Routledge
Taylor & Francis Group

Studies in Conservation

ISSN: 0039-3630 (Print) 2047-0584 (Online) Journal homepage: www.tandfonline.com/journals/ysic20

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To cite this article: Yacy Ara Froner, Willi de Barros Gonçalves, Luiz Antônio Cruz Souza, Antônio Gilberto Costa, Alessandra Rosado, Ana Regina Mizrahy Cuperschmid, Guilherme de Oliveira Walter, Ana Carolina Neves Miranda, Guilherme Michelin, Ana Carolina Montalvão & Tiago Hardy (2024) Data Collection for Cultural Heritage Risk Management: the *Damage Map through Heritage Building Information Modeling (HBIM)* Project Applied to the Façade of St Francis of Assisi, Ouro Preto, Brazil, Studies in Conservation, 69:sup1, 98-107, DOI: 10.1080/00393630.2024.2379132

To link to this article: https://doi.org/10.1080/00393630.2024.2379132

Published online: 08 Aug 2024.

STUDIES IN CONSERVATION
2024, VOL. 69, NO. S1, S98–S107
https://doi.org/10.1080/00393630.2024.2379132

ORIGINAL RESEARCH OR TREATMENT PAPER

Data Collection for Cultural Heritage Risk Management: the *Damage Map through Heritage Building Information Modeling (HBIM)* Project Applied to the Façade of St Francis of Assisi, Ouro Preto, Brazil

Recopilación de Datos para la Gestión de Riesgos del Patrimonio Cultural: el Proyecto *Mapa de Daños Mediante el Modelado de Información de Edificios Patrimoniales* (HBIM) Aplicado a la Fachada de San Francisco de Asís, Ouro Preto, Brasil

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ABSTRACT

The development of precise analytical methodologies, together with the systematic use of verifiable data, aims to raise standards for treatment, risk management, and maintenance programs. This endeavor aims to diminish the frequency of subsequent restoration cycles, thereby positively impacting public spending and fostering the preservation of the authentic characteristics of historical buildings, particularly by mitigating the effects of decay. The *Damage Map through Heritage Building Information Modeling (HBIM)* project, funded by the National Council for Scientific and Technological Development (CNPq) and Minas Gerais Research Support Foundation (FAPEMIG), both Brazil, aims to establish protocols for risk management in historical buildings, with a focus on decorative stone elements integrated into the construction. For this reason, the stone relief on the façade of the church of St Francis of Assisi in Ouro Preto, Brazil, was chosen as a case study. This paper outlines the data collection methodology applied to study the stone. This approach encompasses historical examinations of restoration cycles, along with preliminary findings derived from extensive fieldwork, conducted by a multidisciplinary team in 2023. It elucidates the data collection stage, employing photography and aerial photogrammetry, ultraviolet fluorescence photography, mobile laser scanning, and thermography. Subsequently, all collected data will be used to construct a diagnostic model within the HBIM.

El desarrollo de metodologías analíticas precisas, junto con el uso sistemático de datos verificables, tiene como objetivo elevar los estándares para el tratamiento, la gestión de riesgos y los programas de mantenimiento. Este esfuerzo tiene como objetivo disminuir la frecuencia de los ciclos de restauración posteriores, impactando así positivamente en el gasto público y fomentando la preservación de las características auténticas de los edificios históricos, particularmente mitigando los efectos del deterioro. El proyecto Mapa de Daños a través del Modelado de Información de Edificios Patrimoniales (HBIM), financiado por el Consejo Nacional de Desarrollo Científico y Tecnológico (CNPq) y la Fundación de Apoyo a la Investigación de Minas Gerais (FAPEMIG), ambos de Brasil, tiene como objetivo establecer protocolos para la gestión de riesgos en edificios históricos. con especial atención a los elementos decorativos de piedra integrados en la construcción. Por esta razón, se eligió como caso de estudio el relieve de piedra de la fachada de la iglesia de San Francisco de Asís en Ouro Preto, Brasil. Este artículo describe la metodología de recolección de datos aplicada para estudiar la piedra. Este enfoque abarca exámenes históricos de los ciclos de restauración, junto con hallazgos preliminares derivados de un extenso trabajo de campo, realizado por un equipo multidisciplinario en 2023. La etapa de recopilación de datos se resalta al emplear fotografía y fotogrametría aérea, fotografía de fluorescencia ultravioleta, escaneo láser móvil y termografía. Posteriormente, todos los datos recopilados se utilizarán para construir un modelo de diagnóstico dentro del HBIM.

ARTICLE HISTORY
Received November 2023
Accepted June 2024

KEYWORDS
Historic building information modeling; conservation science; damage map; architectural technology; stone façade

Modelado de información de edificios históricos; ciencia de la conservación; mapa de daños; tecnología arquitectónica; fachada de piedra

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Introduction

The advancement of precise analytical methodologies, together with the systematization of verifiable data, seeks to raise the technical quality of conservation interventions, and fortify maintenance and risk management processes. The decreased frequency of subsequent restoration cycles contributes to a positive impact on both public spending and the preservation of the original characteristics of listed buildings, primarily by mitigating decay. Sustainable preservation programs require an accurate understanding of cultural heritage in time and space, including the use of new technologies and historical-documentary surveys, to support projects and public policies for protection (Froner 2017).

Considering these factors, the *Damage Map through Heritage Building Information Modeling (HBIM)* project, funded by the National Council for Scientific and Technological Development (CNPq) in Brazil, aims to develop protocols for effective risk management in historical buildings. This action is undertaken by formulating a methodology systematically to document degradation typologies over time, integrated within digital platforms. This in turn facilitates the ongoing monitoring of the condition of stone-integrated assets, providing valuable support for conservation interventions and long-term maintenance programs. The application of technology to heritage can yield high-quality analytical documentation, encompassing a systematic recording of information at various levels, including assessment protocols, the identification of materials and construction techniques, as well as the mapping of damage and risks.

The present case study focuses on the reliefs on the frontispiece of the church of St Francis of Assisi in Ouro Preto, Brazil (Figure 1). This church was one of the first architectural assets to be protected by national legislation, through its inscription in the *Book of Fine Arts of the National Historic and Artistic Heritage Institute (IPHAN)*, in 1938 (IPHAN 1937–1986). In 1980, it was included in the UNESCO World Heritage List, increasing its importance.

This paper presents the method used to collect data on the stone reliefs of the church façade. It covers historical restoration cycles and shares preliminary findings from the 2023 fieldwork conducted by a multidisciplinary team. The focus is on elucidating the data collection stage, highlighting key techniques, such as photography, aerial photogrammetry, ultraviolet

Figure 1. Façade of the church of St Francis of Assisi, Ouro Preto, Brazil. Image: the authors.

fluorescence photography, mobile laser scanning, and thermography. All collected data will be used to develop a diagnostic model in HBIM for the façade, providing a damage map of its current condition. This stage, scheduled for 2024, will occur after defining a proposed terminology of stone decay processes on monuments and the processing of all data collected using the methodology presented in this article.

Damage map

A 'damage map' is an illustrated document designed to provide a concise overview of the condition of a cultural asset, be it movable or immovable (IPHAN 2005). When applied to immovable cultural assets, such as buildings, ruins, archaeological sites, urban art, or fixed elements that define a historical occupation in a specific time and space, the map aims to summarize information about their overall condition. Costa and Baisch (2012) define the 'damage map' as an illustrative tool that presents material components together with identified damage, providing essential information to support treatment and consolidation efforts in conservation projects. This tool serves as a preliminary step preceding the development building interventions, conservation, and restoration, playing a crucial role in the identification, quantification, specification, and localization of faults in the structure. The analysis facilitated by the damage map typically involves plans, sections, and occasional perspective studies that use drawings or markings superimposed upon photographs to highlight damage or alterations. These representations adhere to codes or conventions associated with degradation typologies and are crucial to the architectural standards necessary to depict building projects, encompassing proportions and the spatial arrangement of elements.

Despite the systematization of damage characterization nomenclatures, using Italian standards for cultural heritage, such as Normal 1/88 and UNI 11182 (UNIRC 1988; UNIRC 2006), as well as the *Illustrated Glossary on Stone Deterioration Patterns* (ICOMOS 2008), there is currently no regulatory document addressing symbolic schemes and conventions formulated specifically for the creation of a damage map in historic buildings.

Construction history of the church of St Francis of Assisi

The earthworks for the site in the Largo de Coimbra, the central area of Ouro Preto, began in 1765. This task was entrusted to the Portuguese master mason, Domingos Moreira de Oliveira (c.1711–1794), with the contract dated 1766. Portuguese royal permission for the construction was only granted in 1771, several years after the Brazilian administration's request. However, as was usual, contracts and works had begun before the royal charter was given. Sculptural work was entrusted to the Portuguese craftsman, José Antônio de Brito (died 1793). The instructions detailing the techniques and materials for the construction were meticulously specified (Trindade 1951). According to the contract, the commissioned contractor was obliged to transport all the Itacolomi stone and soapstone rocks to the site and assemble them, following the design, and was responsible for all moldings and sculptures (Costa 2009, 220).

Upon completing the main chapel, the masons began the construction of the façade, featuring the entrance door designed by Antônio Francisco Lisboa (c.1738–1814), more commonly known as Aleijadinho (Lemos 2014). The façade's ornamentation has architectural impact, showcasing two distinct reliefs. The first, surrounding the entrance door, features a half-body medallion of Our Lady, surrounded by rosettes and cherubs alongside a large crown. The central detail of the crown is in harmony with the upper relief that fills the oculus. The second relief is distinctive, as it occupies the space of the oculus, imposing the weight of the ornamental sculpture over the transparency of a stained-glass window. This medallion, portraying St Francis receiving the stigmata from Christ on Mount Alverno, is positioned above the entrance door. The *rocailles*, irregularly overlapping and surrounding the oculus frame, interact with the inner clouds, creating a sense of movement, heightened by the recesses and masses of the relief. These, in turn, yield distinct visual effects, depending on the ambient light. Notably, a few details in this medallion are crafted from coarse sand mortar.

History of intervention and restoration cycles

When beginning the development of the proposed damage map for this project, an essential initial step involved delving into the history of conservation interventions, as well as examining the methodologies documented in previous efforts. This exploration relied on the examination of physical and digital documents, sourced from the archives of IPHAN and the João Pinheiro Foundation, supplemented by online databases. As a result, a compilation of approximately 67 documents, 130 photographs, and four architectural plans was amassed.

The earliest recorded interventions and repairs date back to 1822–1823, documented in payment records made to mason João Fernandes Coutinho for the repair of the stone entrance door. Subsequent records indicate restoration work on the entrance door ensemble during the early decades of the twentieth century. Notably, between 1935 and 1937, the

National Monuments Inspectorate, led by Gustavo Barroso (1888–1959), oversaw the church's restoration. The documentation of this intervention includes the initial photographic report of the St Francis of Assisi medallion (Figure 2(a)).

In the 1937 restoration, the façade underwent cleaning, and two ornaments from the entrance door were removed, sparking significant controversy over the authenticity of these pieces. This controversy led to discussions in contemporary newspapers and persisted in subsequent years. Members of the Historical Institute of Ouro Preto contended that the ornaments were original elements from the period of the entrance door's construction and were made of soapstone. Conversely, the National Monument Inspectorate argued that these pieces were crafted from mortar and were removed because they were considered 'dishonest and modern work', as indicated in the file titled *Obras na Igreja São Francisco de Assis* (IPHAN 1937–1986).

While there are no records documenting these interventions, it is assumed that they occurred before the establishment of the National Monument Inspectorate, the point at which modifications became officially documented. Even today, remnants of mortar ornaments can still be found in various areas of the entrance door, as we observed and recorded in 2023.

With the set-up of scaffolding for the removal of these elements, numerous images capturing intricate details were taken. Through these images, it becomes possible to compare the current decay as compared to a hundred years ago. In Figure 2, a crack on the left side of the face of St Francis is evident, with a small loss of material. The present condition reveals significant loss of material and a worsening of the crack (Figure 2(b)).

Between 1944 and 1946, the church underwent another round of restoration, although there are no references to direct actions on the entrance door during this period. It was not until 1975 that new records of conservation measures for the entrance door emerged. Additional conservation measures and studies of the entrance door were conducted in the 1980s and 1990s. In August 1987, the cleaning of the artistic elements of the entrance door involved aspirating accumulated dust particles. However, in November of the same year, during the restoration of the artistic elements of the church conducted by the Pro-Memory Foundation, the inspection report revealed that the entrance door elements had not been cleaned as recommended by IPHAN in 1987. This suggests that the managers did not adhere to the technical guidance, potentially due to a lack of financial resources.

From 1990 to 1994, the *Investigations into Devices against Environmental Attack on Stone* (IDEAS) project was undertaken in collaboration with universities in Germany, the Federal University of Minas Gerais (UFMG), and IEPHA, with funding from the Minas Gerais Research Support Foundation (FAPEMIG). The project aimed to analyze the degradation behavior of stone materials, propose damage assessment methodologies, and develop conservation recommendations for the artifacts in question. Five built assets in Minas Gerais were selected, including the stonework and

Figure 2. Detail of the face of St Francis of Assisi (a) 1937. Image: IPHAN (b) 2023. Image: the authors.

soapstone materials of the church of St Francis of Assisi. During this phase of the project, broader indications were provided regarding the condition of the stone in the church. The analysis emphasized the role of air quality in Ouro Preto as a contributing factor to deterioration. The advanced state of degradation of the stone was directly linked to pollutants, such as fluorides, sulfur dioxide, and particulate matter from the aluminum factory located in the city. The identified deterioration included granular disintegration, delamination, cracks, fractures, and biological colonization, with the most widespread issue being the discoloration of the soapstone (FJP 2001).

The compilation of archival sources and the investigation into the history of interventions on the entrance door, integral to the damage pathology, has significantly enhanced our comprehension of its construction processes. It has shed light on aesthetic modifications, deterioration, additions, and the removal of parts that continue to impact the object's composition today, providing an opportunity for their temporary marking. However, the absence of systematic documentation poses a challenge in establishing reliable parameters for risk analysis and management. This underscores the imperative for the development of a dedicated methodology for damage mapping, one that can be universally applied to monuments of similar scale.

Materials and methods

Between 28 August and 1 September 2023, a multidisciplinary technical team, consisting of researchers from the Federal University of Minas Gerais (UFMG), the Federal Institute of Minas Gerais, Campus Ouro Preto (IFMG-OP), the State University of Campinas (UNICAMP), and the Mackenzie Presbyterian University, Campus São Paulo, convened for initial field activity dedicated to the data collection of the façade. The team included art historians, architects, conservators, a chemical engineer, and a geologist, bringing a wide range of expertise to the research initiative.

Following agreements between the Municipality of Ouro Preto and the Archdiocese of Mariana, the entity responsible for the Church, 15 m high scaffolding was erected, which provided the necessary access for researchers to examine the reliefs. The field surveys incorporated various methods and techniques: close-range photogrammetry; photography and aerial photogrammetry, using an unmanned aerial vehicle (UAV), commonly known as a drone; structured light scanning, ultraviolet fluorescence photography, mobile laser scanning, and 3D printing; and thermography. It is crucial to underscore the significance of equipment sharing in projects of this nature in Brazil, particularly considering the substantial investment required for such infrastructure.

These integrated examinations, primarily forms of non-destructive testing (NDT), offer a comprehensive understanding of both the construction technology and the condition of cultural assets. NDT refers to methods and techniques where the test does not result in any change (damage) to the piece being tested. The primary objective of NDT is to identify defects and wear, often undetectable through conventional means. These methods can also be employed to discern the characteristics of various materials that compose or are embedded in these objects. In Brazil, this field is regulated by federal standards that cover both the equipment used and the training and certification of operators involved in these assessments.

Close-range photogrammetry using control points

The photographic survey used two high-resolution digital cameras, Nikon D7200 and Nikon D7000. The Nikon D7200 was employed to record and document damages and pathologies on the façade, while the Nikon D7000 documented the overall fieldwork. In the close-range photogrammetry procedure, the cameras were positioned at control points on the façade. These control points play a crucial role in assisting photogrammetry software to correct and align the images, enabling the generation of an accurate three-dimensional model.

A total of 378 images of the church's façade were captured across the five levels of the scaffolding, maintaining a consistent focal distance between the object of study and the camera. Special attention was given to ensuring that each subsequent image had, at a minimum, one control point as a reference in the previous image, ensuring continuity and precision for the photogrammetry process. This meticulous procedure resulted in the creation of detailed 3D models at each scaffolding level. To manage and calibrate colors in the captured images, a ColorChecker Passport was used.

Photography and aerial photogrammetry

In the photography and aerial photogrammetry process, using a UAV, the survey offered an angle of the frontispiece and the building that were not accessible from the scaffolding. This provided a detailed view of pathologies, including infiltrations and mortar repairs. This approach facilitated the examination of roofing issues that may well be contributing to pathologies in the oculus and frontispiece. The use of UAV is a valuable tool for data collection in hard-to-reach locations, thereby enhancing the breadth of essential information for research.

Figure 3. Details of the point cloud. Image: the authors

The acquisition of point clouds through photogrammetry, using a UAV, captured a series of aerial images of the target of interest from different angles and altitudes (Figure 3). In this study, the point cloud was generated by processing 953 images in with Agisoft Metashape software, resulting in an initial model with 318,487 points.

The image processing begins with the import of captured images, followed by the identification of corresponding points in various images (control points). This enables triangulation to estimate the three-dimensional coordinates of points in the scene. The software then conducts a 3D reconstruction of the target area, generating a point cloud that accurately represents the geometry of the surfaces. This point cloud can be subsequently used for geospatial analysis, 3D modeling, or other applications that require precise information about the mapped area, such as the generation of damage maps proposed in the research project.

Structured light scanning, ultraviolet fluorescence photography, mobile laser scanning, and 3D printing

The Shining Einscan SE scanner was selected for structured light scanning due to its precision (≤0.1 mm) and versatility, allowing for the scanning of larger areas with the aid of geometric alignment or manual control. Scaffolding was installed to access the portrayal of St Francis of Assisi in the church's oculus, providing the necessary positioning for the scanner. A tripod was adapted to support the scanner, ensuring stability during the scanning process, and scanning was scheduled for night-time, as the equipment performed better in low-light conditions.

However, scanning this unique sculpture presented distinct challenges. The intricacy of the forms sculpted by Aleijadinho required meticulous adjustments to the light patterns to ensure accurate capture. Additionally, limited access to the church's oculus and the need to work at elevated heights further complicated the process. The team adapted the equipment and developed strategies to overcome technical and logistical obstacles.

The detailed scanning of the portrayal yielded impressive and revealing results. The accuracy of structured light technology enabled a meticulous capture of details, offering essential insights into the sculpture's current condition and revealing elements that had been lost due to deterioration over time. Among the most notable observations are the visualization of elements that no longer exist in the original piece due to damage. Significant parts of the portrayal, such as the tip of the nose, part of the upper lip, part of the left cheek of the face, and part of the left ear (Figure 4), were meticulously recorded in the 3D model.

These areas, now absent in the figure, were digitally documented, providing a detailed record of what once was. The scanning also revealed small cracks on the figure's forehead, emphasizing the effects of the passage of time and environmental conditions. The ability to accurately capture these imperfections is crucial for understanding the deterioration process and developing effective conservation strategies.

In addition to visible observations, the scanning of the portrayal of St Francis of Assisi revealed a unique capability to identify pathologies caused by physical, chemical, and biological agents. This significantly expanded our understanding of the deterioration factors that affect works of art over time. Using RGB scanning to capture colors, it became possible to detect subtle variations in the hue of the scanned surface.

The generated 3D model unveiled the presence of pathologies caused by biological agents, specifically bird droppings. These affected areas exhibit distinct color patterns and subtle variations, indicating the locations where the action of these biological agents was more intense. The capacity to identify such damage in detail is of utmost importance for conservators, as it furnishes precise information about vulnerable areas and aids in developing strategies to prevent future damage. In addition to structured light scanning, ultraviolet fluorescence photography was also applied. This technique involved observing various areas of the artwork at night, using a Spectrum UV-Tritan 365 lamp. The images obtained through this process allowed for a more accurate identification of areas with microorganisms and surface alterations, such as the deposition of foreign materials and differentiation between the relief patching and sculpted stones (Figure 5).

Additional studies used LiDAR technology, employing applications such as Polycam and 3D Scanner on an iPhone, to generate three-dimensional mapping. The use of aerial and terrestrial photogrammetry along with LiDAR technology for archaeological heritage documentation has advanced rapidly over the past two decades (Crutchley 2010; Prümers et al. 2022). In particular, LiDAR technology accessible on smartphones can reveal aesthetic details and the condition of cultural assets.

In Brazil, the application of laser scanning began in the early twenty-first century, primarily used to scan historical monuments to support restoration projects approved by IPHAN. Two decades later, the combination of aerial photogrammetry, local photometry, and LiDAR provides a comprehensive view that helps identify both the construction technology and the degradation processes of cultural assets. In the case of the church of St Francis of Assisi, previously inaccessible details such as the lateral areas of the relief could be observed with greater precision.

Thermography

The application of infrared thermography in fieldwork plays a key role in capturing representative data of damage and pathologies, serving as an illustration of possibilities for integration into BIM methodologies – the primary focus of this research. However, it is part of a larger process aimed at developing a methodology for applying thermography to buildings.

For the successful development of this type of research, a comprehensive understanding of concepts, such as maintenance, condition monitoring, inspection, and structural health monitoring is crucial. Equally important is the grasp of concepts related to the thermographic system, which encompasses 'a set of equipment, accessories, and applications necessary

Figure 4. Losses on the nose, part of the lips, and cheekbone recorded in 3D modeling, (a) from the left side and (b) from the right side. Image: the authors

Figure 5. Detail in 365 nm UV fluorescence photography, showing on the left side an area of previous intervention, and on the right the forehead with remaining bird excrement on the top surface of the stone. Image: the authors

for the collection and processing of thermal information' (ABNT 2020) and its components.

The equipment used in this initial round of data collection consisted of FLIR E5 and FLIR E6, which are relatively affordable but have a limited working range when compared to so-called scientific cameras that come with prohibitive costs for conventional researchers and professionals. Therefore, understanding the limitations of each piece of equipment, the context, and the environment in which data is collected, along with practical knowledge of the observed subject, becomes crucial. For instance, an anomaly identified on the forehead of St Francis can be observed and confirmed from different angles and distances, revealing distinct material characteristics (Figure 6).

From this initial set of images with radiometric information, used as a control, it becomes possible to observe points of convergence or divergence with data from other methods. Simultaneously, the potential for replicating this study, using equipment of higher or lower quality, allows one to adjust the cost-effectiveness balance of infrared thermography for each case, considering the degree of uncertainty. It's worth noting that the decision to investigate a historical and heritage-listed building, the most restrictive type of structure within our scope of work, will contribute to establishing best practices and potential standards that can be applied to any other situation involving existing constructions.

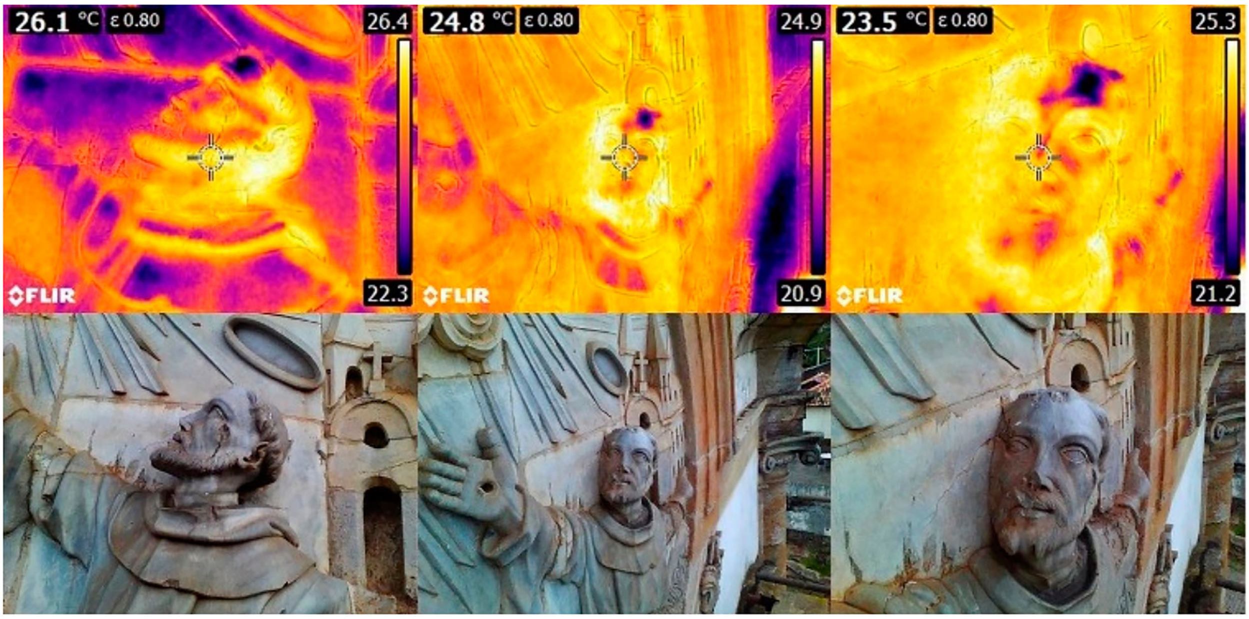

Figure 6. Compose image of the face of St Francis, obtained from different angles by FLIR-E5. Image: the authors

Conclusions and future work

The preliminary results in this paper are presented to clarify and systematize the applied method used in the field. Above all, the integration of archival research and new technologies, especially in terms of technical imaging, has enabled sharing of information and provided a holistic view of the subject over time.

Although preliminary, synergetic use of these imaging systems should be preceded by establishing the terminology, data systematization, and the development of a diagnostic model through HBIM.

As part of the research, we believe that the damage assessment, combined with an understanding of the materials and construction technology used in integrated architectural assets made of stone, can guide risk management protocols. This guidance includes understanding the degradation agents as well as enabling monitoring of deterioration processes over time through systematic and continuous images and records.

Acknowledgment

The authors would like to thank and acknowledge the support received from CNPq, FAPEMIG and CAPES (Federal Agency for Support and Evaluation of Graduate Education); Maria Raquel Alves Ferreira, from IPHAN; Angelo Oswaldo, mayor of the municipality of Ouro Preto; Father Edmar Pereira and employees of the church of St Francis of Assisi; and researchers Livia Freire and Paola de Macedo Gomes Dias from IFMG– Ouro Preto.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico [grant number 405146/2021-3]; Fundação de Amparo à Pesquisa do Estado de Minas Gerais.

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