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DIGITIZING 3D HISTORICAL SCIENTIFIC INSTRUMENTS WITH LASER AND PHOTOGRAPHIC TECHNOLOGIES

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ABSTRACT The digitization of 3D tangible cultural heritage is becoming a widespread process. It assists in the creation of physical replicas for preserving the original object, for conducting studies, precise documentation and enhanced exhibition, among other purposes. Nevertheless, some objects still present major challenges due to their complex geometry, difficult access, or materials that are not compliant with most acquisition technologies. The Digital Bamberg project was conducted in collaboration between the Computer Graphics Lab of UFRJ (Universidade Federal do Rio de Janeiro) and MAST (Museu de Astronomia e Ciências Afins), to digitize a historical meridian circle. One of the main goals was to study how 3D scanning technologies behaved when confronted with important challenges, such as: dark and shiny materials, a mechanical instrument, and of historical value. The digitization process used a laser scanner for geometry acquisition, and high-resolution photographs for appearance retrieval. Most of the challenges were due to the use of these two light-based technologies. The laser spreads when hitting a metallic surface introducing a high frequency noise, which results in imprecise geometry. Moreover, removing the light influence when taking photographs to acquire the true surface appearance is another critical issue, mainly due to reflections that are difficult to eliminate completely. We discuss the main light-based challenges confronted during this project, as well as solutions to these issues. This contribution sheds light on how to efficiently acquire quality geometric and photographic data of complex metallic mechanical instruments, while at the same time, preserving the integrity of historical object.

KEYWORDS Laser scanners; Digitization; Historical scientific instruments

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1. Digitizing cultural heritage artifacts

The digitization of historical artifacts has gained popularity in the last two decades. With new technologies it is possible to accurately capture the geometry and appearance of physical object (Ikeuchi and Miyazaki, 2008). The virtual replica can be used for a variety of purposes (Stanco et al., 2011). A few examples are given below.

Documentation: the 3D object can complement traditional documentation and annotation methods. The visual state of the object is readily available, and details are preserved for inspection. It also facilitates the physical description and is much richer than photographs.

Dissemination: the 3D model can be visualized and manipulated remotely, from computers or mobile devices. Furthermore, it can be used to elaborate animations and renders to enhance the museum's expositions.

Study: virtual models can be shared around the globe, facilitating the study by historians and other interested professionals, such as curators.

Conservation: the 3D object is very useful during restoration campaigns, where it can support tasks during the planning, the restoration process, and comparisons before and after the intervention.

3D physical replica: when an artifact is removed from an exhibition to be restored or for a temporary exhibition, a physical replica can be printed from the virtual model to serve as a temporary replacement. Missing fragments can also be replaced by 3D prints (Scopigno et al., 2015).

A common digitization session starts by acquiring the geometry using laser scanners or photogrammetry, for example. Some initial alignment is usually done on site, while a finer alignment in carried out in a post-processing phase, followed by a surface reconstruction method to achieve a digital model.

In a second stage, texture, or color, is acquired from a photography session. Each photo is carefully aligned with the model to project the pixels onto the geometry. As a last step, all the photos are combined to generate a single texture for the model.

It is important to note that there is no silver bullet in the digitization domain. No single technique or equipment can handle all types of geometric surfaces and materials. There are also some approaches to acquire geometry and appearance in one pass, but they still lack maturity and robustness (Schwartz et al., 2011, Nöll et al., 2015). Furthermore, the practical experience of the digitization group is still essential for an efficient and successful acquisition campaign. Finally, most of the used technologies are light-based and passive, and works by emitting and/or capturing light without physical contact.

There are a few worth-mentioning points about the digitization of historic artifacts. On one hand, the technology is becoming more mature, and many objects can be digitized without great complications. On the other hand, many objects present specific challenges that are not trivially handled, such as its size (too large or too small), its color (too dark or too reflective), its geometry (lots of concave and hidden regions, or highly symmetrical parts), or its access (difficult or impossible to move the object or to place the scanner around it).

Given this scenario, scientific historical instruments present significant challenges, especially due to their predominantly metallic and reflective surfaces, and in some cases their size and weight. The straightforward solution for scanning generic reflective materials is to paint or cover it with white powder. For historical instruments, this procedure is obviously improper, so other ways must be found to digitize them.

Some alternatives might include, for example, specific or high-end scanners. But usually museums and restorers do not have access to multiple scanning equipment or very expensive scanners; thus, they must get along with more generally available digitization technologies. Another issue with mechanical instruments are the symmetrical or flat pieces, that make the geometry alignment a great burden.

Finally, even though scanning hardware and software can accomplish great results, there is still a great deal of post-processing and manual intervention required to achieved quality virtual replicas. Alignment, texturing, cleaning and smoothing are some of the common post-processing stages of producing a virtual object.

One of the goals of the Digital Bamberg Project was to investigate approaches to safely and reliably digitize historical scientific instruments without requiring specific hardware. It should serve as a general guide to future similar digitization campaigns.

In this article we describe the approaches experimented during the digitization of this historical instrument, and the important role of light-based technologies in this process.

2. The Bamberg

The Bamberg meridian circle belongs to the MAST (Museu de Astronomia e Ciências Afins – Museum of Astronomy and Related

Sciences) collection. MAST is co-located with the National Observatory campus, in Rio de Janeiro, and is responsible for the preservation and restoration of a collection of around two thousand technological and scientific cultural heritage artifacts.

Meridian circles are used to determine the positions of stars. To achieve such measurements these instruments are tailored with maximum precision, and are composed of many small and large mechanical pieces.

The Bamberg (FIG. 1) was fabricated in Germany in the beginning of the twentieth century, and was in operation at the National Observatory in Rio de Janeiro until the seventies. During this period, it played important roles in the determination of latitude and longitude, and the official Brazilian time.

FIG. 1 - A photo of the Bamberg Meridian Circle.

The digitization of the Bamberg was aligned with its disassembly, that had among its goal the inspection and assessment of the current state of its components. It was a good opportunity to scan and photograph each part separately in order to later re-assemble the instrument physically and digitally. Note that the goal was not to reproduce its mechanical functionality digitally, but to have a as faithful as possible digital replica in the geometrical and appearance sense.

The disassembly (FIG. 2) and close inspection of the instruments also led to a series of interesting discoveries about its components, such as details of how it worked, and clues about its history, since for example, some manual markings were discovered in some points of the instrument.

FIG. 2 - The Bamberg's lower base completely disassembled. Each part is labelled and kept in its respective place to guarantee the correct assembly afterward.

The Bamberg contains an enormous variety of pieces, ranging from metal bases that weight around forty kilograms each, to very tiny components such as bolts, springs and plates. Moreover, the material range includes metallic parts, some very well conserved while others had deteriorations such as rust and wearing, as well as some plastic and glass pieces. Thus, we were facing a case were no single technique would handle all pieces.

2.1 Geometry acquisition

To acquire the geometry a Konica-Minolta Vivid 9i laser scanner was used (FIG. 3). This is a mid-price scanner that is known to tackle a broad range of geometric and reflective properties. It can handle objects ranging from a few centimetres up to a few meters.

FIG. 3 - The Konica-Minolta scanner during a digitization session of the Bamberg's lower base.

Due to the reflective and dark material properties of the Bamberg, the time to scan the larger parts was considerably longer than it would be with the same geometry and a more scanner-friendly material, such as diffuse and light colors. Each scan was only able to retrieve a small amount of geometry, and accompanied by significant noise. To alleviate this problem, we scanned each part from different viewpoints (FIG. 4), since the scanner would only capture the reflected laser from a few incident angles. We also manually set the focus distance to avoid problems with the auto-focus.

FIG. 4 - Two registers from the scanner. Note how there are many missing parts and holes due to the material dark color. The laser is also unable to reach inside the base's apertures.

Furthermore, due to the weight of the larger parts, manipulation and orientation was limited, making it difficult to acquire the geometry from some viewpoints. A turning table was crafted to support the instruments weight, so it could be easily rotated without moving the scanner around. For each base, for example, we scanned in three full cycles, facing down, facing up, and sideways, in order to capture the geometry as thoroughly as possible.

There were two main issues with the two bases. The first is that, due to its predominantly flat geometry, no single scan can capture a part of the bottom and top planes at the same time. In other words, only the lateral faces were present on both scans, the rest was complementary. An important implication is that it leads to severe alignment issues since the upper and bottom scans can almost freely slide vertically as the lateral walls have no singular geometry to prevent this from happening.

The second issue is that the smaller apertures that form the base design were almost impossible to reach with the laser. It left holes that were large enough to cause problems for the surface reconstruction algorithm that was unable to correctly fill the missing parts.

To tackle these two problems some placeholder geometry was manually inserted in the digital model to force the alignment and hole filling algorithms to behave as expected. Since most of the geometry is flat, the inserted plane patches did not cause major inaccuracies on the final model.

When we moved to the main body, the alignment and holes were not the main issue, but we were faced with a significant amount of noise due to the metallic parts. Smoothing the geometry caused it to deviate from the physical measures, so we had to find another solution. Thus, as a final pass, we converted the pieces to CAD geometry, by implicitly defining the geometry with basic primitives (spheres, cylinders, planes, etc.) and Boolean operations (subtraction, intersection, addition). Most of the pieces had to be measured manually and checked against the scanned data (FIG. 5).

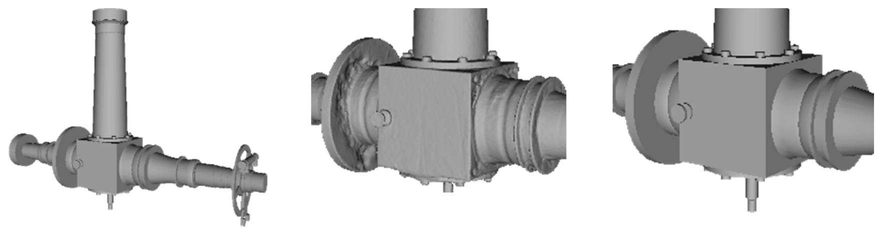

FIG. 5 - The detail of the scanned and CAD model. Notice how the scan model has plenty of noise, but still preserves the overall location and measurements of the pieces.

In fact, one might ask if scanning the model in the first place was a useless effort. As it turned out, it was just the opposite, the scanned model was crucial to validate the CAD model. In many occasions measurement or conceptual errors during the CAD model design were only noticeable when overlaid with the scanned model. Therefore, even if it took a considerable effort to produce two models, the scanned data provided the correct measurements, positions, and orientations, while containing a high degree of noise, while the CAD model was noise free but was strongly prone to deviations from the physical measurements.

Finally, smaller pieces, such as bolts, screws, and the micrometer (FIG. 6), among others, were directly modelled using the CAD system, since they were too small to be captured by our scanner. Since there was no scanned data to compare against, sometimes when assembling the virtual model sometimes the pieces would not fit correctly, and we had to go back and revise the CAD model. This was another advantage of having the larger parts scanned.

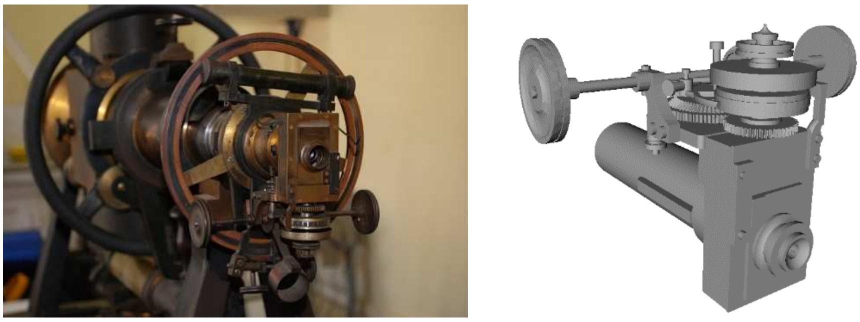

FIG. 6 - A photo and the 3D CAD model of the micrometer. Since it contains so many small pieces, the scanner was unable to capture the geometry and it was manually model using a CAD software.

2.2 Texturing the model

The geometric acquisition was a big challenge, that was mostly solved by placing extra efforts in the process: scanning multiple times to deal with the acquisition of reflective and dark materials, inserting plane patches to fill holes, and building a CAD model in parallel. All the same, the color acquisition required even greater care.

To texture the 3D model a series of photos are acquired that fully cover the model. These are individually aligned with the 3D model and projected onto the geometry, using methods such as (Corsini et al., 2009). In a final pass, all the projected pixels are blended into a single texture (Callieri et al., 2008) (FIG. 7).

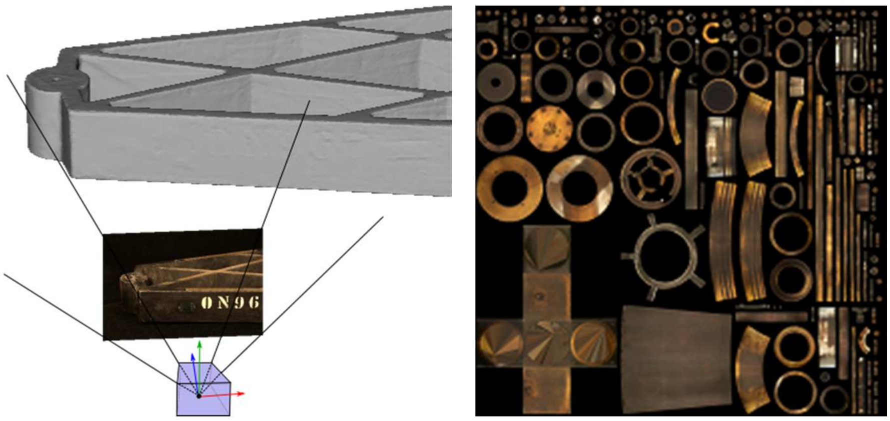

FIG. 7 - To project an image onto the geometry they must be aligned, the image is placed at the exact same position in regards to the virtual model as the camera was when the photo was acquired. The final texture is a composition of all the images that cover the model. The texture shown here is of the main body of the Bamberg.

One desire with texturing the model is to acquire the color with the least environment light influence as possible. This mostly means, avoiding highlights, reflections and high/low exposed parts, as to not carry these effects to the final texture. One common goal with digital objects is to relight it from different directions or different light sources, or place it in different scenarios within a virtual world, thus highlights should be produced by the visualization according to the virtual light and objects, and not imprinted on the texture beforehand.

To avoid highlights, usually diffuse light sources are used and direct illumination is avoided, which can be achieved using diffuse boxes or panels. For the smaller parts, we used an off-the-shelf white box (FIG. 8), while for the larger parts we improvised a tent to place the Bamberg's main body and bases during the photo sessions, in order to create a diffuse environment. As light sources, we used two studio lights with diffuse panels.

FIG. 8 - A photography session using the small diffuse white box and two light sources.

Even with such setup, it is almost impossible to completely remove highlights from metallic or highly reflective surfaces. We then decided to take photos with more overlap, and manually eliminate regions with strong highlights before the texturing phase. The extra overlap was to ensure that at least one, or a few, photos would capture the same region without highlights.

Acquiring more photos has a drawback, however. Apart from the extra effort to align each photo with the geometry, it also means that it is more prone to misalignment in regards to the other photos. This causes ghosting artifacts when creating the final texture. Again, this required extra care during the alignment procedure.

2.3 The final Bamberg digital modelling

The final model contains over 100 pieces of different sizes and geometric properties. Each piece was stored as a separate model with its texture (FIG. 9).

FIG. 9 - Four different digital parts of the Bamberg, including metallic supports, bolts and the lower base.

Using a modeling software we reassembled the virtual Bamberg by placing each part in its corresponding place. Since they were scanned or modeled with accurate precision, the final model fits perfectly (FIG. 10).

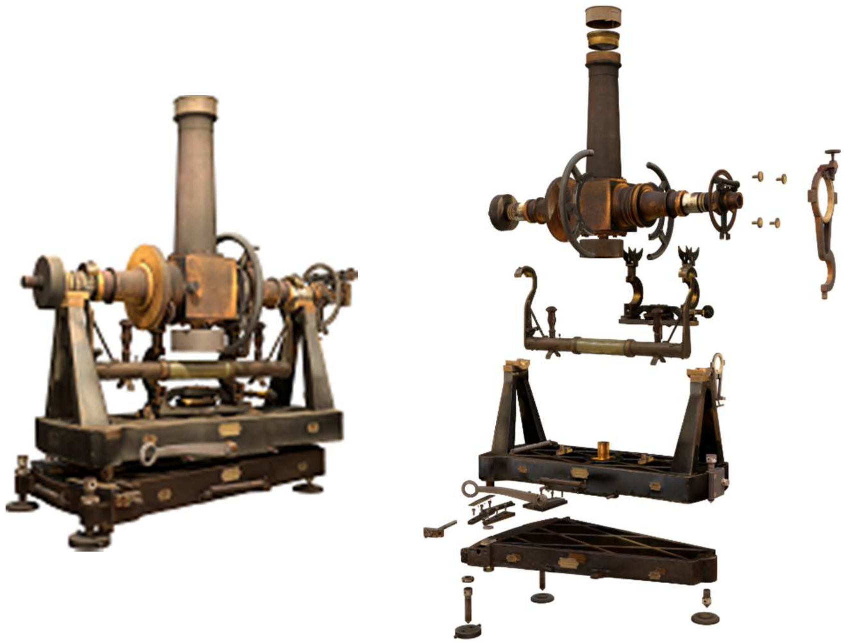

FIG. 10 - The final assembled virtual model and an exploded view of all the pieced of the virtual model.

This virtual model has already been used to generate an animation explaining how the Bamberg worked, and how it was used to measure stars' positions. The digital model is also helping with researchers studying this instrument. A 3D print of the Bamberg (scale 1:5) was also fabricated to be exposed at an exhibition featuring 3D technologies in the cultural heritage domain.

3. The importance of light-based techniques

Both acquisition approaches, for the geometry and the texture, are light based. The scanner emits a laser scanline and captures the reflection of the laser on the surface to determine distances, while the camera works by capturing general light reflected on surfaces and entering the camera lenses.

On one hand, this is extremely important because light-based approaches are passive in the sense that there is no physical-contact. Moreover, the light emission is usually not harmful, except in extreme cases were the material may be deteriorated if exposed to light sources such as lasers.

On the other hand, light-based equipment implicitly carries the challenges to control the light and its behavior when confronted with the objects surface material. The goal is to capture the surface properties and not its behavior in a particular environment.

As we have learned, or in many cases reaffirmed during the Digital Bamberg project, laser technologies perform poorly with metallic and dark surfaces. Reflective surfaces spread the laser, introducing high frequency noise during the registration, while dark surfaces absorb the light and are not captured by the scanner or the camera, leaving holes on the digital surface. In fact, structured light equipment also has problems dealing with this kind of material. Photogrammetry, is a little less sensitive, but has much lower precision in its measurements, and would be unsuitable for the desired goals of this particular project.

Another obvious problem with laser technologies is that it cannot reach some hidden parts of the object, and consequently leaves holes or inaccuracies on the final model. This is of course, also common with most surface light approaches. Volume-based techniques, such as computerized tomography, are able to reach hidden parts, but carry along a list of drawbacks, such as cost, inaccessibility, lack of portability, and lower precision among other problems.

As for texturing, the quality of the acquisition depended more on controlling the light environment, than the photography technology itself. Specular light is difficult to control during the acquisition, but it is even more problematic to solve *a posteriori*. That is why we made a strong effort to control the light during the photo sessions, to avoid as much as possible editing the photos to remove the highlights.

Another drawback with this type of texturing technique, is that we are not really acquiring the surface properties, that is, we are not capturing the reflectance function (also known as BRDFs) that dictates how light behaves when confronted with the material (Dorsey et al., 2008, Weyrich et al., 2009). This function determines how much light is reflected in a direction given an incident light direction. Differently, photos only capture the surface color given a light setup, that is, how the function behaved in that given scenario. In this manner, color only tells a small part of the story, and is very biased with regards to the acquisition conditions. Nevertheless, albeit the recent efforts to create more generic and inexpensive BRDF acquisition methods, it still requires an even more controlled light setup and sometimes specific hardware. It also requires much longer acquisition sessions.

4. Conclusions and future directions

With the Digital Bamberg project we have mapped some important points concerning a digitization campaign of scientific historical instruments.

Passive technologies are essential to prevent physical contact with the artifact, and avoid unnecessary degradation. Thus, light-based techniques are highly appropriate for digitizing museum collections.

Nevertheless, surface light-based technologies are not perfect for acquiring the usual metallic and reflective material of mechanical instruments, but with an extra coordinated effort to fill missing parts and cancel noise it can be done. In this case, the extra effort implied modelling some pieces manually, while using the scanned data as validation, and manually filling some holes.

Finally, to avoid light effects, such as highlights and reflections, being transported to the final textures, a as controlled as possible light environment is required, and probably some post-edition. Most of the approaches to control the light environment are common directives for studio photography, such as using diffuse white boxes.

With the lessons learned during the Digital Bamberg, we are currently working on new directions to alleviate the effort of digitizing other similar artifacts. We are searching solutions that can, at the same time, continue using equipment that are accessible, such as laser scanners and photographic cameras, and that are efficient and ease to use. The last point is important, since we would like the technology to be used by the museum staff themselves, and not only by digitization specialists.

With these perspectives in mind, we are investigating the use of primitive fitting approaches to post-process the scanned models (Schnabel et al., 2007). One may think of it as an automatic CAD converted, where primitives such as spheres, cylinders and planes are automatically retrieved using statistical methods, and the model is created from operations on these analytical surfaces. This would greatly reduce, or even completely dismiss, the need of manually modelling some parts.

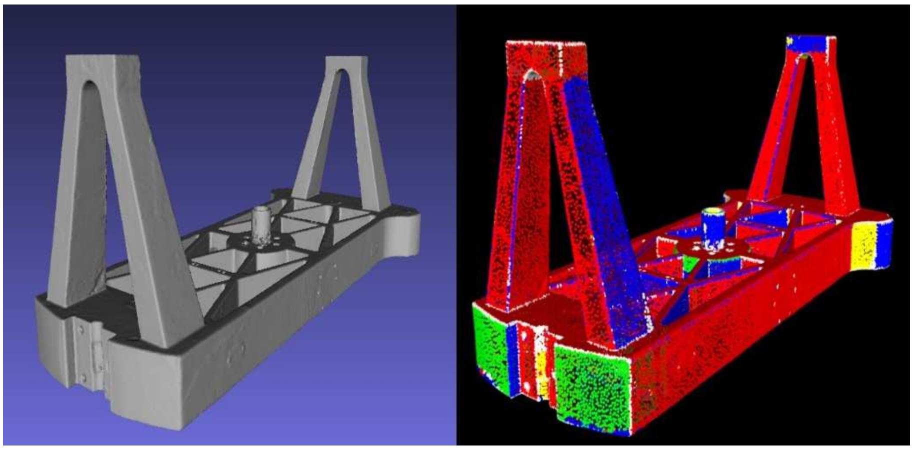

FIG. 11 - The Bamberg's middle base digital model, and some primitives patches automatically extracted. The color code is as follow: green for sphere patches; blue for cylindrical patches; red for planar patches; yellow for inverted cylindrical patches. Sometimes a planar patch is mistaken by a patch from a very large cylinder, for example. But this is ongoing research and we are seeking methods to render it more robust.

As for the texturing part, we are researching ways to capture the underlying reflectance function, instead of the static color from the photos. This implies in extra work, since more photos need to be taken, but results in a much superior digital model, that has embedded the reflective function, and, consequently, is free of light artifacts captured during the acquisition session. We would like to achieve this with off-the-shelf technology, such as camera and light source, and a guided acquisition to accelerate the process.

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