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DEGREE FINAL PROJECT

IMAGOartis //

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Mechatronics Engineering Degree

Supervisors: Mainardo Gaudenzi, Moisès Serra and Pere Martí

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To my lover:
for being there all this time.

Special thanks to:

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Degree final project abstract

Mechatronics engineering degree

Title: IMAGOartis //

Key words: 3D reconstruction, Reflectance Transformation Imaging, Photogrammetry, cultural heritage, open source, prototype.

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This DFP is focused on the design and implementation of a device that allows to study and analysis cultural heritage small objects. Specifically, this device, called IMAGOartis //, allows to perform automatically two distinct digital image acquisition techniques: the first is characterized by fixing the camera perpendicular to the surface to be imaged and by illuminate the scene under different angles; the other by setting the illumination perpendicular to the surface to be imaged and by acquiring images from different angles. The former setting is used to perform a computational photographic method called Reflectance Transformation Imaging (RTI) [1]. The latter setting allows to obtain images that can be used for photogrammetric reconstruction to obtain 3D digital models. Both methods are used in several application fields where the study and analysis of surface morphology is needed. Being both methods non-destructive and non-invasive, these have been adopted by cultural heritage science.

As for the RTI method, the set of images acquired by using the IMAGOartis // device are processed by using the non-proprietary, open source software RTIbuilder. As for the 3D reconstruction, the device is capable to transfer in real time and wirelessly the images to the computer during the acquisition process and execute a 3D reconstruction using the non-proprietary and open source software COLMAP [2].

The use of two non-proprietary and open source softwares to perform the image processing tasks is intentional, as the IMAGOartis // falls under the umbrella of the open hardware concept, that means that the original hardware design is freely available for future replications, implementations and/or customizations.

Indeed, the IMAGOartis // follows the development of IMAGOartis, a device developed during the Integrated projects II course at the UVic-UCC [3] and that was implemented within the EU funded project smARTS at the MECAMAT research group [5] under the supervision of Dr. Gaudenzi. The original device was only able to perform semi-automatic image acquisition process for RTI method. This new version represents an innovative advancement, as it allows to add another imaging acquisition technique (for the 3D reconstruction), shows a full automatization of the acquisition process and as for the photogrammetric reconstruction, of the image processing step, and a new and original mechanical and electronic design conceived to allow future implementations by easily change both imaging and illumination systems.

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1. INTRODUCTION

IMAGOartis //, as the title hints, is the second part of a previous project. I will explain a little bit about that project on these pages to have the same background that I had at the beginning of the project. The project name is IMAGOartis and it is from the subject Integrated Projects II from the mechatronics degree at University of Vic.

IMAGOartis was a project developed last year for three students of mechatronics engineering, Jaime Aparicio, Jungie Zhu and I, Eric Sabariego. Our project was into smARTS project which is a project founded by the European Union Horizon 2020 [6] program and hosted into Mecamat research group of University of Vic. The smArts project focuses on prototyping low cost and open source hardware and software technologies for mapping analyse and monitoring materials on the field of heritage science. Our project merges smARTS target to Integrated Projects II aims.

Our machine allows users to automate the image acquisition for a Reflectance Transformation Imaging reconstructions, most commonly known as RTI reconstructions. RTI technology consists into capture an object surface shape and colour using the reflectance that a controlled light creates into the object. RTI enhances and reveal surface information that is really hard to see under direct empirical examination of the object.

The device created on this project is able to change the illumination environment of the object and then you can take a picture with a camera attached at the top of the device. Then, using the images obtained and the software RTI Builder [7] and RTI Viewer [8] you can obtain a fully functional RTI reconstruction.

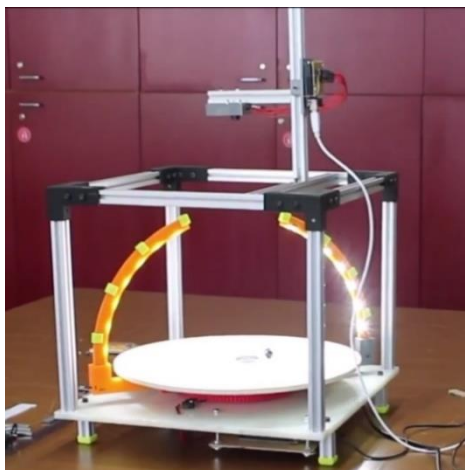


Fig. 1 IMAGOartis. Image extracted from Youtube.com [4].

Although IMAGOartis is a device fully functional and capable to make RTI reconstructions the process is not as much automatic as it could be because you have to make the rotation with the device control software and then take a picture with the camera control software or It also has mechanical issues like the vibration of some parts of the device during the rotation. In this aspect, IMAGOartis had a lot of things to improve and if we wanted to share our project and make it useful to everyone who needs it, these problems had to be solved.

After finalizing that project and while I was starting the subject called Computer Vision [10], I was thinking about aims my final degree's project into a machine capable to make 3D reconstructions using photogrammetry [9]. For this reason, I started as soon as possible to investigate how photogrammetry works and search open source software that generate photogrammetric 3D reconstructions. At the end of the subject Computer Vision, other students and I, presented a study of how a specific photogrammetry 3D reconstruction software called COLMAP works and the results we obtained using it [11].

Once obtained this knowledge I can start working on my final degree's project because I know already how the software works and also how the mechanic part should be. First of all, I had to define the objectives of this project clearly to reach a good work.

The objectives of this project were defined as the following ones:

- Obtain a device capable to take optimized images for pieces 3D reconstructions.
- Develop a software that controls the device and also allow you to make the 3D reconstruction.
- The device and software should be as much automatic as possible.
- It must be an open source project, that means open software and open hardware.
- The device should also be able to make RTI reconstructions.
- And finally, we want to show a real application of the device.

As a Mechatronics degree final project, is wanted to show the experience and knowledges learned during all the courses merging the mechanics, electronics, communications and programming into this encouraging project. Also, is wanted to work with the pressure of have a functional device with real results as a step into non-academic projects.

2. THEORETICAL KNOWLEDGEMENTS

2.1 *Reflectance transformation imaging*

The Reflectance Transformation Imaging (RTI) is a computational photographic method used to capture the shape and colour of an object surface imaged under different illumination angles. The images obtained are then merged in a single 2D image that can be explored by interactively changing the illumination. The RTI method also allows the mathematical enhancement of the object surface shape and colour attributes.

By using the free and open source software RTIBuilder, the RTI images are created from an image dataset where the object to be scanned is in the same position and the only variance from each image is the lightning position and orientation. In each photograph the light is projected from a different place and direction. This process produces that the object shows different shadows and highlights at every picture, so allowing the user to appreciate its shape with high detailed level.

RTI images can be explored with a specific free and open source software called RTIViewer that enables the user to modify the illumination position and intensity according to the area and/or the pattern analysed. RTI was invented by Tom Malzbender and Dan Gelb, research scientists at the Hewlett-Packard Labs. A landmark paper describing these first tools and methods, named Polynomial Texture Mapping (PTM), was published in 2001. More insights about PTM can be find at the Tom Malzbender's Google Docs site.

Mathematically, the direction that is perpendicular to any given surface is represented by a vector called normal. This vector is perpendicular to the tangent plane.

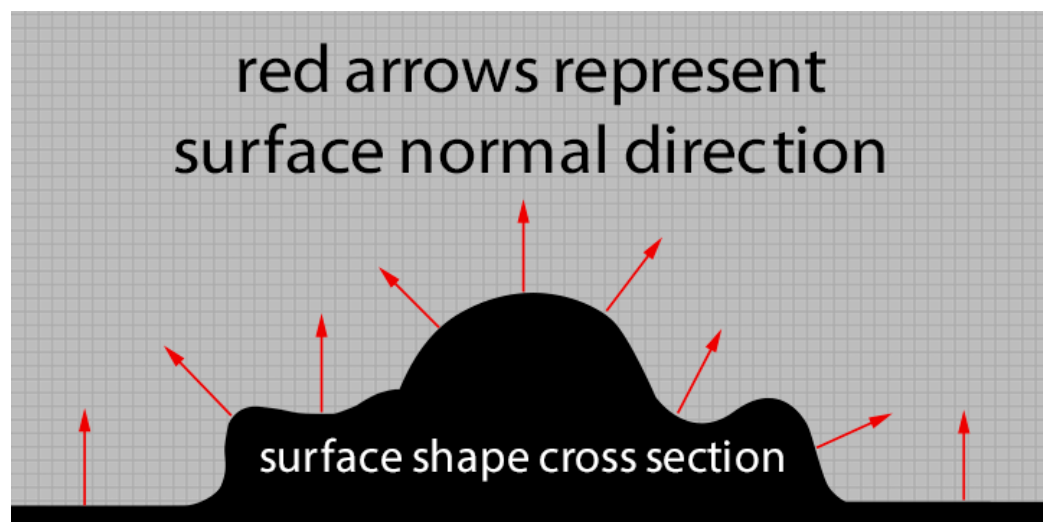


Fig. 2 Surface shape cross section. From culturalheritageimaging.org [12]

When lightning is applied to a surface, light bounces off into the surfaces of the object with an incident angle and a reflectance is produced by the object depending

on its normal at that point of the surface. Since camera is in a fixed position and position of lightning is known at every moment, RTI software can calculates the surface normal per pixel in the image.

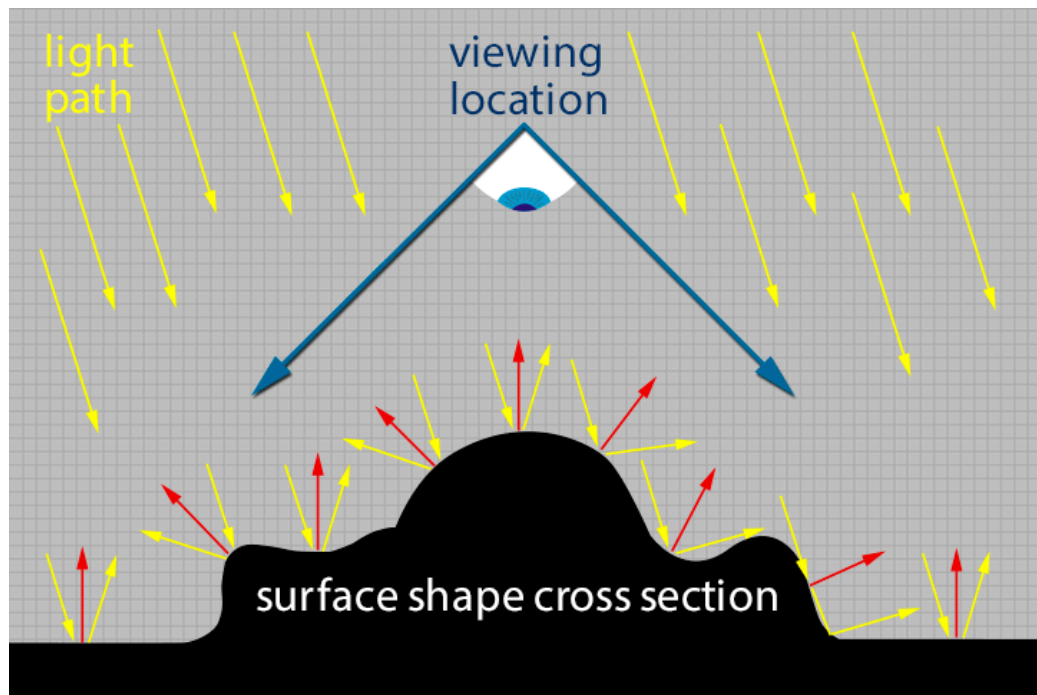


Fig. 3 Light reflectance. From culturalheritageimaging.org [11]

The mathematical description of the normal is saved for every pixel of the image, along with the RGB [12] colour information of a normal photograph. This ability to record every pixel normal with the colour of each pixel allows to the user to see the real 3D shape of the object and that is what makes RTI a powerful tool for cultural heritage study and documentation.

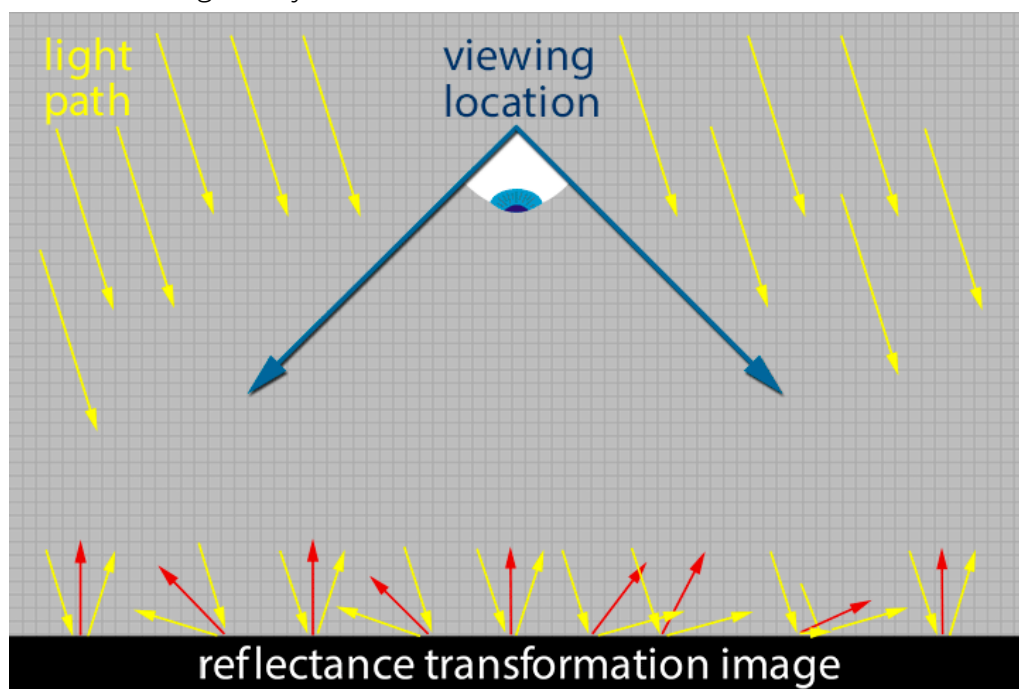


Fig. 4 Reflectance transformation image. From culturalheritageimaging.org [11]

2.2 *Structure from motion*

This technique is a prevalent strategy for 3D reconstruction from collections of unordered images. The process consists in reconstruct a 3D structure from its projections into series of images taken from different viewpoints. Structure from Motion (SfM) algorithm used in this project is that proposed by Johannes L. Schönberger and Jan-Michael Frahm from the University of North Carolina (USA) and the Eidgenössische Technische Hochschule of Zürich. The source code is freely provided to the research community as an open-source implementation named COLMAP.

The SfM process is performed in two stages. First, the stage named Correspondence Search, which consists in finding pairs of images that show common points and verify if this information is true. Second, the Incremental Reconstruction stage, which is an iterative method to calculate exactly where these points are.

Correspondence Search

The aim of this stage is to find the correspondence between images by looking for scene overlaps and identify projections of the same points in the overlapping images. This stage contains the steps Feature extraction, Matching and Geometric verification

Incremental reconstruction

As for this stage, the algorithm of SfM defines a structure as a set of points on a 3D environment. This stage contains the steps Initialization, Image registration, Triangulation and Bundle adjustment.

The major issue of SfM is that it needs a lot of images to reconstruct a scenario completely. However, it must be recognized that there are always some occluded points or some images that cannot be geometrically verified.

The algorithm used in COLMAP improves some aspects of the current algorithms. These improvements achieved with COLMAP are explained in the final project of Computer Vision Subject presented by the author of this Degree Final project [10] and in the paper Structure-from-MotionRevisited [14].

2.3 *Multi-view Stereo*

The Multi-view Stereo (MVS) method used in COLMAP is a method proposed by Johannes L. Schönberger, Enliang Zheng, Marc Pollefeys and Jan-Michael Frahm from Pixelwise View Selection for Unstructured Multi-View Stereo [15].

Their method performs the MVS with pixelwise view selection for depth/normal estimation and fusion. With these features it is possible to perform a graphic model of the 3D world scanned using photogrammetry.

As a first step, this method applies a normal probabilistic estimation to each image. Then, it makes an assumption of a possible environment, and later integrates different terms of each point into the cloud of points to find the percentage of probability with regard to the supposed environment. This process iterates in order to perform a better reconstruction and have a more robust and accurate model. Moreover, the outlier points are filtered in order to obtain a fully inliers dataset which is geometrically and photometrically stable.

Then, the algorithm generates from zero all the point cloud that can then be coloured for visualization purposes and. Since the points already have its normal, we can directly apply meshing algorithms as an optional step.

These intermediate steps are explained in depth in the final project of Computer Vision Subject presented by the author of this Degree Final project [10] and in the paper Pixelwise View Selection for Unstructured Multi-View Stereo [15].

3. METHODOLOGY

3.1 *Open-source project*

Each program used for this project is a non-proprietary and open source [16] software. As the IMAGOartis // falls under the umbrella of the open hardware concept, that means that the original hardware design is freely available for future replications, implementations and/or customizations.

It is considered that thanks to this open approach, the knowledge creation and sharing implements exponentially the birth of new ideas and, as for our application field, contributes to the enhancement of preservation strategies for the cultural heritage.

3.2 *Prototyping*

Once this project was purposed, its aim to implement an automatic performance of photogrammetry reconstructions and RTI reconstructions. Following the open hardware approach, the device was not designed to be a final product and it is made with the materials available from the university laboratory.

Using the open approach as the backbone methodology also allowed to make the prototype cheaper and provide the opportunity to other developers and makers to replicate, upgrades and/or customize this device by using other materials and/or mechatronics components. Even more, the design and development of this prototype represent a unique opportunity to demonstrate that it is possible to develop a scientifically reliable low-cost automatic reconstruction device.

3.3 *Trello task manager*

During the project, the Trello platform was used in order to manage the tasks done and to complete. Trello is a web-based project manager software that allows you to create tables and cards such as the Kanban method. This software has been chosen because of its high versatility and easy to use, both characteristics already proved by the author of this work during the development of the original IMAGOartis device. The tasks were divided into research information, mechanical design, electrical design, programming, construction and documentation. Even more, Trello allows allow real time sharing, a characteristic that allowed the supervisors check the work progress during every step of the project.

4. MERGING TECHNOLOGIES

This section contains the explanation of how the device was designed and why. Do please refer to the previous section on working methodology in order to understand the decisions taken during the project prototyping phase.

4.1 Hardware

It has to be noted that the decision about the type of hardware to be used in the project was originally taken at the very beginning, but during the weeks, the design changed significantly and the result is very different from the original idea.

Both open-source project and prototyping project working methodologies were applied in order to plan the device design. By combining these two methodologies, the final device resulted easy to build, easy to change, easy to adapt to new solutions, and allows a low-cost replication.

4.1.1 Mechanical part

Mechanics are among the most important parts of the project, and where a lot of time and energy were spent. As already said, at the beginning of the project the idea was to maintain the original IMAGOartis design and make little modifications of it, such as an arm showing radial rotation. Notwithstanding, the upgrades and changes have been applied to the whole design.

4.1.1.1 Base

In order to be able to make reconstructions of many different types of objects, the base area where these are located was fixed to 400 mm. Considering that the device has been explicitly designed for cultural heritage science applications, a specific attention must be given to the valuable and fragile nature of the objects to be scan. As for this reason, the base should not move and not shake the object during the scan operation.

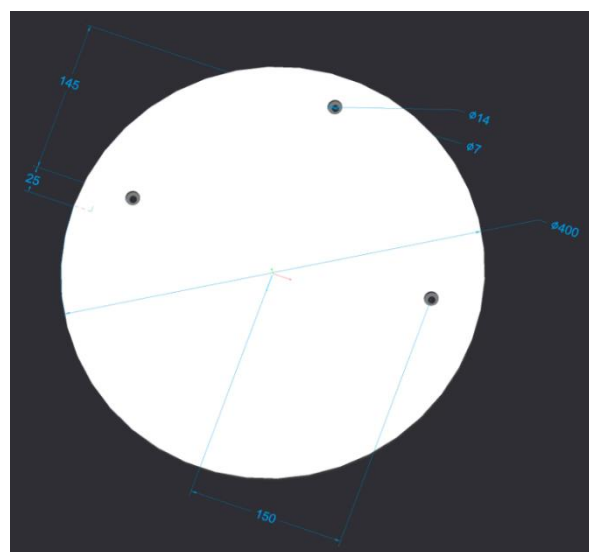


Fig. 5 3D design of base part. Extracted from PTC CREO Parametric 5.0.

4.1.1.2 Rotations

As the aim was to obtain images from every possible angle, an in-depth research about suitable rotation systems able to perform a 360° image acquisition was done. To obtain a good quality image acquisition, the images must be taken symmetrically. This means that the images must be acquired at the same distance from the object, so to perform a spherical image acquisition in which the object to be scanned is ideally located at the centre of this sphere.

This spherical model of image acquisition can't be achieved 100% because the object must be placed on the base, that means that at the base level the camera cannot take valuable images for the reconstruction. Obviously, if the base could be avoided, all images would be relevant for the reconstruction. As this cannot be done, it is correct to talk about hemispherical imaging method, rather than spherical.

Resuming, the image acquisition must be performed from the same distance to the center and by using the hemispherical method. To perform the hemispherical movement of the camera or the illumination system, the hemispherical model must be decomposed into minimal rotational movements, which means less rotation axis and, consequently, less motors.

As for the rotation system, it was decomposed into horizontal movement, described for rotating into Z axis, and radial movement, described for rotating from X-Y plane to Z axis, most commonly known as spherical coordinate system.

This system is described by the following equation $p(r, \theta, \phi)$. In this case, “ r ” is always the same number, the distance of the object to the camera or illumination system.

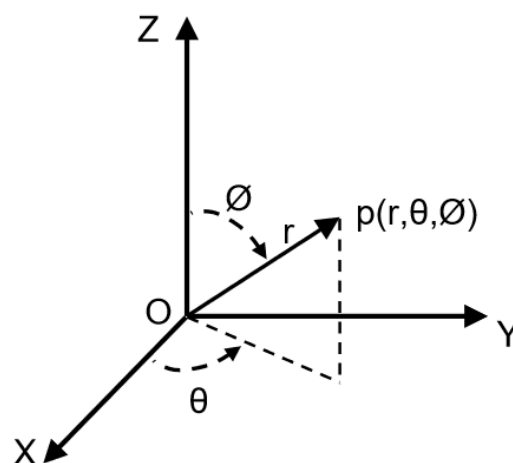


Fig. 6 Image extracted from P-SR-2S-M2-CA from Robotized Systems subject, University of Vic [17].

Radial movement study

The original IMAGOartis does not show radial movement because RTIBuilder merges the image dataset to simulate missing images. For this reason, at the time of designing the IMAGOartis it was decided to not apply this function. In contrast, IMAGOartis // needs this type of rotation and a brainstorming was done to design this new radial movement.

Strap design

At the very beginning, strap design was thought to move the supports, camera support or illumination system support, through the arm. It uses a motor, a gear and a strap to guide the supports. Finally, this design was discarded very quickly because does not ensure than the camera or illumination system faces to the center of the sphere.

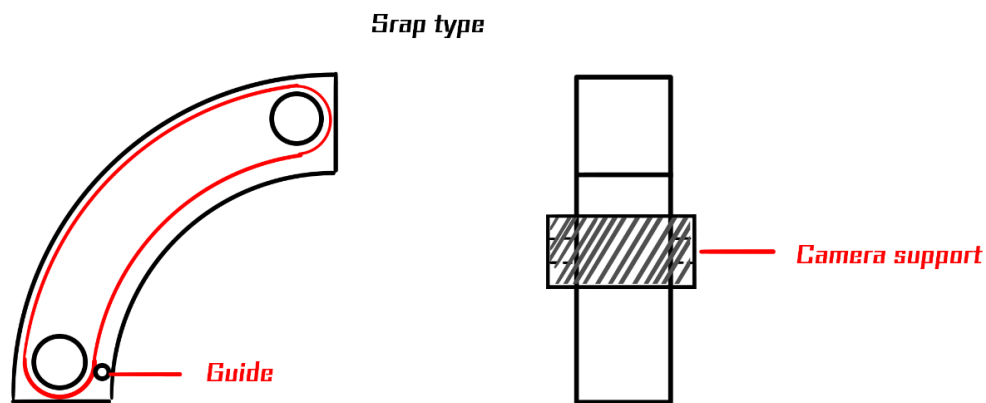


Fig. 7 Sketch of radial movement, strap design.

Arc desing

A two-arms arc design was initially conceived to give stability and to ensure that the camera and/or the illumination system are oriented towards the center of the ideal hemisphere. This design expects two motors whose rotation distance must be exactly the same, otherwise the camera and the arm can be exposed to unnecessary forces. Even more, it results that this is a more expansive choice.

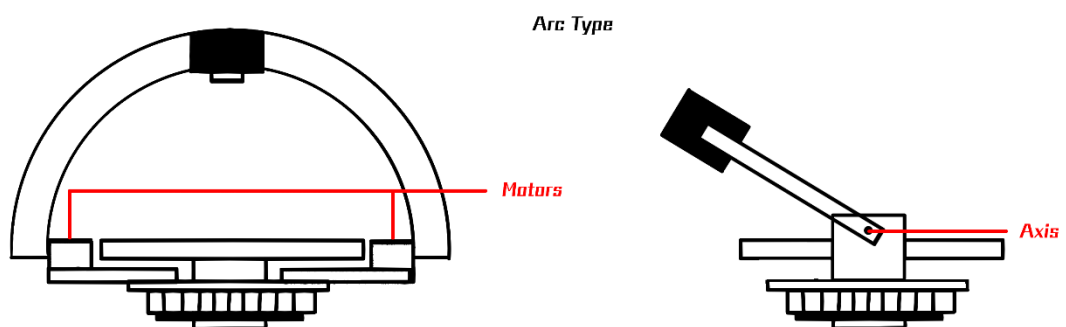


Fig. 8 The arc design: Sketch sketch of the radial movement, arc design.

Radial design

Given the observations on the arc option, an alternative and more functional design that allows to perform a radial movement has been chosen. This choice was based because of several reasons, among others the fact that the camera utilized for this project does not weight more than 200g, so it can be easily supported by an ABS plastic arm having the correct filling percentage. Moreover, this design does not need two motors to accomplish the rotational movement and allow a correct orientation toward the center of the hemisphere.

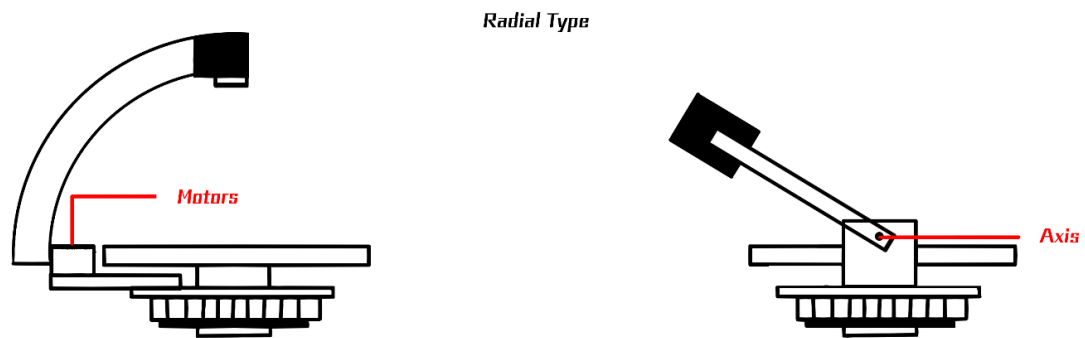


Fig. 9 Sketch of radial movement, radial design.

Although this design has been considered the best option, a certain number of crucial aspects need to be solved. The distances need to be calculated and manufactured perfectly to ensure an exact orientation of the imaging/illumination system toward the center of the hemisphere. Moreover, a powerful motor is needed to support the weight of the arm at 0° or 180° when in standby mode. Considering these issues, this design resulted as the better option to get the radial movement conceived for the IMAGOartis // device.

The result is an arm having form of an arc subtending a 90° angle with respect to its hypothetical base and with a radius of 208 mm in order to keep 8mm of security distance from the base when while the arm is at 0° or 180° .

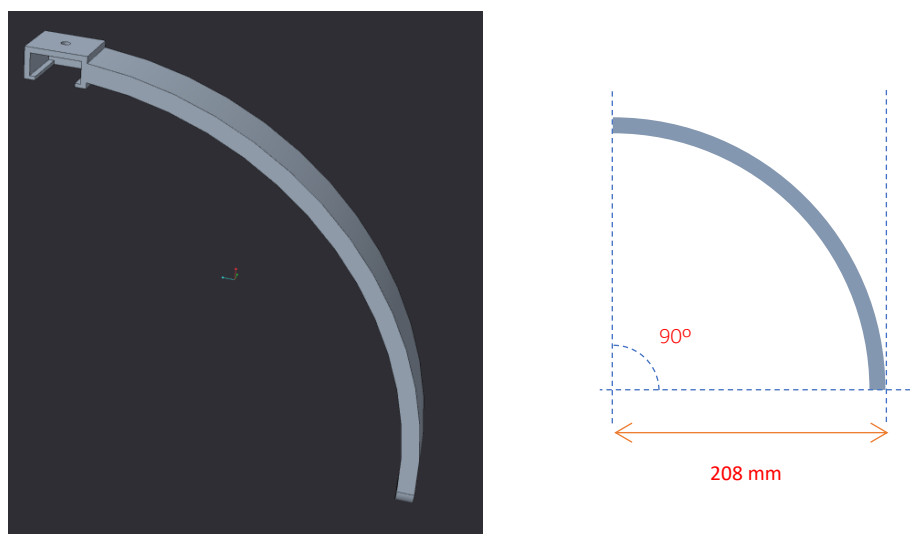


Fig. 10. Left: 3D design of the arm part, extracted from PTC Creo 5.0.
Right: design showing the 208 mm radius.

Horizontal movement study

The original IMAGOartis uses a simple stepper motor for the rotation of the arms using two gears. However, the main problem of this design is the lack of bearings in the rotation system that produces a huge friction, besides the noise produced by the gears when rotating. Therefore, as an important implementation, the friction must be reduced to avoid excessive vibrations of the scanned objects when performing image acquisition process. Furthermore, it is very important to solve the excessive noise of the machine in such a way that can be used in laboratories or special places such as museum areas, where loud sounds shall be avoided.

To solve these problems two key points were defined to design a new and appropriate horizontal movement:

- Bearings need to be used to reduce friction
- No gears can be used without a strap transmission system.

But following these key points, the vibration and the noise have been removed from the horizontal movement system.

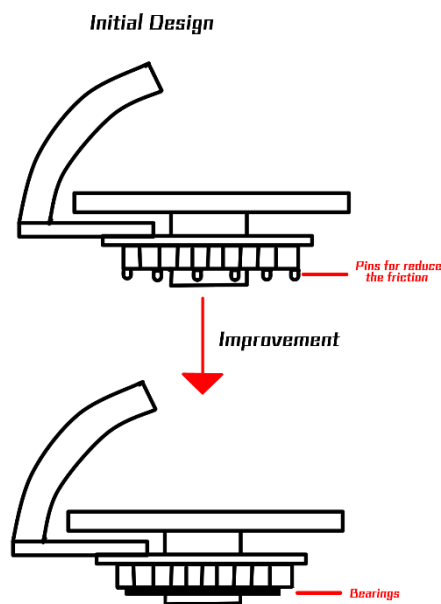


Fig. 11 First horizontal movement sketch where bearings are included into the design.

In order to find the best and simplest way to perform an accurate, vibration and noise free horizontal movement, different options were explored. Three suitable approaches were defined and exploited, as described in the next sub-sections.

Sliding arm design

This design should reduce the noise and vibrations considerably, but it also reduces the accuracy of the horizontal movement because this kind of wheels can slide into the guide and cause highest errors on the horizontal movement.

Another option could be that the two wheels move simultaneously to opposite directions. To make possible this kind of movement, two motors are needed, or one motor and a gear system to invert the movement of the two wheels.

Finally, this design was discarded because it makes the system much more expensive and complicated and it does not add any implementation.

Possible Design

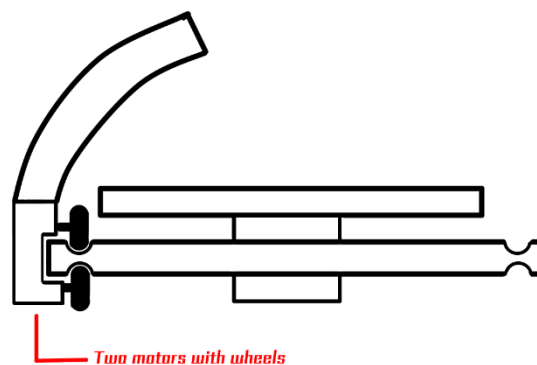


Fig. 12 Sketch of horizontal movement, sliding arm design.

Jordi's approach

After a meeting with Jordi Serra, a new design was proposed. Straps will be used to perform the transmission between the motor and the arms support. As described before, and by putting a bearing down arms support, this allows to lower considerably the noise and to reduce the friction. .

Moving the base supports to the sides makes possible to fix an axis at the center of the base, which makes it easier to attach the bearings to the arm support.

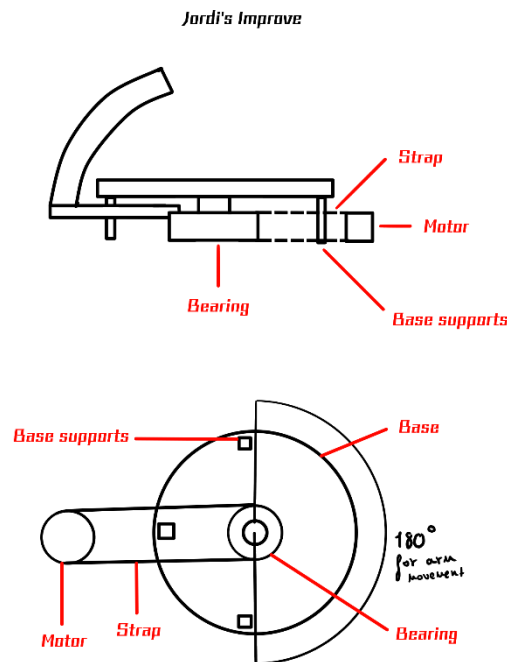


Fig. 13 Sketch of horizontal movement, Jordi's approach.

The final design

The actual design for the implementation of the IMAGOartis // was chosen because is the simplest design: no gears, no straps, just a motor and its axis, as well as bearings to support the arm mount part while rotating. Although this was considered the best option, this design needs a very precise and powerful motor to move the whole system without any transmission system. How this issue can be approached is explained in further sections.

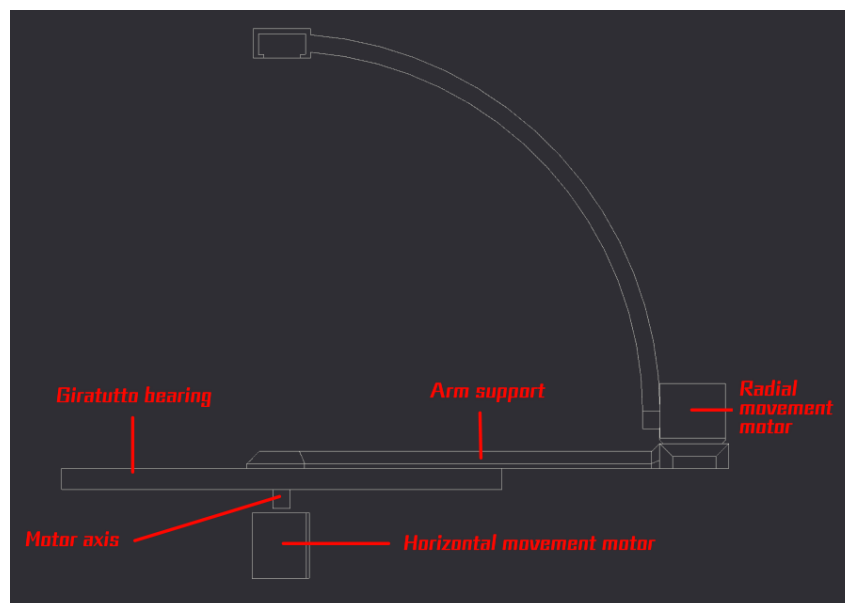


Fig. 14 Sketch of horizontal movement, final design.

Arm holder allows to transfer the rotation from the axis of the motor to the arm side, the motor support is attached to this part. Also the bearing system is a half part of swivel bearings provided by the University of Vic.

Going back to the hemispherical model, it is possible to observe that in the designs, only 50% of the area is supposed to be scanned. This issue is addressed in the following sections. The images are provided just to make more understandable the concept. It is necessary to consider that this is a prototyping project aimed to demonstrate that this device can allow to perform correct image acquisitions in an automatic way.

4.1.1.3 Illumination and camera holder

Taking into account the easy-to-replicate concept at the base of the open approach adopted, the holders of the camera and the illumination system need to be easily replaced. Moreover, as the device is designed to perform both RTI and photogrammetric 3D reconstructions, there is the need that the camera and the illumination system can exchange their positions easily. For this reason, a system made of “plug and play” parts was designed to make these changes easier.

Even more, it is very easy to create new holders according to the end-user needs, and to fix these to the two designed arms.

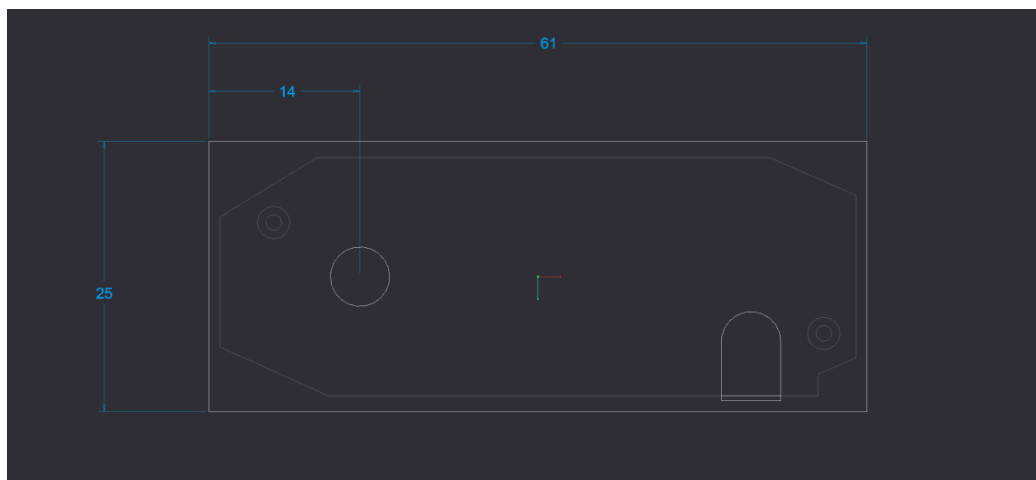


Fig. 15 Camera support scheme. Extracted from PTC CREO Parametric 5.0.

The base for the design of the camera and illumination system holders is a square of 25 x 61 x 10 mm with a hole of 5,5 mm of diameter. These dimensions fit with the rotating arm and with the fixed arm. The only dimension that can be slightly changed is the length of the holder (61 mm), because this distance does not need to be fixed. Even though, care must be taken because a too large holder could hit the base during image acquisitions process.

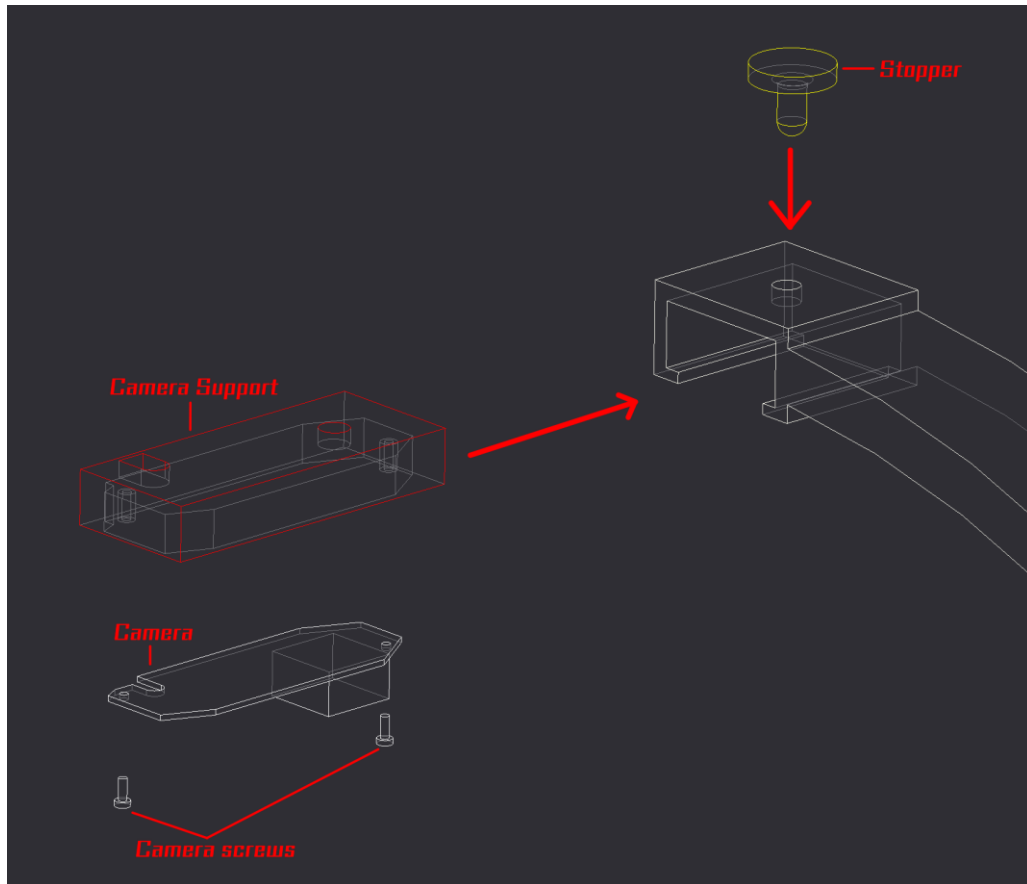


Fig. 16 Sketch of “Plug and play” system.

On the one hand, and as explained before, the rotating arm is designed to keep always the item oriented toward the center of the hypothetical hemisphere, where the object to be scanned is located. On the other hand, the fixed arm always stands above the analysed object, whatever it holds the camera or the illumination system.

Following these standards, it should be easy for end-users to create new holders for different type of cameras, illumination systems or other things that one would attach to the device's arms according to the analytical needs.

4.1.1.4 General purpose holders

By explaining the spherical coordinate system, it can be supposed that the device would have been able to perform its imaging tasks all around an hypothetical spherical environment. Obviously, the need for a base where to place the objects, changes this theoretical perspective, and the environment is reduced to only the half of a sphere of 400 mm diameter, that is the diameter of the base. Although, as for the prototype here presented, only the general-purpose holders were built, with few modifications on motor and illumination holders it can be possible to implement the imaging area from the hemispherical up to almost a spherical environment.

First of all, the motor holder actually in use by the final prototype, fixes the axis of the radial movement motor to the surface of the base, thus obtaining a fully centered rotation. At the same time, the illumination holder is located enough high to prevent collision between the fixed and the rotating arms.

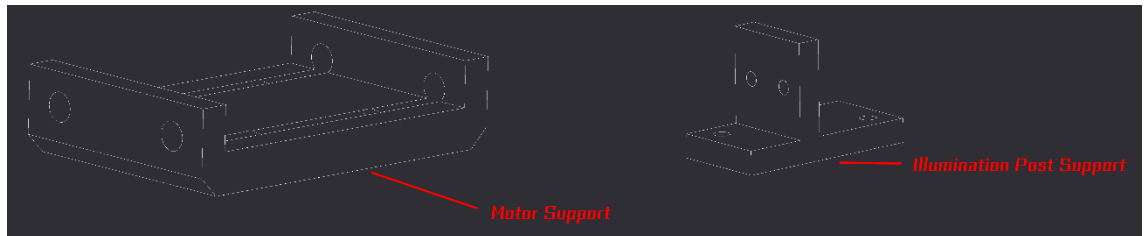


Fig. 17 3D model of Motor support and Illumination post support. Extracted from PTC CREO Parametric 5.0.

Indeed, in order to make this kind of upgrade to the device, and just considering 3D reconstruction performance, first of all there is the to develop a holder that allows to take pictures of the bottom side of the scanned object without blocking the camera movements or affecting the image quality. This means that a new holder must be created to stand up the object and to make possible the arm rotation. By, increasing the heights of the holders of both arms, for example, the device could achieve a bigger rotational range.



Fig. 18 Supposed representation of how should looks a IMAGOartis // device with radial rotation range above of 180 degrees.

As depicted in Figure 18 above, the device is configured for range of rotation bigger than 180°. This allows to obtain images of the bottom side of the object to be scanned. Note that this configuration is only useful for 3D reconstructions, whilst for RTI this configuration does not give additional information.

4.1.1.5 The bottom base and the drawer

A drawer was designed to make easier to access to the electronic part, and to keep it safe. Additionally, the drawer was designed because during the prototyping phase the electronic parts are usually modified more than once. For a normal use of the device, this drawer might be not necessary, and other kinds of protective box can be designed.

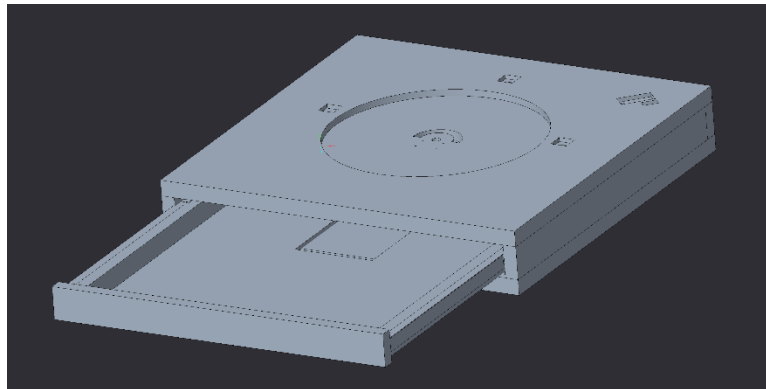


Fig. 19 3D assembly of Floor and drawer parts. Extracted from PTC CREO Parametric 5.0.

The finished and fixed prototype design is shown in Figure 20. It includes all the mechanical characteristics required for the success of the project. It allows horizontal and radial rotation to perform image acquisition. All the modifications are easy to perform because the possible parts to be changed are conceived to be standard and easy to modify according to the end-user needs.

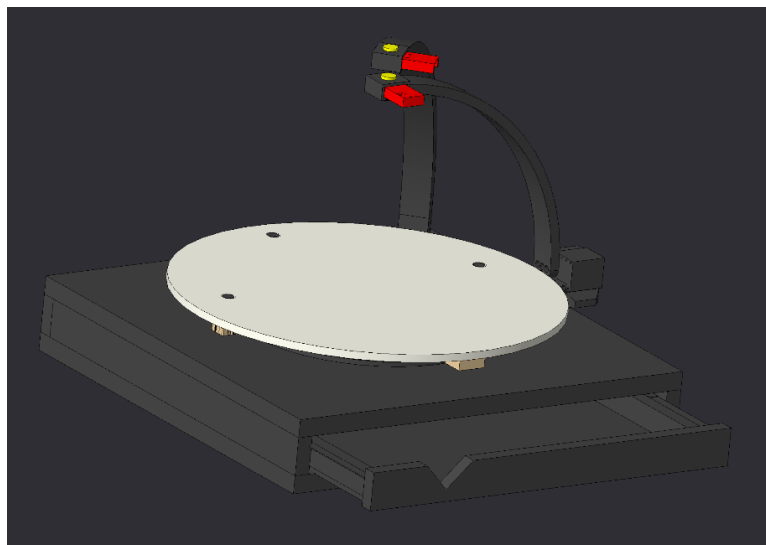


Fig. 20 3D assembly of IMAGOartis // device. Extracted from PTC CREO Parametric 5.0.

4.1.1.6 Construction, issues and solutions

Several different designs

At the start of the project the idea of the mechanical design was very clear, as the design of original IMAGOartis would have been used, although bearings would have been added so to perform the horizontal movement and a motor would have been placed for the radial rotation. After some meetings with project supervisors and with the the responsible of the UVic-UCC technology laboratories, several remakes and implementations were done to the original design, so defining a final number of 4 different designs.

Giving the centred design, where all the arms and its holders need to be perfectly oriented toward the center of the hemisphere, every height change on the model allows to re-calculate all the distances to achieve again the perfect alignment of each of the device's parts.

The bottom base and the drawer design

Due to the utilization of the materials that are available at the university and provided within the already mentioned smARTS project, the design had to be adapted to the new materials. An example of this adaptation approach comes from the design of the bottom base and the drawer.

These parts were designed to be built with high resistance materials like Delrin or other kind of plastics, and its design was adapted to that type of material and to perform the mechanization task in an easy way.

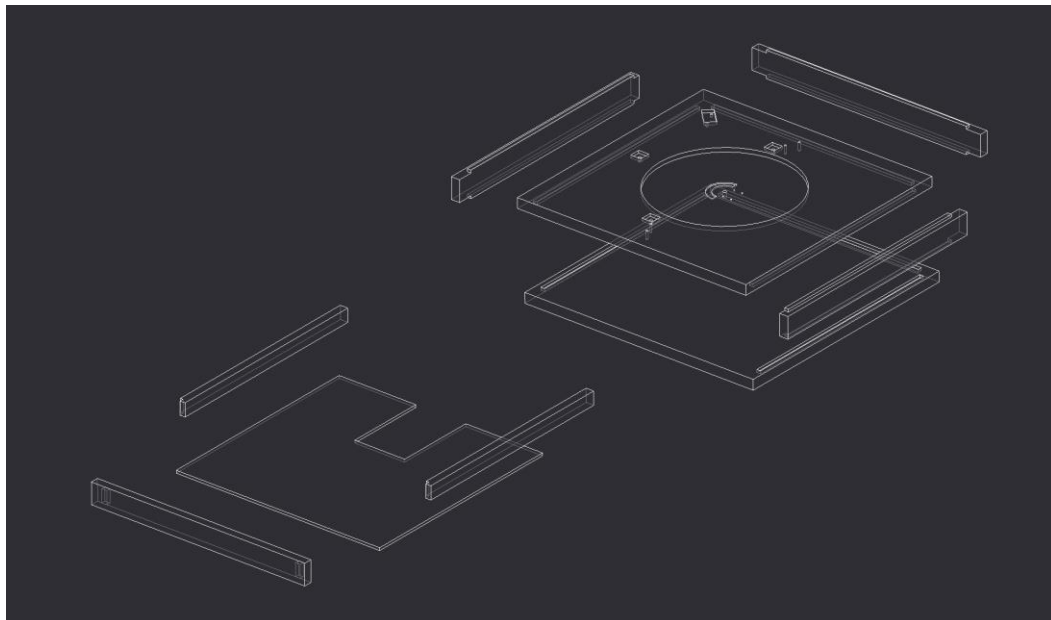


Fig. 21 3D exploded view of old floor and drawer design. Extracted from PTC CREO Parametric 5.0.

This type of material is a little bit expensive, and at the end of the project, when the design was finally fixed, there was no time for buying and mechanizing it. For that reason, wood was used instead of Delrin. The wood parts at disposal from the University of Vic have a 1,9 mm thickness instead of 1,5 mm specified in the design. After a meeting with the technological laboratories responsible, it was decided to avoid the application of junction parts on the wooden design because of its thickness. Junctions would have been suitable for Delrin-made parts, but for wooden parts the junctions will be too weak and it could be damaged easily during the device manufacturing process.

The new design was conceived by adapting these requirements to the device. The result is a new design with a bit bigger drawer but good performance results.

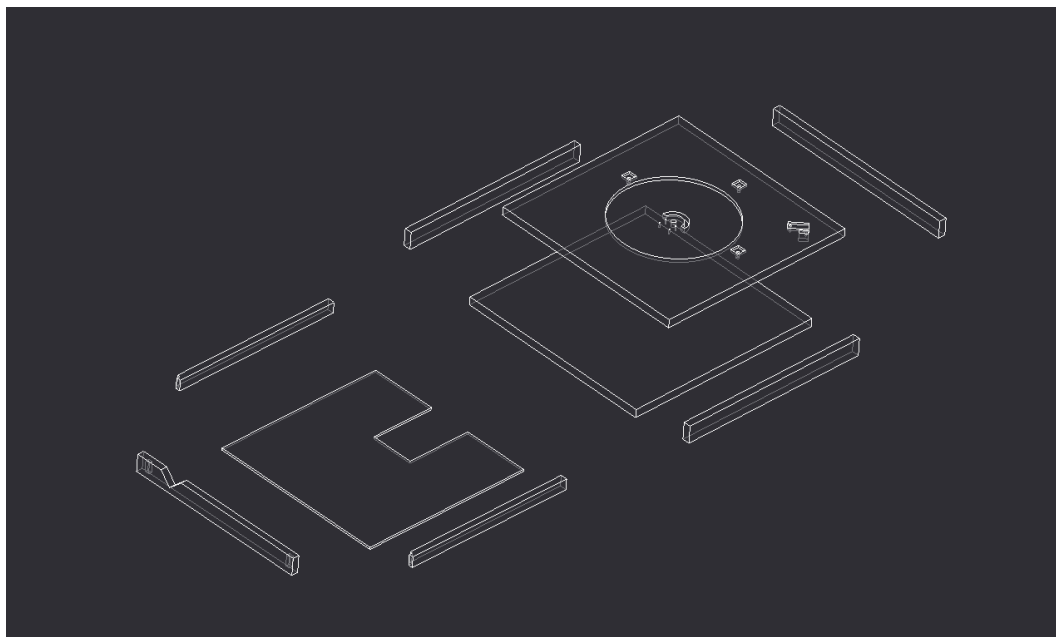


Fig. 22 3D exploded view of new floor and drawer design. Extracted from PTC CREO Parametric 5.0.

The motor axis design

The horizontal movement motor was placed under the bottom base. In order to transfer the rotational movement to the arm holder and the bearings, the motor need to have an axis able to stand the strain of the the rotation. An ABS support was designed to perform this operation, but unexpected design problems appeared during the last weeks of the project.

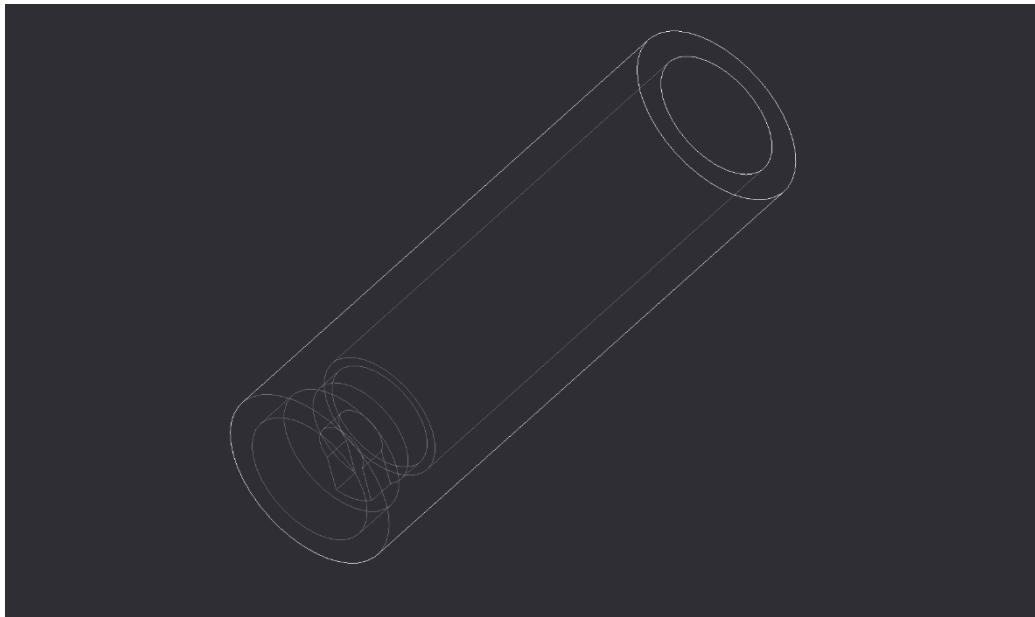


Fig. 23 3D exploded view of old motor axis. Extracted from PTC CREO Parametric 5.0.

The central motor axis was designed to be screwed on the axis of the motor and it fit into a directional pin of the motor itself. The motor carries also a gear to transfer the rotational movement, but it was decided not to try to recreate little gears with 3D printer to avoid manufacturing problems. After several tests, this little directional pin broke. Thus, the motor moves but the movement was not transferred to the arm holder. The screw was screwed with a highest torque, but internal thread of the motor axis was made of plastic and does not hold this force.

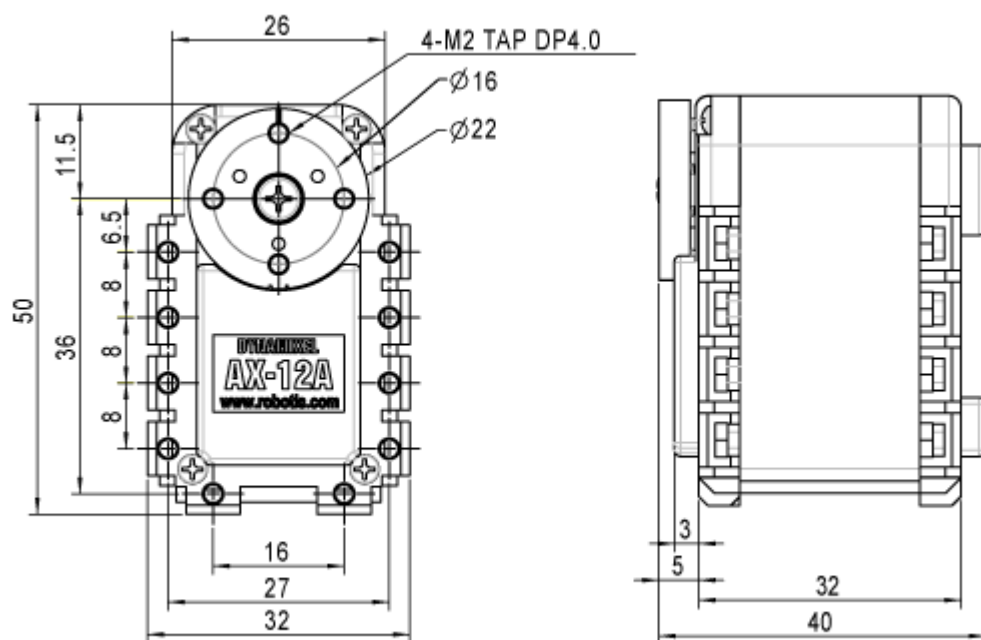


Fig. 24 Dynamixel AX-12A drawing. Extracted from emanual of robotis [18].

To avoid this problem, new design has been applied to the device. First of all, the ring holder that comes with the motor (Fig. 24) should be kept with it, and then the new motor axis should be applied. This new design enhances the rotation movement by using the gear provided by the motor and then the motor axis will be screwed on the metallic threads of the ring holder.

4.1.2 Electrical part

The electronics part of this project is very contained because, being an open source project, each future end-user can change add its own upgrades and modifications. In this section, the parts used for the prototype are explained.

4.1.2.1 Camera

For the prototype, a simple camera was chosen in order to demonstrate that this open technology works. Logitech C270 is one of the cameras with best quality/price relation, giving images of 720p for less than 20 euros.

While choosing a camera, only two features were required:

- At least 720p quality
- USB connection

This camera has fixed focus but it could be adjusted manually to perform better image acquisitions.



Fig. 25 Camera Logitech C270. Image extracted from C270 webpage [19].

4.1.2.2 Illumination

To illuminate the objects to scan, a simple USB-LED is chosen in order to simplify the connections while exchanging camera for illumination at changing reconstruction method.

Also, two characteristics were required:

- o Specific illumination range (4500K-6500K)
- o USB connection

Finally, a touch dimmer led was defined as the illumination system of the device. It has a tactile panel at its back side in order to graduate the illumination and also turn it on or off. Its illumination colour is 6000K.



Fig. 26 IMAGOartis // Led system. Image extracted from Amazon [20].

4.1.2.3 Motors

Two motors were needed to control this device. Once the design of the parts was almost finished, calculations of the motors were done. The motor that have most critical conditions is radial movement motor because it have to keep stable the arm when it is at 0° or 180° .

Is assumed that maximum arm weight will be 0,4 kg. In order to oversize the motor to keep security margin all the weight is considered to be at the opposite extreme of the arm.

$$M = l \cdot m = 23,1 \cdot 0,4 = 9,24 \text{ Kg} \cdot \text{cm}$$

Dynamixel AX-12A were the motors chosen for this project. These motors are servo motors with high grade of software features: they can return its position value, as well as temperature and voltage, and have a stall torque of 15,3 Kg.cm. They are managed using a half serial communication, which implies that the same cable is used for read and receive the information.



Fig. 27 Dynamixel AX-12A. Image extracted from Robotis web page [21].

4.1.2.4 The device controller

In order to control the camera, illumination and motors, a Raspberry Pi model 3+ was utilized. This device can easily control the camera and the illumination system by USB connection, and includes Wifi to connect the device to a PC interface.

4.1.2.5 The motor communication

As explained, the Dynamixel AX-12A communicates using a half serial port at high speed. For this reason, a serial port converter UM232R is needed, as this chip allows to communicate with the motors using 500 kbps.

Moreover, a 74HCT241N chip is needed to perform this half serial communication. What the 74HCT241N does is stay reading while the user is not writing and switch the cable when the user wants to write.

The scheme in Figure 28 shows the connection of the UM232R and the motor.

4.1.2.6 The CPU

The Photogrammetric 3D reconstruction is a technology that needs very powerful engine to works. Minimum computer requirements had to be achieved to carry on the tasks in a proper time. For this reason, the reconstruction cannot be done by using the only Raspberry Pi and needs a more powerful computer.

For the prototype tests, a laptop Lenovo Y50 with the following specifications was used:

- CPU: Intel i7-4710HQ (8 core, 2,5 GHz)
- RAM: 12 GB (DDR3)
- GPU: NVIDIA GeForce GTX 860M
- Storage: Crucial MX500 (SSD 500GB)

4.1.2.7 The electric diagram

The connection scheme of the device is the following one

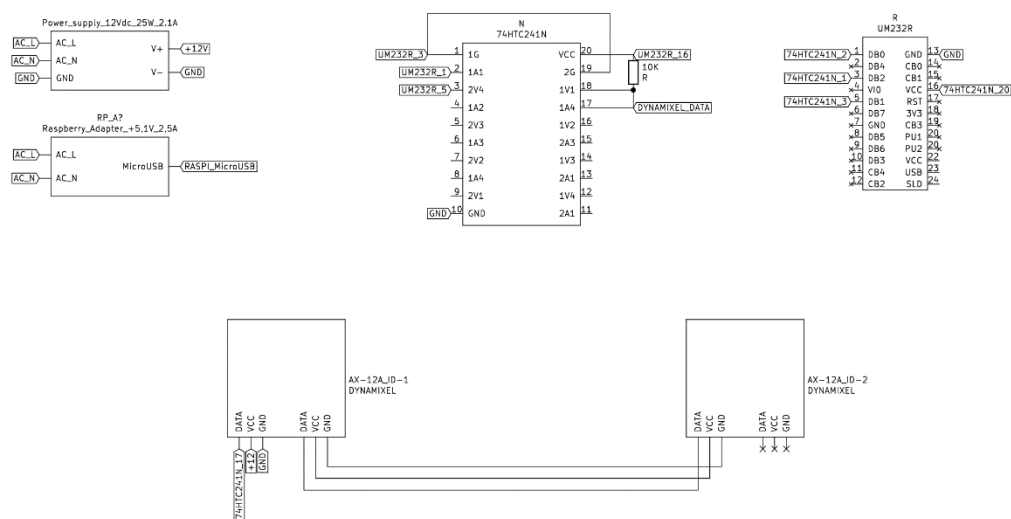


Fig. 28 IMAGOartis // connection scheme [22].

4.1.2.8 Problems and solutions

The wire management

Since both camera and illumination system has wire connection, its management was challenging. The original idea was to make the cables pass through the arms, but because of manufacturing problems the final decision was to make it pass outwards these pieces. It could be a good idea to pass the cables through the arm holder, as done with the motor communication wires, but for lack of time in assembly the USB connector to the cable, the last decision was to make it pass outwards the arm holders and fixed them with glue and flanges.

Another USB cable that could have been modified is the camera cable. The Logitech has a 1.5 m USB cable. To acquire a good-looking final design, this cable should be reduced to a 50 mm cable.

As for the he led holder, this was designed to screw it and unscrew it every time its position needs to be changed. The original idea was to apply an external USB hub to keep the light system always inside the support, so to just plug or unplug the USB cable, but the piece ordered never arrives so this modification was not carried on.



Fig 29. IMAGOartis // doing an image acquisition at Casa Convalecencia.

4.2 Software

4.2.1 COLMAP

The COLMAP software uses Structure from Motion and Multi-view Stereo in order to reconstruct a part of the world as a 3D point cloud. This is the open-source software that has been used for this project. Its technology allows the user performing 3D reconstructions using unordered image datasets, even without knowing the camera specifications, parameters and/or position.

COLMAP has a command line interface. In this project, this is used to launch different commands from our general control program.

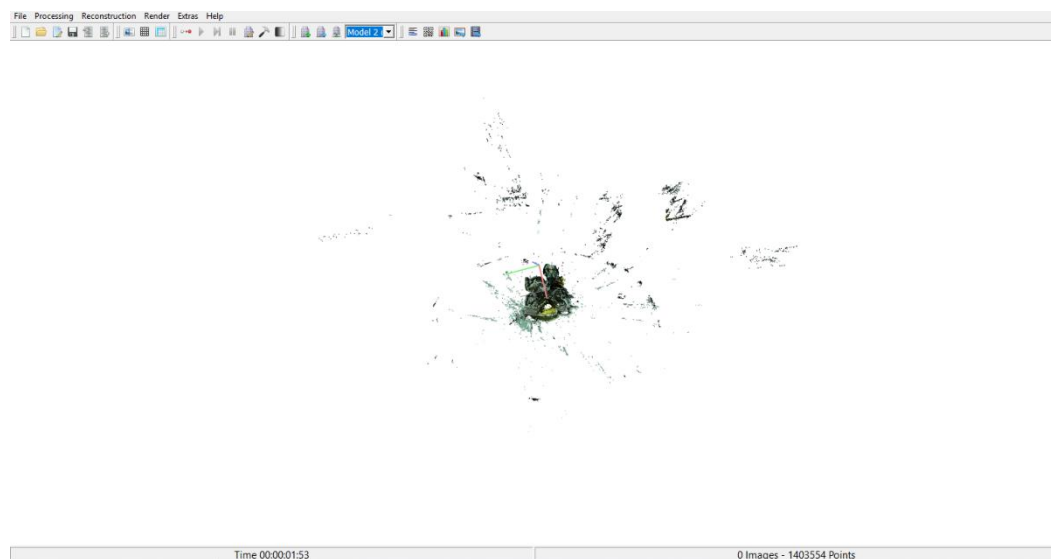


Fig. 30 COLMAP after finishing dense reconstruction.

4.2.2 RTIBuilder

The RTIBuilder is a software interface used to process datasets in order to produce RTI files. This tool is designed for cultural heritage and natural science applications, and enables users to manage all aspects of RTI creation. It was primarily developed by a research group of the Universidade do Minho in Braga, Portugal. The work was funded by Cultural Heritage Imaging and the Universidade do Minho.

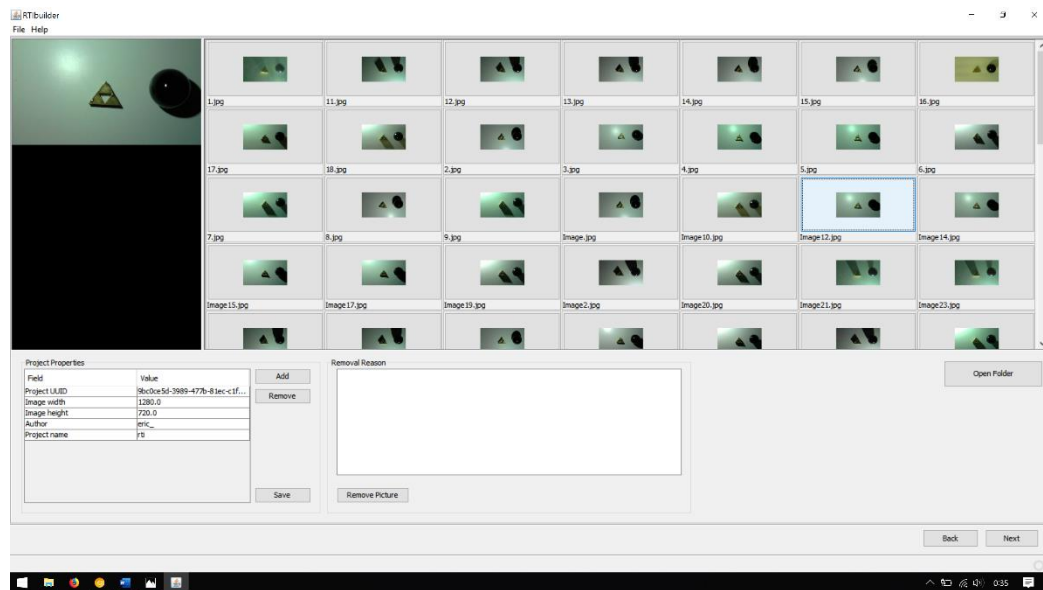


Fig. 31 RTIBuilder at step of selecting image dataset.

4.2.3 RTIViewer

The RTIViewer is a software that enables the user to open RTI files and explore the morphology of the imaged objects' surfaces by changing the angle of illumination. It offers interactive rendering of images, allowing the user to change the view and alter the apparent direction of lighting. It also offers a number of enhancement modes, which apply mathematical transformations to the colour and shape information to enhance or emphasize specific features of the targeted object.

Also, this tool is open source and was designed for cultural heritage and natural science applications. It was and firstly developed by the Italian National Research Council's (CNR) Institute for Information Science and Technology's (ISTI) at the Visual Computing Laboratory [23]. The work was financed by Cultural Heritage Imaging with a major contribution of the US Institute of Museum and Library Services' (IMLS) through the National leadership Grant Program (Award Number LG-25-06-0107-06). The source code was developed in partnership with the University of Southern California's West Semitic Research Project. RTIViewer also contains significant software and design contributions from the University of California Santa Cruz, the Universidade do Minho in Portugal, Tom Malzbender of HP Labs, and Cultural Heritage Imaging.

4.2.4 The communication

One of the challenges of this project is to use the device without connecting physically to it. This feature gives to the user more freedom to work. In order to connect the device with the computer, a wifi connection is established between this and the Raspberry that exchange information by using MQTT messages protocol (Message Queuing Telemetry Transport) [24]. The communication code [25] was written with python [26].

For this purpose, Eclipse Mosquitto [27] was used. This is an open source MQTT broker that allows us to send messages by the internet based on publish-subscribe messaging protocol.

A few commands need to be sent to the Raspberry Pi to make the correct movements and take the images. As for this reason, different channels were created to allow communication between the Raspberry Pi and the computer. These commands are always inside “imago” channel to ensure that nobody else is sending data to the channel.

The rotation data is sent to “imago/rotation/horizontal” when the horizontal movement motor is due, or to “imago/rotation/radial” when the radial movement motor is due. Subsequently, the order to take images and the response on image acquisition is sent to “imago/picture”.

4.2.5 The motor communication

The motor communication is carried by using Python and the UM232R which shows serial port communication with the Raspberry Pi. The communication library was provided by supervisor Professor Moisès Serra, who supported the use of these motors and tested them previously. As for this project, the library had to be adapted to the specific imaging needs. The same library is given by the motor’s supplier but in “C” programming language.

In the library, the Raspberry Pi USB serial port is defined as an output serial port. The communication velocity is defined as 500000 bytes/second.

```
s = serial.Serial('/dev/ttyUSB0',500000)
```

A specific function was created in order to move the motors, by assuming some of the fixed parameters and make variable the ID of the motor, the goal position and the rotation velocity. This function also returns the current position (step) of the motor.

```
def servoMove(servoID,goal_position,goal_speed):  
  
    #Definitions  
    setCMargin(servoID,8,8)  
    setCSlope(servoID,8,8)  
    setPunch(servoID,8)  
    torqueStatus(servoID,True)  
    setLimTorque(servoID,1000)  
    setAngleLimit(servoID,0,1023)  
    time.sleep(1)  
  
    #Movement  
    moveSpeed(servoID,goal_position,goal_speed)  
    time.sleep(3)
```

```
#Read current position
curP = readPosition(servoID)
print(curP)

return(curP)
```

4.2.6 The image transferring

The Raspberry Pi can take images and save them into its memory, but with a large image dataset the images need to be saved into a microSD card with enough capacity or by connecting an external disk. In order to avoid this problem, the program is designed to pick up every image from the Raspberry Pi as soon as it is imaged. Only one image at time is stored into the Raspberry Pi.

To pick up the image from the Raspberry Pi, WinSCP is used. WinSCP is an open-source SFTP, FTP, WebDAV, Amazon S3 and SCP client for Windows. Its main function is to secure file transferring between local and remote devices. For secure transfers it uses Secure Shell (SSH). For this reason, SSH needs to be enabled in the Raspberry Pi to allow the connection with WinSCP. Originally, WinSCP was hosted by the University of Economics in Prague (Czech Republic). Nowadays, it is freely licensed under the GNU GPL and hosted on SourceForge.net.

In order to connect with a device, WinSCP needs its IP, user and password to login. Once the device is registered, allows the user to perform data transferring using command line.

4.2.7 The device control program

In order to control the device from the Raspberry Pi, a Python program is used. This program sets initial conditions to the machine when it starts and then waits for MQTT messages from the computer. The program is designed as much as possible simple, in order to avoid computational capacity loss of the Raspberry Pi, and transfer all the heavy work to the computer.

In the following sentences, the code written for this project is slightly explored in order to let potential users to understand its main functioning. First of all, the working folder was generated by using the “MKDIR” command, then the device goes to home position (180,180). Once device is in its initial conditions, it connects with the server which is the Raspberry Pi itself (localhost). Once connected and subscribed to “imago/rotation/#” and “imago/picture”, then the program waits to read any command published into the MQTT channels.

Two functions were created to rotate the two motors. The function moveH() was defined to move motor that control horizontal movement. This motor has an offset of 390 steps. For this reason, this number of steps is added to the message

received from MQTT. The IP of the horizontal movement motor is 1 and the movement velocity is of 44 RPM.

The function moveR() orders to radial movement motor to rotate. This motor has an offset of 210 steps and, as the other one, this number is summed to the message received from MQTT. This motor has the IP 2 and moves at a velocity of 22 RPM.

The program is automatically launched when the Raspberry Pi is booted. To achieve it, a Raspberry Pi configuration file has to be modified with the order to initialize the Python script. In order to open the file that must be modified, the following command is used:

```
sudo nano /etc/profile
```

Once the file is opened, the following command line is written at the end of the script:

```
sudo python /home/pi/Desktop/python/RASPI/IMAGOartisII.py &
```

The “&” symbol indicates that the script will never end until the user stops it.

4.2.8 The general control program

IMAGOartis // has the aim to be as much automatic as possible. As for this reason, a Graphical User Interface was designed to control the reconstruction with a short number of steps. The application was developed using the integrated development environment Netbeans [28] and coded using Java.



Fig. 32 Main page of IMAGOartis // GUI.

When the program starts, the user can choose between 3 clear options: settings, 3D reconstruction and RTI. The first option that need to be configured is the settings option, where the paths of COLMAP, RTIBuilder, RTIViewer and WinSCP need to be introduced.

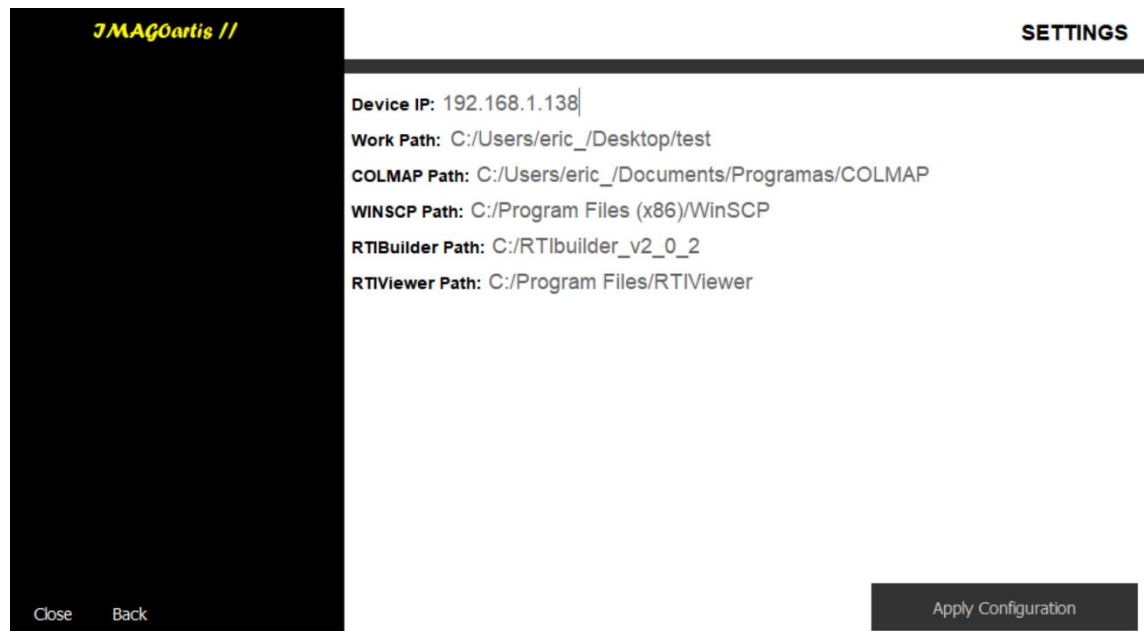


Fig. 33 IMAGOartis // settings page.

As for both reconstruction methods, the same methodology, automatic reconstruction and manual operation are given. As the name indicates, the automatic reconstruction makes automatically the image acquisition process and then opens the reconstruction software to proceed with the reconstruction.

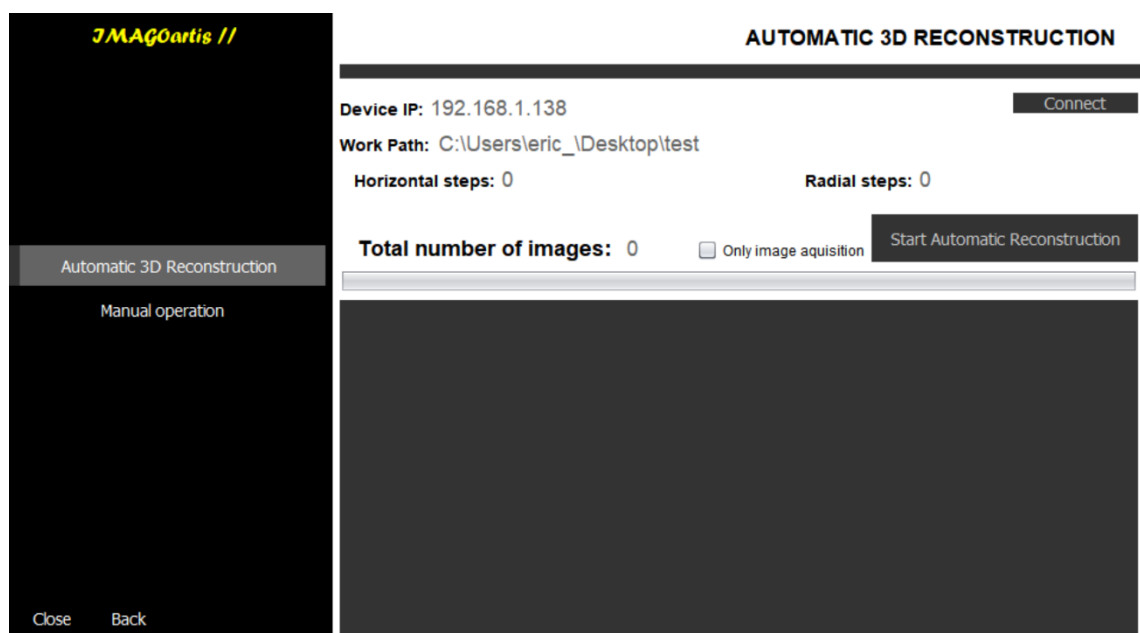


Fig. 34 IMAGOartis // automatic 3D reconstruction page.

The manually operation allows to move manually the device to take some images that the user consider important and that were not taken into consideration by the software during the automatic reconstruction. Additionally, the reconstruction software can be opened on the manual operation tab.

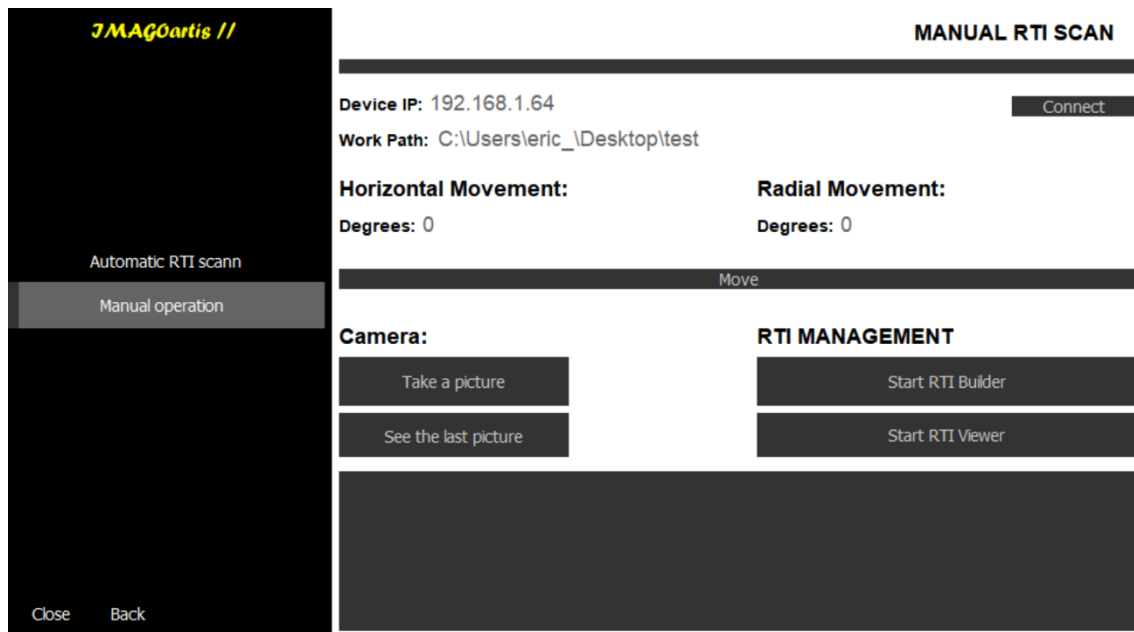


Fig. 35 IMAGOartis // Manual RTI operation page.

4.2.9 Issues and solutions

Motor control program

A Dynamixel motor was provided for testing before order the two motors that were finally used in this project. As soon as Dynamixel motor was provided, several methods to control this type of motor were searched. Many different controllers can communicate with these motors and control them.

The main problem encountered by using the Dynamixel motor was that both communication speed servo ID are unknown.

Different options and software were tried during the project development.

- Raspberry Pi

The first tests on communication with the motor, implied to communicate directly using the Raspberry Pi to avoid increase the number of different electronic equipment.

The library provided by Professor Moisés Serra was tested, but after several days trying to communicate with the motors, the supervisor provided me the information that the Raspberry Pi GPIO cannot switch as fast as the motor needs, and to much items have to be

changed to perform this operation. Then quickest alternatives were searched.

- OpenCM

This board is the board recommended by the supplier of the motor to control it. It is programmed using C++ and it can be programmed using Arduino IDE or OpenCM IDE (ROBOTIS_OpenCM). Both options were tested but no results were obtained.

The main test performed involved every baudrate from 9600 to 1M, and from ID 1 to ID 5, reset baudrate and reset ID. The next step was to move a little bit the motor to know if values were changed. No results were obtained.

- Arduino

The most popular prototyping board has also a library to communicate with these motors. The main difference with OpenCM is that Arduino does not have half serial port connection. For this reason, the 74HTC241 chip was connected to the Arduino. Even so, the Arduino cannot reach the communication speeds needed by the motor.

- Raspberry Pi + UM232R

This was the final test performed to check communication with the motor. A new library was provided from the supervisor, but no results were obtained. Only when looking one by one at the different baudrates and servo ID, the motor configuration was finally discovered. The servo ID was the number two, and its baudrate was 500000 bps.

The device should work using the option number one, that is only the Raspberry Pi GPIO should control the motors but, due to lack of time, option number four remained the one selected for the project final prototype. Further improvements should easily solve this problem.

COLMAP auto mode

One of the main purposes of the project is to create a device able to make automatic reconstructions. This means that the device should make automatically both the image acquisition and the reconstruction processes.

Among the reconstruction softwares used with IMAGOartis //, COLMAP and RTIBuilder, only COLMAP can be performed automatically. RTIBuilder needs that the user shows to the program where are the illumination points used as reference to know the lightening comes from. COLMAP does not need any input from user.

Several commands were defined to send to the program the necessary inputs to reproduce automatically the 3D reconstruction of the object scanned. However, a problem emerged: once the command is launched, COLMAP performs the command, but once it is completed, it does not communicate to the user that the work is finished and remain opened until the user stops the general control program.

```
public void denseStereoFusion() {  
    printMessage("Stereo Fusion");  
    try {  
        //Executing sparse mapper  
        cmdCommand = "cmd /c " + pathCOLMAP + "/COLMAP.bat stereo_fusion "  
            + "--workspace_path " + WorkPath + "/dense"  
            + "--workspace_format COLMAP"  
            + "--input_type geometric"  
            + "--output_path " + WorkPath + "/dense/fused.ply";  
        Process powershell1 = Runtime.getRuntime().exec(cmdCommand);  
    } catch (IOException ioe) {  
        System.out.println(ioe);  
    }  
}
```

As for the moment this issue remains unsolved, and improvements are expected during further project updates.

5. RESULTS

This device is developed to being used on cultural heritage study and preservation, by enabling users to digitalize objects and samples. Among the most important purposes of this project, is that the developed device can be easily used by non-expert users such as conservators, restorers or archaeologists. In addition, it is expected that this device will be appreciated because it introduce an automatic process for two well established image acquisition techniques, so to allow the user to perform other tasks when the device is still operating.

Other important aims are:

Ease the study of cultural heritage objects by digitalization; allow a fast and reliable 3D reconstruction finalized to replica production and virtual reconstruction for restoration and safe exposition needs.

Finally, another important aim of IMAGOartis // is to allow the reconstruction of uncomplete and/or damaged objects by applying reverse engineering technique so to obtain a negative 3D model of the object that allow manufacturing perfect fitting cases to transport or storage purposes. This type of cases can be done with foam which will take up the errors that 3D model could have.

5.2 Tests

In order to prove device functionality, different type of tests were performed. During these tests, new challenges appeared, and different solutions were proposed.

5.2.1 Reflectance transformation imaging

For this test, a handcrafted object made during Process Engineering [29] course from University of Vic was used. Using RTI function from IMAGOartis // a total number of 29 images were taken. Then 1 outlier images were removed from the image dataset to ensure RTI quality.

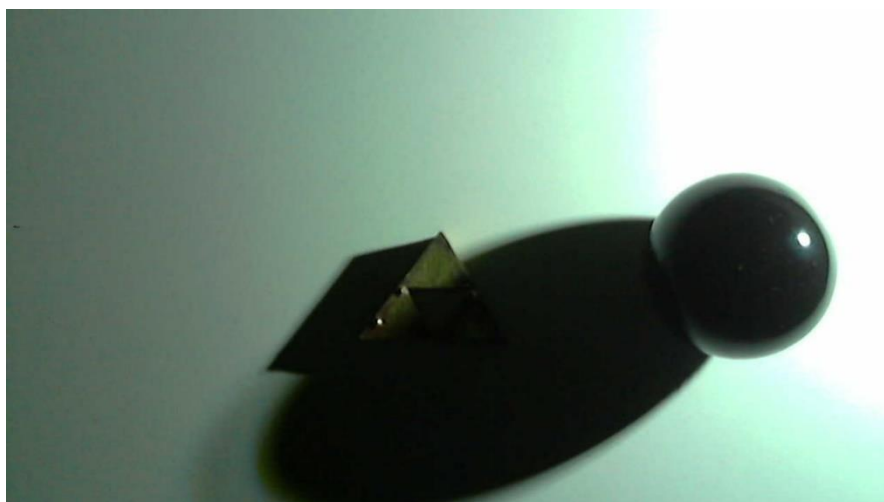


Fig. 36 Outlier RTI image due to object shadow overlapping

As every image of the dataset has a different illumination angle, the software acquires more data from the images and merged result is more accurate.

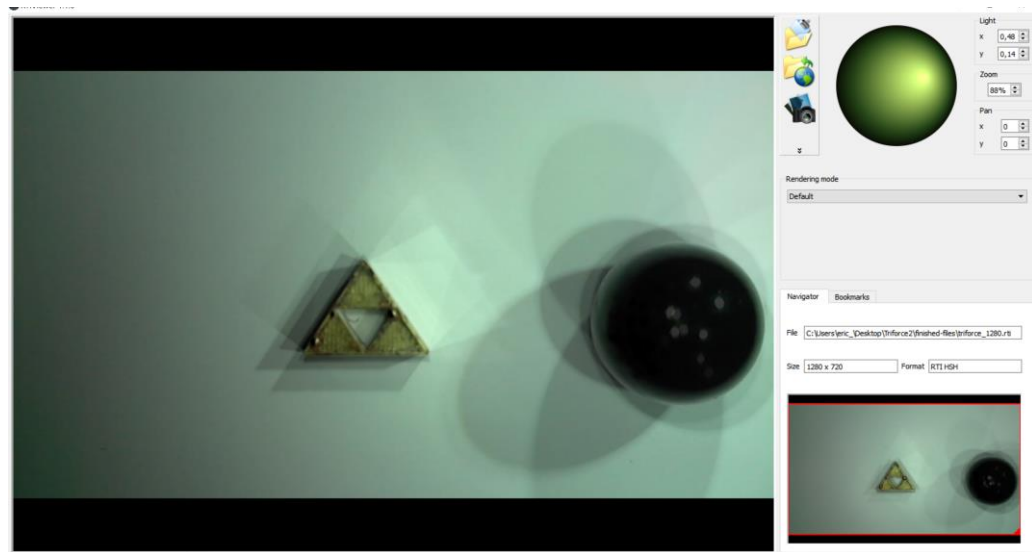


Fig. 37 RTI of forged Triforce.

5.2.2 3D Reconstruction

A plastic figure with high-grade detailed shape was scanned acquiring a total number of 300 images. The point cloud obtained with COLMAP contains a total number of 1,4 million points that allow to appreciate a well-defined shape and it's colours.



Fig. 37 Amiibo Wolf Link point cloud.

Once the meshing systems were applied, the reconstruction quality goes drastically down. With poisson meshing, a lot of irregular surfaces were added to the original points. This type of meshing technology could be used to appreciate the colours of the object.

If Delaunay meshing is used, geometrical forms create the missing points of the object. This type of meshing technology could be used to create different type of cases for the scanned objects. This practice will be very useful to improve cultural heritage objects transportation

With the IMAGOartis // device is possible to obtain the 3D model of an object within few hours. Then, reverse engineering could be applied.

5.2.3 Cultural heritage study

This test was done at Casa Convalecencia which hosts the Knowledge and Innovation Park managed by the Vic town council and the University of Vic (UVic-UCC), with spaces dedicated to entrepreneurship, research and innovation. This building was restored in 2012 [30] and during the restoration works, more than 200 ceramics were found. After analysing these ceramics, it was discovered that its manufacturing can be dated from the 18th century [31].

In order to test the device with real objects, a 3D reconstruction scan was performed on one of these ceramic vessels, specifically on a dish painted with different colours. This test was done to prove process efficiency and ability to ease the study and documentation of this kind of objects.

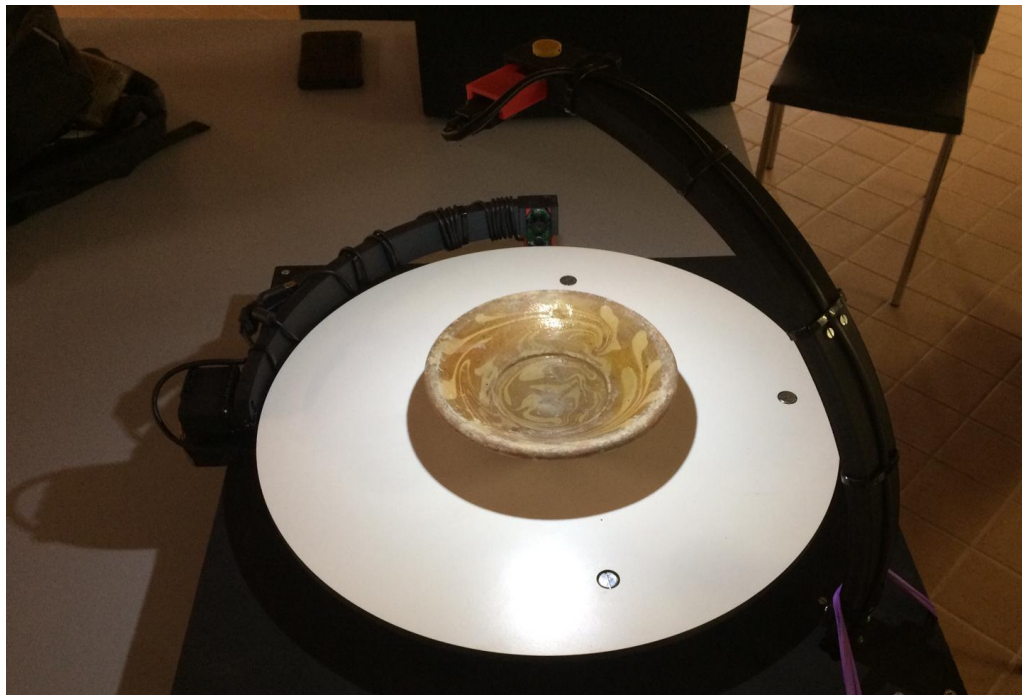


Fig. 38 3D reconstruction scan at Casa Convalecencia.

Only a hundred images were taken to reconstruct the top surface of the dish and a total number of 1 million points were found.

If meshing techniques are applied, the results obtained do not provide enough and detailed information to the archaeologist in order to study the piece (See figure X). If the number of image acquisition repetitions and its steps are increased, the results could provide more valuable information.



Fig. 39 Point cloud of the scanned piece.

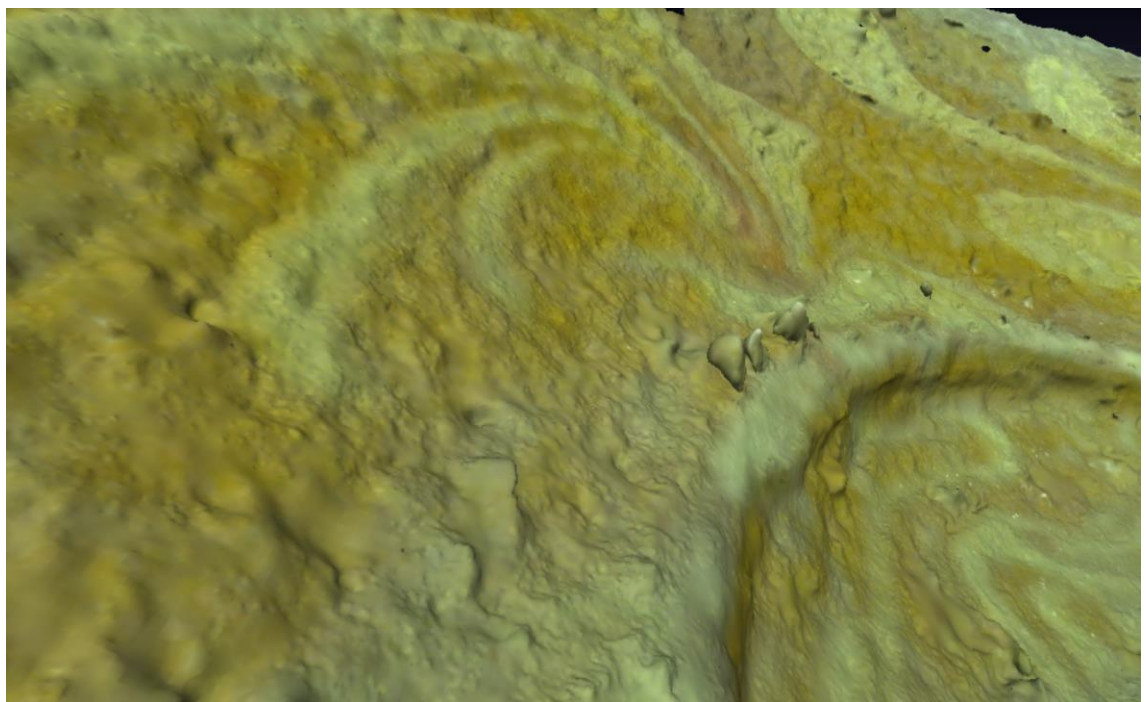


Fig. 40 Poisson meshed cloud of points

5.2.4 Larger objects

The camera Logitech C270 has an objective with a focal length of 4.2 mm and if an object is too near from the camera, it is not able to show it entirely on the photograph. As for this reason, it has been decided to observe the potential results of a 3D reconstruction from an object that does not fit entirely on an image of IMAGOartis //.

Another piece from Casa Convalecencia was used to make this test, in this case a broken vessel. Its dimensions were big enough to achieve our objectives. The images acquired after scanning the object not only do not fit the object on it, but also show a really bad focus on the object.



Fig. 41 Vessel from Casa Convalecencia being scanned.

Even so, the obtained results were better than expected. COLMAP achieved to merge enough images to reconstruct almost a half of the object (Fig. XX). Then, it is able to reconstruct the other half of the object but it is unable to find enough points that confirm a relation between the two parts.

If there is the need to scan large objects, another camera or objective must be used to perform a good 3D reconstruction.



Fig. 42 Point cloud of vessel first half.

5.3 Upgrades

Since the project started, it was very clear that it will not have exceptional results. As for the cultural heritage field, photogrammetry is a really complicated technology which highly used, but there is not a standardised method that works at perfection.

For the prototype, the Logitech C270 was used thinking that it would be enough to have useful results. After the tests, it is very clear that this camera is not the best one to perform these reconstructions. At least a camera with 1080p resolution with auto-focus option is needed to start having good results. Once a good camera is used, scan quality will increase drastically.

On the other hand, COLMAP needs pairs or clusters of similar images to perform its reconstructions. When this clusters of images are bigger, the reconstructions were performed better and have very good results. As it can be seen on the software code, RTI scan the object only once. Instead, 3D reconstruction makes it twice in order to find pair images. Increasing this number of image acquisition cycles the reconstructions will also increase its resolution and accuracy.

Probably COLMAP is not the best option to perform 3D reconstructions of small objects with a reduced dataset of images. For this reason, in further improvements new open-source reconstruction software will be explored to achieve better results.

Moreover, new technologies could be applied into IMAGOartis //. Photogrammetry is not the only option to make 3D reconstructions, other type of environment sensors like lidar sensors [32] can be applied to the device.

Due to late testing of the device, some mechanical issues appeared and should be modified to obtain a better process stability. In further versions of the device is expected to solve space and weight problems, as well as to adapt the device to use bigger instruments.

As a new feature to be implemented on following project steps, there is the device autonomy. It is important to be able to use the device without having a computer. This represents an attractive feature for IMAGOartis // because it will make it more portable. To enable this feature, a touch panel will be implemented to control the device. Then, acquired images will be saved into a pen drive or other memory storage device.

6. CONCLUSIONS

Mechatronics is a very powerful science that combines electronics, mechanics communications and control. This project shows the potentialities of mechatronics, as it implements all these fields to perform a single process.

IMAGOartis // is a mechatronics-designed device capable to perform fully automatic image acquisitions suitable for both Reflectance Transformation Imaging and photogrammetric 3D reconstruction technics. The device is conceived in order to obtain that both operation modes are optimized to acquire good datasets for each technology. The general control program allows the user to perform image acquisitions but also allows to perform 3D reconstructions or RTI.

This project, as pointed out from the beginning, is based on the open source approach. Each software and hardware is open-source. This means that this project will be shared publicly by publishing it on internet open science databases for all those users and makers who wants to see it, build it or modify it. The device is designed in order to be flexible so to accomplish to the final user needs, easy to adapt, and plenty of details prepared for device improvement such as exchangeable holders or modifications of the arms' height to perform image acquisitions with angles bigger than 180°.

The results obtained are very hopeful. This project was made with the materials that were provided by the university and were not bought specifically for the project. Even so, the results obtained were really good. A single camera of 720p resolution with no auto focusing option was used to make 3D reconstructions, which is not very common. Moreover, no parameters of the camera were used to calculate the point cloud, so users have the chance to change the camera whenever is wanted.

This device was conceived as a low-cost machine with respect to industrial -oriented, proprietary machines used to create point clouds from objects. This means that from now on, an alternative have been provided for carrying out image acquisition and processing techniques in the field of cultural heritage science. All in all, it is worth to underline that the IMAGOartis // device can be improved with better motors, cameras and sensors to perform really good reconstructions. Besides these aspects, the achievements of this project show to the cultural heritage scientific community that the open approach to technology can represent a good way to achieve scientifically reliable results.

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