Hybridization of convergent photogrammetry, computer vision, and artificial intelligence for digital documentation of cultural heritage. A case study: The Magdalena Palace

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***Abstract*—Digital documentation of cultural heritage is a very important issue that is receiving increasing attention from the scientific community. The availability of accurate 3D models of historical buildings is crucial to preserve our cultural heritage, because it allows us to reconstruct them in case of fortuitous collapse or intentional demolition or damage. In this paper, we present a new approach for the digital documentation of cultural heritage. Our approach is based on a hybridization of different techniques for data capture and processing and image analysis, with the aim of obtaining 3D models from images and the texturing of these models. In particular, we rely on convergent photogrammetry as way to acquire information about the real objects for generation of 3D models. We also apply computer vision and artificial intelligence techniques for further processing of all acquired data. As a result, we have developed a new way to obtain digital documentation of cultural heritage from data by using accurate reverse engineering techniques. Our methodology has been successfully applied to the digital documentation of a famous historical building in the city of Santander: the Royal Palace of Magdalena, the conference venue of this conference Cyberworlds'2014.**

***Keywords*-Digital documentation; cultural heritage; historical buildings; convergent photogrammetry; 3D models**

I. Introduction

Cultural heritage is one of the most important legacies we can give to our future generations. Many cultural assets (buildings, monuments, artworks, books, etc.) are so valuable that we want to protect and preserve them for current and future generations. They are also often unique and irreplaceable, so it is very important to ensure we take all available measures to ensure their proper documentation and preservation. From this point of view, the digital documentation of cultural heritage is a very important task for effective preservation.

Algorithms for digital reconstruction of real 3D objects are receiving significant attention during the last few years [1], [2], not only in computer vision but also as valuable tools for a variety of applications in medicine, manufacturing, robotics, archeology, and many other fields that require modeling of three-dimensional real environments. For instance, the availability of accurate 3D models of historical buildings is crucial to preserve our cultural heritage, because it allows us to reconstruct them in case of fortuitous collapse or intentional demolition or damage.

In addition, overlaying reality with a virtual model provides augmented reality images, a very powerful tool for the study of reconstructions and restorations prior to its construction, enabling the assessment of its aesthetic appearance, the integration into the environment, and even studies on its visual impact. It also allows the prompt application of corrective actions before the problems actually appear. Finally, these virtual reality models facilitate the online disclosure and dissemination of cultural heritage over the Internet anytime and anywhere. There are many other possible applications of this technology. For instance, to obtain valuable information by data extraction about the geometry of the individual elements of the object, e.g. the size of the blocks of a building, the position of their center of gravity, volume, orientation, and so on.

In this paper, we present a new approach for the digital documentation of cultural heritage. Our approach is based on a hybridization of different techniques for data capture and processing and image analysis, with the aim of obtaining 3D models from images and the texturing of these models. In particular, we rely on convergent photogrammetry as way to acquire information about the real objects for generation of 3D models. We also apply computer vision and artificial intelligence techniques for further processing of all acquired data. As a result, we have developed a new way to obtain digital documentation of cultural heritage from data by using accurate reverse engineering techniques.

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Figure 1: Aerial photograph of Magdalena Palace.

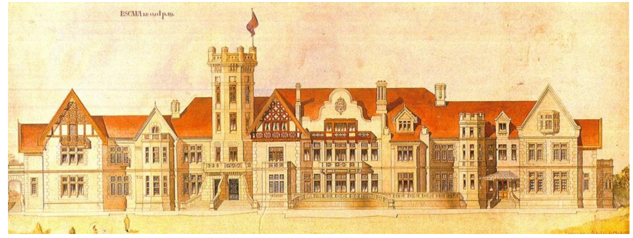

Figure 2: Original drawing by Magdalena Palace's architects.

Our methodology has been successfully applied to the digital documentation of a famous historical building in the city of Santander: the Royal Palace of Magdalena (see Figure 1), the venue of this conference Cyberworlds'2014. It is very important to remark that, although the building is relatively modern (it was constructed during the period 1908-1912), there are no previous blueprints or technical drawings of this building, beyond the original freehand drawings of the architects of the building (see Figure 2) and a few rough drawings of the internal reform accomplished in the 90s. With our approach, we have been able to carry out a very accurate documentation of the palace. In fact, our image information has been processed and stored metrically, so we can obtain the exact measures of all architectural elements directly from the images without the need of a physical contact with the building.

II. State of the Art

There are several approaches described in the literature for the reconstruction of 3D objects. Roughly, they can be classified into four groups:

1) Multi-view techniques: they allow to generate three-dimensional models from a set of images, typically acquired by using two or more image sensors. If two or more images are available, the position of a 3D point can be found as the intersection of two or multiple projection rays through triangulation. These methods require accurate camera calibration prior to the image acquisition step. Once the images are obtained, depth determination is performed in order to compute the missing depth of such images. A central step is the correspondence between pairs of images finding matches between them so that the position of the matched elements can then be triangulated in 3D space. The reader is referred to [3] for a nice survey about multi-view techniques.
2) Mobile Camera techniques: they are active vision techniques that allow to extract 3D information from data obtained through the flight of a moving camera through the scene. Note that in this case, camera parameters are constantly changing, so the classical camera calibration is no longer possible [4].
3) Structured light techniques: they use 3D scanning devices to obtain measurements of the 3D shape of an object using projected light patterns and a camera system. They are based on the distortion effect produced by the projection of simple patterns, generated by coherent light or laser light, from other perspectives than that of the projector to extract the 3D geometric information of the surface shape [5]. They are also active vision techniques in the sense that we can manipulate the viewpoint in order to analyze the environment and obtain better information from it.
4) Laser telemetry techniques: they determine the depth map of the scene based on the elapsed time between the emission and detection of a laser pulse sent to a target and reflected back onto a receiver [6].

Currently, the creation of virtual models from 3D measurements of real objects is increasingly used due to the continuous improvement of the technology involved. Its scope is expanding, from multimedia presentations and navigable network models to the use in professional environments such as architecture, engineering, and construction, where high accuracy is required. The addition of color and textures is also a very important feature.

A major goal of many works in the literature is the automation of the whole texturing process [7]. Control points or marks on the building are often used for this purpose [8]. Also we can look for points and characteristic lines with the photogrammetric methods in images [9]. The first phase in the textured pattern creation is 3D data acquisition. There are various technologies to do it depending on what we intend to acquire: if we have simple shapes, it is solved using photogrammetry and for complex shapes modeling, scanning laser is usually preferred. Photogrammetry requires a lot of work of specialized users to achieve the desired quality and accuracy in three-dimensional modeling.

The second phase is to acquire the color information that will be associated with the geometric information. Again, we have several possibilities: a low-resolution solution is to use the color measured by incorporating a sensor in the scanner; we can also use a high-resolution digital camera to take pictures from every position; finally, we can use a camera attached to the scanner [10]. A less used possibility is to measure color using a spectrograph [11], which provides very accurate color information, but the complexity associated with this method make it only advisable in very specific cases. The use of a camera in free position makes possible to optimize the illumination and the observation point and generally offers more flexibility in terms of image capture. The drawback of this method is that it requires manual calibration for each camera position assigning pairs of corresponding points. With a camera attached to the scanner we lose flexibility; however, it is sufficient to use a single exchange matrix of calibration calculated with many points of quality (determined, for example, using a total station).

The final phase is to project the color information from the photograph onto the 3D model. Normally, such models are formed by triangles, so it is necessary to incorporate the color information to each surface of the pattern. There are many proposals regarding the automatic recognition of patterns or objects on images. A recent one combines artificial vision and automatic recognition using Machine Learning techniques, using pass filters related in spatial form aided by geo-referencing of objects and the use of SVM (Support Vector Machines) [12].

III. Our Method

Our methodology is comprised of three major phases, as described in this section.

A. Phase 1: Data capturing with convergent photogrammetry and drone flights.

Our starting point is the creation of a topographical network using GPS and a total station. To this aim, we make an exhaustive review of available documentation and cartography of the area and the building. We need to know, a priori, the distances of the facades, width of the streets and woodland position. Then, using laser distance or total station, we obtain the raising of the approximate position of woodland, urban furniture, the perimeter of the building, the length and height of building facades, etc. to generate the planning of the photographic shoot. From the schematic drawing of the building facades with a CAD program, we carry out the study of the photographic coverage, taking into account the characteristics of the digital camera: frame size, pixel size, and the desired scale to obtain the final cartography, which in this case is in a 1:100 scale.

Once photographic coverage is planned, we should establish the basis of the network of the survey, which will be used as stations from which we make the radiation of the control points. Then, we performed data acquisition by combining techniques of terrestrial photogrammetry and flights with drones and micro-drones. The decision to use convergent photogrammetry was taken after a comparative analysis of the costs and the feasibility of modeling the building by using alternative techniques such as terrestrial LIDAR technology (laser-scan) to capture information of the facades and the interior of the building. Our approach makes the project less automatic for information capture, but with more possibilities of automation in processing because we deal with images of 3D models formed by clouds of points obtained by stereo-correlation for mesh generation. The stereo-correlation technique uses the principle of binocular vision that means the measurement of the same object following two different angles. It allows to measure the 3D geometry of an object or the displacement for each coordinate of the surface by recording a pair of stereoscopic pictures relating to each stage of deformation. On the other hand, structured light and laser telemetry techniques yield very accurate models but are highly dependent on the geometry of the object and need very controlled environments. On the contrary, the stereoscopic vision based on triangulation between a point of the scene and, at least, two projections of this point on images taken from different perspectives, is one of the most widely used techniques for three-dimensional reconstruction, due to its robustness and its lower computational and economic cost. Our solution of taking convergent photographs to the building also simplifies model texturing and orthophoto production.

On the other hand, we also integrate new methods of data capture into our system. For instance, information acquisition of the facades and the roof of the building was performed by using an airborne camera in a four-airscrew drone. The goal was to capture the facades by taking photos with an oblique flight, and the roofs with aerial or normal position of the perspective beam of the camera to the roof. Our system is comprised of the unmanned Aircraft (UA), control systems such as the Ground Control Station (GCS), devices for information storage and transfer, and other support equipment. The drone also carries sensors that capture information from the field during flight. This information is either retained in the drone flash memory device or transmitted in real time via Wi-Fi to a control station, the unit responsible of information analysis and of control of the ship [13]. A very interesting option of the drone is the "automatic" flight mode in which we can introduce our own previously-designed routes. Other features include a USB port connection, so you can rescue the footage recorded by your camera at 720p. during full action, pressure sensors, gyroscopes, and a miniaturized inertial measurement unit tracking the pitch, roll and yaw, an ultrasonic altimeter for use in stabilization, and a 3D magnetometer to optimize the orientation. Furthermore, the GPS + INS system contains all the sub-systems used to capture geographic information. We also tested the use of a micro-drone to analyze the generation of low-cost models (see Figure 3). This option is specially

Figure 3: (left) micro-drone flight; (right) image of the roof from its frontal camera.

attractive because it provides a very economical alternative to the expensive professional drones and its smaller size allows a closer approximation to the building without risk of collision. On the negative side, the micro-drone provides less flexibility for camera movement and its mounted camera has less resolution.

B. Phase 2: Point cloud optimization and stereo-correlation

Next step involves the application of computer vision techniques to the restitution of the 3D model, the two-dimensional representation of the facades and the creation of the orthoimagery of the building. An image contains a lot of data, most of which provides very little information to interpret the scene. A computer vision system should, as a first step, extract in the most robust and effective form possible, certain features that give us as much information as possible. These features must satisfy (among other conditions) that:

- their extraction from the image must not involve an excessive cost to the system in which it is integrated. Total extraction time must be as small as possible.
- their location must be very precise. Also, feature error estimation must be as small as possible.
- they must be robust and stable.

Next paragraphs discuss the extraction of features we used in image analysis (points, lines and circles).

1) Point extraction: From the computational point of view, two approaches have been proposed to detect this type of geometric features:

- Methods that obtain the points as intersection of edges or as substantial changes of the slope between two edges, and thus are preceded by an extraction of edges.
- Methods that works directly on gray images, i.e., not require prior extraction of edges.

A typical method for extracting characteristic points is given by the vanishing points, which are the geometric and structural support of an image in perspective or oblique. In this sense, they represent points of interest that are determined by the intersection of edges or vanishing straight lines. They can be computed by straight intersection method, a very simple approach (arguably the simplest one) but limited to determine the intersection of two straight perspectives. In general, the efficiency of these methods depends directly on the quality of the method used for obtaining edges. In case the edge detection algorithm do not locate the edge points correctly, it can hardly detect vanishing points exactly. Also, this pre-processing of the edges adds extra computation time to the process.

Another approach for obtaining feature points is described in [14]. Given a rectangular window, the operator calculates the exchange value of the image intensity when we move this window slightly. A corner is then characterized by high intensity changes. The drawback is that this approach is highly sensitive to noise. In a later work [15] this approach is extended by incorporating knowledge of edge and multi-resolution, and an analytical study of the corner model. That work was later expanded in [16] with a new method for detecting characteristic points that exhibits robustness against noise. The method is performed in a similar way to that in Moravec operator, but by calculating the first-order derivatives of the image. However, the location of the points is not entirely accurate.

The alternative to vanishing points methods is given by the corner points. Three methods to detect corners are presented in [17]. Schematically, they consists of:

1) using the product of intensity gradient and the gradient direction at a point of the image as a measure of "corner degree".
2) using the difference between the gradient directions of neighboring points, which are perpendicular to the gradient direction of the point, as a measure of "corner degree".
3) locating 2 points, A and B in a 3×3 neighborhood with similar value of gray to the point C under consideration. The difference in the direction between the vectors CA and CB is a measure of "corner degree".

Once this measure is applied, we delete the false candidates to maintain only the single point in the neighborhood. A similar approach is taken in [18] where corners are detected at the points where significant changes of gradient occur along the edges. In [19], [20], [21], their authors define the operators for the calculation of curvature on a particular neighborhood using the first, second and third order derivatives, of any Gaussian function. In [22] 12 different masks are used to detect different types of corners. They make use of an edge detector to eliminate false candidates. In [23] the concept of space scale is introduced and the location of corners is determined studying their spatial characteristics. The work in [24] is also based on the concept of scale space to determine the location of a corner. Finally, the approach in [25] provides a fast and robust method against noise (not using image derivatives) and the location of the characteristic points provides good results. In a second step,

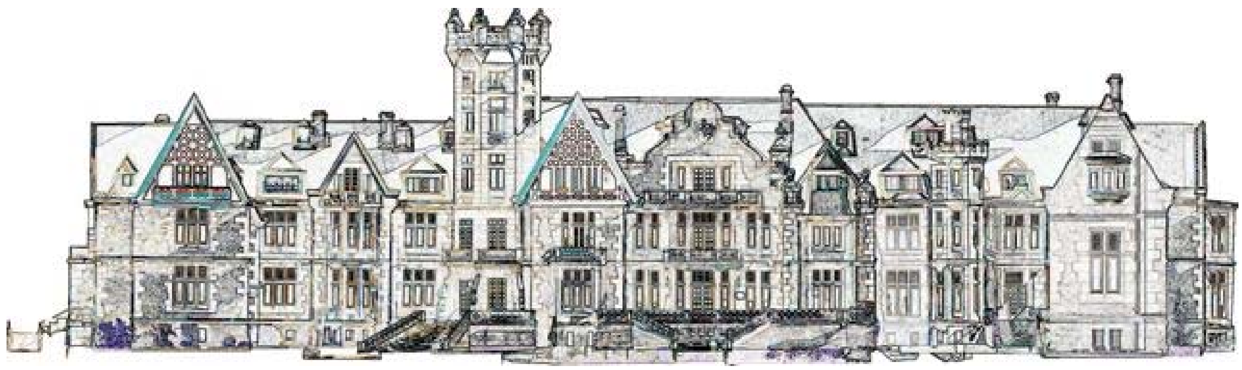

Figure 4: Detection of main lines of the building.

the algorithm finds the most likely corner point within the window of interest. This is relatively simple: the point is determined as the weighted center of gravity of all points within the window, with the product of the gradient of rows and columns as weight.

2) Line extraction: The gradient and Laplacian methods by themselves, do not provide a quality solution for the extraction of lines. To overcome this limitation, we apply the Hough transform for lines. We define a line as a collection of edge points that are adjacent and have the same direction. The Hough transform is an algorithm that takes a collection of edge points found by an edge detector and it searches all lines on which these edge points are. The basic idea is to convert the edge points to the parameter space. The Hough transform is an algorithm of "voting", returning the set of points that are part of a straight line. From this point of view, the array of counters in the parameter space can be estimated by a histogram. Total final votes, will be a coordinate counter, that will indicate the relative probability of the null hypothesis that a line with a set of parameters exists in the image. It consists of next steps: (1) detection of the edge pixels of the straight line using a edges filter; (2) set up of a dimensional parameter space, the search space and a sufficiently accurate quantization; (3) sweep the image so that each edge pixel leads to a straight line: the cells for which "passes" this line receive a "vote". In theory, all the pixels belonging to the same line (in the spatial representation) are straight (in the domain of parameters) that are cut in the same cell (in the representation of parameters): the straight line will be the most voted cell. The Hough transform has several important features. Firstly, as all points are processed independently, it deals well with occlusions. Secondly, it is relatively robust to noise, since the erroneous points will not contribute consistently and only generate background noise.

3) Circle extraction: The point-line duality exploited in the Hough transform for lines can also be exploited for circles. If we know the radius, the domain of the parameters of each circle consists of the coordinates of the center of the circle, so each circle is represented by a point and symmetrically, a point in the spatial domain is represented in the parameter domain by a circle, formed by all points representing all the circles (spatial domain) which can pass through the point (spatial domain). Thus strategy to extract circles by the Hough transform consists of: (1) edge pixel detection of the circles by an edge filter; (2) set up of a domain of parameters whose dimensions are the proper search space and a sufficiently accurate quantization: the quantization of the pixels in the original image, (3) we sweep the image so that each pixel labeled as edge produces a circle with radius K centered on itself. The cells belonging to the circle receives a "vote".

C. Phase 3: Generation of the definitive 3D model, orthorectification of the images and 3D model texturing.

After setting the relational description of the entities of correspondence and how to measure the degree of similarity, we compute a correspondence scheme. The most common way to find the solution is using a tree of search [26]. Trees are formed by nodes and arcs. Starting at a root node, they descend through the ancestor nodes to reach the leaf nodes. The connection between two nodes is performed through arcs. The primitives $\{p_1, p_2, ..., p_n\}$ of a relational description are called units and the primitives of the description that you want to match, i.e., $\{q_1, q_2, ..., q_n\}$ are called tags. The size or depth of the tree is defined by the maximum path with the lowest cost.

The final step is to obtain a three-dimensional model of the object. To achieve this goal, once cards or artificial marks of the object are detected in the image, we obtain the corresponding points to those corners in the rest of the images. By knowing the basic points of the image, we compute the epipolar straight lines in the other image using the fundamental matrix. The corresponding points to the right image will be on those lines, so that the search area in the image is reduced. To search the epipolar straight lines, a correlation between the intensity of the point on the

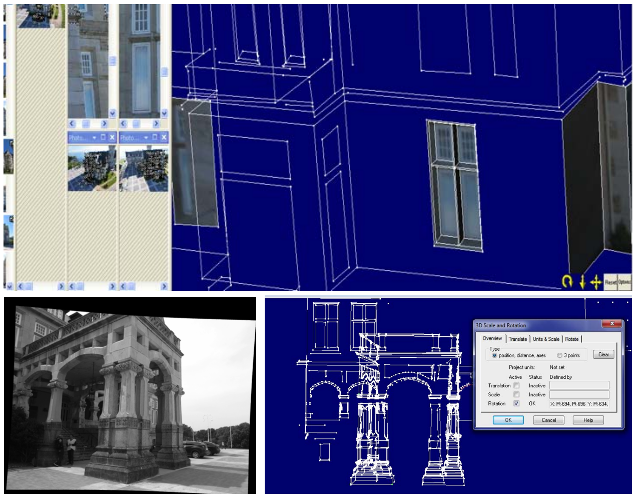

Figure 5: (top) Rendering of a window; (bottom) photo and model of the portico.

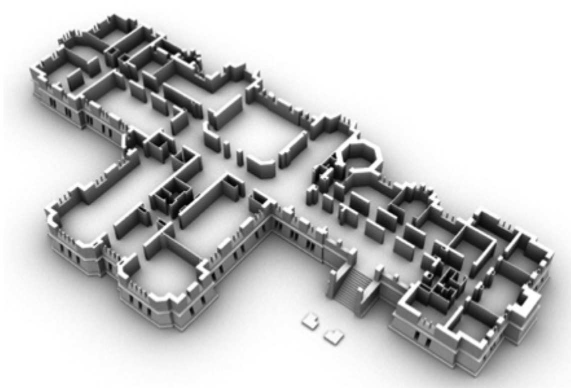

Figure 6: Geometric model with facade and internal layout.

left image and its surroundings is set up, with the points that form the epipolar straight line and its neighbors. For it, we compare each detected corner, windows size $N \times N$ centered on that corner, with the points of the epipolar line and surroundings. Once the surfaces are created by triangulation, we allocate the materials onto these surfaces. We also compute light interaction between the 3D model and the light sources of the scene for more realistic viewing effects. We also improve the wire mesh model by exporting it to a CAD program and cleaning and correcting the fault lines of the building. A 3D model was also achieved for the interior of the building.

1) Orthophotographs creation: At this step we perform orthoprojection to transform a perspective in an orthogonal projection. The goal is to correct the displacement caused by the tilt of the camera and the depth of the items in the image, for example, the balconies. With this procedure, we obtain an

Figure 7: Untextured 3D model.

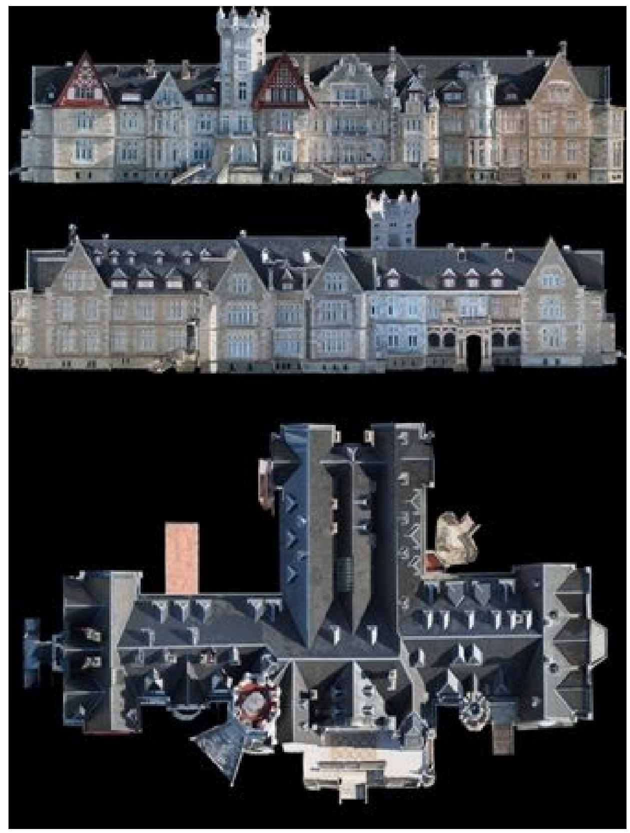

Figure 8: Orthophotos of the Magdalena Palace.

image in which all the elements appear completely perpendicular to the viewpoint and with the same scale. The process takes into account the three-dimensional position of all polylines and points that have been created in the model, and fits the real surface to a mathematical surface formed by flat triangular elements. This triangle mesh allows interpolation between depth values of each vertex, generating an elevation digital model. Finally, applying texture to these triangles, image is deformed, pixel by pixel until it reaches a reliable magnitude. The creation of orthoimages for this work has

Figure 9: Aerial orthophotography of the Magdalena Palace.

Figure 10: Textured 3D model (facade).

been very difficult due to the amount of existing changes in the depth of building (see Figures 7 and 8). This forced us to sub-divide each facade into several fragments, depending on the depth element. The roof was treated separately, by using the aerial shots taken from the drones (see Figure 9). The result is a fully textured 3D model (see Figure 10). Finally, we have also generated a stereoscopic model for full 3D visualization through anaglyph glasses (see Figure 11 for two examples of this kind of images).

IV. Future Work

This work provides the basis for future development of a framework for digital documentation of cultural heritage and its 4D representation, where we can aggregate spatially localized attributes to the 3D representation, such as the temperature emitted by the building or others [27], [28]. In addition we also plan to apply machine learning techniques to improve the automation process of our methodology.

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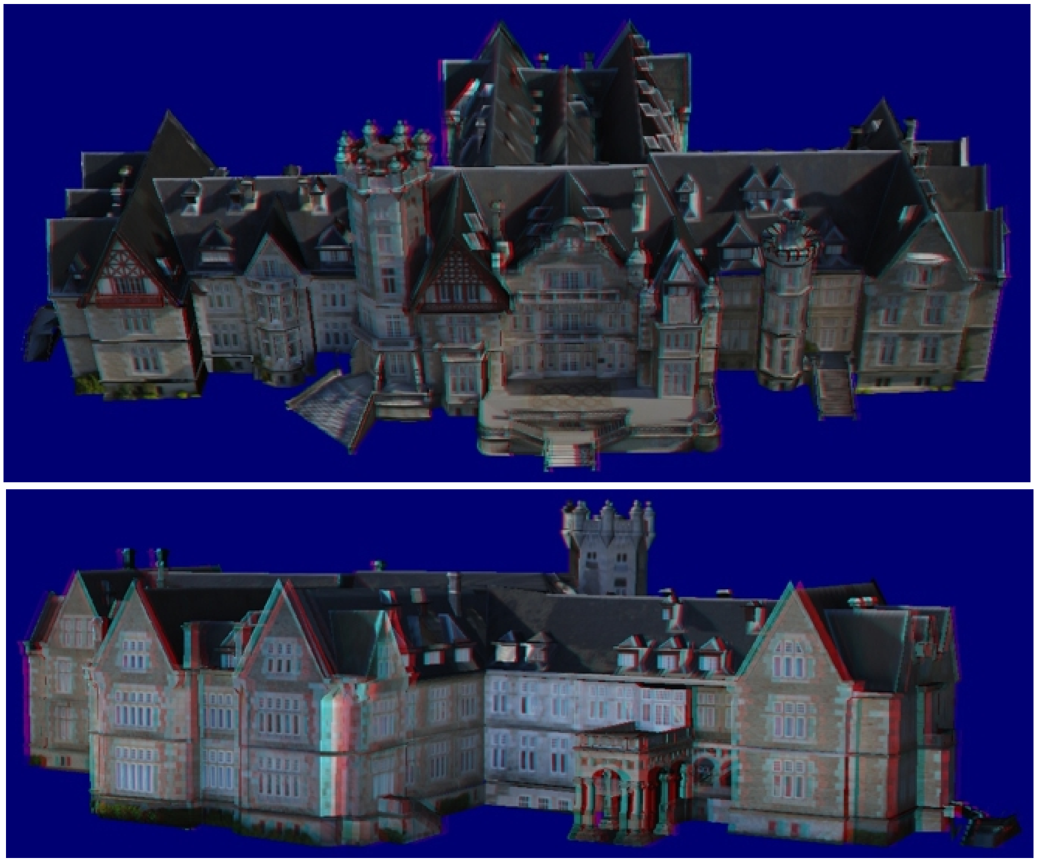

Figure 11: Two views of the stereoscopic model of the Magdalena Palace.

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