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Aerial Photogrammetry for the Conservation of Cultural Heritage in Hidalgo

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Abstract. This research aims to apply architectural photogrammetry for the documentation and conservation of the Monumental Clock of Pachuca de Soto, in the State of Hidalgo. To this end, an unmanned aerial vehicle (UAV) of the quadcopter type was constructed, enabling the capture of high-resolution photographic images, which were processed to generate a detailed three-dimensional model of the structure. The results demonstrate that this technique provides an accurate representation of the monument, facilitating both its conservation and the planning of future interventions. This study highlights the importance of model quality, which is influenced by climatic variables, as image capture may be limited on cloudy or rainy days. The research emphasizes the innovative application of UAV-based photogrammetry in the field of architectural heritage preservation, offering an efficient and non-invasive tool for the documentation of historical monuments. The findings confirm that this methodology holds significant potential for implementation in the digital conservation of cultural heritage.
Keywords: 3D model; UAV (Unmanned Aerial Vehicle); digital documentation; restoration; historical heritage.

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1 Introduction

Photogrammetry is an image processing technique that has evolved with technological advancements in computer science and engineering, enabling the precise acquisition of three-dimensional data from photographs (Lucet, 2017). Through advanced computational algorithms, this technique allows for the detailed extraction of information about the shape and dimensions of physical objects and their surroundings. Initially developed for applications in surveying and cartography, photogrammetry has found a wide range of uses in fields such as precision agriculture, archaeology, engineering, forensic science, and particularly architecture, where it has established itself as a key tool for the documentation and conservation of cultural heritage (Tsoraeva et al., 2021). In this context, the use of unmanned aerial vehicles (UAVs), such as quadcopters, has expanded image capture possibilities, enabling the creation of more precise and accessible three-dimensional models for the preservation of historical structures.

Historical buildings hold significant cultural value, and their repair and protection require diverse approaches. With the advent of 3D digitization, drones have gained importance in heritage studies (Lin, G., et al., 2024). The problem addressed in this work lies in the need to document and preserve architectural heritage, particularly the Monumental Clock of Pachuca, a cultural icon in the State of Hidalgo. As the passage of time affects the integrity of historical monuments, there arises a need for innovative and precise methodologies to facilitate their conservation. In this context, aerial photogrammetry emerges as an efficient solution for obtaining detailed models of structures without direct physical intervention, which is crucial for heritage preservation (Rodríguez and Calvo, 2010). However, although this technique has gained popularity in various fields, its application in architectural documentation remains a developing area, and its use with UAVs in cultural heritage conservation is still subject to debate regarding its accuracy and reliability under variable environmental conditions (Roggero and Diara, 2024). Currently, photogrammetry is recognized as a discipline of photography that can include different categories, such as terrestrial photogrammetry, which is applied to nearby objects, where photographs are captured from the ground; aerial photogrammetry, which is especially used for the analysis of large objects and structures, where images and photographs are captured from aerial vehicles such as airplanes, helicopters, light aircraft, and more recently, drones (unmanned aerial vehicles); and digital photogrammetry, which utilizes specialized software to analyze images and automatically perform steps two, three, and four mentioned earlier, through advanced algorithms in trigonometry, geometry, and linear algebra, to generate three-dimensional models (Mazaheri & Momeni, 2008; Ren et al., 2023). Among its applications, architectural photogrammetry plays a crucial role in the identity, symbolism, and collective memory of society, as it enables the documentation of cultural heritage, the restoration and conservation of monuments and architectural manifestations of a group's ideology, the creation of three-dimensional models to disseminate and showcase the architectural beauty and symbolism of a monument, and, finally, education and awareness-raising to preserve and communicate cultural and architectural heritage to society.

The objective of this work focuses on the application of digital methods to preserve the architectural heritage of the Monumental Clock of Pachuca. It employs non-contact measurement technology, specifically UAV, for data collection, creating 3D point cloud models, which are specifically designed and built for this purpose. This study aims to generate a detailed three-dimensional model of the monument, which will not only enable the recording of its conservation over time but also provide a valuable tool for future interventions and the dissemination of its cultural significance.

The Monumental Clock of Pachuca, Hidalgo, is a historic building located in the Plaza Independencia of Pachuca de Soto, in the state of Hidalgo, in the Mexican Republic. Among the historical aspects that stand out about the Monumental Clock of Pachuca are the following: The clock was designed by Tomás Cordero and built by engineers Francisco Hernández and Luis Carreón between 1905 and 1910. It was inaugurated on September 15, 1910, to commemorate the centenary of Mexico's Independence and was originally named the "Independence Clock." Later, in 1964, it was declared a National Historic Monument due to its historical and architectural significance (Corrales Vivar, 2011).

Regarding its architectural features, the Monumental Clock of Pachuca stands out for its neoclassical and art nouveau styles, constructed with materials such as iron and white stone sourced from nearby hills around Pachuca, such as Tezoantla, a community in the neighboring municipality of Mineral del Monte. It has a height of 40 meters, four levels, and four identical clock faces, each with a diameter of 6 meters.

Culturally, the Monumental Clock is considered an important symbol of the city of Pachuca and the state of Hidalgo. It is a significant tourist attraction, drawing both national and international visitors. Moreover, it has become a landmark for the residents of Pachuca and a symbol of local identity. The Monumental Clock has been restored on several occasions to preserve its structure and beauty, serving as a representative example of monumental architecture from the early 20th century in Mexico, making it a cultural heritage site of great importance.

2 Methodological framework

In the present study, aerial photogrammetry is combined with digital photogrammetry to create a three-dimensional reconstruction of the iconic Monumental Clock of Pachuca, located in the city center of Pachuca de Soto, in the state of Hidalgo. High-resolution photographs of this monument are captured using a quadcopter-type unmanned aerial vehicle (UAV). The obtained images are processed using the 3DF Zephyr software to generate the three-dimensional model of the monument. This study has two primary objectives: first, to preserve the cultural heritage of the state of Hidalgo; and second, to promote the historical and architectural richness of the municipality of Pachuca de Soto.

This section provides a general description of the design and construction process of the quadcopter-type UAV used for capturing and collecting high-resolution photographs. It is specifically designed to carry a compact and portable action camera capable of recording and photographing in extreme outdoor conditions. This quadcopter UAV must be lightweight, capable of carrying the camera (153 grams), and have a flight autonomy of 15 to 20 minutes. Based on these characteristics, the calculation and selection of components, such as the frame, brushless motors, propellers, and battery, are performed. In other words, the selection of components is carried out considering the weight-to-power ratio, which directly influences the choice of the frame, motors, propellers, and camera. Consequently, the component selection focuses on the elements listed below (de Jesús et al., 2023; Ordaz, 2022):

1. Generic F450 frame, widely available on the market, offering easy access and affordability.
2. T-Motor polymer propellers 1045, measuring 10 inches from tip to tip and featuring a 45º pitch angle, allowing for greater propulsion and thrust at lower acceleration.
3. T-Motor AirGear350 brushless motors, with 22-12 diameters and 880 KV.
4. 20A opto-isolated Electronic Speed Controllers (ESCs), without a battery eliminator circuit, primarily designed to prevent overheating under maximum load conditions.
5. RadioMaster Zorro transmitter operating at 2.4 GHz with 16 channels, featuring an OpenTx interface, an approximate range of 1000 meters, and ELRS telemetry receivers' models EP1 and EP2 at 2.4 GHz.
6. LiPo (Lithium Polymer) battery, 14.8 V, 4 cells, 1550 mAh.
7. Radiolink Mini PIX flight controller with both mechanical and software-based vibration damping.
8. TS100 GPS module for obtaining positional coordinates during trajectory tracking tasks and flight modes, including fail-safe modes.
9. GoPro Hero 10 Black digital camera, capable of recording 5.3K video, capturing photos up to 23 MP, and providing 8X slow motion at 2.7K resolution.
10. 3DR Radio telemetry module at 915 MHz, compatible with Pixhawk, enabling air-to-ground data transmission.
11. Drone mounts 3D printed using PLA material.

As mentioned, the unmanned aerial vehicle (UAV) quadcopter must be lightweight and have sufficient payload capacity to carry the compact and portable action camera. Additionally, it must ensure stability during hovering flight to improve the quality of the videos and photographs captured by the camera. Moreover, the UAV, as shown in Figure 1, must be capable of following predefined trajectories, as it is essential in specific scenarios to determine the points where photographs need to be captured during hovering flight.

Fig. 1. Unmanned aerial vehicle (UAV) quadcopter designed and built for this research work.

The assembly process of the quadcopter begins with the installation of the electronic components, such as the power distribution board, which is connected to the bottom of the drone's frame, providing power to certain elements, such as the flight controller and the electronic speed controllers (ESCs). After soldering and assembling the components, the assembly of the drone's frame is completed by attaching the arms to the top plate of the device, providing stability and structural support to the aircraft. The combination of these components shapes and strengthens the drone's frame, creating the basic platform upon which the other elements are mounted and connected.

It is important to highlight that the flight controller used is a MiniPix with FMU V2 from the Radiolink brand, which is mounted on the base plate of the frame along with a vibration-damping support. Next, the 880kV brushless motors, selected for their compatibility with the generic F450 frame model, are installed. These motors play a crucial role in the handling and propulsion of the quadcopter and are carefully connected to the Hobbywing Xrotor 20A electronic speed controllers (ESCs), allowing for precise control of the quadcopter during flight. The connection is made accurately through the bottom plate of the frame, ensuring efficient and reliable power supply to the motors.

Similarly, a 5A UBEC voltage regulator module from Hobbywing is mounted and connected to provide stable and appropriate power to the system's electronic components. The UBEC, along with the ESCs, is connected to the MiniPix flight controller to establish communication between it and the motors, ensuring a constant 5-volt power supply with the necessary pulse-width modulation. This guarantees stable and safe flight by maintaining a constant voltage for the proper operation of all the system's components.

Once all the physical elements, electronics, sensors, and actuators are integrated, the global positioning system (GPS) is installed. Next, the receiver is mounted and connected, then configured and linked with the transmitter. For configuration and calibration, the Mission Planner software is used, which facilitates the modification of the necessary flight and operation parameters and properties, as well as the programming of the firmware in the flight controller. Finally, precise GPS calibration is carried out, the ESCs are programmed and calibrated, and the channels of the transmitter are carefully adjusted, ensuring the accurate programming of their maximum and minimum values (Martínez et al., 2024).

The construction of the unmanned aerial vehicle (UAV) quadcopter prototype was successfully completed, and it currently operates with the MiniPix flight controller, programmed with its original firmware. This controller enables the implementation of multiple flight modes, such as: constant position, altitude control, trajectory tracking through waypoints, and automatic stabilization, among others. The overall operation of the quadcopter is described in Figure 2. In this system, the real position of the aircraft is determined by the global positioning system (GPS) module, while the desired position is specified through waypoints or visual feedback provided by the operator via the transmitter. The difference between the desired position and the actual position generates an error variable, which is processed by the flight controller. The controller applies a discrete proportional-integral-derivative (PID) control algorithm to calculate the necessary control signals. These signals are transmitted to the electronic speed controllers, which adjust the voltages sent to the motors. This process ensures the necessary corrections to the quadcopter's position and stability, allowing for precise and controlled flight. This design integrates advanced navigation and control technology, highlighting the system's ability to operate autonomously or with minimal supervision, making it a versatile tool for various applications, such as the one proposed in this work.

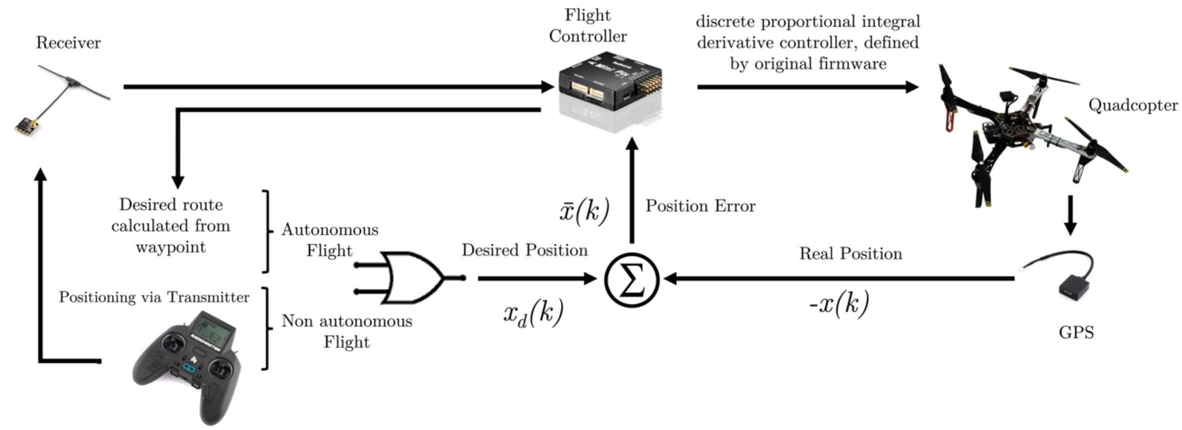

Fig. 2. Diagram of the automatic operation and manual manipulation of the quadcopter.

The quadcopter, carrying the compact and portable action camera, can be seen in Figure 3, performing a constant position flight.

Fig. 3. Unmanned aerial vehicle, quadcopter type, designed and built for this research work, in operation.

As science and technology advance, the scope, and applications of unmanned aerial vehicles (UAVs) continue to expand. One such application is aerial photogrammetry, which reduces the costs associated with image collection and enhances the safety of the personnel responsible for performing this task. During the development of the platform, it has been observed that these devices represent sophisticated tools that allow for the acquisition of precise data in relatively short periods of time. The improvements in quality, efficiency, and safety in obtaining aerial photographs used in various photogrammetry studies through UAVs ensure the generation of accurate results.

3 Results, Discussion

This section presents the results of both the photographic data collection of the Monumental Clock of Pachuca de Soto, captured with the unmanned quadcopter (UAV) built within the framework of this research project, and the digital photogrammetry process, performed using the specialized software 3DF Zephyr (Hilal et al., 2022). Using the original firmware, updated until October 2024, the UAV quadcopter is programmed and calibrated with the support of the open-source software Mission Planner (Chintanadilok et al., 2022). Through the firmware update and the calibration of the electronic speed controllers (ESCs) and the transmitter, it is possible to perform functionality tests with the various flight modes. The main test consists of elevating the UAV to an approximate altitude of 38 meters and setting it to stationary mode. From this test, a panoramic photograph of the complex of buildings, courts, and modules of La Salle Pachuca, La Concepción campus, is captured, as shown in Figure 4.

Fig. 4. Photograph of La Salle University Pachuca, La Concepción Campus, captured with the platform built for this research project.

For this work, the aerial photogrammetry technique with an unmanned aerial vehicle (UAV) is applied. This technique has gained popularity, mainly due to the advantages that these devices offer in terms of accessibility, efficiency, and cost. In this project, the built drone allows capturing high-resolution aerial images of the Monumental Clock from different altitudes and angles, covering large areas of the structure in a short amount of time, which is particularly useful for the stated objective.

The UAV used for this project is equipped with a camera featuring a new GP2 chip, which enables it to record 5.3K video at 60 fps, along with other improvements in functionality and performance. Below are some of its technical specifications: 55×71×33.67 mm in size and weighing 153 grams, a 2.27-inch LCD touchscreen, a 1.4-inch front LCD display for preview, a 23-megapixel sensor with a 155° field of view, video capture at 5.3K at 60 fps, maximum resolution of 4K at 120 fps, 2.7K at 240 fps, and 1080p at 240 fps, simple photo mode, burst shooting, video loop, 2x zoom video, time lapse, and 1080p video streaming. It supports RAW, AVC, and HEVC formats and has connections and ports for MicroSD UHS-3, USB, Type-C, Bluetooth, and Wi-Fi. It features three microphones for noise reduction, software-based image stabilization, water resistance up to 10 meters, a built-in speaker, and an integrated mount.

Fig. 5. Clerestory of the Monumental Clock in an ascending spiral sweep.

It is worth mentioning that Pachuca de Soto city is situated between 20° 01’ and 20° 12’ north latitude and 98° 41’ and 98° 52’ west longitude, with an altitude ranging from 2,300 to 3,100 meters. Pachuca has a temperate semi-dry climate (54.25%), a temperate sub-humid climate with summer rains and lower humidity (41.97%), a semi-cold sub-humid climate with summer rains and higher humidity (3.49%), and a temperate sub-humid climate with summer rains and even higher humidity (0.29%). During January, February, and March, the prevailing winds in the basin mainly come from the south. The strongest winds, ranging from 5.7 to 8.8 m/s, originate from the southwest and west directions. From April to December, the prevailing winds from the northeast have average speeds ranging from 0.5 to 2.1 m/s.

The acquisition of the high-definition photographs used in this study was carried out during a time interval between 7:00 and 8:00 hours on a day with total cloud cover. This choice of time and meteorological conditions is based on minimizing the influence of two critical factors: wind speed and direct sunlight incidence. The low wind speeds, characteristic of the early morning hours, reduce the risk of abrupt UAV movements during capture, optimizing image sharpness. Furthermore, the diffuse light provided by the cloud cover eliminates projected shadows, which is crucial for obtaining three-dimensional reconstructed models with greater precision and uniformity in surface texture.

For the photogrammetry presented in this document, a series of flights were conducted with different sweeps of the Monumental Clock structure, including an ascending spiral sweep, a descending spiral sweep, and a vertical zigzag sweep. In the development of this work, the last sweep was discarded due to its low efficiency and performance in the 3D reconstruction. In the ascending spiral sweep, 1,703 georeferenced photographs were captured at the coordinates 20°07′39″N 98°43′55″W / 20.1275, -98.731944, each with dimensions of 3840×2160 pixels, horizontal and vertical resolution of 96ppi, and 24-bit depth. The flight was manually operated with a duration of 5.23 minutes. Among the captured images is the clerestory of the Monumental Clock, as shown in Figure 5.

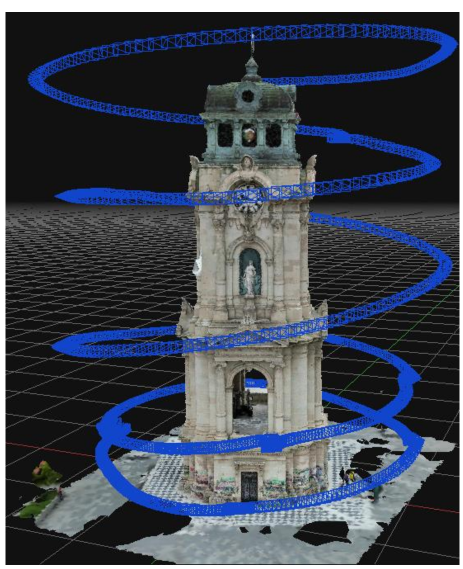

Fig. 6. Point cloud of the descending sweep of the Monumental Clock.

In the descending spiral sweep, 1166 georeferenced photographs were captured at coordinates 20°07′39″N 98°43′55″O / 20.1275, -98.731944, each with a resolution of 3840×2160 pixels, a horizontal and vertical resolution of 96 ppi, and 24-bit depth, during a manual flight lasting 3.38 minutes, as shown in Figure 6.

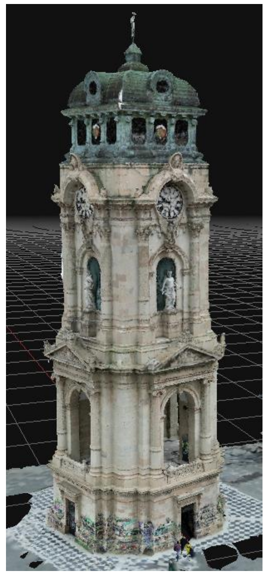

Fig. 7. 3D Reconstruction of the Monumental Clock.

For the processing and 3D reconstruction of the Monumental Clock, the photogrammetry software 3DF Zephyr is used. This is a 3D photogrammetry software developed by 3Dflow, widely used for reconstructing 3D models from photographs or videos. It utilizes advanced Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms and is compatible with multiple input and output formats such as OBJ, FBX, PLY, and STL (Hilal et al., 2022). The reconstructed model can be seen in Figure 7. It employs advanced algorithms for precise and detailed reconstructions and can handle both small and large photo collections. The software offers an intuitive interface with mesh editing and cleaning tools, as well as texturing and coloring capabilities. It includes marking and measurement functions, supports drone images, and allows the export of orthomosaics and digital elevation models. It supports point clouds and integrates GPS data for georeferencing, in addition to providing advanced visualization tools. For the study presented here, 3DF Zephyr is installed and run on a laptop with the following specifications: Intel i5 11th generation processor at 2.7GHz, 32GB of installed RAM, Windows 11 64-bit, and NVIDIA GeForce RTX™ 3050 GAMING X 8G graphics card running at 1845 MHz with 8GB of GDDR6 graphics adapter memory, a 128-bit memory bus, maximum resolution of 7680 x 4320 pixels, DirectX version 12.0, OpenGL version 4.6, PCI Express X8 4.0 interface, and dual-fan active cooling.

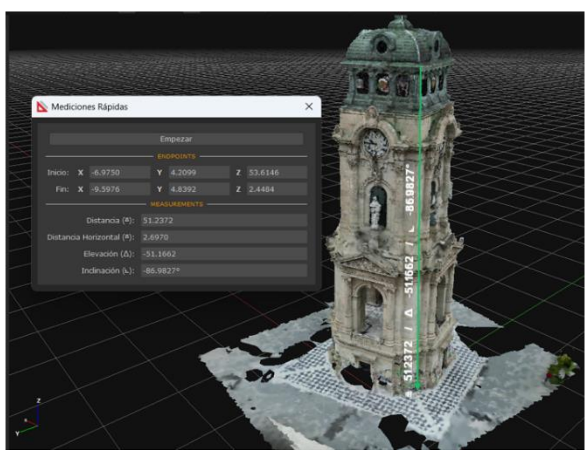

Fig. 8. Quick measurements on the 3D model of the Monumental Clock

Architectural photogrammetry using Unmanned Aerial Vehicles (UAVs) is a highly valuable tool in the study and preservation of architectural cultural heritage. This technology allows for precise and detailed documentation, enhancing conservation efforts by providing essential data that can be employed in a wide range of practical and academic applications. This paper documents a portion of the valuable architectural heritage of the city of Pachuca de Soto, located in the State of Hidalgo, focusing on its iconic Monumental Clock, a representative example of neoclassical architecture that, to date, lacks this level of detailed documentation.

Through the generation of a three-dimensional model and a set of high-definition images obtained within the framework of this project, a detailed and accurate record of this emblematic structure has been created. This model and its corresponding images enable detailed studies and the design of restoration interventions, providing reliable information regarding the dimensions and current state of the building.

As illustrated in Figure 8, preliminary analysis reveals that measurements can be obtained with an accuracy ranging from 1 to 2 millimeters, thanks to the inclusion of georeferenced control points, as used in this study (Hilal et al., 2022). This level of precision offers significant benefits in terms of georeferencing, measurement accuracy, and integration with other spatial data. The incorporation of geospatial control points substantially enhances the overall quality of the model, making it applicable in more demanding fields such as engineering, surveying, urban planning, and infrastructure monitoring. Furthermore, these control points provide greater oversight during the reconstruction process, ensuring precise alignment with other models or existing data, thereby guaranteeing the coherence and reliability of the resulting three-dimensional model.

Beyond the generated 3D model, a fundamental outcome of this research is the creation of an extensive image database comprising over 2869 high-resolution photographs captured using an unmanned aerial vehicle (UAV). Each image has been georeferenced, allowing for integration into geographic information systems (GIS) and analysis in conjunction with other spatial data. The high resolution and accuracy of the images, obtained under controlled flight conditions, enable detailed analysis of the clock's architectural elements, identification of pathologies, and assessment of the structure's conservation status. This image database constitutes an invaluable resource for future research, as it enables a detailed study of the geometry, dimensions, and ornamentation of architectural elements; identification and quantification of cracks, fissures, detachments, and other deteriorations, allowing for the evaluation of damage evolution over time; creation of a detailed visual record of the monument's current state, serving as a reference for future comparisons and historical studies; and generation of virtual models and animations that allow for visualization of the clock from different perspectives and simulation of conservation interventions. The availability of this georeferenced image database opens new possibilities for the study and conservation of architectural heritage, enabling a deeper understanding of the clock's historical evolution and facilitating informed decision-making regarding its restoration and maintenance.

4 Conclusions

Through the photogrammetry of the Monumental Clock in the municipality of Pachuca de Soto, in the State of Hidalgo, various activities can be carried out, including the creation of a detailed 3D model of the Clock, documenting the current state of the monument, studying the architecture of the building, creating a virtual reconstruction of the Clock in its original state, generating precise blueprints, conducting simulations and visualizations to analyze its behavior under different conditions, and sharing the information and 3D models with students, researchers, and the general public. Additionally, the data obtained from photogrammetry can be used to document the changes the building has undergone over time, including its history and restoration processes. This type of information facilitates better planning of conservation, restoration, or rehabilitation interventions on the monument and enables the creation of multimedia content, such as videos, animations, and virtual tours, to promote tourism and foster interest in the historical and cultural heritage of the State of Hidalgo.

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