 200 ms and the flash delay 100ms, so that the specimen will be exposed evenly to the flash for better results.

3.3.3 Post-Processing Parameters

In this section, it is necessary to check the “Stack images” option, since the stacked images will be used for photogrammetry and not the RAW files. When the camera captures the specimen from one angle, it will take multiple photos from that angle, but from different distances (Z-values). The stacked image for that angle will be generated by “merging” all the photos the camera took from that angle, and thus the stacked image will have the whole specimen (or most of it) in focus. The mask Image option is also recommended, as it will take the stacked image to produce one cutout image that will attempt to remove the background of the specimen, as well as a mask image that will highlight the specimen in white and the background in black.

3.3.4 Stepper Control Parameters

With all the parameters being set up for each specimen accordingly, the next step is to set up the Stepper Control values, before performing a scan. To begin with, the interface has three fields that should be populated for the scanning process: “Min” value, “Max” value, “Step” value. The “Min” value represents the “starting point” of the scanning process on a specific axis, whereas the “Max” value represents the “ending point” of the scanning process. The “Step” value is the value that the current value will gain every time, until it reaches the “Max” value, allowing the specimen to be captured in various angles. Therefore when the scanning process starts, the current value is initially equal with the “Min” value, and everytime an angle is captured, the “Step” value is being added to the current value, until it reaches the “Max” value. For example, if we have a “Min” value of 50 and a “Max” value of 200, and we set up the “Step” to be 50, when the angle is captured successfully the “Step” value will be added to the current value and thus the current value will be 100, and then 150 and 200 respectively. This process with the “Min”, “Max” and “Step” value happens for each Axis in order to capture the specimen from every angle. As a result, we have to populate the fields for each Axis independently.

- **Pitch [X-Axis]:** This set of parameters is responsible for the specimen's rotation on the X- axis. The "Min" and "Max" values should be populated correctly, so that with the "Min" value the specimen's lower half will be visible (bottom view) and with the "Max" value the upper half (top view). In our case we used a "Min" Value of "0" and a "Max" value of "1600" for every specimen, since in every scan we needed the camera to capture bottom and top view, along with the in-between angles. Lastly, since we wanted the Photogrammetry software to perceive the images as a whole object, we needed to adjust the "Step" value so that the overlapping would make the program recognize that it is one unified object and not more. In our case, a "Step" value of 40 was enough and we set these specific settings for the X axis for every specimen.
- **Rotation[Y-Axis]:** This set of parameters is responsible for the specimen's rotation on the Y-axis. Similarly to the X-Axis parameters, we had to set these correctly so that the scanner would be able to get a 360° view of the object, with the "Step" values allowing each image to have around 70% overlapping with its next and previous one. In our case, again these values remained the same for each specimen, since in every case we wanted to get a 360° view of them with enough overlapping so that the photogrammetry software would be able to align them correctly. As a result, we had set up the "Min" value to "0", the "Max" value to "1600" and the "Step" value to "80", which worked as expected in the 3D reconstruction process.
- **Focus[Z-Axis]:** This set of parameters is responsible for the camera's positioning on the Z-axis. With the Z-axis, this is where a bit more manual effort is required. Similarly with the rotation of the specimens, the "Min" value is the starting position of the camera and the "Max" value is the ending position. These values need to be adjusted each time, since the specimens may vary in size and shape. To begin with, in order to define the Z-axis range for image capture, it is necessary to first identify the part of the insect specimen that extends furthest from the pinning point, which in our case is typically the tip of an antenna or a wing, depending on the angle. This

point will be referred to as the “most extreme point”. Using the X and Y sliders, this point should be oriented to face the camera. The “Min” value can be found by adjusting the camera position until the “most extreme point” is just within focus. This step is also influenced by the focus ring on the camera lens, which is located at the furthest from the camera on the lens. A higher focus setting (closer to infinity) will shift the focal plane farther away and increase its depth, whereas rotating the ring in the opposite direction moves the focal plane closer to the camera and reduces its depth. There is no optimal configuration of the focus ring and Z-axis parameters; however, the goal is for the specimen to occupy more than 60% of the image frame when the Z-axis is at the “Min” value, with the “most extreme point” oriented towards the camera. Subsequently, the “Max” value should be determined by reorienting the specimen so that the “most extreme point” faces away from the camera, then increasing the Z position until this point is again just in focus. This process will define a Z range within which the majority of images will contain at least some part of the specimen in focus. In certain orientations, images captured near the minimum and maximum Z positions may exhibit out-of-focus areas, which is acceptable.These images may either be filtered using the focus threshold or left unaltered since the focus stacking script can normally handle this by itself. Lastly, the “Step” value should be selected such that approximately 20 to 35 images are captured per orientation. To determine this value, we divided the total Z-range by an average of 20-25 steps. The important part here is ensuring that there is an approximate 50% overlap in the parts of the specimen that are in focus between consecutive Steps. To verify this, we can position the camera at the Min value, then move it by the selected “Step” value. If a substantial portion of the “most extreme point” remains in focus after this shift, the “Step” value can be considered appropriate. If not, a smaller “Step” value should be chosen. While larger “Step” sizes can reduce the number of images acquired and thereby decrease the scanning time and minimize storage requirements, it comes at the cost of reduced overlapping and image quality in the final focus-stacked output.

Once all steps had been carried out, It was time to start the scanning process, but only to the extent of producing two or three stacked images, in order to make sure our parameters are good enough for the scanner to capture the whole specimen in full focus. Therefore, after a few minutes of scanning we aborted the scan and examined the resulting stacked images. If everything looks great, and the moth is in full focus in each stacked image, then we should be able to confidently proceed with performing a full scan. Otherwise, if there are any improvements to be made, the parameters that were mentioned above should be altered with the purpose of getting the best possible result. If the parameters we used give us the desired results, then the full scan can be performed. In our case, with the parameters we set for each specimen, a full scan took approximately 3 - 3.5 hours to complete, producing on average 5,780 RAW images and around 752 stacked images (each image having a resolution of 5472x3648). It should be noted that the amount of images that are being produced for each specimen can vary, primarily due to differences in size and shape, which in turn affect the parameter settings applied on each axis, but mainly the Z-axis.

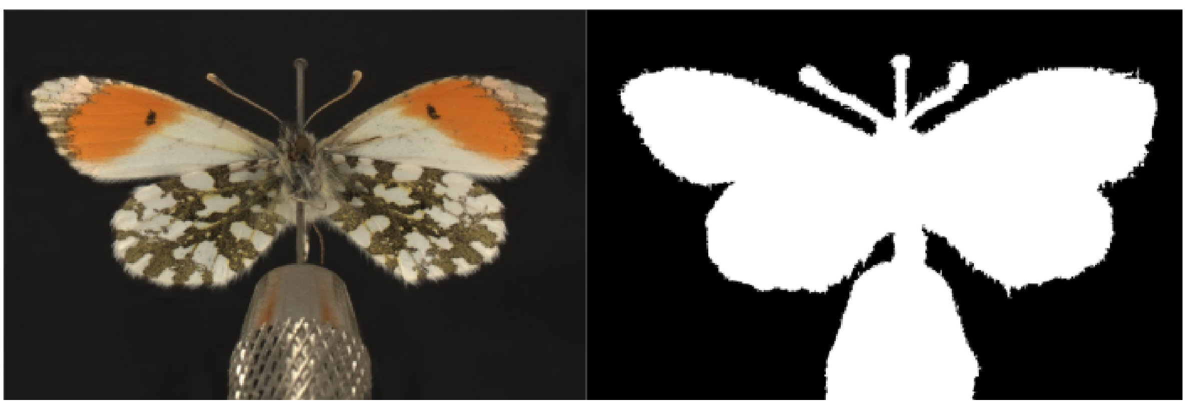

Figure 2: Result of one stacked image and its corresponding mask

3.4 3D Model Creation

Regarding photogrammetry, our initial approach involved using Reality Capture, which is a free photogrammetry software developed from Epic Games. However, since we were unable to identify an optimal configuration that produced satisfactory results, we proceeded with 3DF Zephyr, as recommended by the developers of ScAnt. Therefore, in order to create the 3D models of every species in high detail, we utilized these tools that are mentioned below:

3.4.1 3DF Zephyr

3DF Zephyr, is a powerful photogrammetry software that allows users to create accurate 3D models from photos without much complication. It is widely used across industries like cultural heritage, architecture, forensics, construction, and game development to turn real-world objects and environments into detailed digital representations. The software has a good user-friendly interface and flexibility, and therefore it supports both beginners and professionals in managing small to large datasets without needing extensive technical knowledge. It offers various tools for editing, measuring, and exporting 3D models, making it a great asset for a 3D reconstruction project, such as ours [9].

3.4.2 Blender

Blender is a free and open-source 3D creation software used by artists, designers, and developers worldwide. It is a very flexible program, as it allows its users to create everything to the extent of their imagination (from 3D models and animations to full-fledged movies, visual effects, and even video games). Moreover, Blender has a lot of different features, including sculpting tools for detailed character design, rigging and animation tools for movement. Furthermore, Blender has a strong rendering engine, meaning users can create high-quality images and animations with realistic lighting and textures. Beyond animation and filmmaking, Blender is used in architecture for visualizing buildings, in product design for creating 3D prototypes, and even in virtual reality development [10].

To begin with, to use the set of images that the ScAnt's post processing scripts created, and more specifically the stacked images and their corresponding masks, we opened up our photogrammetry software, 3DF Zephyr and by clicking the "Workflow" tab, we created a project for one specimen. While creating the project we enabled "Set up masking" in order to be able to import the masks of each angle successfully. Therefore, we imported the stacked images, and by pressing "next" the software automatically detected the masks. Since ScAnt's post-processing produces masks with the correct suffix for 3DF Zephyr to recognise, no manual effort was required to import the masks. Additionally, we checked if the imported focal length was correct before proceeding to the next step. Moreover, since our goal is for the specimen to have the highest quality possible with our set of images, in the "Presets" section we selected "Ultra" and in the "Category" section we selected "General" (even though "Surface" can also be selected but through testing, we didn't notice any improvements and the result remained the same). Furthermore, we clicked on run and the software generated the sparse point cloud of the mesh. The sparse point cloud is a 3D representation made up of a small number of points that mark key features or structures of our mesh model, based on identifying and matching points across the set of images we imported. This gives us a rough shape of how the model will look like (40,603 points.)

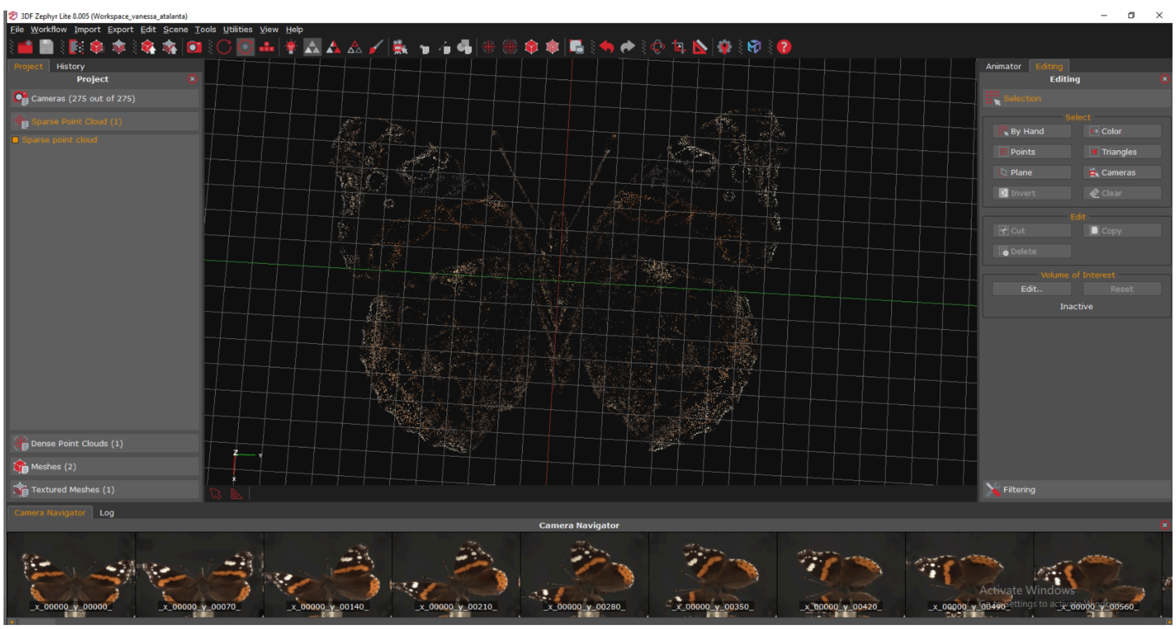

Figure 3: Sparse Cloud point generated with the stacked images

The next step was to click on “Workflow” and in the “Advanced” section we selected the “Dense point cloud Generation” option to generate the dense point cloud of our mesh, which is a detailed 3D representation made up of a large number of points that cover the entire surface of our model. Since it is a detailed 3D representation of our model, it includes much more information than the sparse point cloud, capturing finer textures, shapes, and depth. However to create the dense point cloud, the sparse point cloud generation was essential. The dense point cloud that was generated for this specimen had a total of 5,508,142 points.

Figure 4: Dense point cloud of the object

In addition, using the dense point cloud, we created the mesh model by going in the “Workflow” tab, in the “Advanced” section and by selecting “Mesh extraction”. In the “Presets” and “Category” sections we used the same options as before - “Ultra” and “General”. This produced a 3D model that consisted of approximately 1,864,875 points and 3,727,546 triangles. However, before texturing the model, it was noticeable that the wings of our specimens had a few small holes in them. That is because of the wings being too thin, 3DF Zephyr was not able to capture the wings completely. Therefore, before proceeding to texturing the model, we applied the “Fill holes” mesh filtering on our model, by navigating to the “Tools” section, “Mesh filters” and selecting the “Fill holes - WaterTight” option. This filter was able to close every possible hole in the mesh, providing us with a more complete model. When the mesh model was created we just needed to create the Textured model by clicking on “Workflow” and selecting “Textured Mesh Generation”. In the presets section we selected the “High details” with the purpose to achieve the highest quality possible. Lastly, when the final textured mesh model was generated, we exported it as an OBJ/Mtl, by selecting “Export Textured Mesh” in the “Export” tab.

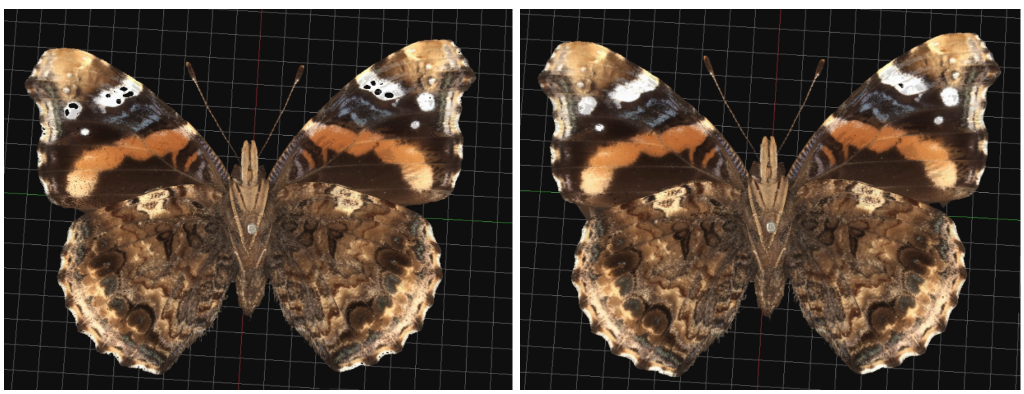

Figure 5: Before and after the “Fill holes - WaterTight” option

3.5 3D Model Cleaning Process

With our 3D model now being completed, we have to perform a “cleaning process” in blender, with the purpose to remove the scanner’s base as well as the pin that our specimen was initially placed on. When we open the blender and create a new project, the basic scene setup gives us a cube object, a camera and one point light. We do not need those so we can delete them from the scene, except the light for now, since we need it to be able to see the model's details. In our case, we created a new light and added the sun option in our scene since the sun light will provide us with a constantly intensive light, emitted in a single direction, as if originating from an infinite distance. Then we imported the OBJ file in our scene by selecting file, and in the import section we selected wavefront. As a result, we now have our scanned object in the scene. However, before we proceeded with the base and pin removal, it was noticeable that the center origin of the object was way off the object itself, making it more difficult to move the object around the scene. For our own convenience, we changed the origin of the object with a simple process. Firstly, we selected the “Cursor” tool in the toolbar which is located on the left side of the blender’s interface. Secondly, using the “Cursor” we clicked on where we wanted the center origin of the object to be (in our case, we placed it roughly on the middle of the specimen’s body). Moreover, after we made sure we were on the “Layout” tab, which can be seen at the top of the interface, we clicked on “Object”, then expanded the option “Set Origin” and lastly we selected the “Origin to 3D cursor” option. Now that we have the new center of the object, we can easily transform the object, by rotating it to our desired place. Furthermore, we selected the “Viewport shading” option on the top right of the scene, with the goal to be able to see the object along with its texture, for more accurate cleaning. Now that we have the textured object, the next step was to switch from “Object Mode” to “Edit Mode”. By navigating on the top left side of the interface, there is the option “Object Mode” which is in a drop down menu form. Therefore, by clicking it we can find the “Edit Mode” from there and select it. Right next to the drop down menu where we selected the “Edit Mode” from there are 3 options: “Vertex select”, “Edge select” and “Face select”. In our case we used a combination of “Vertex select” and “Face select” to remove the pin and the scanner’s base. By using our cursor to drag and select the desired vertices or faces to remove, we pressed “X” or “Delete” on the keyboard to open the delete menu, and select delete vertices or delete faces accordingly with the type of “select” we chose each time. For example if we selected “Vertex Select” we would then choose “Delete vertices”. This process took some time, since each object was created with the highest detail possible, and thus had a lot of vertices. We repeated the “select” and “delete” process in “Edit Mode” until we successfully removed the whole base and pin. Lastly, now that we have the specimen model isolated and cleaned, we can delete the light we set up because it is not needed. Then, we exported the object as an OBJ file by selecting “File”, “Export” and again the “Wavefront” option.

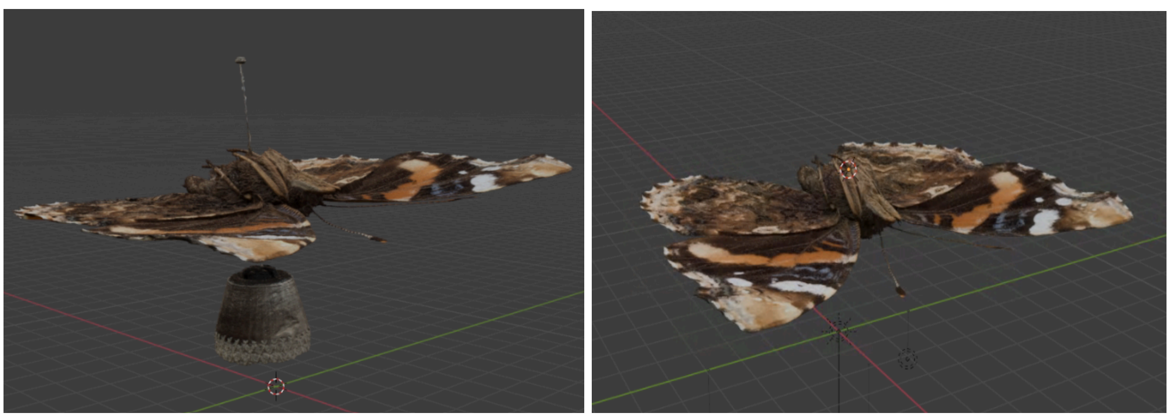

Figure 6: 3D Model before and after cleaning in Blender

3.6 3D Model and Data Upload

Now that the specimen has been successfully digitized into a 3D model, we uploaded the model in Sketchfab. The platform offers several necessary functionalities that allows us to showcase the 3D models in our online exhibition. One of Sketchfab's main key features is the "Embed" tool, which generates an HTML code to embed the models directly in other external websites. In addition, as I mentioned before, Sketchfab can also function as a visualizer for models in VR/AR mode, enhancing the interactivity of our exhibition.

Figure 7: 3D Model Display on Sketchfab

For us to incorporate the uploaded models into our project, we took the source links, which were created by Sketchfab, and inserted them to our small database, along with the detailed information about each butterfly species from the excel sheet. Having completed this database, we leveraged PHP to enable a dynamic connection between our database and our HTML website. This setup allows the butterfly page to load specific information, including the 3D models, images, and other relevant details, based on the species that was selected by the user through the Gallery.

The entire process described above was carried out with the goal of digitizing one specimen at a time. As a result, each step was repeated for every species we transformed to a 3D detailed object, with each time carefully adjusting the scanning parameters.

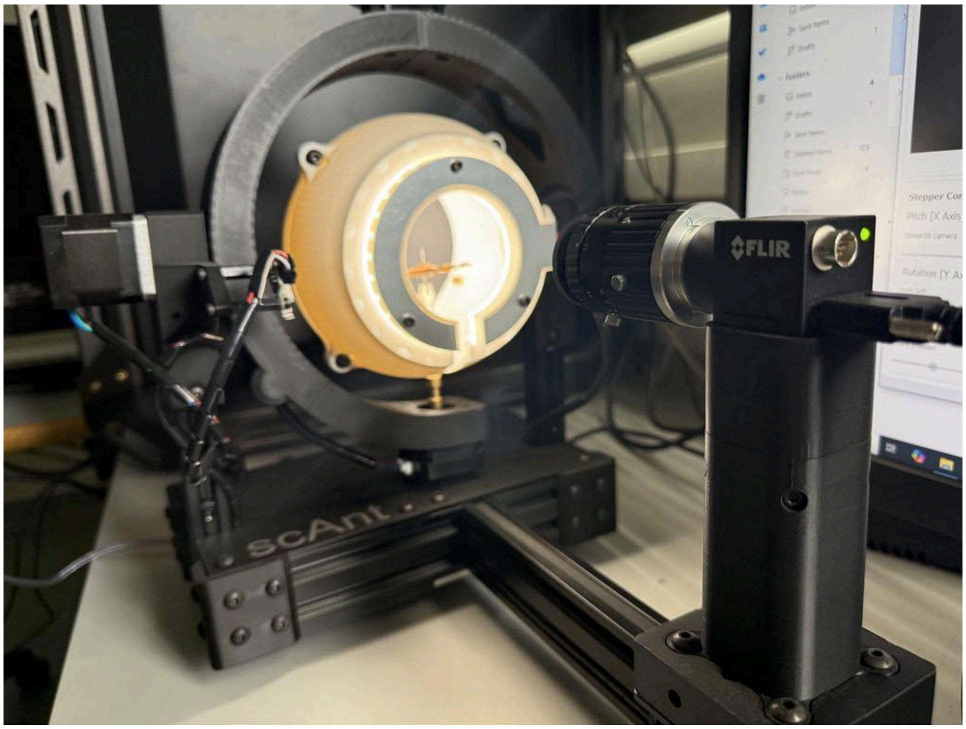

Figure 8: ScAnt performing a full scan

Chapter 4

Visualization

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4.1 Website Development Tools

In order to develop a complete and visually appealing website to serve as our online butterfly virtual exhibition, we utilized these tools that are mentioned below.

4.1.1 HTML

HTML is the acronym name for HyperText Markup Language. It is not considered a programming language, but a standard markup language that is used to create and structure content on the web. It uses a system of elements (such as titles, headings, tables, paragraphs and lists) and tags to define how content should appear or behave in a web browser. Tags consist of the name of an element, with that name being surrounded with “<” and “>” on each side (for example <footer>). Additionally, HTML supports hypertext links to connect resources, and allows embedding of multimedia such as images, audio, and video.

4.1.2 CSS

CSS is the acronym name for Cascading Style Sheets. It is a style sheet language used to control the design and the way the HTML content is being represented on the web. It allows the website developer to control the layout, colors, fonts, and the overall appearance of web pages. In general, it only consists of rules that specify how elements should be styled. Overall, CSS is an essential tool for the development of a stylised website, as it offers more styling capabilities such as animations, colors and alignment features, compared to HTML.

4.1.3 PHP

PHP stands for Hypertext Preprocessor and is a widely-used, open-source scripting language designed specifically for web development. It is particularly suited for creating dynamic and interactive web pages by embedding scripts directly into HTML. PHP is server-side, meaning the code is executed on the server, and the results are sent to the user's browser. Furthermore, it supports database integration with databases like MySQL, PostgreSQL, MSSQL(Microsoft SQL Server) and SQLite, which makes it ideal for developing content management systems, e-commerce platforms, and web applications. Despite the emergence of newer technologies, PHP continues to power a significant portion of websites globally due to its reliability, scalability, and ongoing updates.

4.1.4 jQuery

jQuery is a powerful and lightweight JavaScript library that is designed to simplify tasks such as event handling, HTML document traversal and animation. This library gives developers the ability to create dynamic and interactive web applications. Its straightforward syntax is what makes it a popular tool among developers, regardless if they are at a beginner level or experienced. Additionally, when it comes to the tech industry, jQuery proves to be essential as it improves compatibility between browsers, as well as reduces coding complexity, and thus speeds up the development process. Lastly,even though modern frameworks like React and Angular have become popular among website developers, jQuery still manages to remain relevant for maintaining legacy systems and continues to be widely used across many websites and applications [11].

4.1.5 Javascript

JavaScript is a high-level and lightweight programming language that is used to create interactive content and enhance the dynamic behavior on websites. Additionally, alongside HTML and CSS, JavaScript enables developers to build engaging user interfaces by adding functionality such as animations, form validation, real-time content updates, and interactive elements. Moreover, it is a client-side language, meaning it runs directly in a user's browser and therefore is fast and reduces the load on servers. With built-in support for object-oriented programming and seamless integration with HTML, JavaScript is ideal for creating web-based applications and enhancing user experiences [12].

4.2 Website Presentation

4.2.1 Home Page

This is the home page of the online exhibition. It displays very briefly the purpose of the website. The user can also scroll down to read about the overview of the project.

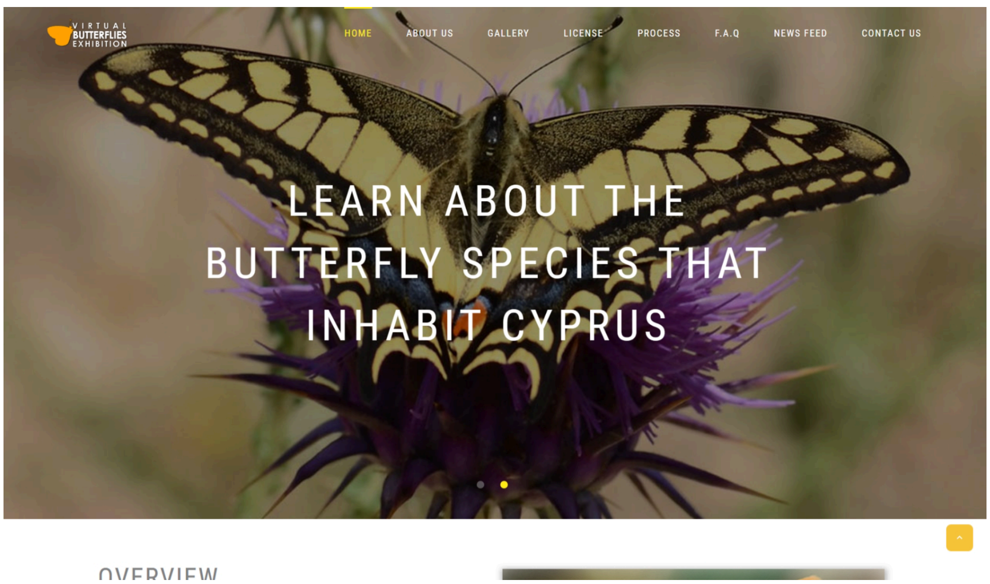

Figure 1: Home page of the website

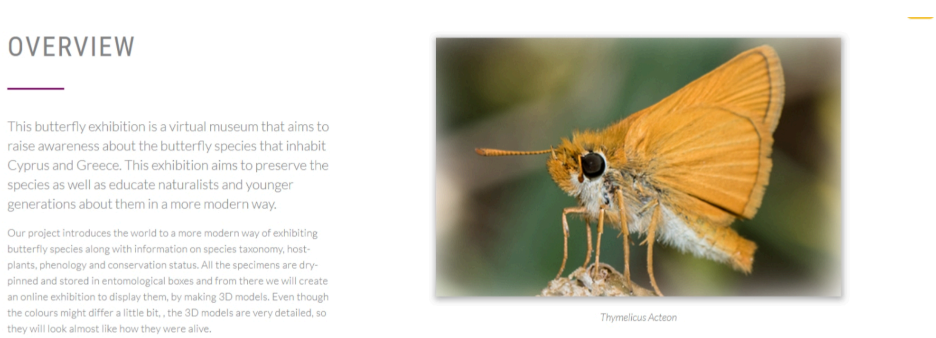

Figure 2: Overview of the project in the home page

The footer can also be seen at the end of each page, where it gives information on who funded the project and relevant information regarding the partnership with the European Union.

Figure 3: Footer of the website

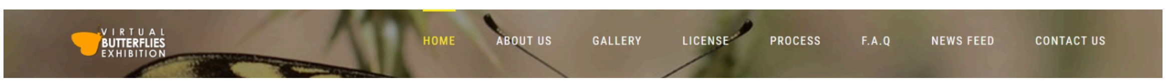

Figure 4: Navigation bar of the exhibition

At the top of each page the website's logo can be seen along with the navigation bar that provides to the user the capabilities of the website and what it has to offer. On each page the navigation bar is the same with the only difference being the color of each page's title that indicates on which page the user is on at the moment. For example in the image below, since the image was taken while being on the home page, the color of the text "Home" is yellow instead of white, compared to the other page titles.

The picture below showcases the butterfly exhibition's logo, which was carefully designed by Dr. Antreas Aristeidou and it can be seen at the top left of the exhibition in every page.

Figure 5: Logo of the website

4.2.2 About Us

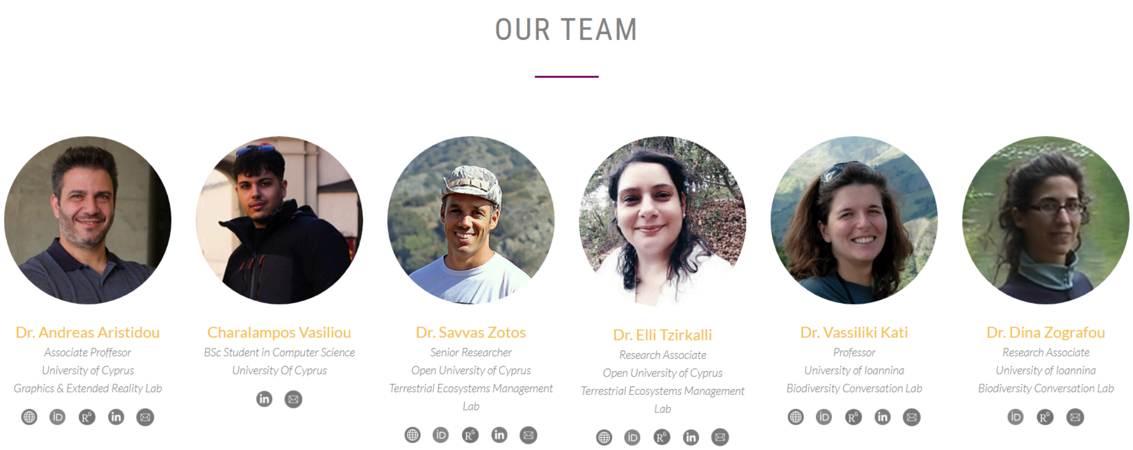

Figure 6: Display of the team that is working on the project

In this page, the user can find the members of this project, with contact information for each member. This page is also scrollable, and below the team members the user can read about the project's partners.

4.2.3 Gallery

When navigating to the Gallery section, users will see a list showcasing every butterfly species that inhabits Cyprus and Greece. Each list item features an image and the name of the butterfly, and every item is clickable. If a user wants to learn more about a specific species, they can simply click on its image to be redirected to a detailed page. This page provides information about the species, a digitized 3D model of the butterfly, and an image of it in its natural, living state.

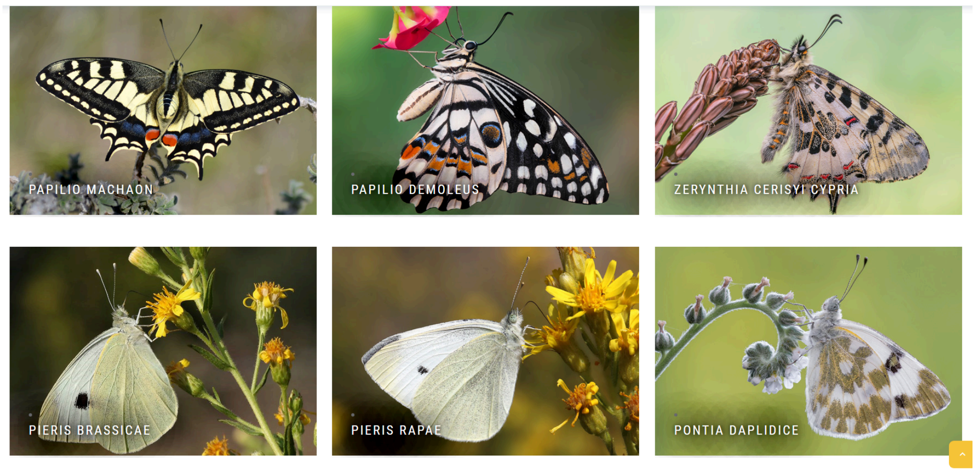

Figure 7: Gallery with all the species that inhabit Cyprus

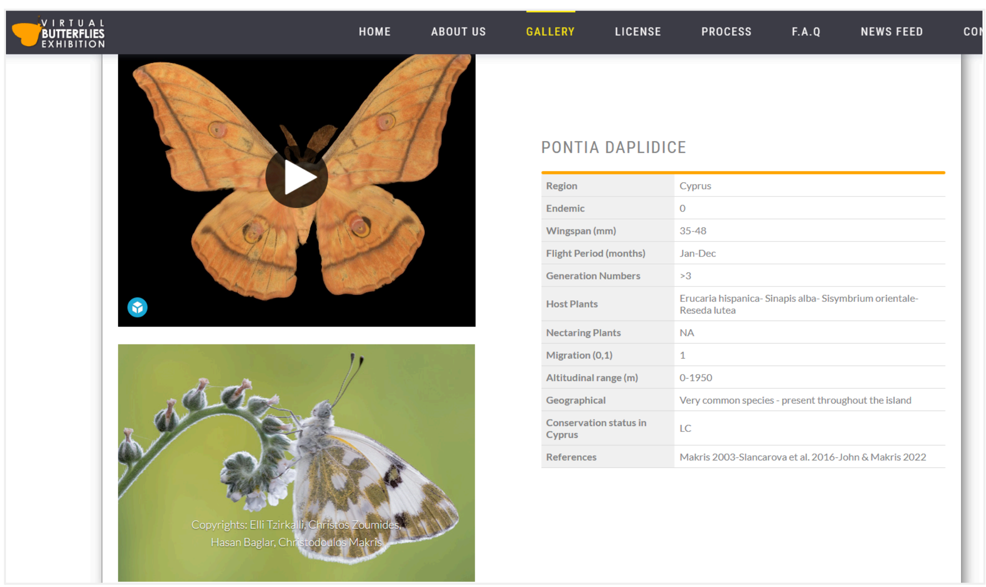

Figure 8: Butterfly details page

4.2.4 Process

This page briefly informs the users who are interested to know more about the whole process of developing a 3D object of each specimen, from the scanning process to the photogrammetry application and model cleaning.

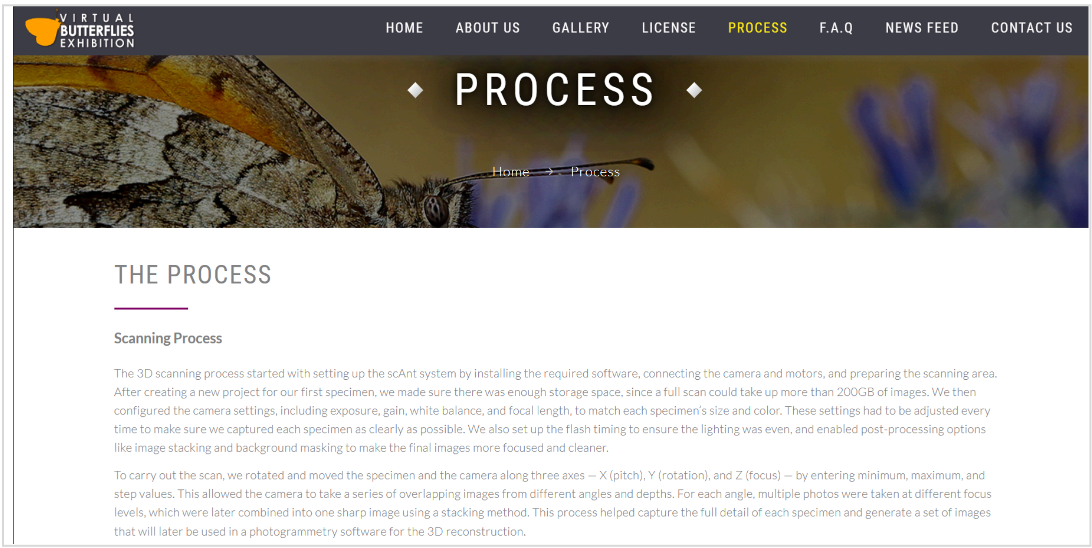

Figure 9: Process Page of the website

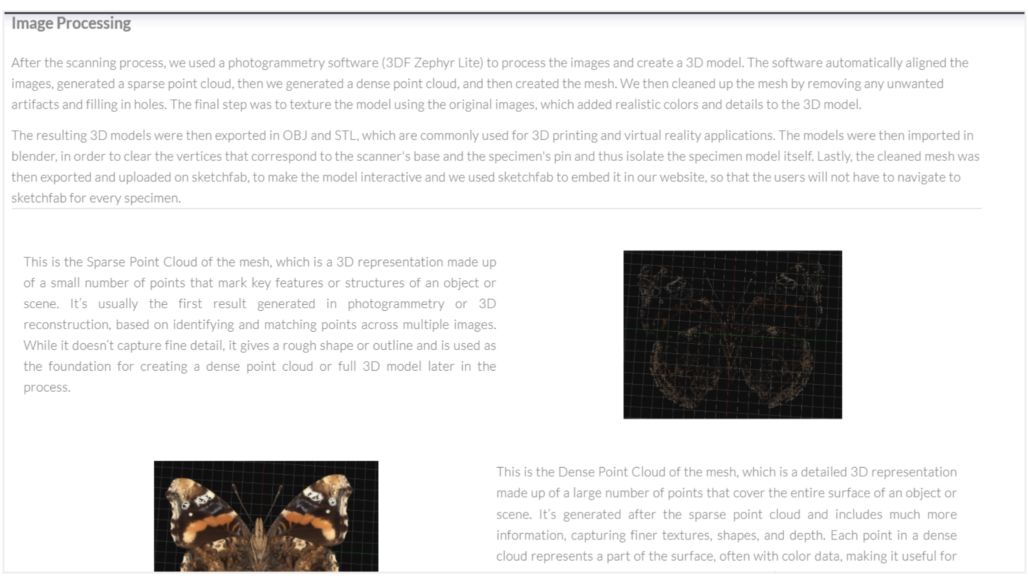

Figure 10:Continuation of the Process page

4.2.5 F.A.Q

This page currently consists of a total of 14 questions that we believe that each user might have, during their navigation on the website.

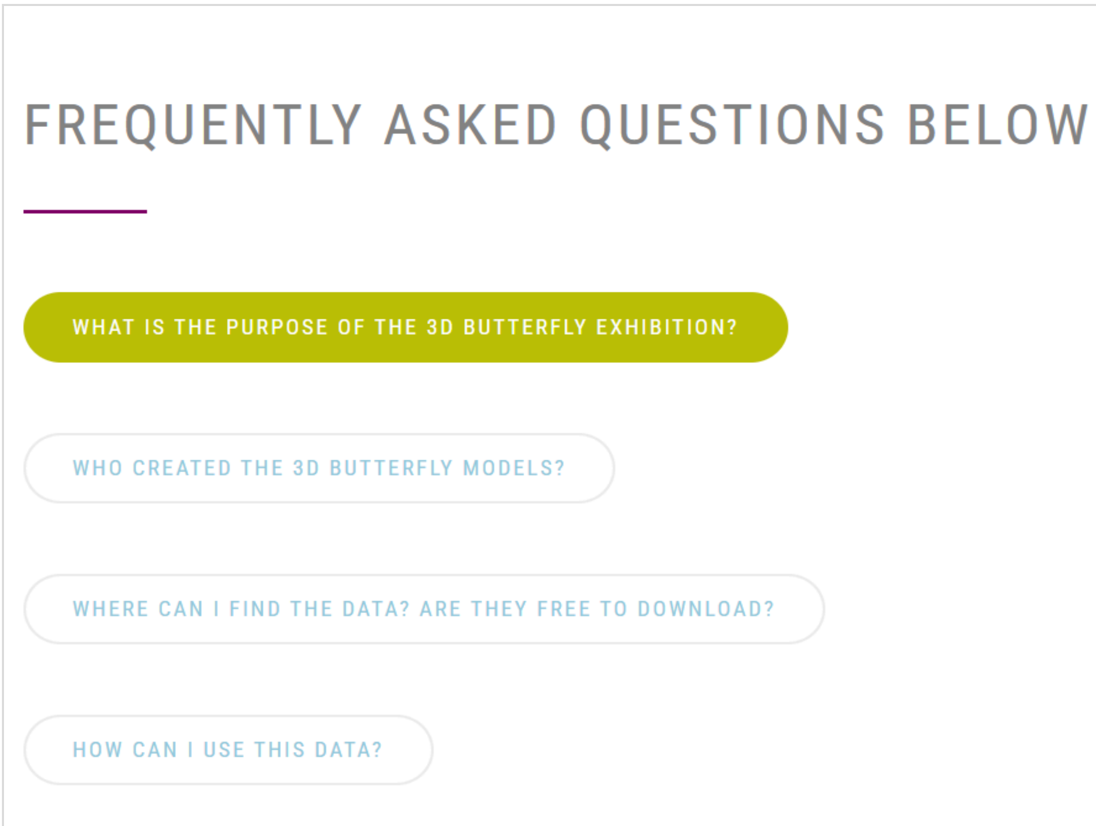

Figure 11: Frequently Asked Questions Page

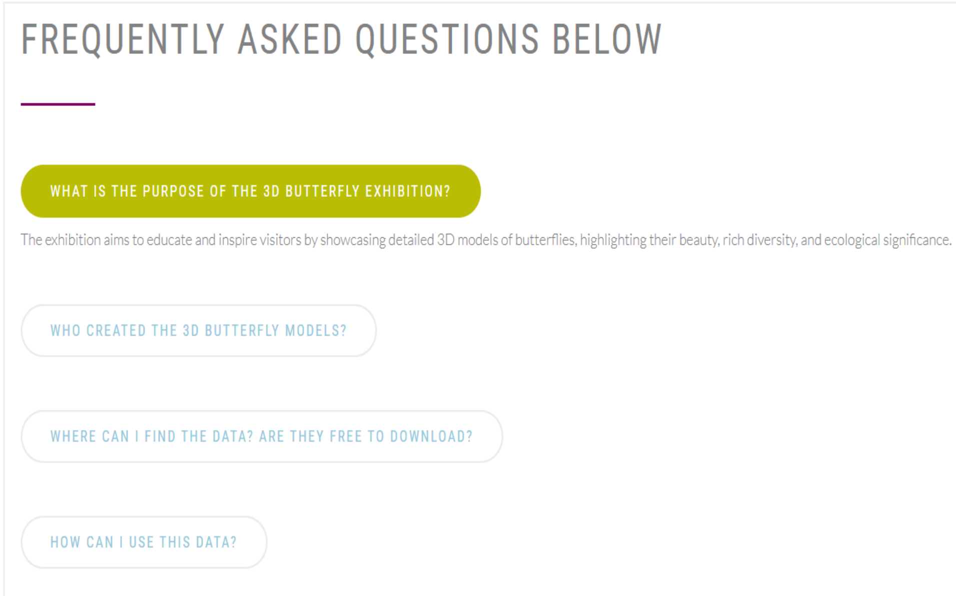

Figure 12: Frequently Asked Questions Page with expanded answer

Additionally, in the home page and process page, there is an informative section regarding the EMBRACE project, with a brief explanation of the project's motive, along with a button that navigates the user to the project’s page

Figure 13: Informational section about EMBRACE project in Home and Process page

4.2.6 News Feed

This page functions as the project log, displaying new updates and actions that occur in the online exhibition. It keeps the users updated about changes that are made.

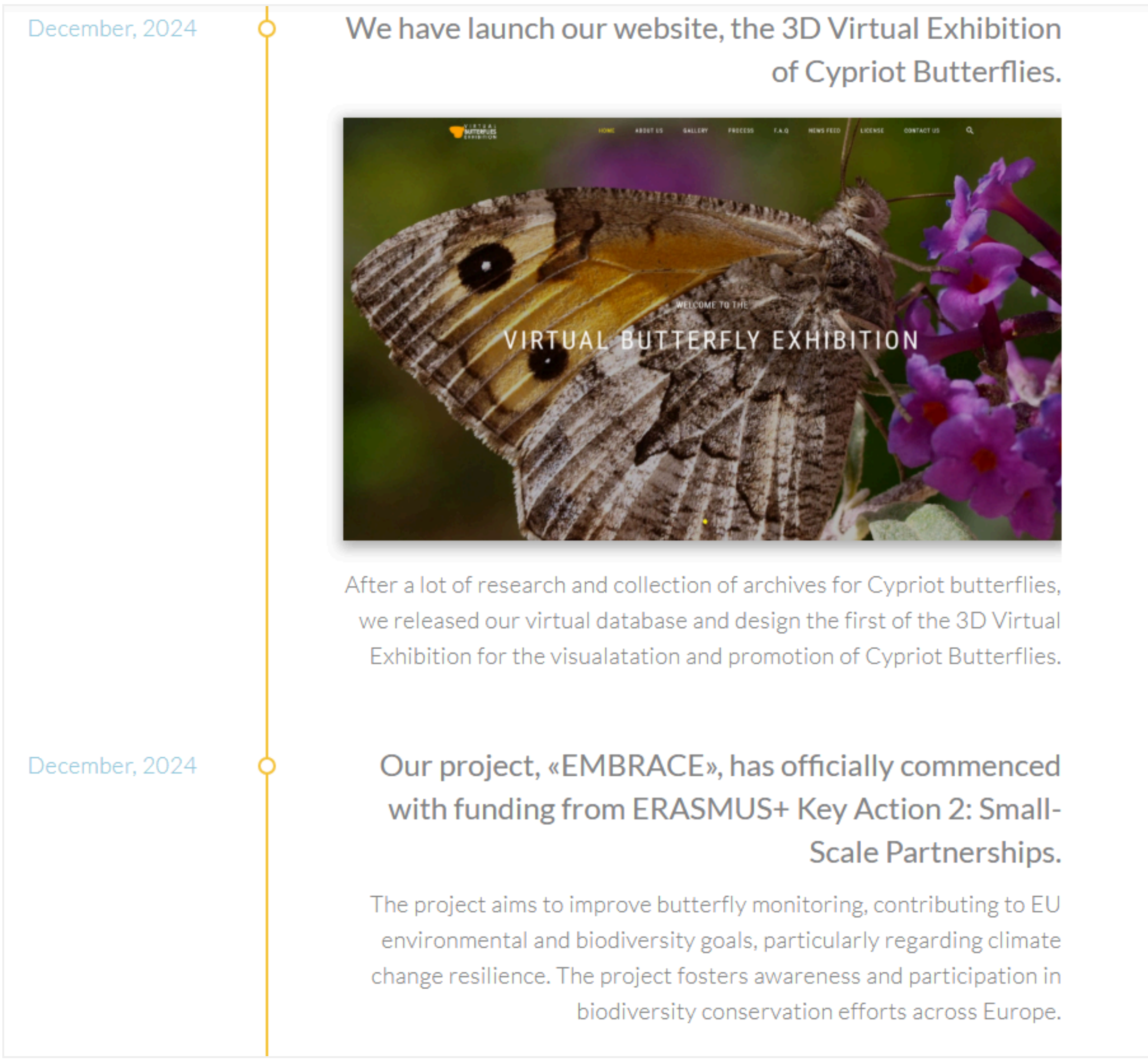

Figure 14: The News Feed page of the website

4.2.7 Contact Us

In this final page title of the navigation bar, the user can navigate to the contact us page, where he will be able to view the contact information of the main contributors of this project, as well as a location for each Centre or Laboratory that took part in this project.

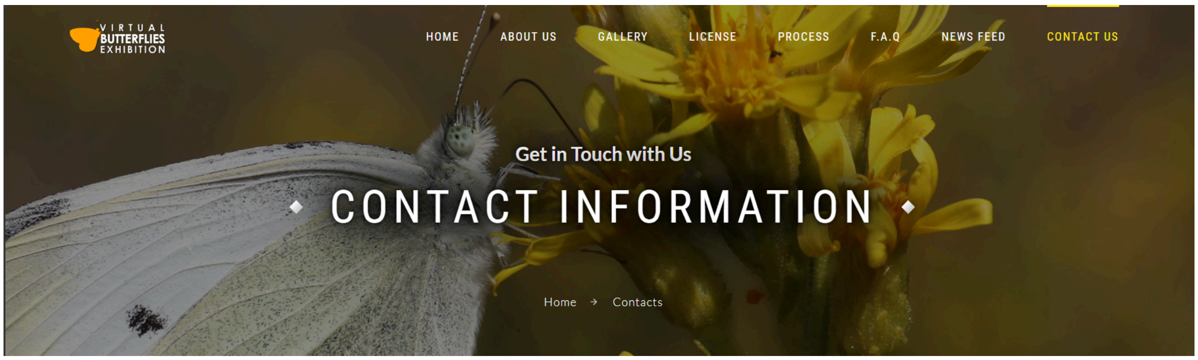

Figure 15: Contact Us Page of the website

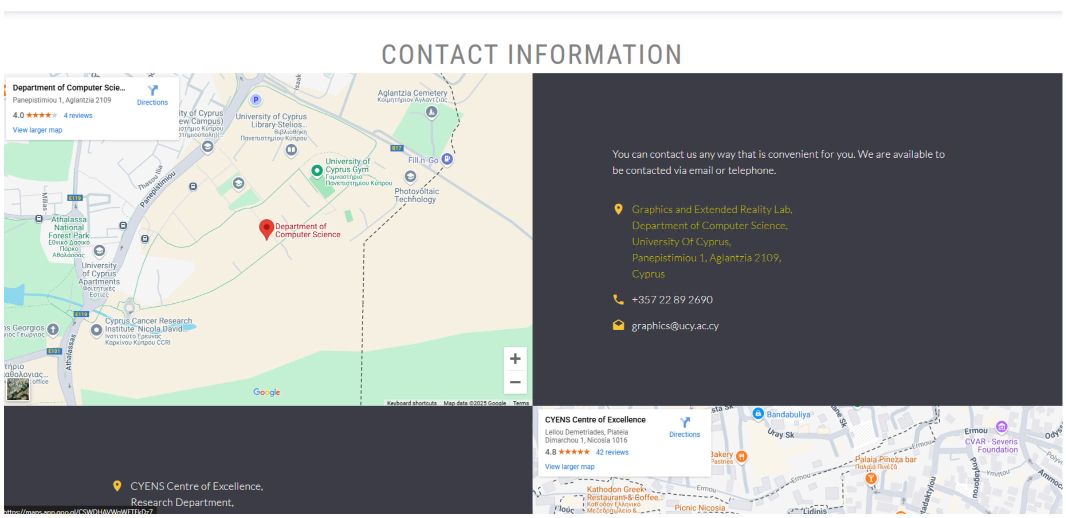

Figure 16: Continuation of the Contact Us Page

Chapter 5

Discussion of the process and results

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5.1 Scanning Process Challenges and Limitations

To a large extent, the outcome of this process met our expectations, meaning we successfully developed high-quality 3D models. However, since our 3D scanner was sourced from a Kickstarter company and we were among its first users, there was no available documentation regarding the digitization process and any relative issues that might arise with it, let alone the digitization of butterflies. This lack of guidance posed several challenges before we could produce a complete and accurate model, since there were many parameters that needed to be changed and it was a challenge to produce good results. Moreover, the variation in wing colors, with both bright whites and dark tones, made white balancing particularly challenging. As a result, the white areas were often overexposed, producing holes on the wings due to the data loss. Furthermore, one of the persistent challenges we encountered was the extremely small hair covering the butterflies. Since such detail is microscopic, we were unable to capture it with accuracy as we were not using a SLR camera. Additionally, since some of our specimens were larger in size, their wings were very close to the light ring of the scanner and consequently we were limited to how much noise we could remove from the stacked images and masks using the focus threshold. Fortunately, we maintained direct communication with the scAnt development team, who provided support and guidance throughout various stages of the process, particularly since we were the first to use the scanner for butterfly digitization.

5.2 Photogrammetry Process Challenges

Regarding the photogrammetry process, we attempted to apply photogrammetry using the images generated by the scAnt system through the RealityCapture software. Unfortunately, RealityCapture did not perform as required for our application, as it failed to properly construct the model, resulting in data loss (e.g., missing details like specimen's antennas) and significant noise in the final output. After discussions with the scAnt team, we switched to the software they recommended (3DF Zephyr),which proved to be the better choice for our needs. 3DF Zephyr not only offered a more user-friendly interface but also produced significantly improved results. Additionally, it successfully recognized the masks for each stacked image, something that we had trouble accomplishing with RealityCapture. However, even with 3DF Zephyr, we had some trouble with fixing the holes that appeared on the specimens' wings. Even though there was a filter that fills the holes of the mesh, the result was not good due to making the wings look like low poly objects and thus destroying the purpose of creating high detail models. Lastly, compared to the work that Yale has accomplished, their work also highlighted several challenges commonly encountered in photogrammetry-based reconstructions, including artifactual errors such as floating antennae, holes in the wings, and color deviations that did not exist on the actual specimens. These issues highlight the limitations of current techniques when applied to subjects with fine structures and complex textures, such as butterflies.

5.3 Sketchfab limitations

Regarding the 3D model upload, sketchfab's free plan was restricting us from uploading the model using the "Ultra" Preset, which gave us slightly better details. Consequently we were forced to lower down the quality of the mesh creation in order to not exceed the limit of the free plan. Unquestionably, the higher quality models could still be successfully created, but unfortunately we were unable to upload them on Sketchfab and display them on our website.

Therefore, through extensive trial and error, we were able to determine possibly the most optimal scanning parameters for each specimen and as a result produce great quality models with the help of 3DF Zephyr and Blender.

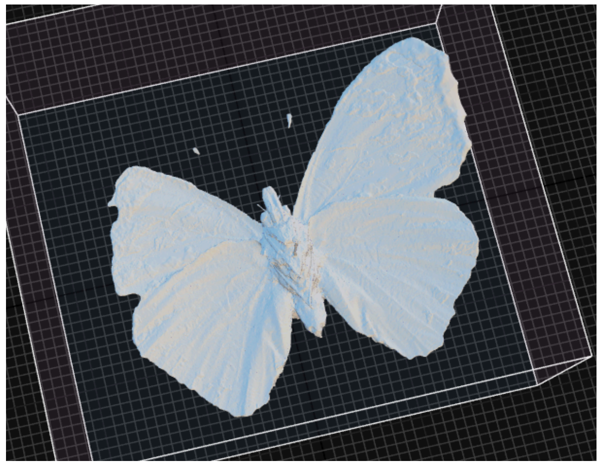

Figure 1: Reality Capture calculated model in Normal Detail

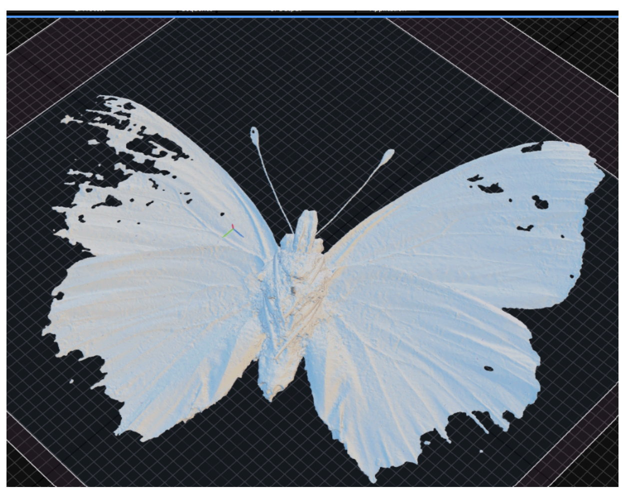

Figure 2: Reality Capture calculated model in High Detail

Chapter 6

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6.1 Overview

In summary, this project successfully achieved the digitization of Cyprus's butterfly species through a structured pipeline that combined all the data we collected and processed, the 3D models we created with high-resolution 3D scanning, and the website that served as the online exhibition.

We managed to collect the biological metadata needed for each specimen, including its traits such as distribution, endemicity, wingspan, host and nectaring plants, and conservation status. The metadata were formed in an Excel document which was then cleaned, structured, and inserted into our SQL database. Using the scAnt system, we scanned the preserved specimens using a FLIR camera, and we ensured that the lighting, and all of the parameters regarding the quality of the image would create the desired results. These images were then successfully processed with photogrammetry using 3DF Zephyr to generate high-detail 3D mesh models. Even though these models had a few holes on the wings, due to the limitations of our equipment, we managed to capture great details to each specimen's body and overall its texture. The models were then refined in Blender to remove the irrelevant parts of the mesh, such as the pin and the scanner's base. The final models were uploaded to Sketchfab and integrated into our website using PHP, thus allowing users to explore both visual and scientific aspects of each species. This end-to-end process was repeated for each butterfly, resulting in a dynamic and immersive educational platform that not only showcases the beauty of Cyprus's butterflies, but also supports awareness for their conservation. Overall, the project was a success, since we managed to produce the desired results to the highest degree that our equipment had to offer.

6.2 Future Work

6.2.1 Project's Database

This project also opens the door for future projects and developments. The database that we managed to create, which contains all the metadata for every butterfly specimen in Cyprus, along with the 3D models that we uploaded in sketchfab and then incorporated in our website, can be used for technologies like recognition apps that can be used on the field, educational games for the natural life in Cyprus for younger generations or even animated virtual environments where these butterflies could "come to life" again.

6.2.2 Alternative 3D representation of the species

Additionally, the 3D representation of the butterfly species could be approached using an alternative method to photogrammetry and 3D object creation, which is Gaussian Splatting. Gaussian Splatting is a 3D rendering technique that represents a scene using a collection of 3D Gaussians-points in space with size, shape, orientation, and color. Each Gaussian acts like a soft particle that contributes color and opacity to the image based on its position and camera view. This method enables real-time rendering of complex scenes with high photorealism by blending these splats together during rasterization. This method has gained attention for producing fast, high-quality results from image-based 3D reconstructions, and could lead to better results regarding our digital representation of the species.

6.2.3 SLR Camera

Lastly, we intend to use an SLR camera with higher specifications to examine whether it improves the results. An SLR camera could improve the digitization of butterfly species compared to the FLIR camera we used by capturing higher-resolution, color-accurate images of fine details such as wing patterns, textures, and even the tiny body hairs.

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Appendix A

Scanning Parameters per Specimen

While the general scanning setup remained consistent across specimens, certain values, particularly those related to exposure, gain, and Z-axis (focus), had to be fine-tuned based on the size, color, and reflectivity of each specimen. The table below provides a detailed summary of the parameters used for each scan.

Name	X-Axis (Pitch) Min/Step/Max	Y-Axis (Rotation) Min/Step/Max	Z-Axis (Focus) Min/Step/Max	Exposure (µs)	Gain	Flash Length (ms)	Flash Delay (ms)
Vanessa Atalanta	0/40/450	0/70/160	95/55/1305	5000	2.0	200	100
Pieris Brassicae	0/40/450	0/80/160	200/80/1800	3000	3.0	200	100
Anthocharis Cardamines	0/40/450	0/80/160	205/65/1530	3500	2.0	200	100
Hipparchia Cypriensis	0/40/450	0/80/160	0/75/1560	5000	3.0	200	100
Gonepteryx Cleopatra	0/40/450	0/80/160	250/80/1880	3000	3.0	200	100

The rest of the parameters, such as Gamma, Balance Ratio (red) and Balance Ratio (blue), were left to default value in every performed scan.

- **Gamma:** 0.80
- **Balance Ratio (red):** 1.58
- **Balance Ratio (blue):** 1.79