HYPER HERITAGE: TOWARDS A FRAMEWORK FOR A DIGITAL TWIN OF CULTURAL HERITAGE

Luiz Felipe Ribeiro Correia

Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia de Produção, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia de Produção.

Orientador: Roberto dos Santos Bartholo Júnior

Rio de Janeiro
Agosto de 2021

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DISSERTAÇÃO SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE EM CIÊNCIAS EM ENGENHARIA DE PRODUÇÃO.

Orientador: Roberto dos Santos Bartholo Júnior

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RIO DE JANEIRO, RJ – BRASIL
AGOSTO DE 2021

Correia, Luiz Felipe Ribeiro

Hyper Heritage: Towards a Framework for a Digital Twin of Cultural Heritage/Luiz Felipe Ribeiro Correia. – Rio de Janeiro: UFRJ/COPPE, 2021.

XIV, 102 p.: il.; 29, 7cm.

Orientador: Roberto dos Santos Bartholo Júnior

Dissertação (mestrado) – UFRJ/COPPE/Programa de Engenharia de Produção, 2021.

Referências Bibliográficas: p. 66 – 75.

1. Digital Twin. 2. Cultural Heritage. 3. Visual Computing. I. Bartholo Júnior, Roberto dos Santos. II. Universidade Federal do Rio de Janeiro, COPPE, Programa de Engenharia de Produção. III. Título.

To my Cousin, Marcos Ribeiro Lindo. Rest in peace, my little brother, and take care of our Grandma

Acknowledgements

The original plan was to address Digital Twins in an industrial environment by taking advantage of a computer vision project in my former Startup, Displace. But things went sideways, and the project was postponed several times, too much of my terror and my former advisors Ricardo Naveiro and Renato Cameira displeasure. Therefore, the chances of obtaining a master's degree became almost null.

As I was about to quit the program, professor Roberto Bartholo - one of the most phenomenal human beings I had the opportunity to meet – accepted the challenge of being my new advisor in such a short period with a new dissertation from scratch. Back then, I knew very little of cultural heritage and digital humanities for my prior research to fit within the scope, it was very challenging, but I have managed to complete my qualify in a matter of months, something unthinkable back then.

About three months after my qualify, several hurdles happened in sequence, for a sustained period of six months (or more):

- My father had a stroke;
- I made a forced exit from the Startup I've founded;
- COVID-19 happened;
- My father had yet another stroke...
- ...and COVID
- My Cousin passed away
- My Grandmother passed away

To make matters worse, about 50% of my dissertation was based on the assumption that the historical site was available to scan, but the COVID-19 pandemic crushed this assumption. Minute by minute, I was grinding and racing against the clock.

A race that I hope it is finally over, as the dissertation is complete, and one that hopefully will open many perspectives on Digital Twins, not only for Cultural Heritage, but for other purposes as well..

Since the catharsis is now over, onward to the acknowledgments:

Family: My parents, my wife Fabiana, and my daughters Brenda and Carolayne. Love you!

PEP/UFRJ: Professor Francisco Duarte, the coordinator of this excellent program and one of the examiners. Kudos to Professor Edison Renato, A.K.A. the Nick Fury of P.E.P., currently assembling the new "Avengers" initiative to take this prestigious program even further. Many thanks to Professor Domício Proença, for his awesome –albeit brutal– class about "introduction" to academic studies. Every minute spent in his class without "walking the hall of shame" was a triumph. Professor Carla Cippolla, whom I derive many contributions of the current study, mainly on the field of Design. Huge thanks and apologies to my former Advisors Ricardo Naveiro and Renato Cameira, who understood that the former study wouldn't be ready within the limited timeframe of a Master Degree. Cheers to my friends at LTDS - Aline Brufato, Edney Sanchez and Flavia Mattos who helped me a lot!

Brazilian Army: Colonel Joel Corrêa and General Lima Gil

NCE/UFRJ: Professors Henrique Serdeira, Mônica Ferreira, Carlos Mendes, Fabio David, Amauri da Cunha and Claudio Miceli.

UFF: My former advisor at PGE/UFF and now examiner, Professor Gabriel Marcuzzo. Professors Esteban Clua and Daniela Trevisan from IC/UFF

Friends: Leonardo Nascimento, Ildefonso Barros and especially Marcelo Eiras, from whom I borrowed some of his "toys" for this work to happen. XD

Lastly, I cannot thank enough my advisor Professor Roberto Bartholo for all his dedication and what he did for me, I will never forget.

This dissertation was made possible by people.

Resumo da Dissertação apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Mestre em Ciências (M.Sc.)

HIPER-PATRIMÔNIO: EM DIREÇÃO A UM FRAMEWORK PARA UM GÊMEO DIGITAL DO PATRIMÔNIO CULTURAL

Luiz Felipe Ribeiro Correia

Agosto/2021

Orientador: Roberto dos Santos Bartholo Júnior

Programa: Engenharia de Produção

No palco central da quarta revolução industrial, o conceito Digital Twin está se tornando cada vez mais relevante na academia e na indústria. Destarte as tecnologias habilitadoras, como a Computação Visual tenham seu próprio conjunto de conceitos e aplicações estabelecidos, o conceito de Digital Twins ainda está em discussão, já que tanto especialistas da indústria e acadêmicos concordam que tal conceito tem suas aplicações não apenas para sistemas de produção, mas em uma ampla variedade de propósitos, incluindo o Patrimônio Digital. Nesse sentido, este trabalho tem como objetivo investigar as tendências atuais do Patrimônio Digital e apresentar um referencial teórico para a digitalização do patrimônio cultural, ao mesmo tempo em que engloba aspectos do conceito de gêmeo digital. Com base no referencial teórico e no primeiro ciclo da metodologia Design Science Research, é apresentada uma metodologia de computação visual para a geração de gêmeos digitais colaborativos e de baixo custo, com um estudo de caso da Fortaleza de São João no Rio de Janeiro, berço da cidade. Além disso, são apresentadas algumas propostas para pesquisas futuras e as últimas tendências que podem permitir gêmeos digitais ainda mais precisos do patrimônio cultural, incluindo o patrimônio intangível.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

HYPER HERITAGE: TOWARDS A FRAMEWORK FOR A DIGITAL TWIN OF CULTURAL HERITAGE

Luiz Felipe Ribeiro Correia

August/2021

Advisor: Roberto dos Santos Bartholo Júnior

Department: Production Engineering

At the center stage of the fourth industrial revolution, the Digital Twin concept is becoming increasingly relevant in academia and industry. While enabling technologies, such as Visual Computing have their own set of established concepts and applications, the concept of Digital Twins is still in discussion, as both industry experts and scholars agree that such concept has its applications not only for production systems but in a wide array of purposes, including Digital Heritage. In this respect, this work aims to investigate current trends on Digital Heritage and presents a theoretical framework for digitizing the cultural heritage while encompassing aspects of the digital twin concept. Based on the theoretical framework and the first cycle of Design Science Research methodology, a visual computing methodology is presented for generating collaborative and low-cost digital twins, with a case study of the Fortress of São João in Rio de Janeiro, the city's birthplace. Furthermore, some proposals for future research and the latest trends that could enable even more accurate digital twins of cultural heritage, including intangible heritage, are also presented.

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Chapter 1

Introduction

On the verge of the fourth industrial revolution started by the German federal government with the Industrie 4.0 initiative [1], digitization plays an essential role in attaining this goal. As the holy grail of Industry 4.0 comes Digital Twin, which encompasses most of the technologies and underlying components needed to drive the Industry 4.0 agenda forward and visual computing technologies [2] for 3D scanning and BIM - Building Information Modeling [3] at its core.

Although these are hot topics, most publications focus on the manufacturing industry, but the Digital Twin concept exists in other contexts. This dissertation will examine the idea of a Digital Twin for cultural heritage while investigating its enabling technologies and concepts with a proof of concept presented for the São João Fortress in Guanabara Bay, Rio de Janeiro.

1.1 Motivation

Heritage is considered as everything that has a universal value from the historical point of view [4]. In turn, cultural heritage is divided into two large categories, tangible and intangible cultural heritage. Tangible cultural heritage, particularly buildings and monuments, are considered architectural heritage and are an irreplaceable source of cultural inspiration. Unfortunately, the elements, monuments, or buildings considered architectural heritage are threatened by the deterioration of materials, natural disasters, such as the earthquake that struck the Assisi Cathedral in Italy, predatory tourism, acts of terrorism, or war [5], a recent example of the latter being the Buddhas of Bamiyan, destroyed by the Taliban during the Afghan Civil War. And also fires, as recently happened in Notre-Dame in Paris and the National Museum (Museu Nacional) in Rio de Janeiro. For this reason, and as stated in the ICOMOS Charter of Venice [6], the need to register and document architectural heritage is crucial to managing, preserving, or restoring a

historical legacy for generations to come.

In Brazil, hundreds of fortresses were built since the 16th century in many places: from the coast to strategic points, inland, and border areas. Among these fortifications, nineteen (19) fortresses and forts are listed as cultural heritage sites, which are also part of the tentative list of UNESCO (see Appendix B.1 - Tentative List), suitable for inscription on the World Heritage List.

Among the 19 fortresses in the UNESCO tentative list, two (2) of these fortresses are within Rio de Janeiro, Fortaleza de Santa Cruz da Barra, in Niterói, and Fortaleza de São João, in Rio de Janeiro.

Figure 1.1: Fortaleza de São João (Author, 2020)

Currently, the São João Fortress, the object of our study, is undergoing a series of restoration initiatives to prepare it for candidature in the World Heritage List. By digitally reconstructing this fortress, a digital replica could be used not only to aid in this respect, but to provide many, if not all, benefits related to the research objectives.

1.2 Personal Motivation

Besides my mother Sueli Ribeiro being a skilled painter and my paternal grandfather Pedro Correa being a renowned artist, I was born with no artistic skills, which was a big letdown for a person fascinated with games, animation, and art.

Figure 1.2: Pescadores - Pedro Correa

To overcome these obstacles, at ten years old, I started to learn computer graphics programming; four years later, I already was a skilled programmer and participated in a subculture movement called demoscene, which consisted of programming procedural scenes synced with audio, just for fun.

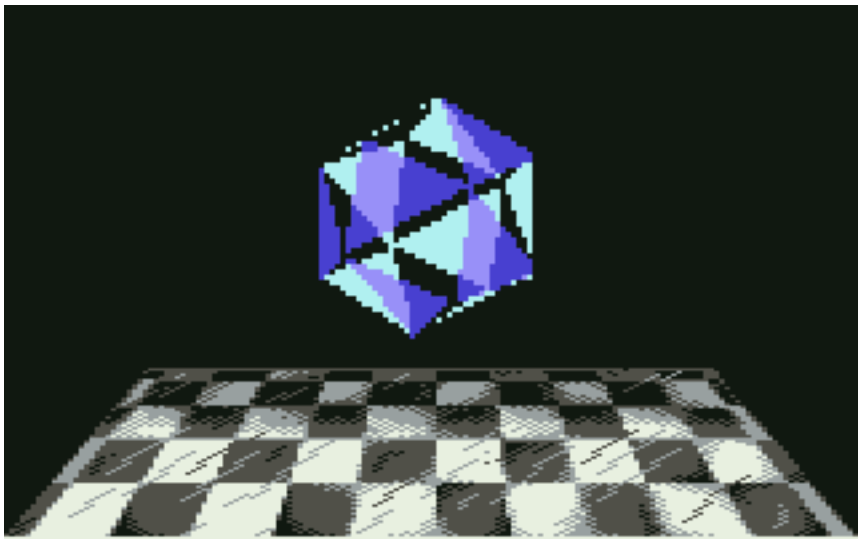


Figure 1.3: Demoscene Example

Later on, I focused on game development, but as the technology evolved, artists were more in need than programmers, and game development in Brazil was very incipient. As such, I could not design a good game, as my art skills were pretty close to zero, and with

my skills needed in other areas, the market got me instead, and so long for the game developer childhood dream.

Only years later, in 2011, I decided to work with an artist friend on a side project, which was initially conceived as a 2D brawler (more like River City Ransom), where the player could choose between one of three characters after a Fluminense x Flamengo match at Maracanã Stadium, with the sole objective to get to the home safe. Due to my artist friend health issues, the project was interrupted, but I was determined to carry on game development, even with poor art skills. For that, I started to develop and/or improve some tools to aid me in this quest: a humanoid character creation, motion capture from a camera, and efficient 3D capture through photogrammetry.

The last one became a software known as SituatorVR, a software enabling 3D scene reconstruction by leveraging computer vision techniques and a heavily modified fork of OpenMVS with agnostic data input and sensor fusion capabilities. The first real use case of SituatorVR was in a PoC called ReX VR (Rules of Engagement - VR), and consisted in the 3D reconstruction of some real-life scenes for simulated training of private security forces, in which the behavioral middleware VT-MAK Humans (previously DI-Guy) was used. Only in 2015, to meet some of the demands of a cooperation agreement with the Homicide Division of the Rio de Janeiro's Civilian Police (PCERJ), we have decoupled the software as a standalone product for the capture, processing and visualization of 3D scenes, followed by its usage in Crime Scene reconstruction.

This instance of the software would become a successful product of my previous startup, which I made my exit from in 2019, and the 3D reconstruction engine that will be used in the present work, primarily for large-scale aerial capture.

1.3 Technological Background

Visual Computing technologies are becoming essential tools in many fields requiring the digitalization of real-world data. Computer Vision, a subset of the broad Visual Computing field, enables machines to see, whereas in 3D Reconstruction (a subset of computer vision) has enabled machines to perceive the world, thus aiding us to yield 3D reconstructed models by Computer Graphics and Visualization, another subset of Visual Computing. Aside from the massive deployment of such technologies in shop floors regarding Quality Control and BIM, nowadays, we have increased interest in 3D reconstruction technologies to enable Digital Twins in an Industry 4.0 agenda and the protection of Cultural Heritage. Many are the benefits of a digital twin of cultural heritage sites:

- Creation of a digital replica to aid Cultural Heritage Reconstruction in case of force

majeure;

- Running simulations to check for "what-if" scenarios;
- To visualize otherwise inaccessible areas;
- Provide educational resources for students and researchers;
- Digital interaction with the historical site, thus avoiding damage related to occupancy;
- To provide virtual tourism and virtual exhibitions.

1.4 Research Objectives

The general objective of this work is to advance knowledge about the creation of Digital Twins regarding military historical sites and cultural heritage by proposing a low-cost conceptual framework, while carrying out a 3D reconstruction of the São João Fortress in Rio de Janeiro, Brazil in a case study. Furthermore, by creating a digital replica of the current fortress state, we can address specific objectives that include:

- Conduct a literature review on current approaches in the digitization of cultural heritage, including digital twins;
- Present a framework towards the creation of digital twins of cultural heritage;
- A Case Study in The São João Fortress, where an instantiation implementation of a techological artifact instantiation will occur;
- Leveraging the artifact in multiple levels and dimensions accordingly;
- Evaluation - Validate the digital replica, potential use cases and benefits.
- Results - Web application to visualize the 3D reconstructed model in a Virtual Reality setting.
- Recommend some paths for further studies and next research cycles, including those implementations that were not possible due to force majeure (COVID-19 pandemic).

1.5 Scope of Work

This study investigates digital twin applications for cultural heritage and its enabling technologies, namely, visual computing. A literature review of digital twins and current digital heritage trends follows, which would play a pivotal role to develop a theoretical framework to enable digital twins of cultural heritage, followed by a case study in which some of the technologies presented in the framework will be applied at the São João Fortress in Guanabara Bay.

Many questions raised during this dissertation are beyond the scope of the present study. Mainly due to the limited timeframe of a master dissertation, technical issues, and force majeure derived from the COVID-19 pandemic. These questions are:

- Interpretations of Cultural Heritage;
- Intangible Data Acquisition;

Regardless, these questions will be put forward in Section 5.1 and will be addressed in future works and -hopefully- a doctoral thesis.

1.6 Outline

The study is structured as follows. After this introduction comes a Literature Review for Digital Twins, Digital Heritage applications, and Visual Computing technologies in this context. Cultural Heritage will be contextualized in detail to discuss the methodologies and the theoretical framework, as presented in the third section. Subsequently, the Case Study, where the artifact will be presented along the respective case study iterations, and findings are then presented and related to the literature. Finally, the Conclusion and Further Research concludes the study, setting forth the lessons learned, the academic and managerial implications accrued from this study, and recommendations for further research.

Chapter 2

Literature Review

The main topic presented in this dissertation, the Digital Twin concept, is becoming increasingly popular in many disciplines, especially in production engineering, with 2117 academic papers published and indexed in Web of Science, 1809, or about 85,45%, from 2019 to 2021 alone.

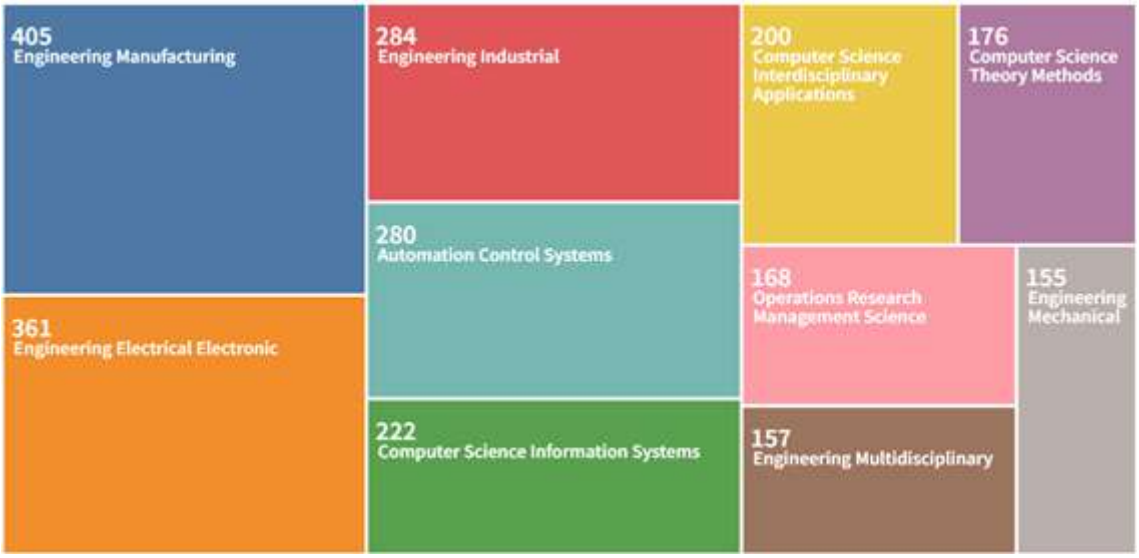


Figure 2.1: Publications by Discipline - Web of Science

In contrast, few works are available concerning digital twins of cultural heritage, with most works being from 2019 – 2021 for a sum of 14 publications indexed in the Web of Science on digital twins and cultural heritage.

Even though there are few works directly related to digital twins for cultural heritage [7] [8] [9] [10] [11] [12], there are many related to other aspects of digitization of heritage, such as virtual heritage (3787), virtual archeology (124), and BIM (443), the latter having a specific category for its application on Cultural Heritage - HBIM.

This section presents a literature review on the topics covered by this study to contextualize this research field and develop a theoretical construct that will be used as a proposal for a digital twin framework for cultural heritage.

2.1 Digital Twin

Industry 4.0, depicted as the Fourth Industrial Revolution, is an initiative started in Germany. Kagermann *et al.* [13] characterized it as the association of three critical components in industrial environments: Internet of Things (IoT), Cyber-Physical Systems (CPS), and Smart Factories. Hermann *et al.* [1] noted that while scholarly and practical discussion on the topic was ongoing, the term was not solid enough to address many aspects of it, and different practitioners used different concepts in this context. Literature reviews found that many technological components, rather than a singular point of contact or a set of technologies, were put in place to tackle one or more challenges within the Industry 4.0 scope, namely, Industrial Internet of Things (IIoT), Cloud Computing, Big Data, Robot Collaboration and Visual Computing [2], being the latter one of the main objects within the present study.

The technologies related to Visual Computing (familiar to some of the main topics of Computer Graphics and Computer Vision, and covering the entire cycle of acquisition, analysis, synthesis, and interaction with visual data) are crucial elements to cope with some of the Industry 4.0 challenges. To cite some of the technologies that could fit under the Visual Computing term, virtual reality, augmented reality, computer vision, and visual analytics could be highlighted.

The Digital Twin is a concept that derives from an Industry 4.0 agenda, and it consists of a physical entity and a virtual counterpart sharing information and data in real-time to enhance the performance of physical entities through computational techniques, most of which in the realm of Visual Computing and Design Computing [14]. Interest in digital twin applications has been dramatically increased in the past years in industry and academia, followed by a big increase in academic research, processes, and use cases. While the concept of digital twins was anticipated in "Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox," a book by David Gelernter in 1991 [15], as a concept in both industry and academic publications, it has only been accepted and acknowledged recently, primarily due to the work of Professor Michael Grieves which first introduced the concept in a University of Michigan presentation to industry [16]. So far, interest in Digital Twin has been dramatically increased in the past years in industry and academia, as illustrated earlier in this chapter, and at this point, industry [17] and scholars are yet to come to a conclusive definition of what is a digital twin, as it components vary

depending on the use case [18].

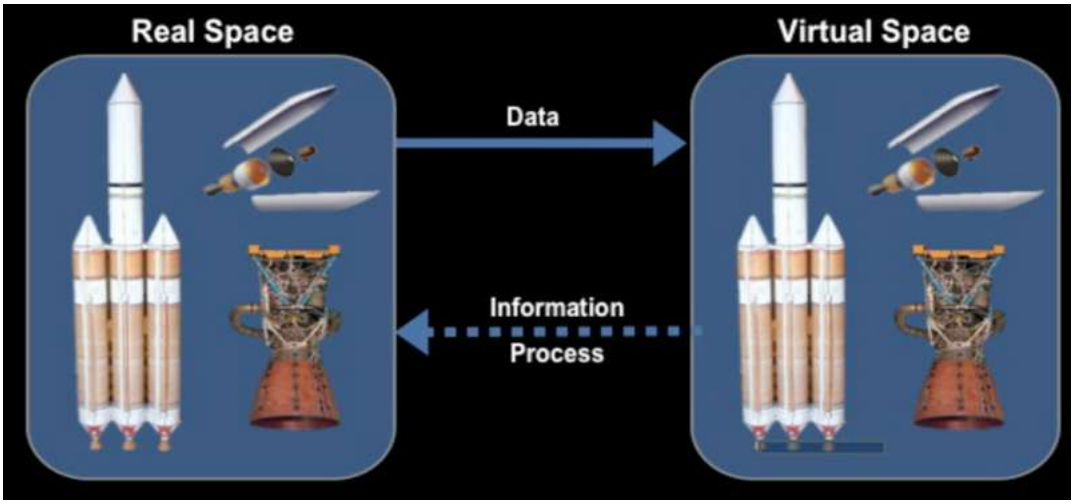


Figure 2.2: Digital Twin Concept (Grieves and Vickers, 2016)

Due to its roots in industrial engineering, the digital twin is commonly paired with Cyber-Physical Systems (C.P.S.) and the Internet of Things (IoT). They are the main concepts in Industry 4.0 and smart manufacturing since both refer to digital representations of a smart equipment asset. C.P.S. consists of I.T. systems combined with physical components, sensors, and actuators, and some scholars argue that the human operator is an integral part of the C.P.S. Moreover, IoT and IIoT (Industrial IoT) include all trackable data objects in a broad sense.

In this context, the digital twin is a virtual replica of a physical entity that contains its parameters, conditions, behavior, and characteristics through models and data, including the data connections between the physical and virtual entities [19] and mostly considered for the industrial operation of Cyber-Physical Production System (CPPS) that consists of a collection of C.P.S. In such a setting, the digital twin can leverage CPPS by optimizing the performance of operations, analytical assessment, and predictive diagnostics [20].

Therefore, Glatt et. al [21] listed three major digital twin functions (apud. Shafto *et al.*, 2021):

- Prediction: the function that consists in studying the behavior of a system before the actual runtime
- Monitoring: real-time state of the system for monitor and control
- Diagnosis: analyzing failures after the operation of the real system

While these functions seem most appropriate for an industrial digital twin, they are relevant concepts for any entity where there is a need to monitor its current state, un-

derstand or diagnose issues based on historical data, and predict future issues through simulation.

2.1.1 Digital Twin for Cultural Heritage

In the same vein as mentioned above, the management of Historic Sites, its conservation policies, and the interpretation of Cultural Heritage point towards a direction for monitoring, diagnosis, and prediction, respectively. Although in the case of Cultural Heritage, the term diagnosis is only a good term for facilities management, whereas for experience, interpretation, and reconstructing the past, the term Understand seems like a superior choice [22].

Although the Digital Twin functions listed in the prior section might seem that it is only applicable to production and industrial contexts, of the few works that aim towards a Digital Twin for Cultural Heritage, Jouan and Hallot [12] identified some endogenous and exogenous factors, issues, and risks associated to the management of Cultural Heritage, which have a direct connection to Digital Twin function of diagnosis, as well strategies, associated with prediction, and monitoring and control aspects which are related to monitoring. Unfortunately, the literature is still scarce, and most of the works on Digital Twins for Cultural Heritage leverage semantically enriched HBIM models, as in the work cited earlier.

Recent work by Dezen-Kempter *et al.* [9], addressed the idea of a layered Digital Twin of the St. Francis Assisi Church and the Ballroom, part of the Pampulha Modern Ensemble (PME), designed by Oscar Niemeyer in the 1940s. In this work, the authors suggest a hybrid framework leveraging a Scan3HBIM methodology with Drones, Terrestrial Laser Scanning, photogrammetry as a first step, and a subsequent AR layer interestingly using, among other tools, a Game Engine.

While these works provide a significant contribution, as the authors dig deep into many aspects of Cultural Heritage, such as critical intangible aspects of Cultural Significance (not only the conservation policies and strategy aspects - the focus of this dissertation), HBIM-based documentation, as we will discuss later in the chapter, by definition, considers only the built environment, disregarding other types of Tangible Heritage, such as Monuments and Sites. Another point of concern is regarding BIM performance and aspects such as openness and collaborative usage [23], although lately, there are improvements through data standardization and asset pipelines that allow importing BIM files.

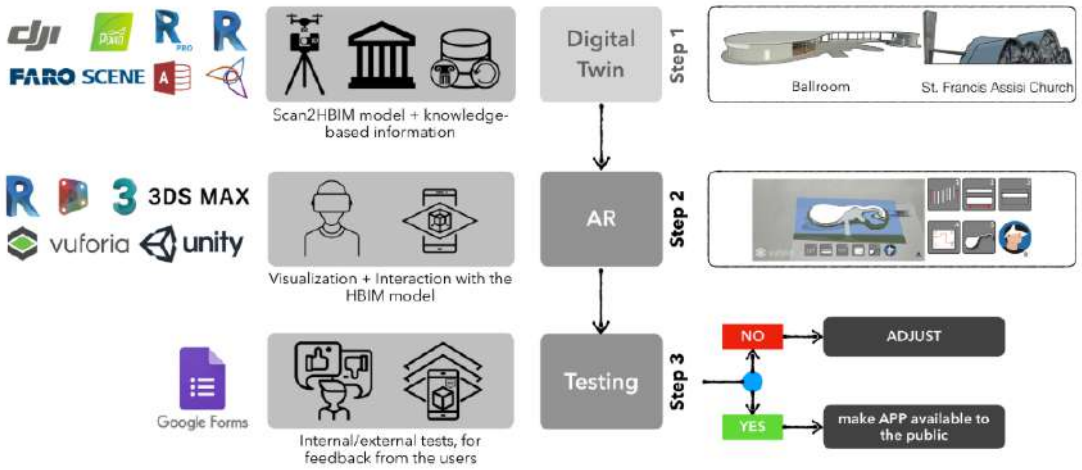


Figure 2.3: Framework for a Digital Twin for Heritage Interpretation (Dezen-Kempter, 2020)

2.2 Digital Heritage

Cultural heritage is a broad concept that encompasses the ways of living developed by a community and passed to the generations to come, including customs, practices, artistic expressions, objects, and values. It is often characterized as either intangible or tangible cultural heritage according to the charter of ICOMOS [24].

Most of the tangible cultural heritage can be divided into types such as the built environment, natural environment, and artifacts, but the driving force behind all definitions, be it tangible or intangible, is a human creation with the intent to inform [25].

Digital Heritage, on the other hand, encompasses ways of leveraging digital media for the preservation and understanding of cultural heritage employing digitization [26].

This section will outline some of the digital heritage modalities available in the current literature while identifying some of its enabling technologies, which will be addressed in more detail in the next section.

2.2.1 Virtual Heritage

By far, the vast majority of literature on the digitization of cultural heritage regards the use of Virtual Heritage (3.787 publications). It consists of a body of works that deal with technological approaches to document cultural heritage in general.

Virtual heritage generally involves the computer-based Reconstruction and digital visualization of cultural heritage artifacts or historic sites, often in immersive Virtual Reality environments. Although the concept is not new, especially in military and enterprise applications, X-Reality technologies (Virtual, Augmented, Mixed, and Pervasive

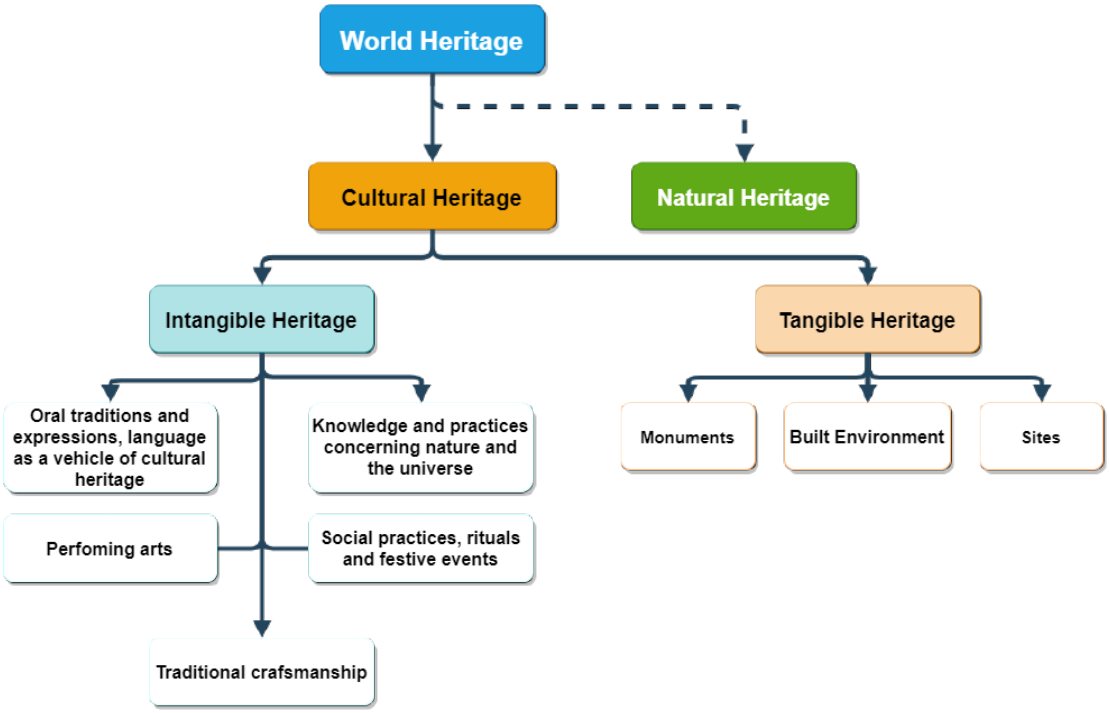


Figure 2.4: UNESCO Classification of Heritage

Reality [27]) only have been popularized recently, and as such, they are still emergent technologies. Despite this, the earliest use of virtual heritage was a virtual tour of a 3D modeled Dudley Castle in England, but as it was in 1550 by Boland and Johnson [28].

While the example above might fall into the Virtual Heritage category, as it delves some ideas of immersion, since it is focused on the reconstruction of a historic site as it was in the past, it might be a case of Virtual Archeology as well. Some scholars argue that Virtual Archeology, a term first introduced by Reilly [29] is a subset of Virtual Heritage according to Bawaya *et al.* [30], where here the word visualization not only seeks to represent the current state of the tangible cultural heritage, but, according to the London Charter Initiative [31]:

> It should be made clear to users what a computer-based visualization seeks to represent, for example the existing state, an evidence-based restoration or an hypothetical reconstruction of a cultural heritage object or site, and the extent and nature of any factual uncertainty.
> —London Charter Initiative (2009)

Since its introduction, the purpose and focus of Virtual Archeology have been shifted and extended since then, incorporating other technologies, including additive manufacturing (3D printing), to bring its virtual representations to physical dimensions.

As for the concept of Virtual Heritage, it is up to debate which author coined the term, as it first appeared in many articles in IEEE Multimedia, Volume 7, Issue 2, Apr-Jun 2000, and a year later at VAST 01 – Conference on Virtual reality, archeology, and cultural heritage. One of the most prominent and often cited authors on Virtual Heritage, Addison [32], in his work "Emerging Trends in Virtual Heritage", the author addresses many aspects of Virtual Heritage that are still present today: 3D documentation (e.g. site surveys); 3D representation (e.g. reconstruction), and dissemination (e.g. X-reality). Furthermore, the author presents some trends on 3D digitizing techniques, from Laser Scanning (LiDAR) to digital photogrammetry, which is a technology that consists in generating 3D models from a collection of images, and one that we dive into more detail later.

Most of the current works on Virtual Heritage consist of 3D Reconstruction of Cultural Heritage, being X-Reality the core technologies for visualization, but the literature has few works that aim for a systematic approach. An end-to-end layered approach is instrumental in establishing a framework, and as such, some of its components will be incorporated into the framework proposal presented in the next chapter.

The criticism around Virtual Heritage is that it often overlooks the intangible aspects of cultural heritage, but some works tend to incorporate such intangible aspects, especially when gamified. There is a current debate that such experiences might not fall within the category of Virtual Heritage, but a new trend, Smart Heritage or Hyper Heritage, which we will discuss later in section 2.2.3.

Regarding works in Virtual Heritage that aim towards the direction of a framework, Bruno *et al.* [33] first proposed a layered methodology for virtual exhibitions of digitized cultural heritage, consisting of a data acquisition and reconstruction subsystem in which a collection of 3D scanned objects are paired with audio description (based on archaeological data) in a collection of 3D models which ends imported in a 3D Engine for further development of the interactive exhibition. In parallel, global historical and Geographical Data are collected, along with pictures, and inserted after the 3D engine, in a integration layer. The last step is the multimedia application *per se* which is paired with a hardware design and development layer in which such subsystems converge into a visualization system. Although in 2021, with the emergence of consumer Virtual Reality devices, Smartphones and Cloud Computing, we can argue that such systems can enable a transportable museum without much effort on hardware design and development, as these technologies already provide an accessible way from any part of the world.

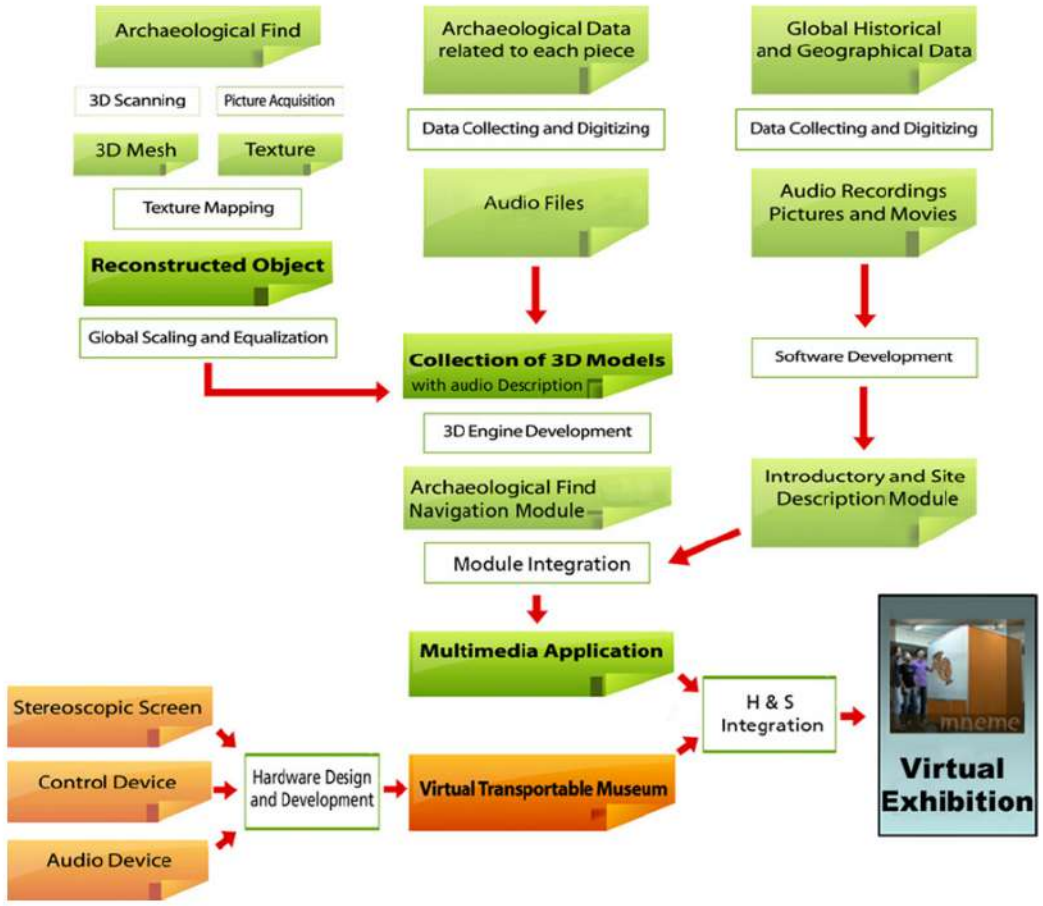


Figure 2.5: The schematization of the methodology proposed to develop a Virtual Exhibition System (Bruno *et al.*.,2010)

2.2.2 HBIM-Based Digital Heritage

HBIM-based digital heritage is the second most discussed topic in academia regarding digital documentation of cultural heritage. There is some consensus among scholars and industry that this method of cultural heritage documentation could facilitate the conversion into digital twins, as most of the elements required for a digital twin are already present in the BIM model, minus the connectivity required for it to interact with its physical counterpart and vice-versa.

BIM

The concept of BIM (Building Information Modeling) has existed since the 70s attached to few software tools and concepts specific for modeling buildings. Early concepts gave birth to workstation products such as the Chuck Eastman's Building Description System (B.D.S.) [34]. BIM platforms have been identified in recent years by the AEC / FM sector as the medium more effective in integrating the design of buildings, as they

can provide a digital 3D representation of the physical, functional and semantic characteristics of an environment, structure or building in all stages of its life cycle according to Pezeshki and Ivari [35] . Although these platforms are multidisciplinary, the coordination and the workflow to be implemented vary according to each profession concerned.

This dissertation is interested in the three-dimensional Reconstruction of architectural heritage by manipulating point clouds and historical data as in BIM systems. Therefore, the workflow that will be considered in this dissertation will focus on the data acquisition processes derived from BIM.

It is essential to understand that BIM technologies allow, through a parametric model unique three-dimensional, manage all the information and programming that in other environments.

It is divided into several layers, files or folders. The BIM platform is not just a technology architectural, engineering, or construction design representing buildings as a model parametric 3D. However, its scope addresses the ability to integrate all disciplines involved in its design and management, from its conception to the end of its useful life.

BIM is a constantly evolving and growing technology, based on components or objects stored in parametric libraries. Each component of the BIM environment has a particular parametric representation so that BIM platforms can import, manipulate, and manage geometric and non-geometric information and semantic data and topological that describe each element of the model [36] [37]. These components can be used to produce technical documentation such as drawings, elevations, cuts, sections, details, and perspectives semi-automatically. In addition, the concept of BIM promotes improvements in interdisciplinary communication and project coordination through interoperability and simultaneous access to relevant information in real-time [38]. These particularities extend the traditional design methodology and provide quick documentation, modifications, and transfers of all model information, thus generating a comprehensible project for all the people involved in construction [39].

HBIM

While BIM is a vital tool to manage building information, it was primarily intended to support new buildings and constructions' design and construction processes [40]. Maurice Murphy and Eugene McGovern [41] proposed a new system of modeling historic structures leveraging BIM, whereas the process begins with gathering data from multiple sources, with a collection of terrestrial laser scanners (LiDAR) and digital cameras (photogrammetry). Despite being the seminal study that first coined the term HBIM, it was primarily focused on the 3D reconstruction aspects of BIM technologies. However, during the last decade, multiple projects have been carried out to protect, conserve, and

restore cultural heritage, due to its growing socio-economic interest. Therefore, today BIM technology does not is limited to new construction but has also evolved significantly in the field of the management and documentation of the essential and incremental knowledge of the historical heritage cultural activities, fundamental activities for an accurate evaluation of the historic site to be digitized. Now, it is possible to represent the actual state of conservation of the buildings analyzed in a virtual environment [42].

It has been previously mentioned that the digital heritage reconstruction procedure of cultural heritage is not an easy task since the objects to be modeled consist of components whose heterogeneous, complex, and irregular characteristics and morphologies are not represented in the BIM platform libraries. Therefore, we consider that it is necessary to carry out in-depth research on architectural, historical usage, rules and patterns, to recreate the past, or to restore or preserve the current state of a certain historical monument. The architectural, historical approaches and knowledge acquired in conjunction with the point clouds already introduced to the BIM environment will be used to model the different digital parametric components and achieve an as-built BIM model of the architectural heritage analyzed [43] [44]. In addition, the levels of development and precision of the resulting components will allow the production of the conservation documentation and the maintenance drawings.

Therefore, once we have created the 3D digital models, the libraries of the parametric elements must be generated under the concept of historical structure modeling, or HBIM. HBIM is different from other approaches as the product creates complete 3D models that contain both tangible and immaterial information inherent to the buildings analyzed (Rivera *et al.*, 2018) [45].

2.2.3 Smart/Hyper Heritage

Smart Heritage is a relatively new approach to digitizing cultural heritage that departs from a mere technical documentation standpoint, such as in the HBIM approach, and puts education, community, conservation, tourism, and economic factors at its core [46].

While it can be easily confused with Virtual Heritage, the Smart Heritage differentiates itself from it in many ways. It departs from a passive digital tool for human-curated experiences to an active curatorship made possible by automated and autonomous technologies [47].

Most authors, including the latter, consider it as an intertwined discipline of the Smart City, deriving many contributions back and forth. On the other hand, some authors depart from a Smart City subdiscipline perspective. Bertuzzi and Zreik [48] put forward the notion of enhancing the Cultural Heritage by using X-Reality technologies, namely Augmented and Virtual Reality, or mixed reality. The concept of Hyper Worlds first

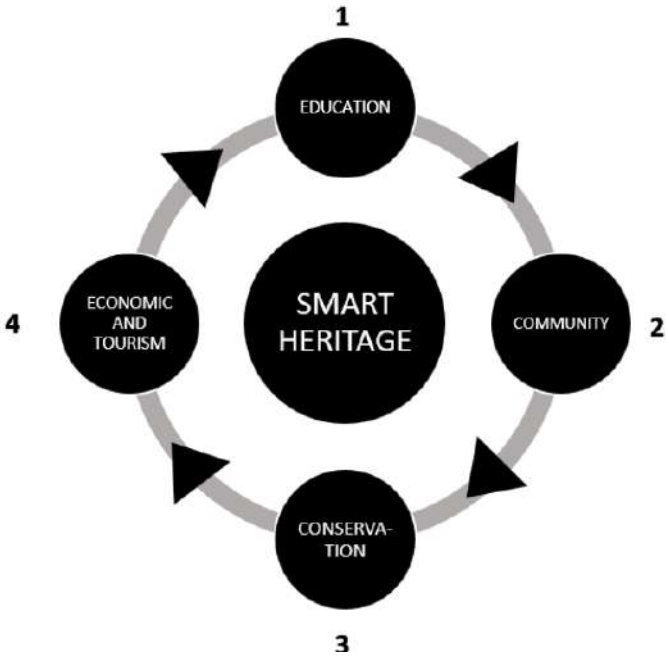


Figure 2.6: Smart Heritage as a system to realize conservation goals (Adrian and Kurniawan, 2020)

appear in the latter, whereas in another work Zreik [49] argues that Cultural Heritage can be enhanced in several ways by providing a Hypercultural environment so that the cultural heritage can be transposed from one place to another, in this work, the term Hyperheritage first appear, and puts technology as one of the components of the augmented culture.

While the augmentation of cultural heritage poses a challenge for Digital Twins, it is an exciting approach regarding the dialogical and relational perspectives of cultural heritage and its place as an authentic world heritage as Smart Heritage inherits four dialogical dimensions from the Smart City concept: Engagement, Inclusion, Collaboration, and Transparency [46]. Since culture and heritage are plural and encompasses the continual co-creation through interaction between people over the generations to come, we can assume that cultural is of a creative nature. Through the intersubjective social relations that permeate creativity, we identify some situations that we believe to exist in many, if not all cultures. Appropriating from Buber thought on cultural creativity, this dialogue is necessary for the amalgamation of the dialogue essential for keeping a civilization at hand, in a just way. Moreover, this creative perspective of cultural heritage becomes an experience one of an I-Thou order rather than the I-It [50].

Furthermore, Adrian and Kurniawan [46] argue that Smart Heritage can be a medium to answer the challenges of Cultural Heritage in three phases: Pre-conservation, Conservation, and Post-Conservation. Such concepts, when put in perspec-

tive with Digital Twins, have an uncanny resemblance to the concepts of Understanding/Diagnosing (Pre-conservation) Monitoring (Conservation) and Predicting/Simulating (Post-Conservation), while looking particularly useful in this context.

Despite this frame of reference, most of the works identified on Smart Heritage did not put forth practical use of these three dimensions together in an explicit way, which are essential for a Digital Twin. Rather, Chianese [51] leveraged IoT for the monitoring (Conservation) of Cultural Heritage inside a Museum, whereas Jara *et al.* [52] addressed the use of monitoring as well, but since the work presents a City perspective, we can infer that such system can be used for diagnosis (Pre-Conservation) and predicting/simulating (Post-Conservation).

Finally, another approach that describes the use of parameterization as a process to contribute the general framework of smart heritage is presented in Rua *et al.* [53]. A methodology consisting of five main phases: data collection, architecture study, data processing, digital modeling, and virtual modeling.

Therefore, the concept of Smart Heritage will be central to this study's proposed framework while embracing every other concept through integration. The Hyper Heritage framework will be discussed in detail in Section 3.

The Metaverse of Technical Images

By the end of the 70s, the philosopher Vilém Flusser (1920-1991) taught about communication theory, at the beginning of the 80s, the first personal computers were born, the Commodore 64 and the Apple Macintosh, they were the "new" media that attracted Flusser is therefore looking more deeply into this emerging digital galaxy, which converged on sophisticated studies of media theory at the height of his career. The fact is that Flusser offered, through his studies, frightening predictions that until then were unthinkable, because although such personal computers were considered new means of communication, at the time they did not have enough computational power to process technical images (only digital photography was born in the mid-1990s) perhaps the necessary communication infrastructure (or the World Wide Web, which was only born in 1990). Digital convergence between keys and gadgets was unthinkable, but not for Flusser, who states that the reproducibility of the technical image constitutes a "cultural revolution" based on a radical break with the old system of linear images [54]. writing that he understood as a receptacle for the historical form of temporality as such, the narrative form, for which language and writing tradition serve as vehicles within an integral ideology of temporality, as in postmodern technosphere, this linearity is spontaneously decaying [54].

Therefore, we have no choice but to risk a leap into the new. This newness is con-

figured by a post-historical state, without dimensions, a state that does not exist or is no longer found in any place or time but in surfaces that absorb geography and history. Flusser does not offer the same temporal sensitivity to the postmodern condition, which he understands to be predicated, rather than the spatial modularity that transcodes and recontextualizes a finite database of items. The internet is the latest incarnation of this increasingly complex attempt at a vast metaverse. However, emerging technologies such as X-Reality (Augmented Reality, Virtual Reality, Mixed Reality and Pervasive Virtual Reality), according to Valente *et al.* [27], constitute a radical step towards the posthistorical metaverse of technical images that Flusser foreshadowed in his work.

Chapter 3

Theoretical Framework

This section presents the chosen methodology for this research. As this thesis provides empirical research where an artifact for Digital Twin for Cultural Heritage was developed while applied to the object of study (the São João Fortress), design science research was chosen as the primary research method.

3.1 Methodological Roadmap

Although this work was also viable by a multimethod approach, such as a literature review followed by the case study, which Yin [55] defines as "an empirical enquiry that investigates a contemporary phenomenon within its realtime context, especially when the boundaries between phenomenon and context are not clearly evident", the need to construct a theoretical framework and directions towards higher contributions made Design Science Research the elected methodological framework, mainly to establish a foundation, as further cycles require, and as a direct consequence of the present study and to aim for higher contributions in future works.

3.1.1 Design Science Research

The term Design Science emerged in the sixties, and the first authors using it were Fuller and Gregory [56][57]. Both agreed on the need to seek a more systematic to design artifacts or enhancements, leading to DSR (Design Science Research or Design-Based Research Science) Sydney A. Gregory, an engineer, was the first to distinguish, in 1966, Design from Design Science Research, dealing with depth and scientific vision existing in the DSR. For the author, the act of designing something without generating any knowledge characterizes a mere Design. Although design is often related by the layman by looks, instead of functionality, which is untrue.

"Design is not just what it looks like and feels like. Design is how it works"
— Steve Jobs

Hence, Design Science started to be widely discussed in the academia back in the 70s, especially in engineering. At the beginning of the nineties, the systematical approach in the design of artifacts and improvements became widely adopted in projects involving electrical engineering, computer engineering, and computer science [58]. In a broad sense, Design Science Research (D.S.R.) is a research methodology concerned with creating and evaluating I.T. artifacts within an organizational context to solve specific problems [58]. These artifacts may include constructs, methods, models, and instantiations (real-life products).

When Simon [59] wrote "The Sciences of Artificial", the community involved with information technologies realized its potential in information systems studies. From that point on, DSR has great relevance for the present work. However, before verifying its direct application in systems development information and how it can relate to the Science of information, it is necessary to analyze the concept of Design Science from some authors who sought to understand it throughout the years.

Understanding the concept's adherence to technology-related projects information and communication (ICTs) is essential in the research. For Simon [59], this research paradigm demands innovative artifacts to solve real-world problems.

Wieringa [60] stated that the DSR is a type of research that aims to give account of two types of problems: "practical problems," which demand a change in the world that better agrees with the goals of decision-makers related to the problem, and "problems of knowledge," which demand a change in our knowledge about the world.

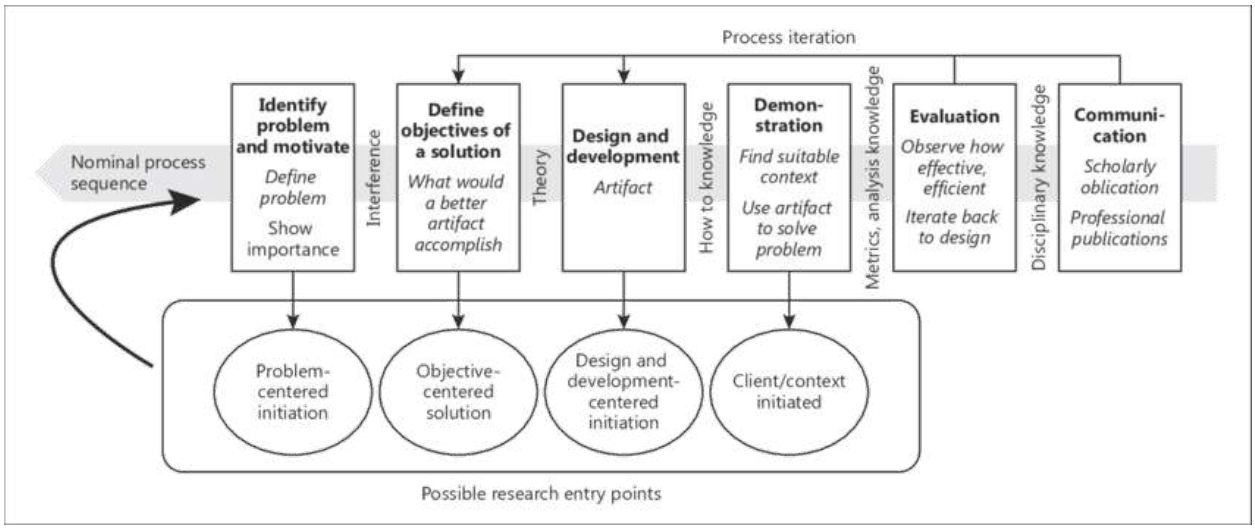


Figure 3.1: Design Science Research Entry Points

Table 3.1: Design Science Research Contribution Types (Gregor and Hevner, 2013)

Table 1. Design Science Research Contribution Types		
	Contribution Types	**Example Artifacts**
More abstract, complete, and mature knowledge	Level 3. Well-developed design theory about embedded phenomena	Design theories (mid-range and grand theories)
↕ ↕ ↕ ↕	Level 2. Nascent design theory—knowledge as operational principles/architecture	Constructs, methods, models, design principles, technological rules.
More specific, limited, and less mature knowledge	Level 1. Situated implementation of artifact	Instantiations (software products or implemented processes)

In order to solve a practical problem, the real-world context is modified to suit human purposes, but to solve a "knowledge problem", we acquire knowledge about the world without necessarily changing it. In Design Science, these two problem types are mutually nested, but such nesting should not blind us to the fact that their problem resolutions are different methods of justifying solutions [60].

The combination of problems of different natures under the same methodological umbrella should not exclude, even so, the idea of different approaches and results. Practical problems await solutions, as problems related to knowledge wait for answers. There is no way to unite such distinct elements, but will it be possible to integrate them in the same methodological research process? In DSR, a practical problem is responsible for guiding the research and other practical problems and questions about knowledge. For Wieringa [60], these problems and issues chain a proper cycle, which the author called the "regulatory cycle".

The cycle begins with the "problem investigation" (problem investigation), a step considering a question about the knowledge. Its theoretical nature is remarkably evidenced by the search for information to understand the problem without changing it. The next step, the "development of solution" (solution design), is characterized by confronting a practical problem.

Therefore, the research methodology of the present work is a first D.S.R. cycle consisting of a design proposition of a technological artifact, which is an instantiation (software, processes) as a situated implementation in a real-world context. Thus, at least a level 1 contribution type regarding Design Science Research [61] is expected in the course of this work.

Furthermore, the nature of a design proposition in a problem-solving approach is highly heuristical. Koen [62] argues that heuristics have four distinct elements (1) the heuristics do not assure an optimal solution; (2) a heuristic can contradict another heuristic; (3) a heuristic reduces the needed time to a solution; (4) the acceptance of such relies upon the context in which it is inserted, rather than a general parameter. Moreover, the role of an engineer is strongly tied to heuristics as engineers leverage these to cause

a change to improve the performance of a system or organization. Worth noting that still according to Koen [62], the engineer causes this change within some constraints: the available resources such as time, budget, technology, etc. Still, the validation depends on the usefulness of an engineering artifact, that is, if it works as planned and adequately in the context for which it was designed.

In this respect, the concepts presented above are strongly related to the concepts regarding applying the fundamentals of Design Science for the conception of the Hyper Heritage framework. This course of action was considered the best one, as it covers the disciplines of systems engineering and production engineering as well.

3.2 Scope and Conceptual Framework

Despite the literature being scarce for Digital Twins of Cultural heritage, so far we have identified, that in short, the Digital Twin concept is a technology-agnostic approach that can leverage many technologies to enable digital replicas to understand (past), predict (future), and observe (real-time) its physical counterpart. Despite being an open concept and still in debate in both academy and industry, the most prominent and solidified aspects, are:

- The virtual model (the replica) has to be a tridimensional counterpart;
- As stated earlier, it has to be a way to understand, predict and observe;
- To provide a connectivity layer, for the model to ingest data from multiple sources;

As a digital twin requires a tridimensional counterpart, the approaches of bidimensional data acquisition on tangible heritage were excluded, but not the tangible heritage, which can be data ingested by the system, put into a data lake for later retrieval or within a semantic layer. Despite tangible heritage being part of the Hyper Heritage framework presented further, this work will only address minor aspects of connectivity by ingesting data from live sources unrelated to intangible heritage due to constraints addressed earlier in section 1.

As a starting point, we have to identify the technological characteristics identified in the literature review for each type of Digital Heritage: Virtual Heritage, Virtual Archeology, HBIM-Based, Smart/Hyper Heritage, and Digital Twin for Cultural Heritage. These technological characteristics will be presented in a table below and discussed further. As such, it will serve as a base for our Hyper Heritage framework which will be presented later in this section.

Table 3.2: Technological Characteristics Identified in the Literature Review

Scope	Digital Twin	Virtual Heritage	Virtual Archeology	HBIM	Smart/Hyper Heritage	Digital Twin for CH
Data Acquisition Suitability						
Intangible Heritage	✓	✗	!	✓	✓	✓
Tangible Heritage	✓	✓	!	!	✓	✓
Historical Sites	✓	✓	!	✗	✓	✓
Built Environment	✓	✓	!	✓	✓	✓
Objects/POI	✓	✓	!	✗	✓	✓
Data Acquisition Modes						
Autonomous Flight	✓	✓	!	✓	✓	✓
Terrestrial	✓	✓	!	✓	✓	✓
Other (documentation-based)	✓	✗	!	✓	✓	✓
Sensors						
Optical	✓	✓	✓	✓	✓	✓
Depth Sensors (except LiDAR)	✓	✓	✓	✓	✓	✓
LiDAR	✓	✓	✓	✓	✓	✓
IoT	✓	✗	✗	✗	!	✓
Data Processing						
Modeling	✓	✓	✓	!	✓	✓
Photogrammetry-based (including sFM)	✓	✓	✓	!	✓	✓
Laser Scanning (LS)	✓	✓	✓	!	✓	✓
SLAM	✓	✓	✓	!	✓	✓
Visualization						
Web-based	✓	✓	✓	✗	✓	!
Game Engines	✓	✓	✓	✗	✓	!
X-Reality	✓	✓	✓	✗	✓	!
Closed System	✓	✗	✗	✓	✗	✓

Legend:		✓	✗	!
		Applicable	Not Applicable	Partial/Limited

In general, as already identified in the literature review chapter, Virtual Heritage is not suitable for Intangible Heritage and other documentation-based methods of digitization of Cultural Heritage for data acquisition. Moreover, it does not have any connectivity characteristics aside from networked visualization in some instances. Virtual Archeology characteristics, are akin to Virtual Heritage due to it being a subset of the former, despite that, as some applications of Virtual Archeology deal mainly with the reconstructed (understand) aspects of digitized Cultural Heritage and 3D modeling, most of its data acquisition pipeline is therefore, mixed and limited, depending on the use case. However, in Virtual Archeology, there is partial Intangible Heritage acquisition and reconstruction efforts.

As for HBIM often neglects the Historical Sites and Historical Artifacts of interest towards a focus on the built environment, be it by visual computing acquisition modes or via mostly parametric 3D modeling. Additionally, although the HBIM data processing leverages mostly of the data processing pipelines as other modalities of Digital Heritage, 3D modeling is generally parametric, photogrammetric approaches are mostly tied-in in BIM tools and Scan2BIM workflows and the same is true with Laser Scanning systems and SLAM techniques. Despite current conversations on OpenBIM and formats such as IFC which allows BIM interoperability, to this date, BIM tools are generally closed and mostly for stakeholders, disregarding the general public which might and must be interested in conservation policies of Cultural Heritage via Digitization, for transparency and other reasons.

For the same reason, most of the works on Digital Twin for Cultural Heritage addressed HBIM. However, Jouan and Hallot [11] presented a comprehensive framework for data processing and digital representations (visualization). In contrast, Dezen-Kempter *et al.* [9] presented a mixed approach with visualization in Augmented Reality through the importing of the HBIM model inside the Unity Game Engine.

Finally, although the Smart Heritage approach is the most flexible by far in terms of technological characteristics, no work identified has leveraged or proposed the use of connectivity features in the three dimensions that a Digital Twin requires: Understand, Predict, and Monitor explicitly or within the context of the Cultural Heritage per se, instead, inside a city perspective, in a Smart City setting. Therefore, the usage of IoT in the Smart Heritage context is still limited to the city as a whole. While this should not be considered a problem when the Cultural Heritage resides in an urban context, it should be an issue when it is not.

In the next section, we will be presenting the Hyper Heritage framework and looking into some of the technological characteristics regarding visual computing technologies, deriving from the essential features and technological characteristics to enable a Digital

Framework Layer	Description	Main References
Authorizations	Authorizations needed for data acquisition	[63]
Intangible Data Acquisition	Intangible data acquisition processes and definitions	[64]
Tangible Data Acquisition	Tangible data acquisition processes and definitions	[32][9][33]
Digital Heritage	Deals with information transform and processing pipelines, the integration subsystem and the visualization engine	[30][32][2]
Digital Twin	Deals with logic, IoT/CPS sensors, AI subsystem for simulation and a Digital Twin reporting engine (UMP)	[9][7][12]
Hyper Heritage	The system output, enabling immersion via XR	[47][49]

Table 3.3: Main References on Hyper Heritage Framework Constructs

Twin of Cultural heritage.

3.3 Hyper Heritage Framework

While the characterization of a Digital Twin plays a pivotal role in this study, this dissertation's purpose in regards to Digital Twin has no intent to make a significant contribution, but to yield a small one by incorporating some of its concepts and functions in a theoretical framework, while departing from the BIM-based digital heritage method, albeit leveraging some of the visual computing techniques employed in such modality and still offering solutions for its integration via importing.

Deriving from many contributions identified in the literature review on the various types of Digital Heritage, it is presented below a layered conceptual framework called the Hyper Heritage framework, as presented below:

The Intangible Data Acquisition layer deals with acquiring data from historical documents, itineraries (historic site), and images (in a wide, Flusserian context) and passing through an information engine or database inside the Digital Heritage Layer. This information will be indexed in a integration subsystem in the form of metadata and further processed in a processing subsystem which will convert to a respective visualization as required (text, images, etc.).

The Tangible Data Acquisition layer involves the processes of acquiring data from the Tangible Heritage: Historical Site, Built Environment, Interiors and Objects (Historical Artifacts), or Points of Interest. The acquisition of Tangible Data generally encompasses various computer vision and photogrammetry, which will be discussed in further detail in the next section. Afterward, the data acquired must be processed in place or in the processing subsystem inside the Digital Heritage layer, which consists of the chosen data processing approach. In this study, we opted for a primarily photogrammetric approach, but any other approach can be considered as well. After the information is processed, for example, a historical site processed via aerial photogrammetry leading to a 3D model, this model is imported inside the visualization and engine subsystem, which generally consists

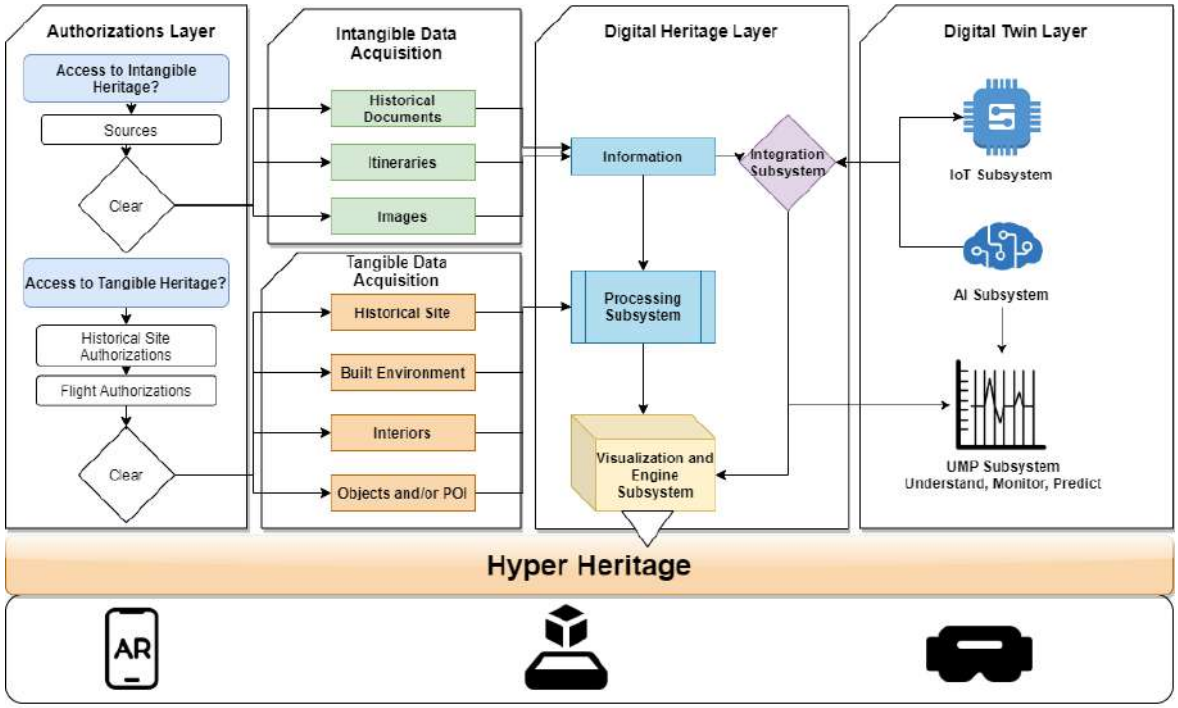


Figure 3.2: Hyper Heritage Framework

in a real-time computer graphics engine, such as a Game Engine or other visualization tools that allow for connectivity, as required for our Digital Twin Layer.

Although connectivity symbols such as a cloud are omitted in the diagram, for simplification purposes, The Digital Twin layer provides connectivity to the former layer as well three critical subsystems: an IoT Subsystem, which comprises of databases, sensors and real-world data gathered inside the Cultural Heritage or in the vicinity (for Smart Cities); an AI Subsystem which comprises of an Artificial Intelligence engine that might allow for Pre-Conservation and Post-Conservations simulations. Lastly, the UMP Subsystem is the one that will provide past (Pre-Conservation), present (Conservation), and future (Post-Conservation) reports by leveraging data input in the Digital Replica.

Finally, the Hyper Heritage layer will provide the visualization needed to the stakeholder, from simple web-based visualization to Augmented, Mixed or Virtual Reality.

3.4 Visual Computing and Cultural Heritage

Visual Computing is an umbrella term that encompasses all computer science disciplines related to the visual aspect of computing technologies: computer graphics, image processing, visualization, x-reality, video processing, computer vision, and aspects of pattern recognition, human-computer interaction, and machine learning.

Thus far, since we have identified contributions within the literature review in prac-

tically every discipline, we can argue that Visual Computing plays an essential role in heritage digitization. In this respect, we will briefly investigate which technologies are generally applied in tangible cultural heritage digitization and their typical use cases, especially the following disciplines:

- Computer Vision and Photogrammetry;
- Computer Graphics;
- X-Reality (Virtual, Augmented, Mixed and Pervasive);

The technologies related to Visual Computing (common to some of the main topics of Computer Graphics and Computer Vision, and covering the entire cycle of acquisition, analysis, synthesis, and interaction with visual data) are vital elements in coping with some of the challenges of Hyper Heritage.

3.4.1 Computer Vision and Photogrammetry

In recent years, 3D model reconstruction methods have been thoroughly studied within the computer vision field, being photogrammetry, LiDAR and combined LiDAR the most frequently used methods.

Photogrammetry is the science of making measurements from photographs, and in this field alone, the software industry has made many advances in 3D model reconstruction using this particular technique. SituatorVR, which is the tool of choice in this study for generating 3D models, differ from other tools as aside from photogrammetric capabilities, it offer more flexibility in incorporating other sensors and techniques, regardless, many tools commercially available nowadays, including ones that are aerial-based enable photogrammetric surveys. At the end of chapter 3, there is a comparison table of the major tools used for an end-to-end photogrammetric pipeline, which includes data acquisition, processing and visualization. The mathematics underlying 3D model reconstruction using images are discussed in some of the articles referenced in Appendix A.

Light detection and ranging (LiDAR) system has been widely used for 3D model reconstruction in recent years. Ackermann [65] has contributed a comprehensive analysis of the status and expectations of the airborne laser scanning system. Now in the twenty-first century, many works are still focused on the mathematical theory and technical detail of 3D Reconstruction with LiDAR data. While many works focused on 3D building model reconstruction for BIM applications, more recent works include Rodriguez-Gonzalves *et al.* [66], who proposed a thorough study on the progress of geomatics in the forensic field.

Baltsavias [67] has reported an early comparison research between photogrammetry and laser scanning for the hybrid approach. These two methods both have advantages

and disadvantages, thus combining them should be a wise choice. Ma [68] had studied the theory and technical details of building model reconstruction from LiDAR data and aerial photographs in his doctoral dissertation. Sohn and Dowman [69] went further and performed the data fusion of high-resolution satellite imagery and LiDAR data for an automatic 3D model. Chen integrated LiDAR and camera data for 3D Reconstruction for indoor and outdoor environments [70]. Some other methods of 3D model reconstruction are also applied, such as low-cost RGB-D cameras and Structured Light Sensors, such as Kinect and Structure.io.

Laser Scanning

Today 3D scanning technologies are adopted for their ability to accelerate the collection of spatial data of existing buildings or complex surfaces, as well as for the precision and accuracy of the acquired data. Laser scanners can be thought of as advanced systems, which allow automatic and near real-time measurement of three-dimensional coordinates on the surface of an object [71] [72].

Laser scanners are subdivided into two specific areas, aerial and terrestrial. Each has a range and precision specific to its intended use.

The terrestrial laser scanner (TLS) is normally set up on a tripod and work through a laser beam that travels to the scanned area back and forth, measuring the angles and distances with great accuracy that ranges from millimeters to centimeters [73].

The aerial laser scanner (ALS) is usually set up on drones and work on the same fashion, with the difference that, in aerial systems, depending on the drone maximum payload, bigger and longer-range LiDAR sensors are out of question.

In the present study, they will not be considered, mostly due to the high costs associated, and some limitations on generating optimized meshes for a real-time model, among other factors, such as the difficulties in scanning highly reflective, transparent or dark surfaces (Klein *et al.*, 2012) [74].

Photogrammetry

Photogrammetry is a noncontact, precise 3D measurement technique based on various images of high quality, which allows to accelerate the collection of geometric data of a building or object [75]. It is a technique based on triangulation, where the lines of sight of a camera located in various places come together at a common point on the object.

The intersection of the the camera's lines of sight determines the three-dimensional location of the point. The results obtained with the photographic survey include orthographic images and point clouds that can then be meshed with a surface composed of

triangles and textured through the overlapping figures.

This measurement technique as well as laser scanning are very suitable for generating models. Photogrammetric modeling of buildings has many applications on cultural heritage digitization, and during the last decades it has become a very popular technique for registering historic sites from a set of photographs [76]. In addition, it is a capable technique to considerably exceed in precision and data acquisition time in comparison to traditional topographic systems, and very economical when in comparison to the most technologically advanced systems such as the Aerial/Terrestrial Laser Scanning systems based on LiDAR hardware.

Moreover, despite that a lot of research works have been done, fusing multiple sensor data, especially LiDAR data with photogrammetry data is challenging, as current solutions are not satisfying in both stability and efficiency.

In 2017, the author, during his collaboration with Displace, a Visual Computing IndTech startup, developed a method which enabled low-cost tridimensional data acquisition by multiple sources, leveraging AI and computer graphics techniques for solving mesh interpolation between point clouds generated by different sources in any combination.

This 3D reconstruction engine was used for the aerial large-scale 3D reconstruction of the historic site of Fortaleza de São João.

Since technology specifics are beyond the scope of this work, technical details are presented later in Appendix A.

Autonomous Flight

Although autonomous flight is not a Visual Computing subdiscipline per se, some of its underlying technologies are present in Unmanned Aerial Vehicles (UAV), or simply drones. Most modern UAVs leverage Computer Vision systems for flight navigation purposes. Most recently, some companies have implemented embedded photogrammetric capabilities and SLAM (Simultaneous Localization and Mapping), in the latter case, for both a navigational aid and for realtime 3D Reconstruction.

For the purposes of Cultural Heritage digitization, flight planning software is an essential tool for tangible data acquisition from large-scale environments. It is mainly applicable to outdoor environments, though some works have leveraged indoor mapping, such as Plevny [77], but not using a flight planner. Recently advances in consumer, prosumer, and enterprise drones made indoor and confined space flight possible, although this dissertation will not use such capable drones for our indoor mapping purposes. Therefore, for this work, only outdoor drones will be used.

Another important feature to mention regarding aerial survey operations using photogrammetry techniques, the Ground Sample Distance (GSD) is the metric that corre-

sponds to the scale of the image in relation to a pixel, commonly described in centimeters per pixel.

As an example, a 1cm GSD image understands that each pixel captured in the image represents 1cm of terrain. Thus, the smaller the size of the GSD (pixel on the ground), the better the quality of the final image, which will be composed of more pixels.

When the camera is used closer to the ground, it will produce a smaller GSD, and because of that it will need to use more images to cover the same area. On the other hand, the same camera and aircraft flying slightly higher can produce a larger GSD and, consequently, be able to capture a larger area in a single flight.

Putting it another way, the farther the camera is from the aircraft in relation to the ground, the larger the photographed image will be and, therefore, the pixels of this camera represented an equally larger area on the ground.

Therefore, in photogrammetry there is a relationship between the height of flight and the type of camera used that will cause a variation in the GSD, because the smaller the pixel that makes up the image, the smaller the GSD and the better the resolution of aerial photography, and vice versa.

3.4.2 Computer Graphics

Within the umbrella term of Visual Computing, Computer Graphics is a discipline involved in studying methods for the digital synthesis and manipulation of visual content [78]. As the term often refers to three-dimensional computer graphics, a subset that is image processing and two-dimensional computer graphics will be addressed separately in the last section of this chapter.

Thence, we will focus on the three-dimensional techniques and tools within this discipline that allow digital heritage representation through 3D models and the spatial data reconstruction, processing, and visualization that such tools allow. The mathematical and computational foundations of Computer Graphics are outside the scope of this dissertation.

The tools identified in the literature review that falls into the computer graphics field, are of the following categories:

- BIM - Building Information Modeling;
- CAD - Computer Aided Design;
- 3D Modeling
- Graphics Engines

BIM tools have already been covered in section 2.2.2 on the literature review of HBIM-Based Digital Heritage. However, CAD and 3D modeling tools, are generally used to enable the 3D virtual Modeling of buildings in BIM through parametric Modeling or direct or explicit Modeling. 3D CAD tools generally perform better at the former, while 3D Modeling tools are better at the latter, although both can function within the two types of 3D solid Modeling.

3D CAD and 3D Modeling

Although in the 1960s the first Computer Aided Design (CAD) systems used an edge modeling scheme, where geometry is defined as a series of lines and curves representing objects' edges. The edge modeling type is unable to express surfaces or faces. Additionally, you are limited in calculating mechanical properties or performing analysis.

For its part, surface modeling represents some or all the flats of the component. 3D Modeling really started in the early 1970s with the development of a 3D rendering technique called Solid Modeling. Modeling solids is a 3D volumetric representation scheme that arises from the need for a higher-level representation of complex objects.

For ruined buildings, prone to mixed approaches for 3D reconstructions, the London Charter for Computer-Based Visualization of Cultural Heritage [79] lays out best practices and guidelines, but it does not recommend or mandate tools, workflows, or data formats, stating that technology changes over time.

Graphics Engines

A Graphics Engine is a specialized software for rendering (displaying) 2D or 3D scenes commonly built on top of low-level graphics APIs (Application Programming Interface) such as OpenGL (cross-platform), DirectX (Windows), Metal (Apple), among others.

Currently, aside from graphics engines that are part of Operating Systems rendering engines, very few graphics engines are purely graphical, such as OpenSceneGraph, Crystal Space and Ogre3D. However, they offer integration capabilities for other libraries which provides other components, such as audio, physics, networking.

Nevertheless, a modern Graphics Engine is generally a Game Engine, which encompasses the Graphics feature alongside input, audio, physics, networking, artificial intelligence, among many other capabilities, built-in.

With the advent of HTML5, the WebGL (Web Graphics Library) specification arrived as a JavaScript-based API for rendering 2D and 3D graphics inside a compatible browser without the use of plugins.

In the course of this dissertation, we will investigate the use of a web-based visu-

alization engine based on WebGL and a Game Engine for developing the Digital Twin pilot.

3.4.3 X-Reality

One of the most used technologies for the diffusion and dissemination of the heritage and its environment are virtual reality (VR) and augmented reality (AR) Technologies VR can represent past, current or future scenarios in a virtual world. In addition, VR enhance the visualization of representative data, with the ability to navigate and interact (with each component) within the simulations. For its part, AR technologies are used to define a vision of a fictional environment in the real world, where the elements of the real world are combined with virtual elements to create a mixed reality in which the user can navigate in real time.

3.5 Planning and Execution of the Case Study

3.5.1 Scope of Work

As previously addressed in Section 1.5, the present study would not deal with data acquisition of intangible heritage or interpretations of cultural heritage.

Instead, this work will focus on the Tangible Data Acquisition and Digital Heritage Layers, while providing some ideas on how to implement some components in the Digital Twin Layer through data integration and eventually leading to the conclusion of the pilot project in which the São João Fortress was presented in an immersive setting (Virtual Reality).

The proposed workflow will consist in tangible data acquisition and processing of the Historic Site of São João Fortress by using mixed approaches. Afterward, a web-based intermediate visualization will be presented in a SaaS (Software as a Service). Further, a pilot Digital Twin will be developed and presented by leveraging a Game Engine.

In the figure and table below, the Scope of Work of the Hyper Heritage and a software breakdown of tools that can be used in a similar workflow. In bold, the tools that were actually used in the Case Study presented in the following chapter:

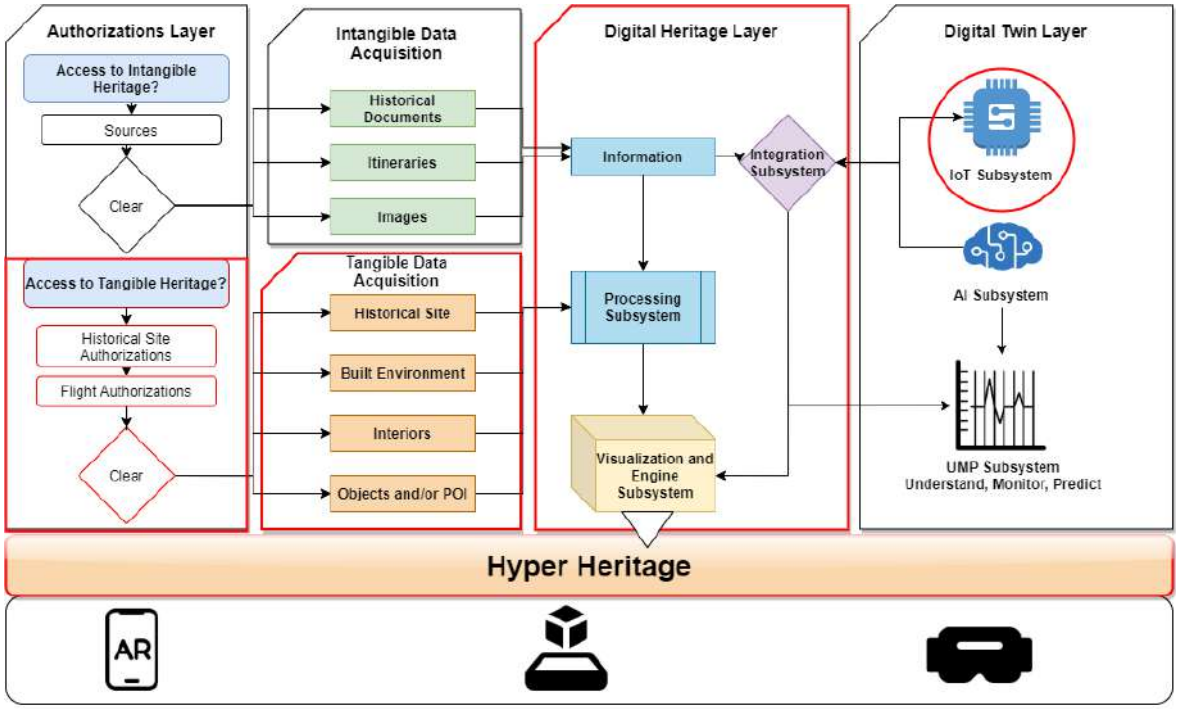


Figure 3.3: Hyper Heritage Framework - Scope of Work

Workflow Type	Processing Software	Usage	Licensing	References
Flight Planning	Mission Planner	Flight Plan	Free (limited use)	[80]
	DroneDeploy	**Flight Planning + 3D reconstruction**	**Proprietary**	[81]
	Pix4D	Flight Planning + 3D reconstruction	Proprietary	[82]
	OpenDroneMap	Flight Planning + 3D reconstruction	Open Source	[83]
Photogrammetry	**Situator_VR**	**Large-scale sensor-agnostic 3D reconstruction**	**Proprietary**	[84]
	OpenMVS	Stereo-view 3D reconstruction	Open Source	[85]
	OpenMVG	SFM-based 3D Reconstruction	Open Source	[86]
	AliceVision/Meshroom	SFM and MVS 3D Reconstruction	Open Source	[87]
	Matterport	Interior 3D Reconstruction and visualization	Proprietary	[88]
Visualization	Three.js	Web-based Library for 3D Visualizations	Open Source	[89]
	SketchFab	**Web-based Service for 3D Visualizations**	**Proprietary**	[90]
Graphics Engines	Unity	3D Game Engine	Proprietary	[91]
	Unreal Engine	**3D Game Engine**	**Proprietary**	[92]
	Godot	3D Game Engine	Open Source	[93]
	CryEngine	3D Game Engine	Proprietary	[94]

Table 3.4: Software Breakdown

Chapter 4

Digital Twin of the São João Fortress

4.1 The São João Fortress

The São João Fortress da Barra do Rio de Janeiro, also known as Fortaleza de São João ou Forte São João is a fortification erected by Estácio de Sá to protect the Guanabara Bay from French invasion. It is one of the 19 fortifications across many states in Brazil listed as heritage by IPHAN (See Appendix B.1) and UNESCO tentative list for world heritage (See Appendix B.2; Secomandi, 2020) [95].

Figure 4.1: Fortaleza de São João (Google, 2021)

The foundation of the city of Rio de Janeiro is directly related to the São João Fortress. Within the floodplain between the foothills of Morro Cara de Cão and Morro do Pão de

Açúcar, in the Reduto (stronghold) de São Martinho in 1st of March, 1565, Estácio de Sá, founded the city, disembarking along 300 men from five ships – to become the first governor of the captaincy of Rio de Janeiro, in the context of the struggle for the expulsion of the French from Guanabara Bay. (Sousa, 1885) [96].

In 1572 during the mandate of the governor Salvador Correia de Sá, the fortress was reinforced with a new artillery platform in the reduto de São Teodósio, located on the tip by the same name, facing the Guanabara Bay.

Disarmed during the Regency, it was, by order of D. Pedro II, entirely reformed in 1872, equipped with 15 Whitworth cannons (75 mm) and an anti-charge howitzer, 20 other cannons, 17 bunkers and three batteries.

Having participated in essential episodes in the country's history, the Fortaleza was garrisoned by several Coast Artillery Groups until 1991. The Army's Physical Training Center (CCFEX) and the Superior War School (ESG) currently operate there.

4.2 Tangible Data Acquisition

4.2.1 Historic Site and Buildings

The first step of acquiring tangible data consisted of a large-scale 3D mapping using drones and the techniques presented in chapter 3. In the planning phase (section 3.3), the whole historical site was assumed to be the object of large-scale data acquisition, but it became an impossibility due to flight authorization (Santos Dumont Airport is nearby the vicinity). Because of that, by the orientation of the historic site manager, Colonel Joel Corrêa, a mapping area of roughly 34.135,11m² (367.438,06ft²) was considered, to capture the essential parts of the built environment – Reduto de São Teodósio and Forte de São José, as well significant pathways and locations of the historical site between these two fortifications.

The drones used were a DJI Mavic 2 Pro with a 1" Hasselblad camera for photogrammetry and a modified DJI Phantom 3 Standard with a 2.7k camera plus a payload consisting of a Zed Stereo Camera and NVIDIA Jetson Nano to further improve the quality of the point clouds and overall geometry.

In Brazil, autonomous flight operations are regulated by ANAC (Agência Nacional de Aviação Civil - National Aviation Agency), DECEA (Departamento de Controle do Espaço Aéreo - Airspace Control Department) and ANATEL (Agência Nacional de Telecomunicações - National Telecommunications Agency).

Regardless of the purpose of the flight, in Brazil (RBAC-E 94/2017) there are three classes of drone:

Figure 4.2: Capture Area

Figure 4.3: DJI Mavic and DJI Phantom 3 Drones (Sources: SZ DJI Technology Co., Ltd. and Author, 2020)

- Class 1 - Maximum takeoff weight of 150 kilograms;
- Class 2 - Maximum takeoff weight between 25 and 150 kilograms;
- Class 3 - Maximum takeoff weight below 25 kilograms.

The drones employed for large-scale aerial capture are below 25 kilograms MTOW (Maximum Take-Off Weight) and thus considered class 3 category. Despite this fact, all drones have to be registered into the SARPAS (Solicitação de Acesso de Aeronaves Remotamente Pilotadas - Remote Controlled Aircraft Access Request) system from DECEA.

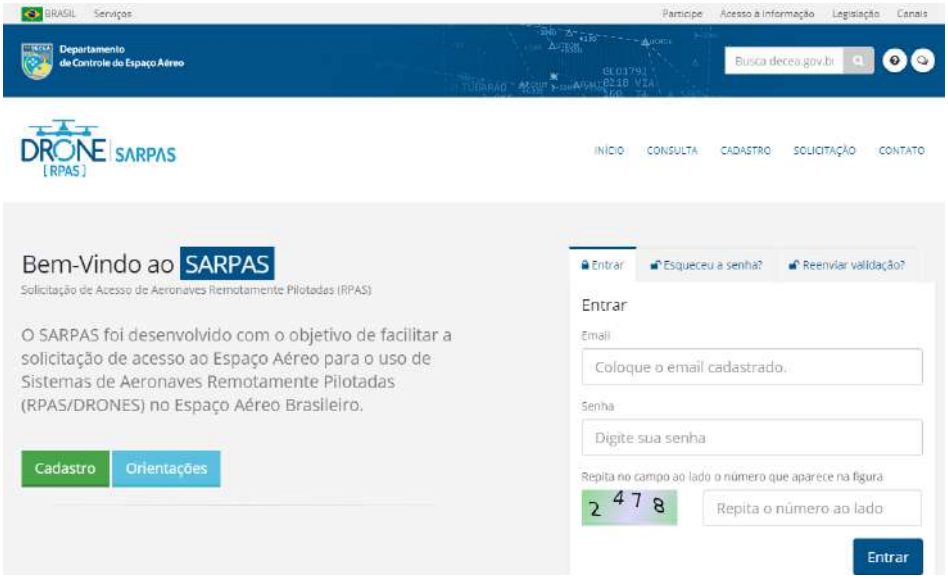
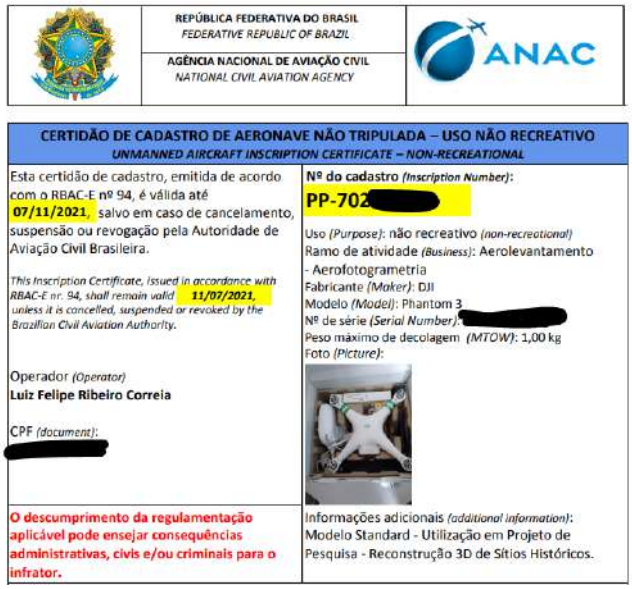


Figure 4.4: SARPAS - DECEA

Once the aircraft is registered and accepted by DECEA officials, a Unmanned Aircraft Inscription Certificate is provided.

After the aircraft is registered and the certificate is approved, the next step consists of requesting a flight operation within SARPAS, following the steps from the main page, while logged in:

1. Click on Request;
2. Select from the list of registered aircraft;
3. The type of operation (Standard, Urban, Rural, Aerial Survey);
4. Takeoff location in longitude/latitude;
5. Operation details - Name, Operation type, Flight Rules;



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AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL
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ANAC

CERTIDÃO DE CADASTRO DE AERONAVE NÃO TRIPULADA – USO NÃO RECREATIVO
UNMANNED AIRCRAFT INSCRIPTION CERTIFICATE – NON-RECREATIONAL

Esta certidão de cadastro, emitida de acordo com o RBAC-E nº 94, é válida até **07/11/2021**, salvo em caso de cancelamento, suspensão ou revogação pela Autoridade de Aviação Civil Brasileira.

This Inscription Certificate, issued in accordance with RBAC-E nr. 94, shall remain valid **11/07/2021,** *unless it is cancelled, suspended or revoked by the Brazilian Civil Aviation Authority.*

Operador *(Operator)*
Luiz Felipe Ribeiro Correia

CPF *(document)*:
[redacted]

Nº do cadastro *(Inscription Number)*:
PP-702[redacted]

Uso *(Purpose)*: não recreativo *(non-recreational)*
Ramo de atividade *(Business)*: Aerolevantamento - Aerofotogrametria
Fabricante *(Maker)*: DJI
Modelo *(Model)*: Phantom 3
Nº de série *(Serial Number)*: [redacted]
Peso máximo de decolagem *(MTOW)*: 1,00 kg
Foto *(Picture)*:

O descumprimento da regulamentação aplicável pode ensejar consequências administrativas, civis e/ou criminais para o infrator.

Informações adicionais *(additional information)*:
Modelo Standard - Utilização em Projeto de Pesquisa - Reconstrução 3D de Sítios Históricos.

Figure 4.5: Unmanned Aircraft Inscription Certificate

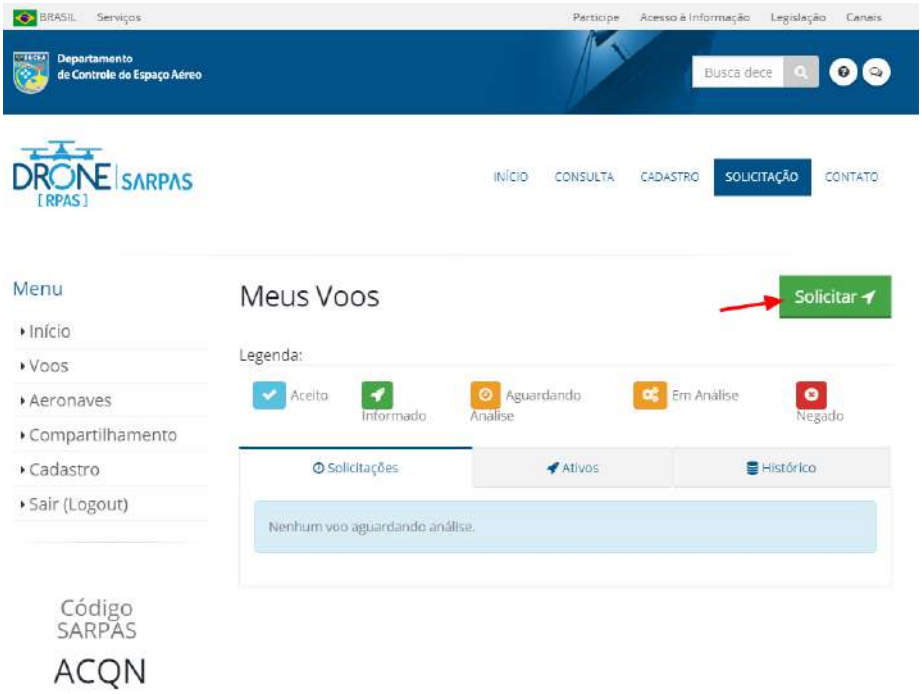

Figure 4.6: Flight Request - SARPAS/DECEA

6. Operation window (period in UTC-Zulu time);

7. Flight Plan - Area, Polygon or Corridor and Altitude

After the flight plan is authorized, the next step is the operation *per se*, for that, the next step requires a flight planner software for the drone to take the required set of

pictures. Some flight planner software, such as DroneDeploy, Pix4D and OpenDroneMap (see Table 3.1), also provide Data Processing. For the São João Fortress, a trial version of DroneDeploy was used for the DJI Mavic and OpenDroneMap for DJI Phantom 3.

Figure 4.7: POV from DJI Mavic 2 at São João Fortress

In this study, both software were employed mainly for flight planning purposes, although in the case of DroneDeploy, we have processed an orthophotomosaic for debug purposes, as addressed in Section 4.3.

The custom DJI Phantom 3 was also piloted manually for capturing some sections of the São João Fortress in proximity, as the NVIDIA Jetson Nano plus Zed Depth Camera module used for mesh optimization requires to be in close range to maximize accuracy.

As already stated earlier, reconstructing the whole site, including important historical points of interest such as São Martinho and São Diogo strongholds became an impossibility due to a No-Fly zone which would require a high level of clearance.

Due to this restriction, a flight plan comprising of the forte de São José and reduto de São Teodósio was created in our flight planning software. In the example below, DroneDeploy is being used, configured for a DJI Mavic 2, with a resolution of 1.0 cm/pixel, which means that 1 pixel in a photo sample represents 1 centimeter (See Appendix A – Ground Sample Distance).

The workflow that has been implemented to obtain the three-dimensional cloud model consists of the combination of: a) Phantom 3 Drone flight plan, that besides a manual flight, the drone was kept constant height and speed, taking images (stereo video) both horizontally, vertically and in circular flight every 3 seconds to get enough data; and b) DJI Mavic 2 Pro, via the automated Flight Planning Software that swept through the

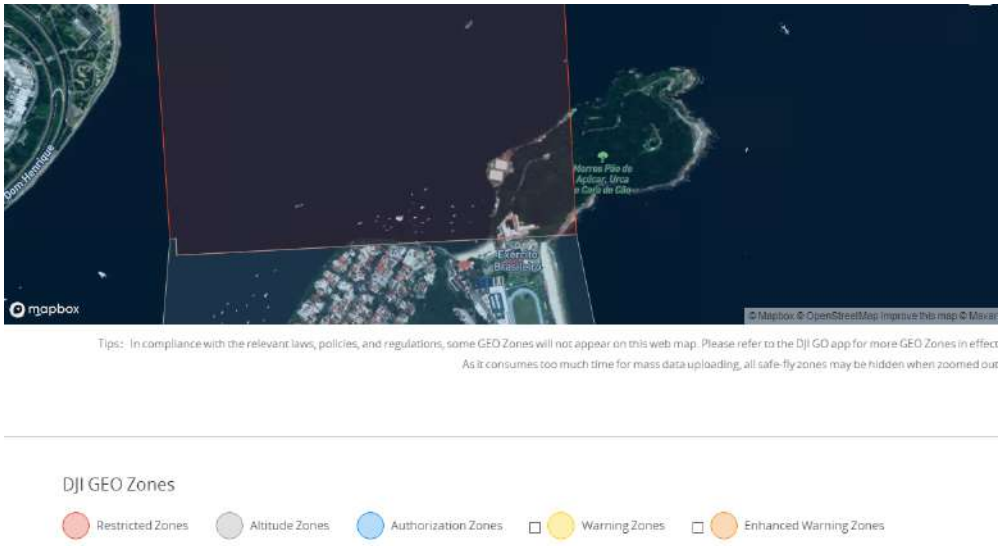

Figure 4.8: No-Fly Zones - https://www.dji.com/br/flysafe/geo-map

previous generated flight plan in the same pattern and taking images (photographs).

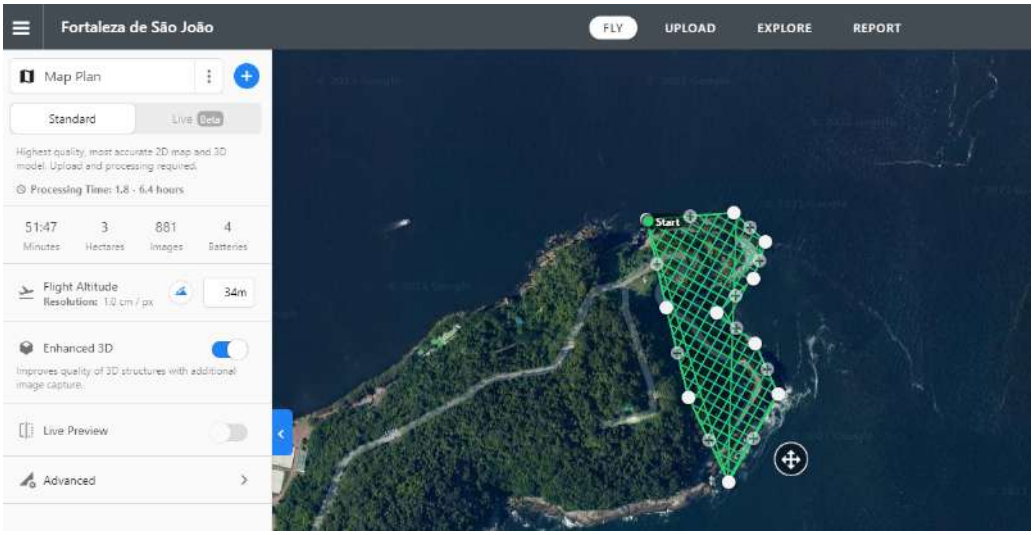

Figure 4.9: DroneDeploy Mission Planning - https://www.dronedeploy.com

4.2.2 Interiors

Due to constraints in time, computational resources, and limited access to the fortress during the COVID-19 pandemic, the data acquisition of the built environment interior departed from the previous approach towards a sole 360-degree image acquisition with simple photogrammetric capabilities. Therefore, we have used a proprietary solution from Matterport (see Table 3.1), which is a software that enables the capture of environments,

primarily interiors, with limited 3D Reconstruction capabilities. However, it offers a powerful web-based visualization engine and a Google Street View exporter.

Museum

Atop the Forte of São José within the historic site of Fortress of São João lies a small exhibit area of the Historic Museum of Fortress of São João.

Figure 4.10: Museu Histórico da Fortaleza de São João

For the capture of its interior, the Matterport solution was the tool of choice, but for Proof of Concept purposes of this study, which makes a statement about how low-cost devices and technologies can be used to create a digital replica of large environments efficiently, neither a 360-degree capable camera nor a Matterport proprietary camera was used. Instead, a regular smartphone was preferred to take pictures, a second-generation iPhone SE, which is compatible with the Matterport solution.

After downloading the application "Matterport Capture" from the App Store, an option to log in or sign up for a new account is presented. Since an account was created previously, there is no need to sign up but to log in with the credentials generated earlier.

Opening the Matterport Capture App, there is a screen with recent captures and a plus sign in the bottom-right corner, clicking on it will pop up a project detail window in which data such as address and other information will be automatically filled with reasonable accuracy if there is G.P.S. information available (works best outdoors). Regardless, there is always the option to input the project data manually. When done, we click "save" and another window pops up, which is the capture window.

Inside the capture window, the user has a camera shutter button on the bottom of the interface, along with settings on the left and a source selection option just above. On the right, there are some shortcuts.

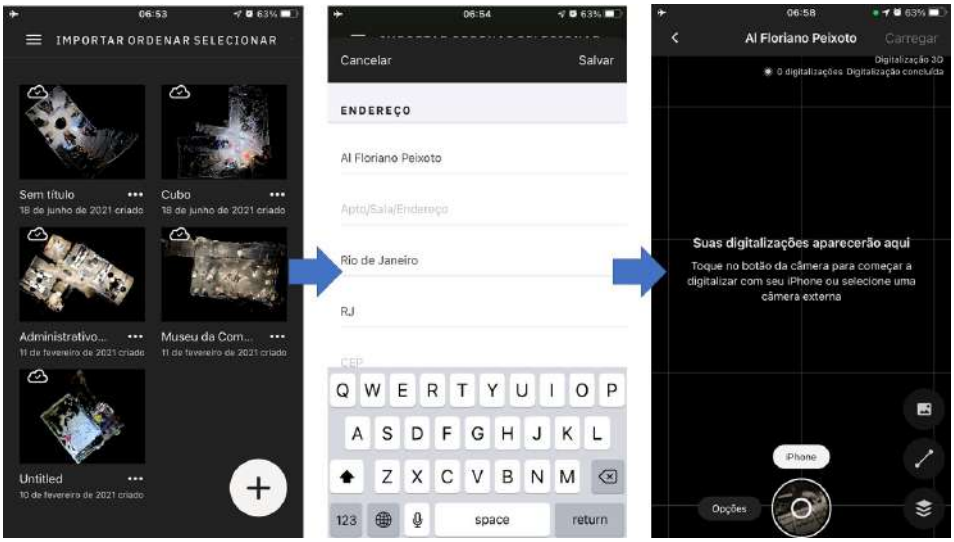

Figure 4.11: Matterport Capture App Flow - Create Project

As the capture will use the smartphone camera, the default source (iPhone) is left as it is – the default. However, for the capture, there is a need to adjust other settings in the options button. By doing so, an overlay window appears, with some digitization options: a) 3D or b) 360-degree for the capture mode – if the first option is selected, a 3D model will be generated by depth estimation via photogrammetry, if the second option is selected, a simple 360-degree photographic capture will be done instead. Further options are c) simple or d) complete for the mode of digitization. The first one will not cover floors or ceilings, whereas the latter will cover the entire interior, including the floor and ceiling. Since the purpose is to generate a 3D model and as much detail as possible, options' a' and 'd' are selected.

Since the smartphone camera is not a 360-degree capable one, the software provides screen-based guidance for generating a virtual 360-degree panorama. For each photo, the user has to center a dot in a circle, and once it is correctly aligned, a photo is taken automatically. Depending on the area size and selected options, the photos can range from 20 to 64 taken per scan. For the museum, there is a total of 8 scans which account for one space, with a total of 385 pictures taken.

Casemates

For the casemates in Forte São José, the same steps were followed, although in this instance, a 360-degree camera compatible with the Matterport solution was preferred over

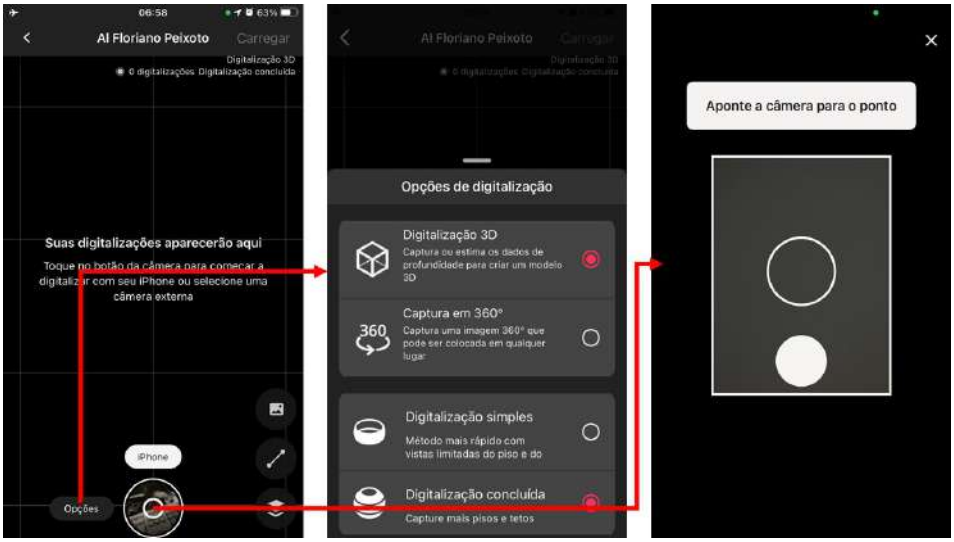

Figure 4.12: Matterport Capture App Flow - Capture

Figure 4.13: View from a Casemate of Forte São José

a smartphone, mainly because the casemates (17 in total) required at least three times the number of scans. Since the casemates had to be recaptured from multiple points of view (further details in the next section), 42 scans were generated.

Figure 4.14: Insta 360 One R Camera

4.2.3 Objects (Historical Artifacts)

The original planning consisted in the capture of some of the artillery and the city of Rio de Janeiro foundation stone replica. Due to several constraints addressed earlier (COVID-19 and undergoing restoration), it became impossible to conduct the full 3D capture as planned, but this work managed to reconstruct the foundation stone from some photographs taken before the COVID-19 pandemic replica partially. The Reconstruction from scarce data is addressed in the next section – Data Processing.

Figure 4.15: Foundation Stone of the City of Rio de Janeiro - Original (left) and Replica at São João Fortress (right)

4.3 Data Processing

The next step is to process the raw data obtained in the tangible data acquisition process to generate the tridimensional models. As addressed earlier, this work is based mainly on photogrammetry, except for using stereo data for the outdoor built environment, as stated in Section 4.2.1 for mesh optimization purposes. As presented in Section 3.3.3, other methods of data processing can be used as the Hyper Heritage Framework provides a holistic and technology-agnostic approach.

4.3.1 Historic Site and Buildings

The data acquisition of the Historic Site and Buildings within the São João Fortress yielded around 41.272.491.966 bytes or 38,4 GigaBytes of data, in 3.995 files among stereo

images captured with the Phantom 3 Standard drone, images captured with the Mavic 2 Pro built-in 1" camera, and some terrestrial-based photos from smartphones, for reference and possible calibration purposes.

As the dynamic range of natural scenes in some cases exceeds the dynamic range of imaging sensors, it is expected that some captured images appear so bright that they render them unusable for photogrammetric estimation. For this reason, an automated brightness histogram tool can be used to reject such images that are beyond a certain threshold. Regardless, a visual inspection can be used instead. Using an image editor such as Photoshop is not recommended to fix the pictures, as it might induce artifacts imperceptible to the human eye that might render the image useless.

Both automated and visual inspection approaches were used to curate the images gathered from the data acquisition process in this work. The curated data comprised roughly 716 images and 294 stereo pairs, which were then uploaded to Amazon Web Services Simple Storage service for processing with the SituatorVR software on GPU (Graphics Processing Unit) instances. Although the technical specifics are beyond the scope of this dissertation, the detailed photogrammetric process is detailed in Appendix A, minus the data fusion capabilities of the SituatorVR application, which is a trade secret from the company Displace Tecnologia e Informatica LTDA.

In overview, the photogrammetry processing involves the following steps:

- Image Acquisition - The image acquisition process *per se* as addressed in previous sections;
- Calibration and Orientation - The process in which the software reads the exif from a file and retrieves the respective sensor specifications from a database (if available) or via manual input;
- 3D Point Cloud Generation - After the images are calibrated and aligned, similar features are estimated across adjacent images (regarding camera frustum), if a similar feature is beyond a certain threshold of certainty across two or more images, a point (or vertex) is generated in the 3D space, the process repeats until it computes for all similarities, thus generating a dense representation of vertices, which represents the overall geometry estimated via photogrammetry, hence the name point cloud.
- Structuring and Modeling - This step consists in generating the structure by computing the surface across the points, generating a polygonal representation - the 3D mesh;

- Texture Mapping - The final step computes the UV map, leveraging the source images and computations during the process. UV mapping is a 3D modeling process that consists of projecting a 2D image onto the surface of a 3D model. After this process, the final 3D model is generated

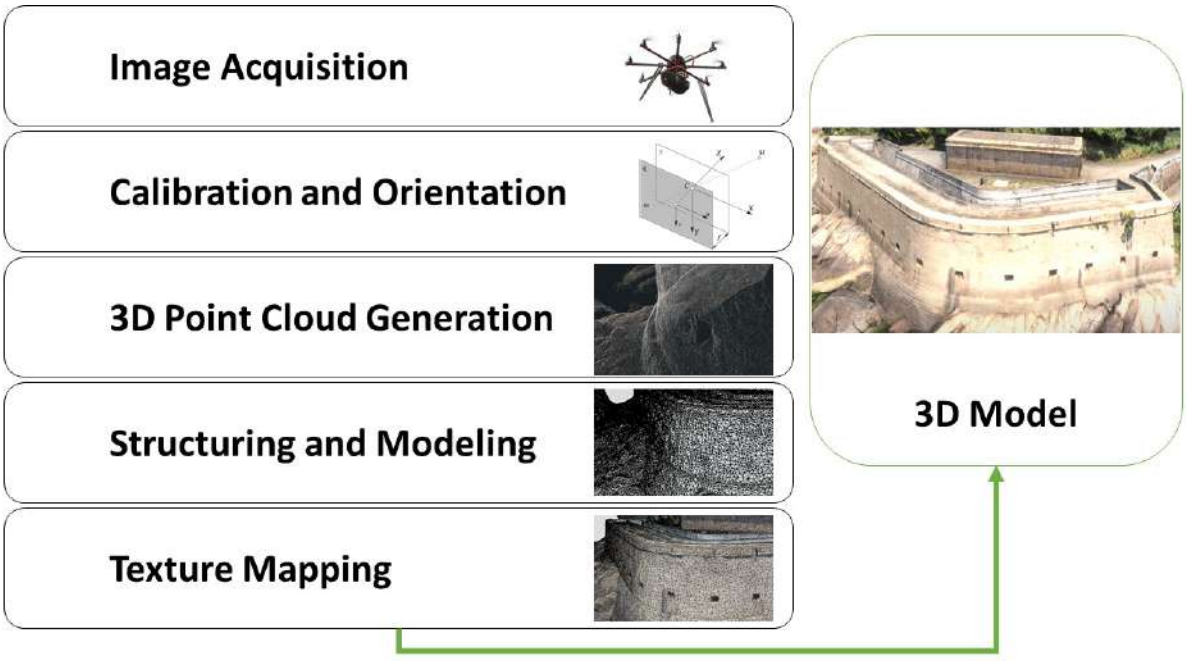

Figure 4.16: 3D Data Processing Overview - Photogrammetry

The time to completion varies greatly depending on the computational power at disposal. Sometimes, it is needed more than a complete pass for further optimizations and some errors that might occur in any step of the process, primarily due to issues with the source images. Therefore, it is of utmost importance to curate the images acquired in the data acquisition process to avoid any substantial rework.

4.3.2 Interiors

As stated earlier, in the data acquisition process for interiors, we took another approach using a proprietary solution – Matterport. Although the solution conveys some photogrammetric features for generating 3D environments, it is far from ideal, as the final product is not an exportable 3D model but an environment locked inside the Matterport ecosystem. There are only limited publishing capabilities that will be addressed in the visualization section.

In this work, two interior environments were captured: a) Museum and b) Casemates. As mentioned earlier, for the Museum, we have used a smartphone to acquire data, where

a 360-degree camera was preferred in the latter. In any case, the steps needed for data processing are the same in both scenarios, which is very straightforward and as simple as pressing the upload (Carregar) button.

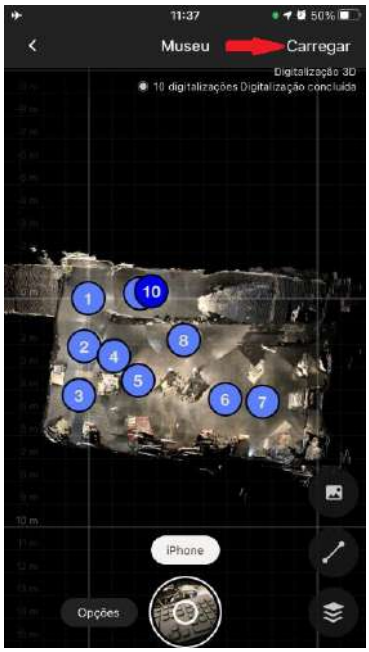

Figure 4.17: Matterport Data Processing

Depending on the number of scans and options selected in the data acquisition process, the time to process the model varies greatly, from minutes to hours, once the processing is done, the user receives an e-mail, indicating that the model is ready to view. Since the data processing engine and the computational infrastructure are outside the user's reach for intellectual property reasons, there is no way to know about its inner workings and no reasonable way to speed up the process by increasing the computing power. It is assumed that the Matterport solution leverages some photogrammetric techniques to generate a 3D model, although in a limited way, as the 3D model generated does not look like a 3D model but rather a 'boxed' geometry.

Moreover, the company has recently announced a collaboration with Facebook AI, which might indicate a step outside photogrammetry in favor of an AI-based approach, such as Neural Radiance Fields for Unconstrained Photo Collections [97].

While the data processing pipeline is not user-transparent, some postprocessing tools are available inside the platform after the model completes its processing:

In this work, the following postprocessing tools were used:

- Set Start Location - Sets the model visualization starting point;

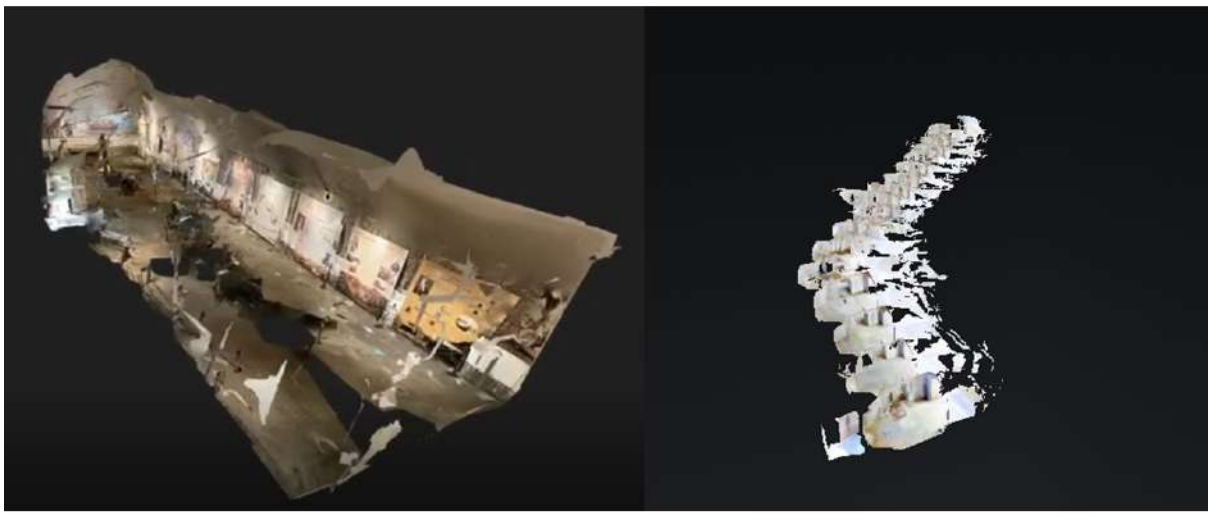

Figure 4.18: Matterport Data Processing Results - 3D View: Museum (Left) and Casemates (Right)

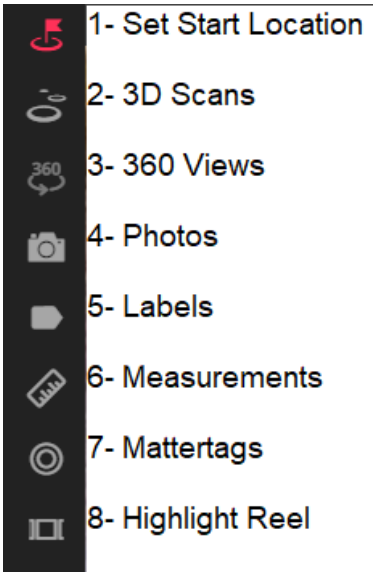

Figure 4.19: Matterport Toolbar Options

- 3D Scans - Hides or show specific scans;
- Labels - Attributes labels to the model in floor plan view;
- Mattertags - Smart tags that enable multimedia content in visualization mode.

The set start location feature is used to indicate the first navigation point that will

appear in the visualization once it is published (See Section 4.4.2), this feature was used for both cases, for the Casemate, the first navigation point was the first Casemate, and for the Museum, by the entrance.

The 3D Scans feature was used in the Museum to hide a defective scan, and some of the casemates had to be hidden, since some of its cannons were undergoing a restoration process, and the final result was less than ideal. Besides, a new interior capture operation for the Casemates is scheduled to occur soon after this dissertation.

The labels were used to attribute numbers to the casemates and not used for the Museum. The Mattertags, on the other hand, was used to present informative text and multimedia in context. Although this dissertation didn't focus on intangible heritage, some intangible assets were used within the Mattertags.

4.3.3 Objects (Historical Artifacts)

Most of the essential historical artifacts within São João Fortress were proposed to be captured in high resolution and digitally placed in the Digital Twin 3D model with great detail. However, as addressed earlier, as some objects were undergoing restoration and with the COVID-19 pandemic, it became an impossibility. Still, as a proof of concept, Reconstruction was done by mainly leveraging scarce high-resolution data from some of the cannons then baked in the final outdoor model. An attempt to digitally generate a 3D model of the foundation stone replica was also made, with some degree of success in capturing its relief and geometry. Nevertheless, the original foundation stone is not within the São João Fortress, but inside the Capuchin Basilica in Rio de Janeiro.

4.4 Visualizations

As a penultimate step towards our Cultural Heritage Digital Twin, we put it all together inside a visualization set that can be used to represent the data acquired and processed so far. As the visualizations presented in this section might address a virtual heritage adequately, it is still far from ideal towards a digital twin concept for the reasons that we will discourse throughout this section and beyond.

4.4.1 Historic Site and Buildings

After the Historic Site and Built Environment (outdoor) acquired data is processed, the result will be a monolithic 3D model. Depending on the software used to do the data processing, the output file format will vary greatly, in our case, SituatorVR can output

Figure 4.20: Foundation Stone - 3D Model, Source Image, 3D Mesh and Dense Point Cloud (Left to Right, Clockwise)

files in FBX, Collada (DAE) or STL formats. In this case, we opted for the FBX version for better compatibility.

SketchFab

Sketchfab is a marketplace where users can share, buy and sell 3D and X-Reality content. It provides a WebGL viewer platform to display 3D models on the web, and while it is very optimized for mobile platforms, it can be used with any desktop browser and virtual reality headsets. As a last-minute update, Epic Games, creators of the Unreal Engine that we will address further on, has acquired Sketchfab.

It offers a convenient way to display our 3D models and has some functionalities (albeit limited) for extensibility and customization. In this respect, it was elected as the first choice during this dissertation to host the 3D replica of the São João Fortress.

However, there are some caveats, the Free version of SketchFab is very limited to host a sizeable 3D replica, as the maximum file size allowed is around 100MB. The Pro version offers a bigger file size allowance of 200MB, while the Enterprise version offers a 500MB limit.

Since our full 3D model yielded around 537MB, we had to decimate the geometry, which reduces the polygon count with the tradeoff of overall quality. For this step, the Decimate Geometry and Dissolve tools in Blender 3D package were used.

After this step, an optimized model with minimal tradeoffs in quality was exported in the .blend format. The file compression 7Zip was used afterward in order to compact the

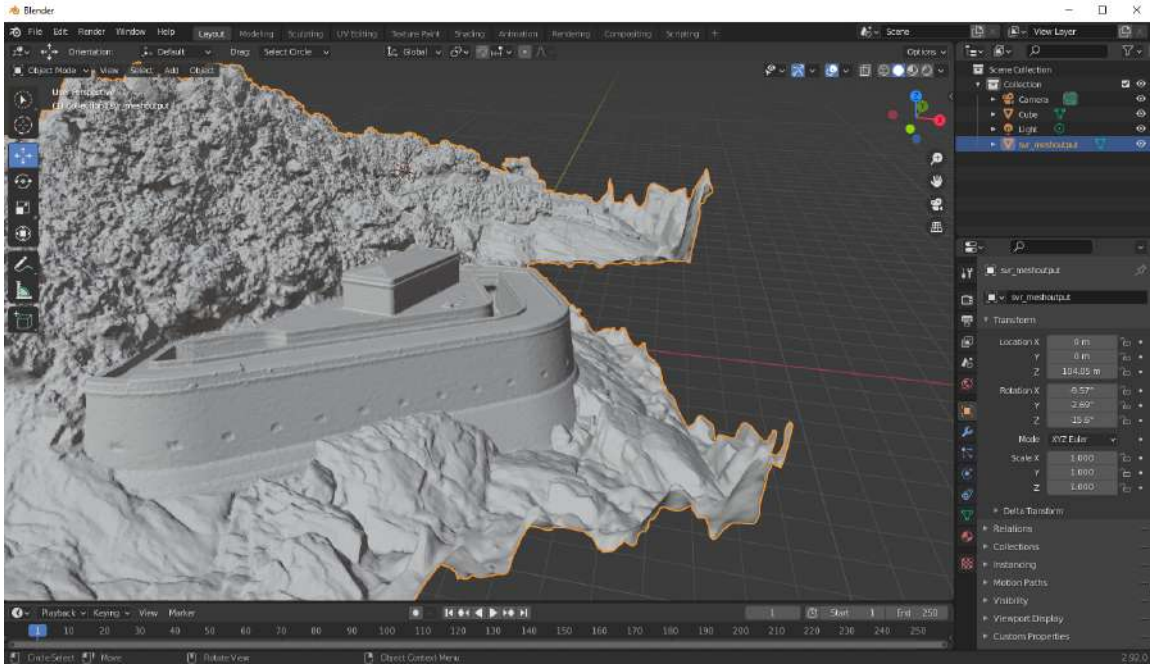

Figure 4.21: Blender - Decimating the 3D Mesh

3D file further and to be able to upload within SketchFab Free limits. The ready model was then uploaded to the SketchFab platform.

Figure 4.22: SketchFab Upload Dialog

Upon uploading, the SketchFab platform takes a while to process the 3D model. Once it is ready, the user receives an e-mail indicating that the visualization is available. Aside from the visualization, while logged in to the platform, there are two options available for the user per 3D model: a) Edit 3D properties and b) Edit 3D Settings. The first option has to do with the model descriptions, metadata, publishing, and download options, while the latter has to do with customizing some parameters for the model per

se. Depending on the software chosen for data acquisition and processing, the resulting 3D mesh will have a different orientation to world coordinates, and SketchFab offers a straighten model option inside Edit 3D Settings.

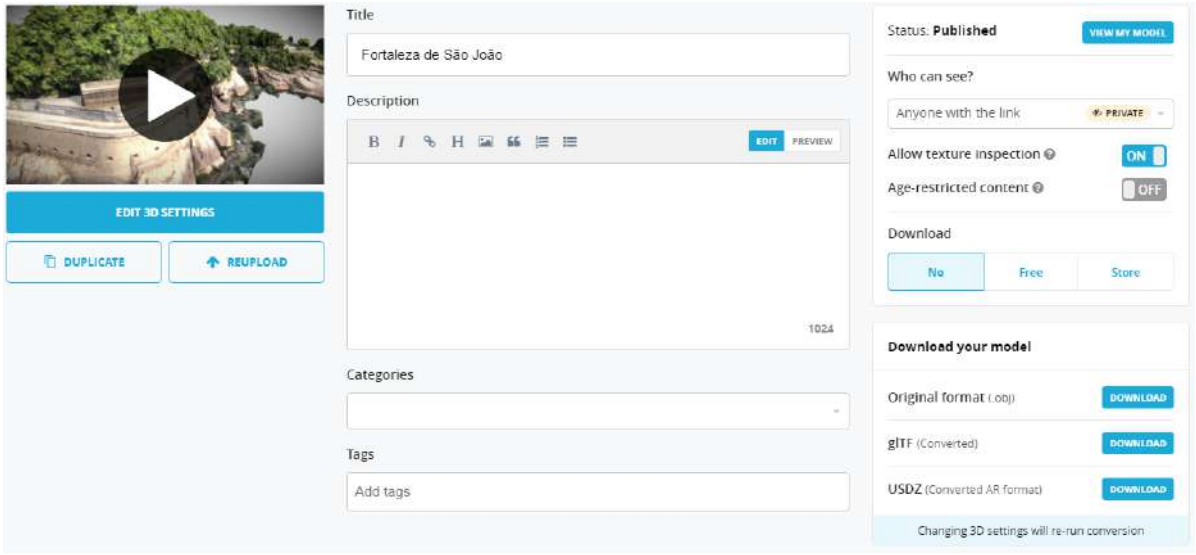

Figure 4.23: SketchFab Edit 3D Properties

Figure 4.24: SketchFab Edit 3D Settings

Since the imported 3D model did not have any significant issues, it was not needed, but some settings regarding lighting, materials, and postprocessing filters were tweaked to give the 3D model an appearance akin to its physical counterpart. Other settings will be discussed in the following section.

4.4.2 Interiors

The Matterport solution used in both the Museum and the Casemates provides a 3D Showcase System as its visualization engine. Like the one provided by SketchFab, this engine uses the 3D web graphics technology WebGL to run in most modern Web Browsers, both desktop, and mobile.

Since it is a proprietary solution, there are some limitations, and as addressed earlier, there is no easy way to export the resulting model or incorporate it within a 3D Replica. Besides that, the visualization can be accessed in various ways:

- Matterport's website;
- Matterport Showcase App for Mobile
- Embedded visualization on an external site, but hosted on Matterport;
- Published by VRBO and HomeAway (Suitable for Real Estate);
- Published on Google Street View.

Museum

For this work, both an embedded visualization of the Museum and a Google Street View export was done, the latter by request of Colonel Joel Corrêa, manager of the Historic Site of São João Fortress.

The process of exporting to Google Street View from the Matterport website is very straightforward and can be done quickly by accessing the add-ons section and then navigating to the Google Street View add-on. After that, a screen with a georeferenced map should appear, in which the user has to position, rotate and scale the model in its physical location.

After the export process is done, the visualization will be available directly in Google Maps Street View platform.

Casemates

For the Casemates, the option was for the regular Matterport visualization as it will be integrated into the São João Fortress Pre-Digital Twin Visualization presented in the next section.

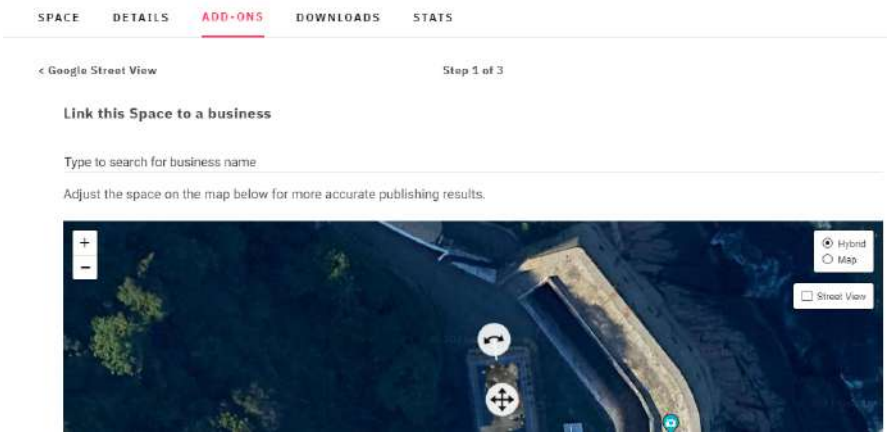

Figure 4.25: Museum of São João Fortress - Google Street View Export

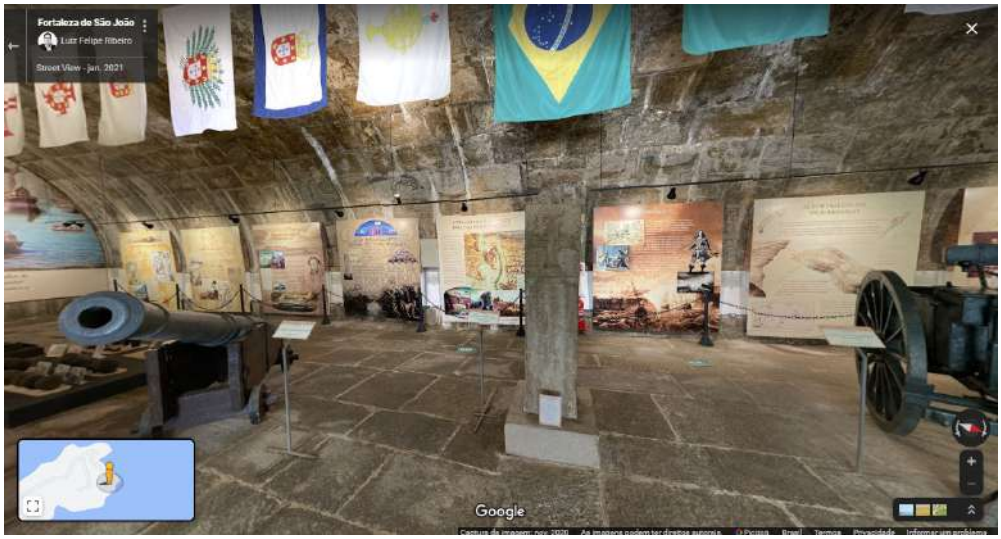

Figure 4.26: Museum of São João Fortress - Google Street View

4.4.3 Virtual Twin

In the last step of our visualization, we integrate all models generated so far in a single visualization available for the public. Since we relied on mixed techniques, primarily due to the significant constraints already addressed before, the idea was to converge all the platforms into a single one, in this case, the SketchFab platform. Since it is an intermediary representation with no Digital Twin functions at this stage, we call it a Virtual Twin.

The approach to converge the models generated into a single view consisted in opening the 3D settings panel for the São João Fortress SketchFab model and use the Annotations feature.

In the annotations tab, we double-click on the location on the 3D model we want it positioned, and after this step, a dialog box with Title and Description input fields.

Figure 4.27: Casemates of Forte São José in São João Fortress - Matterport

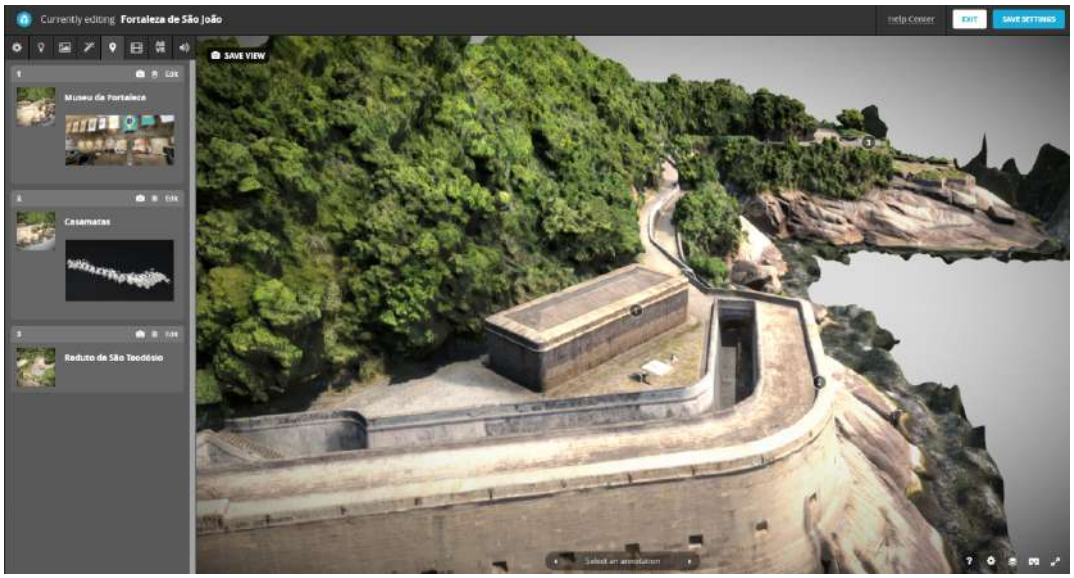

Figure 4.28: SketchFab Annotations

Interestingly, we can use Markdown language within the description field, and aside from Markdown formatting, it allows for images and hyperlinks. Therefore, we input hyperlinks for the visualization of the Museum and the Casemates in annotations 1 and 2, respectively, allowing for a user to click the 3D model and be redirected to the respective visualizations.

Aside from this use, annotations in SketchFab and Matterport are potent tools to easily integrate information and even digitized intangible heritage within a 3D view. The Virtual Twin of São João Fortress is available at:

http://ltds.ufrj.br/projects/hiperpatrimonio/

Although feasible to implement some connectivity functions a Digital Twin requires

through SketchFab APIs, the access to the Enterprise APIs, which enables better connectivity, is only available in the paid enterprise versions of the platform.

4.5 Towards a Digital Twin

Thus far, this work has focused mainly on data acquisition, data processing, and data visualization of Cultural Heritage. Except for the visual computing techniques also presented in HBIM-based digital heritage, we cannot consider this work so far as such an approach, as our framework allows for better interoperability, avoiding BIM platforms. Still, at this stage, the work can be considered a Virtual Heritage-based approach, as the Virtual Twin has only allowed for web-based tours.

Ergo, the next step towards a Digital Twin proper, consists of importing our model inside an engine that allows for programming the logical and connectivity layers that a Digital Twin requires for its primary functions.

4.5.1 Game Engine

As addressed earlier, a Game Engine is a kind of Graphics Engine that provides other components to enable interactivity and networking aside from the rendering engine. In the case of this study, the engine of choice was Epic Games Unreal Engine.

The reason for the choice is that Unreal Engine is one of the most powerful game engines with an unrivaled data pipeline through Unreal Datasmith, which provides even importing of BIM-based assets at no cost, making it a genuinely multiversal engine.

The first step is needed to create an account at `https://www.unrealengine.com/` and proceed to download the Game Engine. The current version at the time of this writing is 4.26.2. However, during this dissertation, versions 4.20.3 through 4.26 were used.

Once downloaded, we click on "launch", then a project window will be presented with some categories. For our purposes, we will select Architecture, Engineering and Construction.

Afterwards, we create a landscape that will fit our model and a simulated ocean, since the Fortress of São João resides within the Guanabara Bay. After these steps, we import our São João Fortress model, and since we do not have limitations for filesize in this platform, we import the original FBX generated with SituatorVR.

Once the basic scene is set up, we reposition the CameraActor and PlayerActor entities inside the desired starting point. From here, we can create a visualization by (1) using own Unreal Engine cinematic Matinee Editor or (2) or running a NVIDIA Omniverse

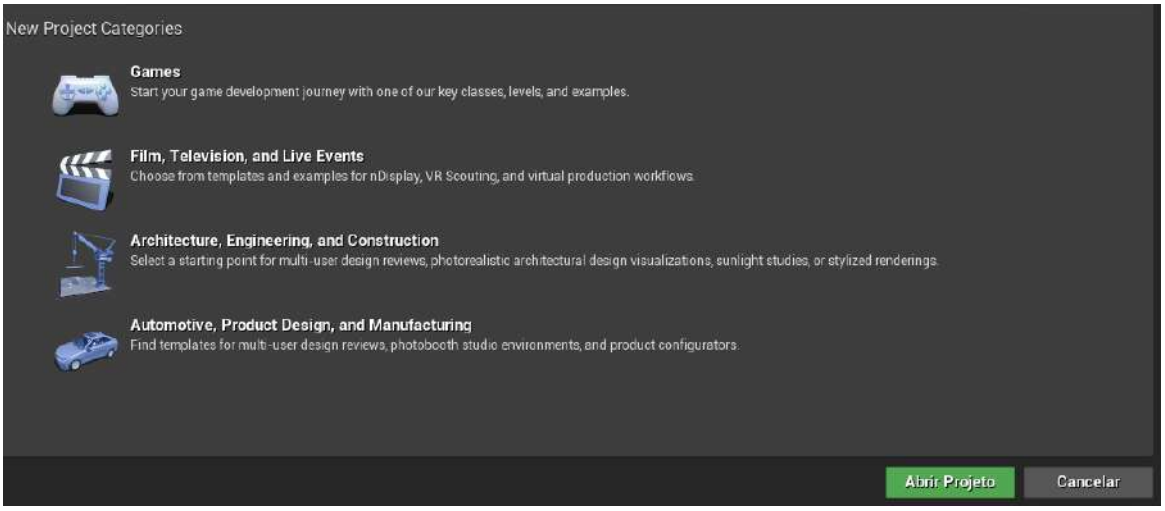

Figure 4.29: Unreal Engine New Project Dialog

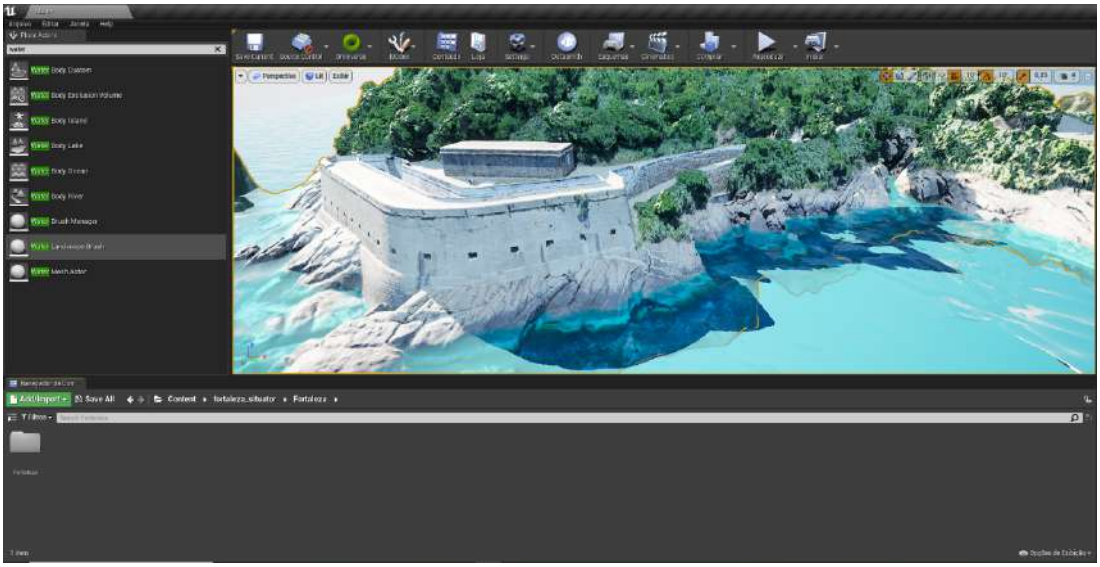

Figure 4.30: São João Fortress Model Imported into Unreal Engine

server or (3) exporting to TwinMotion.

4.5.2 Digital Twin Layer

As a first step towards a digital twin, we need to collect some real-world data from the physical counterpart of our model. The original planning consisted in capturing the following live data which is then integrated into weather, time, and ocean systems:

- Occupancy data from an Edge AI computer vision device with person counting capabilities;
- Meteograms from the São João Fortress and/or open data in the vicinity, including:

Temperature, Humidity, Mean Sea Level Pressure, Wind Direction, Wind Speed, Wave Height, Precipitation.

- Synchronized clock to enable day-night cycles.

Figure 4.31: São João Fortress Digital Twin - Day and Night Cycles

As occupancy data became an impossibility due to time and budget constraints for this study, Meteograms and synchronized time were still on track, although without the usage of IoT devices, but relying solely on open data.

In any case, aside from the Blueprint Visual Scripting System and C++ programming options mentioned earlier, to connect live data to Epic's Unreal Engine, we need to use a WebSocket to feed data into it and handle JSON data as well.

Instead of coding such a networking system from scratch, there are two plugins within Unreal Engine's Marketplace for these purposes. For the WebSocket, the UEWebsocket plugin from Wu Xufei, available at - https://www.unrealengine.com/marketplace/en-US/product/easywebsocket and for handling JSON files, the VaRest plugin available at - https://www.unrealengine.com/marketplace/en-US/product/varest-plugin.

A dummy actor, a message interface, and a message dispatcher (for parsing output) were developed to handle three distinct data sources: Meteogram (minus waves) from METAR (METeorological Aerodrome Report) reports, Ocean data from NOAA (National Oceanic and Atmospheric Administration) and Time from WorldTimeAPI web

service. The METAR data was chosen as the Meteogram data source because the São João Fortress is near the vicinity of Santos Dumont Airport.

Open Data is no substitute for real-time IoT data, though, since the Meteogram from METAR reports is updated each hour (except for severe weather reports), and Ocean data is generally available every 3 hours. The METAR data was chosen as the Meteogram data source because the São João Fortress is near the vicinity of Santos Dumont Airport.

Figure 4.32: São João Fortress Digital Twin - Precipitation and Ocean Data

Chapter 5

Conclusion and Further Research

This work proposed a low-cost conceptual framework enabling multipurpose digital twins leveraging visual computing technologies and standardized data formats for the cultural heritage, alongside a case study of the São João Fortress in Rio de Janeiro.

As such, the multifactorial and multidisciplinary approach required for research, protection, conservation, restoration, and dissemination of the built heritage requires us to develop interoperable methods further, while maintaining complexity and precision and enrich these models semantically and by leveraging some HBIM information and models via connectors, such as the Datasmith from Epic Games Unreal Engine we have addressed in the last chapter. Furthermore, in July 2021, Epic Games has acquired companies whose products were used or at least tested during this dissertation, such as Reality Capture (Computer Vision and Photogrammetry) and SketchFab (Visualization), and this move indicates that Epic Games is probably committed to enable a vast metaverse ecosystem.

Hence, we consider this a work in progress, with some significant gaps and further research entries identified. As stated earlier in Chapter 3, tackling such challenges will be possible through a methodological roadmap towards a more significant contribution than this master dissertation allows. Therefore, the following sections of this chapter will address further research and new trends that might allow more significant contributions from the author of this study and among peers and other researchers interested in advancing the digitization of heritage towards a Digital Twin.

5.1 Immersive Visit

The original plan for the conclusion of the pilot, developed with the Hyper Heritage framework was to provide an immersive visit to the São João Fortress Digital Twin at the anniversary celebration event, scheduled for June, 2020 while evaluating its usage through a UTAUT (Unified theory of acceptance and use of technology) theory [98]. The visit

was supposed to be a flythrough using Virtual Reality HMDs (Head Mounted Displays).

Because of the COVID-19 pandemic, this study had already suffered a significant delay, and the event was postponed as well. In September 2020 the work was resumed as the São João Fortress was partially reopened, not for the general public, but as an exception, for the completion of this study.

On 29th June 2021, for the celebration of the 403th anniversary of the São João Fortress Historic Site, we were able to present an immersive visit of the São João Fortress Digital Twin, although unable to present it in a Virtual Reality HMD due to sanitary concerns, as such device would have to be sanitized thoroughly. Instead, we opted for a CAVE (Cave Automatic Virtual Environment) approach by using projection mapping inside the São João Fortress casemates.

Figure 5.1: Immersive Visit Recording at Fortress of São João

5.2 Further Research

In general, since this study is based on design science research, it is expected that other research cycles will follow from it. As of the defense date of this dissertation, the author has had an article accepted at the HyperHeritage International Symposium congress and another article is being written for submission to cultural heritage and computing journals.

Furthermore, there is also a need to search patent bases to study the state of the art of digital twins, to pave the way for innovative ways to validate, advance, and productize the present framework.

Furthermore, in relation to the components that were not possible to be studied during this project, they in the roadmap for upcoming research, especially ways to deal with the intangible heritage and advanced computational techniques for the simulation in 3D meshes of the digital twin.

5.2.1 Intangible Data Acquisition

As the present study only investigated means of tangible data acquisition and provided some generic insights on gathering real-world data by leveraging IoT and open data, as stated in section 1.5, intangible heritage data acquisition was not covered in this dissertation.

Because intangible heritage is an essential part of cultural heritage, innovative ways of digitizing it are within the roadmap of further research. By the time of this writing, the author and his peers investigate the use of pose estimation techniques to capture intangible heritage capture in performing arts, corporal expressions, and rituals. Pose estimation is also a visual computing technology that allows for markerless motion capture via computation of natural human movements via keypoint estimation.

Realtime pose estimation with OpenPose [99] is a computationally intensive technique and requires hardware with dedicated high-end GPUs. Currently, other pose estimation software states better efficiency in computational resources, such as the proprietary Wrnch.ai [100] and TensorPose [101].

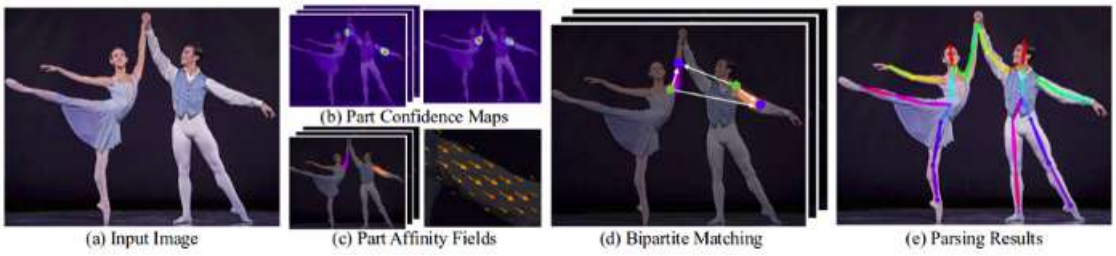

Figure 5.2: Dance Pose Estimation. (Cao *et al.*,2019)

5.2.2 Virtualized Micropolygon Geometry

A trend with substantial implications for Digital Twins is the emergence of technologies such as Virtualized Micropolygon Geometry [102]. This technique allows for vast and realistic real-time 3D worlds and a myriad of applications in Digital Twins of Cultural Heritage as it enables models for realistic simulations of erosion, destruction, and force majeure events.

At the time of this writing, Epic Games launched an early access version of Unreal Engine 5 with Nanite technology, allowing for a virtualized geometry by leveraging a new rendering technology for pixel scale detail and high object counts [103].

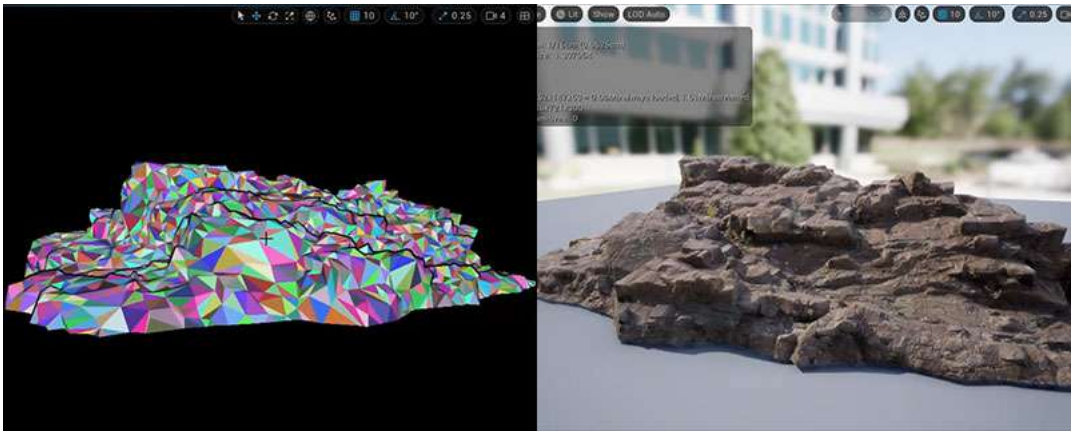

Figure 5.3: Nanite (Ryan Laley - https://www.youtube.com/watch?v=YucYfUbazKY)

5.3 New Trends

5.3.1 Data Standardization

This dissertation pointed out the cons of closed/proprietary file formats and their impact on collaborative workflows, especially in the HBIM-based documentation. Although many file formats were used in the present study and some engines facilitate the use of even BIM-based file importing, such as Unreal Datasmith and Unity Reflect, the best direction towards better data exchange pipelines is by leveraging some emergent industry standards that are becoming regular practice across many fields that deal with 3D computer graphics data.

Currently, there is an emergence in the usage of Pixar's Universal Scene Description format [104], which is a framework for 3D graphics interchange focused on collaborative and non-destructive editing. This file format is currently being supported by major players in the visual computing industry, most notably Apple's SceneKit [105] and NVIDIA Omniverse [106].

5.3.2 Connectivity

According to the Hyper Heritage framework presented in this study, an essential part of fulfilling the Digital Twin for Cultural heritage, enabling real-time monitoring, resides in the Digital Twin layer, and it is the IoT Subsystem, which requires connectivity. Without proper connectivity, the IoT Subsystem is useless.

While some of the Historic Sites are located near big cities, such as the object of this dissertation - the Fortress of São João, there are many Cultural Heritage Sites in remote locations that suffer from proper connectivity.

5G, the new mobile communications standard, is the successor of the previous 4G

technology, and benefit from its massive gain in bandwidth and dramatic increases in speed over the previous generation [107]. Despite new mobile communications technologies being adopted first in big urban cities and scholars such as Cavalcante [108] concerns over its adoption in rural areas, such areas can benefit indirectly, as it is a common practice that decommissioned last generation systems infrastructure are reinstalled in such areas.

Finally, another noteworthy connectivity trend ongoing is Starlink [109], a satellite constellation in Low Earth Orbit operated by SpaceX that will eventually provide internet access to most of the planet earth, including remote locations, although it requires licensing from governmental agencies.

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Appendix A

Computação Visual

A.1 Fotogrametria

A.1.1 Extração de Características

A primeira etapa em um pipeline de fotogrametria consiste em extrair grupos distintos de pixels invariáveis às visualizações da câmera durante o processo de aquisição de imagens. Portanto, um recurso deve ter descrições semelhantes em todas as imagens que aparece.

Um dos pilares do método de detecção de recursos de visão por computador é o algoritmo SIFT (Scale-Invariant Feature Transform), que tem as propriedades de extrair com precisão as características de uma primeira imagem em comparação com uma segunda, independentemente de sua translação, rotação e escala.

A.1.2 Correspondência de Imagem

O objetivo aqui é encontrar imagens que enfrentem as mesmas áreas da cena. Para fazer isso, usamos técnicas de recuperação de imagem para encontrar imagens que compartilham algum conteúdo sem o custo de resolver todas as correspondências de recursos em detalhes. O objetivo é simplificar a imagem em um descritor de imagem compacto que calcula com eficiência a distância entre todos os descritores de imagem.

Um dos métodos mais comuns para gerar esse descritor de imagem é a árvore de vocabulário. Ao passar todos os descritores de recursos extraídos para ele, ele faz uma classificação comparando seus descritores aos de cada nó desta árvore. Cada descritor de recurso termina em uma folha, que pode ser armazenada por um índice simples: o índice dessa folha na árvore. Essa coleção de índices de folha usados representa o descritor de imagem.

A.1.3 Correspondência de Características

Esta etapa consiste em combinar todos os recursos entre os pares de imagens candidatas. Para isso, realizamos correspondências fotométricas entre o conjunto de descritores das duas imagens de entrada. Para cada característica na imagem A, obtemos uma lista de características candidatas em B. Como o espaço do descritor não é um espaço linear e bem definido, não podemos confiar em valores de distância absolutos para saber se a correspondência é válida ou não (podemos têm apenas uma distância limite superior absoluta). Para remover candidatos ruins, presumimos que haja apenas uma boa correspondência na outra imagem. Portanto, procuramos os dois descritores mais próximos para cada descritor de recurso na primeira imagem e usamos um limite relativo entre eles. Essa suposição eliminará recursos em estruturas repetitivas, mas provou ser um critério robusto. Isso fornece uma lista de candidatos de correspondência de recursos com base apenas em critérios fotométricos. Encontrar os dois descritores mais próximos na segunda imagem para cada recurso é computacionalmente intensivo com uma abordagem de força bruta, mas existem muitos algoritmos otimizados. O mais comum é o vizinho mais próximo (kNN), mas existem alternativas como Hashing em cascata.

Em seguida, usamos as posições dos recursos nas imagens para fazer a filtragem geométrica usando um framework de detecção de outliers chamado RANSAC (RANdom SAmple Consensus). Selecionamos aleatoriamente um pequeno conjunto de correspondências de recursos e calculamos a matriz fundamental (ou essencial), em seguida, verificamos o número de recursos que validam esse modelo e iteramos por meio da estrutura RANSAC.

A.1.4 Structure from Motion

O objetivo desta etapa é entender a relação geométrica por trás de todas as observações fornecidas pelas imagens de entrada, e inferir a estrutura rígida da cena (pontos 3D) com a pose (posição e orientação) e calibração interna de todas as câmeras. O pipeline incremental é um processo de reconstrução crescente. Ele primeiro calcula uma reconstrução inicial de duas visualizações que é estendida iterativamente pela adição de novas visualizações.

Primeiro, ele funde todas as correspondências de recursos entre pares de imagens em faixas. Cada trilha deve representar um ponto no espaço, visível de várias câmeras. No entanto, nesta etapa do pipeline, ele ainda contém muitos valores discrepantes. Durante essa fusão de partidas, removemos rastros incoerentes.

Então, o algoritmo incremental deve escolher o melhor par de imagens inicial. Esta escolha é crítica para a qualidade da reconstrução final. Na verdade, deve fornecer cor-

respondências robustas e conter informações geométricas confiáveis. Portanto, este par de imagens deve maximizar o número de correspondências e a repartição dos recursos correspondentes em cada imagem. Mas, ao mesmo tempo, o ângulo entre as câmeras também deve ser grande o suficiente para fornecer informações geométricas confiáveis.

Em seguida, calculamos a matriz fundamental entre essas 2 imagens e consideramos que a primeira é a origem do sistema de coordenadas. Agora que sabemos a pose das 2 primeiras câmeras, podemos triangular os recursos 2D correspondentes em pontos 3D.

Depois disso, selecionamos todas as imagens que possuem associações suficientes com os recursos que já foram reconstruídos em 3D. Esse algoritmo é chamado de próxima seleção de melhores visualizações. Com base nessas associações 2D-3D, ele realiza a ressecção de cada uma dessas novas câmeras. A ressecção é um algoritmo de perspectiva n ponto (PnP) em uma estrutura RANSAC para encontrar a pose da câmera que valida a maioria das associações de recursos. Em cada câmera, uma minimização não linear é executada para refinar a pose.

A partir dessas novas poses de câmeras, algumas trilhas tornam-se visíveis por 2 ou mais câmeras ressecadas e são trianguladas. Em seguida, lançamos um Bundle Adjustment para refinar tudo: parâmetros extrínsecos e intrínsecos de todas as câmeras, bem como a posição de todos os pontos 3D. Filtramos os resultados do Bundle Adjustment removendo todas as observações que apresentam alto erro de reprojeção ou ângulos insuficientes entre as observações.

À medida que triangulamos novos pontos, obtemos mais candidatos de imagem para a próxima seleção de melhores visualizações. Repetimos assim, adicionando câmeras e triangulando novos recursos 2D em pontos 3D e removendo pontos 3D que se tornaram inválidos, até que não possamos localizar novas visualizações.

Existem muitas outras abordagens, como abordagens globais, hierárquicas, ou de vários estágios.

A.1.5 Estimação de Mapas de Profundidade

Para todas as câmeras que foram resolvidas por SfM, queremos recuperar o valor de profundidade de cada pixel. Existem muitas abordagens, como Block Matching, Semi-Global Matching (SGM) ou ADCensus.

Para cada imagem, selecionamos as N melhores / mais próximas câmeras. Selecionamos planos fronto-paralelos com base na interseção do eixo óptico com os pixels das câmeras vizinhas selecionadas. Isso cria um volume W, H, Z com muitos candidatos de profundidade por pixel. Estimamos a similaridade para todos eles. A similaridade é calculada pela correlação cruzada normalizada média zero (ZNCC) de um pequeno patch na imagem principal reprojetada na outra câmera. Isso cria um volume de semelhanças.

Para cada imagem vizinha, acumulamos semelhanças neste volume. Este volume é muito barulhento. Aplicamos uma etapa de filtragem ao longo dos eixos X e Y que acumula custos locais que reduzem drasticamente a pontuação de valores altos isolados. Finalmente, selecionamos os mínimos locais e substituímos o índice do plano selecionado pelo valor de profundidade armazenado em um mapa de profundidade. Este mapa de profundidade possui artefatos de bandas, pois é baseado na seleção original de valores de profundidade. Portanto, uma etapa de refinamento é aplicada para obter valores de profundidade com precisão de subpixel.

Todos esses mapas de profundidade podem ser calculados independentemente em paralelo. Em seguida, aplicamos uma etapa de filtragem para garantir a consistência entre várias câmeras. Um meio-termo é escolhido com base no valor de similaridade e no número de câmeras coerentes para manter as superfícies com suporte fraco sem adicionar artefatos.

A.1.6 Reconstrução de Malha

O objetivo desta etapa é criar uma representação geométrica densa da superfície da cena.

Primeiro, fundimos todos os mapas de profundidade em uma octree global onde os valores de profundidade compatíveis são mesclados nas células da octree.

Em seguida, realizamos uma tetraedralização 3D Delaunay. Em seguida, um procedimento de votação complexo é feito para calcular pesos nas células e nas facetas que conectam as células, conforme explicado em (Jancosek, 2011) e (Jancosek, 2014).

Um Graph Cut Max-Flow (Boykov, 2004) é aplicado para cortar o volume de forma otimizada. Este corte representa a superfície da malha extraída. Filtramos células ruins na superfície. Finalmente aplicamos uma filtragem Laplaciana na malha para remover artefatos locais.

Neste ponto, a malha também pode ser simplificada para reduzir vértices desnecessários.

A.1.7 Texturização

O objetivo desta etapa é texturizar a malha gerada. Se a malha não tem UV associado, ela calcula mapas UV automáticos. A abordagem de mapeamento UV padrão é fornecida por Levy (2002), onde para cada triângulo, usamos as informações de visibilidade associadas a cada vértice para recuperar os candidatos a textura. Filtramos as câmeras sem um bom ângulo com a superfície para favorecer as câmeras fronto-paralelas e, finalmente, calcular a média dos valores de pixel. Em vez de uma média ingênua, usamos uma gen-

eralização da combinação multibanda descrita em Burt (1983), de modo que calculamos a média de mais visualizações nas frequências baixas do que nas frequências altas.

Appendix B

Official Documents

B.1 IPHAN

Serviço Público Federal
Ministério do Turismo
Instituto do Patrimônio Histórico e Artístico Nacional

Departamento de Patrimônio Material e Fiscalização
Coordenação de Reconhecimento

PARECER TÉCNICO nº 2/2021/COREC/CGID/DEPAM

ASSUNTO: Proposta de tombamento do "Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas", em Rio de Janeiro/RJ (Processo de Tombamento nº 0827-T-70)

REFERÊNCIA: Processo de Tombamento Nº 827-T-70/SEI nº 01458.001154/2012-55

Brasília, 13 de maio de 2021.

1. INTRODUÇÃO

Este Parecer analisa a proposta de Tombamento Federal do "Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas", situado em Rio de Janeiro/RJ, a partir do Processo de Tombamento 827-T-70 (SEI nº 01458.001154/2012-55) encaminhado pela Superintendência Estadual do IPHAN em RJ.

Cabe ressaltar que, desde 2017, esta servidora vinha sendo eventualmente designada para participação de alguns dos encontros técnicos realizados pela Coordenação de Cooperação e Fomento para discussão da elaboração do Dossiê para submissão da candidatura das Fortificações Brasileiras à Patrimônio Mundial. Sem ser, no entanto, designada para a participação efetiva dos Comitês Técnicos montados para as atividades decorrentes desse processo. Por ocasião do levantamento de informações referentes aos processos de tombamento das fortificações selecionadas para a candidatura, verificou-se que o tombamento em âmbito federal existente limita-se ao Portão da Fortaleza de São João (**Nota 1**) – Urca. E, que a Superintendência estava responsável pela instrução deste processo de tombamento para abranger o conjunto dos fortes e os principais equipamentos de defesa instalados no Morro Cara de Cão (**Nota 2**), relacionados com a consolidação da Fortificação que ali se formou desde a ocupação da área pelos portugueses e fundação da cidade de São Sebastião do Rio de Janeiro.

Nota (1): bem tombado em âmbito federal - inscrito no Livro do Tombo de Belas Artes, volume 1, folha 018, inscrição nº 102; e no Livro do Tombo Histórico, volume 1, folha 008, inscrição nº 037, em 24/05/1938.

Nota (2): bem tombado em âmbito federal - inscrito em função do seu valor paisagístico no Livro do Tombo Arqueológico Etnográfico Paisagístico, Volume 01, Folha 013-, Inscrição nº 058, em 08.08.1973; incluso na inscrição dos Morros do Distrito Federal no Livro do Tombo de Belas Artes, Volume 01, Folha 027-, Inscrição nº 151, em 30.06.1938 e no Livro do Tombo Histórico, Volume 01, Folha 013-, Inscrição nº 070, em 30.06.1938.

Em novembro de 2019, o processo foi encaminhado ao DEPAM, para conhecimento e deliberação. Em maio de 2020, a Coordenadora Geral de Identificação e Reconhecimento solicitou análise do processo em questão para discussão interna à Coordenação e posterior discussão junto à Superintendência do IPHAN do Rio de Janeiro para definir encaminhamentos necessários.

A orientação da Coordenadora Geral de Identificação e Reconhecimento era que os trabalhos decorrentes dessa análise fossem discutidos inicialmente com a Superintendência do IPHAN no Rio de Janeiro e que os encaminhamentos pudessem, juntamente com o desenvolvimento do Dossiê para candidatura das Fortificações, realizado em paralelo por Comitê Técnico designado para esse fim, consolidar uma proposta de tombamento federal que garantisse que todos os elementos relevantes, selecionados por ambas equipes, fossem protegidos, compartilhando valores e atributos, permitindo que os princípios de gestão do bem atendessem a preservação pertinente aos dois processos de reconhecimento.

No início do segundo semestre de 2020 foram realizadas três reuniões com a Superintendência do Rio de Janeiro (dias 07 e 28 de agosto; e 04 de setembro). A primeira com a presença da Coordenadora Geral de Identificação, Arquiteta Carolina Di Lello e com a Coordenadora Técnica da Superintendência do Rio de Janeiro, Arquiteta Livia Porcino dos Passos, e equipes técnicas dessas áreas (Engenheira Claudia Bastos do Nascimento, Arquiteta Monica Mongelli, Historiadora Amanda Cardoso – CGID); e Arquiteta Regina Prado - Superintendência; a outras duas com a participação das equipes técnicas contando com a presença do Arquiteto Mauro Pazzini de Sousa, fiscal do IPHAN que tem atuado em função do Portão da Fortaleza, e do Historiador Adler Homero Fonseca de Castro, do Centro Lúcio Costa – doutor em história, pesquisador de história do Brasil imperial com enfase em patrimônio militar.

Foi consenso durante a reunião, a importância da aproximação das duas ações de reconhecimento, em nível federal e mundial, bem como de vistoria complementar, para possibilitar esclarecimentos e ajustes referentes aos objetos, os atributos a serem preservados em função dos valores indicados. A vistoria deveria contar, preferencialmente, com a participação de equipe formada por: (a) servidores da Superintendência - Arquiteta Regina Prado, Arquiteto Mauro Pazzini de Sousa, bem como servidor com atuação em processos de reconhecimento de bens móveis, em função da atualização das informações referentes ao acervo de artilharia e seleção das peças para proteção, tendo sido citado o nome da Sra. Monica Cadorin; (b) Historiador Adler Homero Fonseca de Castro do Centro Lúcio Costa, em função da sua experiência com patrimônio militar e de sua participação no Comitê para Candidatura das Fortificações; e, se possível, da servidora da CGID Engenheira Claudia Bastos do Nascimento, caso seja ela designada para acompanhar a finalização da instrução desse processo de tombamento. A equipe entendeu que após a melhor compreensão do bem, de seus valores e atributos, deveria ocorrer a integração com as informações produzidas pela Consultora responsável pelo levantamento das informações para a Fortificação no âmbito do Comitê Técnico. Em função do contexto sanitário devido à Pandemia de COVID 19, e em respeito as medidas de prevenção, ficou acertado que a vistoria deveria ser realizada em momento oportuno.

Informou o Historiador Adler Homero Fonseca de Castro, na reunião, que a área de tombamento está contida por aquela indicada no DECRETO nº 77.180 de 17 de fevereiro de 1976 folhas 342 e 343 do Processo SEI nº 01458.001154/2012-55, mas não consta do processo digitalizado a resposta do Exército Brasileiro ao Ofício/GAB/IPHAN-RJ nº 1.145/14 Proc nº 01500.003325/2014-80 de 06,10,2014 que solicita esclarecimento sobre a Informação Técnica nº 192/2014 COTEC/IPHAN-RJ que transcreve o conteúdo do Decreto.

A posteriori, foram trocadas mensagens com sugestões de verificações e esclarecimentos junto a equipe do Comando da Fortificação, que foram mediadas pelo Historiador Adler Homero Fonseca de Castro; que por sua vez reiterou a necessidade de formalizar a sua participação nas atividades futuras referentes à instrução do processo de tombamento junto ao Centro Lúcio Costa.

Em virtude da instabilidade de segurança para ações presenciais, com a finalidade de vistoria para discussão *in loco dos* pontos elencados durante as reuniões, incluindo posteriormente, a presença de Consultor contratado para o levantamento das informações sobre o Forte e representante do Comitê Técnico da Candidatura à Patrimônio Mundial - para integrar as informações de campo com as do Dossiê de Candidatura (**Nota 3**), as atividades foram interrompidas, aguardando momento propício para a sua continuação. E esta servidora dedicou-se a atividades demandadas em função da mudança de Diretor do DEPAM, com foco subsidiar o Plano de Gestão de Bens Culturais Materiais.

Nota (3): Segundo informações trocadas entre a Coordenação Geral de Identificação e Reconhecimento e a Coordenação Geral de Conservação, responsável pelo Plano de Conservação que inclui atividades como a Declaração de Significância, os produtos dos consultores contratados para o levantamento e sistematização de informações para Dossiê de Candidatura das fortificações, apresentados virtualmente em reunião realizadas em abril de 2020, precisavam ser revisados e detalhados.

Em abril de 2021, foi solicitado pela Coordenadora Geral de Identificação e Reconhecimento a elaboração de Parecer Técnico para apresentação dos resultados da análise do Processo de Tombamento 827-T-70. Este documento limita-se, portanto, a análise das informações do processo, frente ao que foi esclarecido a partir dos contatos com a Superintendência do Rio de Janeiro e Historiador Adler Homero Fonseca de Castro.

O item 2 apresenta o histórico do processo.

2. PROCESSO

2.1. Dos Fatos

Sobre a instrução do processo de tombamento da Fortaleza de São João, cita-se a seguir alguns documentos e fatos considerados relevantes para a análise realizada.

Em 1970: o Comandante da Fortaleza de São João e 2 Grupo de Artilharia da Cesta – Alkindar Machado Bona solicita o Tombamento na área da Fortaleza de São João, particularmente o Forte São José e Reduto São Teodósio, na entrada da barra, e as muralhas do antigo Forte da Entrada. (Ofício 111-8/4 Ministério do Exército de 09 de julho de 1970)

Em 1971: na 55ª Reunião do Conselho Consultivo do Patrimônio Cultural (IPHAN), 22 de junho, registra-se a decisão em ata: ""De acordo com as conclusões do Relator e por proposta do Conselheiro José Soares de Melo, o Conselho resolveu, por unanimidade, converter o processo em diligência para recolher dados mais completos, inclusive mapas e levantamentos a fim de ser novamente apreciado pelo Conselho."

Em 1973: o Presidente do IPHAN, Renato Soeiro encaminha ao exército a Certidão de Tombamento do Portão da Fortaleza de São João, e informações sobre a continuidade do estudo técnico para os Fortes de São José e São Teodósio.

Em 1993: o processo de instrução fica sob responsabilidade da Superintendência do IPHAN no Rio de Janeiro.

Em 1988: o Diretor interino da 6ª Diretoria Regional SPHAN, por meio do Ofício Gab nº 106 88 MinC 6 DR SPHAN, declara interesse na valorização do sítio histórico que compõe o conjunto histórico, paisagístico e arquitetônico que integram a área da Fortaleza de São João, em virtude de observar valores no acervo existente na área para além do portão tombado, e ressalva ao final "a praia histórica".

Em 1998: o Historiador Adler Homero Fonseca de Castro encaminha, por meio doMemorando DEPROT RH nº 677 98data 20 de outubro de 1998, informações sobre material de artilharia da Fortaleza de São João, identificado como "Inventário sumário do material de artilharia da Fortaleza de São João" e que identifica as evidências e os equipamentos para cada Casamata da Bateria São José com suas características.

Em 2014: a Arq Claudia Maria Girão Barroso manifesta-se por meio do PARECER Nº 236 2014 COTEC RJ, 28 de novembro de 2014, sobre o Tombamento da Praia de Fora, na área da Fortaleza de São João, Urca, Rio de Janeiro, RJ, com recomendação de tombamento com inscrição no Livro doTombo Histórico e Livro do Tombo Paisagístico; e por meio do PARECER Nº 237 2014 COTEC RJ, 28 de novembro de 2014, sobre o Tombamento dos Remanescentes do Forte da Entrada, Forte de São José e Reduto de São Teodósio na Fortaleza de São João, inclusive o Canal Marítimo junto à Fortaleza (Rio), com recomendação de tombamento com inscrição no Livro doTombo Histórico e Livro do Tombo Paisagístico, ambos condicionados a reversão de danos ao morro Cara de Cão e à várzea entre este morro, o morro da Urca e o Pão de Açúcar." Referia-se a construção de edifício da Praia da Urca, questão de impasse entre o IPHAN e o Exército brasileiro desde a década de 70.

Em 2017: o Historiador Adler Homero Fonseca de Castro emite Laudo nº 31 2017, de 14 de julho, onde descreve o bem, verificar seu estado de conservação e situação geral do Conjunto arquitetônico e paisagístico da Fortaleza de São João, para complementar e atualizar as informações.

Em 2018: a Arquiteta Regina Prado Lima de Souza se manifesta por meio do Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, onde recomenda a inscrição do "Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas" nos Livros do Tombo pelo seu valor histórico, artístico e paisagístico. E indica como diretriz de gestão para área tombada: "Área referente ao tombamento: deve ser ocupada somente com as edificações existentes e equipamentos que se façam essenciais, desde que devidamente justificados e submetidos à análise deste IPHAN"

2.2. Fortaleza São João, Praia de Dentro e Praia de Fora

Conforme mencionado anteriormente, em proposta encaminhada ao DEPAM, pelo Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018 de autoria da Arquiteta Regina Prado Lima de Souza, nome proposto para o bem é "Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas".

A Fortaleza de São João se localiza na entrada da Baía de Guanabara, formando um sistema defensivo da Baía com à Fortaleza de Santa Cruz e o Forte da Lage, instalado em rochedo no canal.

Inúmeros são os aspectos históricos que consolidam a importância da proteção da Fortaleza São João por meio do tombamento federal. Igualmente a Praia de Dentro e a Praia de Fora que estão intimamente relacionadas a própria história da Fortaleza de São João. Conforme documento que consta do processo, elaborado pelo Exército Brasileiro, pode ser considerada marco da primeira batalha para a Defesa da integridade do território, contando participação e apoio de outras Capitanias, em 1559. Outros tantos, fatos lhe oferecem destaque como elemento de defesa da costa brasileira, em especial, da Baía de Guanabara e da antiga capital da cidade do Rio de Janeiro. Cabe, também, referência a Praia de Fora como berço da cidade do Rio de Janeiro, que sediou a Capital Federal.

Outros dados relacionados a Fortaleza de São João e suas ações de defesa, que se encontram citados no processo:

1841: abrigou os convalescentes da "Força Expedicionária do Rio Grande do Sul".

1862 (Questão Christie): projeta-se as casamatas para São João, motivado pelo investimento e readequação das defesas do litoral. D. Pedro II tem atuação direta nessas ações. As obras do Forte São José tiveram início em 1863 e acarretaram na destruição da antiga estrutura.

1865 (Guerra do Paraguai): permanece com sua função de defesa; e receberam prisioneiros de guerra.

1893 (Revolta da Armada): na Fortaleza de São João, especificamente na Bateria Pau da Bandeira, o canhão Vovô acionado por uma guarnição de alunos da Escola Militar da Praia Vermelha. Defenderam o Estado Republicano recém-instituído (Governo do Marechal Floriano Peixoto) do ataque da Marinha que direcionaram seus canhões para a cidade do Rio de Janeiro. Esse episódio relaciona-se ao desmonte do canhão 150libras na Fortaleza Villegaignon, a destruição da bateria da Ilha das Cobras, e o tiro no camarote do comandante do "Aquidaban".

final do século XIX: a Fortaleza de São João recebe armamento moderníssimo a época. Dois canhões de calibre 95mm (dos que pertenceram ao cruzador "Tamandaré"), um de 120mm e dois (geminados) (**Nota 4**) Krupp de 150mm c 40, todos constituindo uma bateria mista a "Marque Porto" e mais a "Bateria Mallet", inaugurada a 02 de dezembro de 1901, com 02 canhões e completada no ano seguinte com dois outros idênticos , também Krupp 150mm cq40, modelo 1893-5. A ocasião do documento, essas duas baterias continuavam em serviço com canhões de 150mm, constituindo o artilhamento costeiro com que conta a Unidade para desempenhar sua missão. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472) - p. 19/100) (**Nota 5**)

Nota (4): De acordo com o Historiador Adler Homero Fonseca de Castro, não eram geminados.

Nota (5): Conforme Historiador Adler Homero Fonseca de Castro, o forte foi desativado, junto com todos os seus canhões, na década de 1980. Essas peças de 150mm saíram de serviço na década de 1960.

1914-15 Primeira Guerra Mundial: A Fortaleza de São João participou da articulação de defesa do porto.

1930: a Fortaleza de São João serviu de apoio a Revolução de 30

Segunda Guerra Mundial: foi considerada elemento de defesa (em prontidão). Constroem-se na Barra três pavilhões de emergência para alojamento, novo xadrez, Posto de Comando (PC) e Posto de Operação (PO) para o Grupo e as Baterias, pavimenta-se a estrada de acesso, removem-se os canhões antigos. O Comando de tiro é melhorado com o enterramento das comunicações, adoção de novo sistema de iluminação para pontaria, instalação de lunetas Krupp (**Nota 6**), pintura e camulhagem das peças, construções em rocha viva de uma câmara de preparação do tiro para as duas Baterias. O velho Forte São José recebe toneladas de munição, sofrendo alterações e adaptações como instalação elétrica, piso e portas de madeira, envidraçamento das canhoneiras, etc. Nessa ocasião altera se sensivelmente a fisionomia da Fortaleza, sobretudo no lado da Barra, junto às suas Posições de Bateria. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472) - p. 19/100)

Nota (6): o Historiador Adler Homero Fonseca de Castro indaga se tratavam-se de lunetas Krupp ou DFV Vasconcelos, na vistoria relatada pelo Laudo nº 31 2017, de 14 de julho, onde descreve o bem, identificou estrutura para lunetas DFV Vasconcelos.

2.3. **Descrição e localização do bem proposto para tombamento pela Superintendência do Rio de Janeiro**

A Fortaleza de São João é constituída de Fortes e estruturas de defesa sobre o morro Cara de Cão (Figura 1). O Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza, propõe dar destaques aos seguintes elementos: Forte São José (Figura 2), Reduto São Teodósio (Figura 2), Bateria do Pau do Bandeira (Figura 2), remanescente das muralhas do Forte São Diogo (Figura 3), Ponte da Praia de Dentro, posto de comando da região leste (Figura 4), Bateria Marques Porto (Figura 5) e Bateria Mallet (Figura 6); além das faixas de

areia que constituem a Praia de Fora (Figura 7), Praia de Dentro (Figura 8), que estão externas as muralhas da Fortaleza São João.

O Quadro 1 reúne fatos históricos correspondentes aos elementos destacados do Conjunto Arquitetônico e Paisagístico da Fortaleza de São João pela proposta da Superintendência do IPHAN no Rio de Janeiro, e descrições obitidas junto a documentos que constam do processo em tela.

Fatos históricos correspondentes	Descrição
Forte São José	
1650: há registro no Livro que dá Razão ao Estado do Brasil em 1612 que dá indícios da de construção do Forte. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de Souza) 1862 (Questão Christie): projetam-se as casamatas para São João, motivado pelo investimento e readequação das defesas do litoral após o almirante inglês Warren aprisionar, diante das fortalezas inertes vários navios que pretendiam entrar no porto, conduzidos para a enseada das Palmas, próxima da Ilha Grande. D. Pedro II tem atuação direta nessas ações. Um acidente durante exercício de fogo, em presença do Imperador, resulta na construção do conjunto das casamatas. 1872: foram realizadas reformas na Forte, com a construção de um quartel a provas de bombas (atual paiol) 1939 a 45 Segunda Guerra Mundial: O velho Forte São José recebe toneladas de munição, sofrendo alterações e adaptações como instalação elétrica, piso e portas de madeira, envidraçamento das canhoneiras, etc. (Fonte: Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472)	Plano de forte acasamatado de modelo norte-americano. (fonte: Inventário sumário do material de artilharia da Fortaleza de São João – Historiador Adler Homero) 17 casamatas construídas em pedra lavrada de 1,40m de espessura, encimadas por plataforma e parapeito, também de granito, com a mesma espessura, e completadas por um grande paiol em abóboda, à prova das armas da época. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472)) Fortificação aberta, portanto uma bateria, composta de um andar de casamatas e um terrapleno com um parapeito para o lado do mar. Casasmatas em número de 17, abertas em arco com alvenaria revestida e caiada em sua parte posterior (Morro Cara de Cão), e na parte dianteira do forte (voltada para o mar) fica visível a cantaria lavrada. Há um corredor com piso da cantaria, que dá acesso ao interior das casamatas, a parede opostas sendo composta de alvenaria de pedra (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro) No interior das casamatas fica visível a alvenaria de pedra lavrada. O antigo paiol, atual Museu, apresenta planta retangular com as arestas arredondadas e telhado de quatro águas embutido na platibanda. A fachada Oeste possui uma porta central em arco pleno, com dois óculos de cada lado. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de Souza) Levantamento Fotográfico evidenciando o sistema construtivo, detalhes arquitetônicos e incluindo imagens do uso do local para visitas escolares, acervo de artilharia disposto nas casamatas, do Museu instalado no Paiol e da pavimentação de acesso ao forte e ao redor do museu. Imagens de 2018 (Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza) e anteriores (PARECER N 236 2014 COTEC RJ, 28 de novembro de 2014, Arquiteta Claudia Maria Girão Barroso, referente à Praia de Fora) e (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro)
Reduto São Teodósio	
1650: há registro no Livro que dá Razão ao Estado do Brasil em 1612 que dá indícios da de construção do Forte. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de	Constituído por muralha de pedra de mão argamassada em formato retangular, com um baluarte apontado para o mar. e Sobre esta, foi feita uma nova estrutura, uma muralha, aparentemente com merlões de tijolos maciços, banquetas e plataformas de canhão de cantaria lavrada. No interior dessa segunda estrutura há ruínas de construção, não identificadas,

Souza)	também de alvenaria de tijolos maciços. (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro) Apresenta muro de arrimo de pedra (contenção do patamar onde se encontra a Bateria do Pau da Bandeira). O reduto é delimitado por ameias de tijolos maciços, com trechos de tijolos vazados e revestimento de cimento. Piso de grama, com revestimento de pedra bruta, junto as ameias. (Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza) Registro fotográfico constituído por algumas imagens antigas e fotografias de 2018, evidenciando o sistema construtivo e o avançado grau de deterioração, principalmente dos muros (Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza)
Bateria do Pau da Bandeira	
1710: o forte recebeu uma bateria alta denominada Forte de Santo Antônio, posteriormente denominada Forte Pau da Bandeira, o qual foi utilizado para enfrentar as invasões francesas comandadas por Duclerc. 1872: Construído um maciço de pedra lavrada na bateria do Pau da Bandeira, acima de São Teodósio. para receber canhão. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de Souza)	Bateria com piso de cantaria de pedra lavrada e um muro coberto de reboco de cimento, não podendo observar sua estrutura. Em uma das extremidades dessa bateria há um poço semicircular, onde está um canhão de grosso calibre. (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro) Localizada ao nível da rua e cercada por grade de ferro de seção tubular, a bateria do Pau da Bandeira comporta um canhão Armstrong denominado Vovô. O piso da plataforma do canhão é de peças retangulares de pedra bruta e o piso na parte frontal da bateria, que hoje funciona como mirante, é de placas de cimento. (Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza) Registro fotográfico constituído por imagens de 2018, evidenciando a visitação escolar e pavimentação da pista de acesso (Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza)
Remanescente das muralhas do Forte São Diogo (Forte da Entrada)	
1565 (1º de Março): Estácio de Sá aportou na Guanabara e se estabeleceu no Morro Cara de Cão, local de fundação da Cidade do Rio de Janeiro, onde implantou uma base militar, cujo objetivo principal era proteger o território contra a invasão francesa. 1565 (13 de setembro): a fortaleza do Morro Cara de Cão foi solenemente inaugurada por meio de uma cerimônia, narrada por Balthazar da Silva Lisboa que também faz referência à “porta principal da Cidade e da Fortaleza”. 1624: foi construído o Forte de São Martinho, cujo objetivo principal era impedir o desembarque de tropas inimigas na Praia de Fora, servindo como posição complementar ao Forte de São João.	Voltado para a várzea, encontra-se o Forte de Entrada, com muralha, compostos por bateria baixa, com dois meio-baluartes e o restante sendo uma linha de tenalhas, indo da Praia de Fora até a de Dentro, com uma interrupção criada por uma ponte de acesso, moderna. Além da ponte de acesso moderna há remanescentes de uma bateria baixa, a linha de última prolongando-se pela encosta oeste do Morro Cara de Cão. A maior parte da linha de tenalhas tem canhoneiras, apesar de não haver sinais de plataformas para essas no piso, que é moderno em toda a estrutura. Entre os dois meio-baluartes está o antigo portão de acesso ao forte (tombado). A ponte de acesso é de cantaria lavrada, tendo a parte central de cimento. (...)Todo o espaço interior dos fortes da entrada está ocupado com construções sem relação com a fortificação, todos modernos interiormente, apesar de em um deles haver uma placa com a data de 1867. Essas construções dificultam a leitura

1649: Aparecem descrições de um terceiro forte, Santa Luzia, conforme traçado italiano, composto por duas faces e dois flancos (conhecidos como Redutos de São Diogo e São Martinho), saídos de uma parede de pedra e cal, fazendo o arremate do Morro Cara de Cão. 1650: se iniciou na Praia de Fora a construção de um laço de muralha e reduto de pedra e cal para proteger esse importante acesso à Fortaleza. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de Souza)	das estruturas defensivas a partir de seu entorno imediato. Foi aberto um acesso em rampa, moderno, que demoliu um pequeno trecho do parapeito no lado da praia de dentro. A esplanada externa foi parcialmente obliterada com a edificação do Ginásio Leite de Castro, o mesmo tem ocorrido com a sua contraescarpa, da qual apenas vestígios permanecem. (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro) Fica-se evidente a técnica construtiva a partir de vestígios da muralha que forma a contraescapa da esplanada, muralha de pedra de mão argamassada com cal. (Memorando DEPROT RJ Nº 486 2001, de 27 de setembro de 2001. Historiador Adler Homero Fonseca de Castro) Registro fotográfico com imagens antigas e mais recentes, por volta de 2006, incluindo tomadas aéreas (PARECER N 236 2014 COTEC RJ, 28 de novembro de 2014, Arquiteta Claudia Maria Girão Barroso, da referente à Praia de Fora); Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro; e Registro Fotográfico 2018 IPHAN, de autoria da Arquiteta Regina Prado Lima de Souza e Adler Homero Fonseca de Castro) .
Ponte da Praia de Dentro	
Final do Século XIX: Outros melhoramentos foram a instalação de ponte de embarque e desembarque na praia interna. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472))	-*-*-*-*--*-*-*-*--*-*-*-*--*-*-*-*--*-*-*-*--*-*-*-*--*-*-*-*--*-*-*-*-
Posto de Comando da Região Leste	
1939 a 45 Segunda Guerra Mundial: Frente ao risco de ataque na segunda Guerra Mundial, constroem-se na Barra três pavilhões de emergência para alojamento, novo xadrez, Posto de Comando (PC) e Posto de Operação (PO) para o Grupo e as Baterias, pavimenta-se a estrada de acesso, removem-se os canhões antigos. O Comando de tiro é melhorado com o enterramento das comunicações, adoção de novo sistema de iluminação para pontaria, instalação de lunetas Krupp, pintura e camulhagem das peças, construções em rocha viva de uma câmara de preparação do tiro para as duas Baterias. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472))	Estrutura subterrânea idêntica aos postos de comando do plano Pratti de Aguiar (1943) (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro). Nota: É preciso explicitar quais as características
Bateria Marques Porto	

final do século XIX: a Fortaleza de São João recebe armamento moderníssimo a época. Dois canhões de calibre 95mm (dos que pertenceram ao cruzador “Tamandaré”), um de 120mm e dois (geminados) Krupp de 150mm c 40, todos constituindo uma bateria mista a “Marque Porto” e mais a “Bateria Mallet”, inaugurada a 02 de dezembro de 1901, com 02 canhões e completada no ano seguinte com dois outros idênticos , também Krupp 150mm c/40, modelo 1893-5. A ocasião do documento, essas duas baterias continuavam em serviço com canhões de 150mm, constituindo o artilhamento costeiro com que conta a Unidade para desempenhar sua missão. Suas peças embasadas em concreto e instaladas nas cotas médias (**Nota 6**) de 42m (Marques Porto) e 72m (Mallet), não mais visam somente o canal da Barra. Outros melhoramentos foram a instalação de ponte de embarque e desembarque na praia interna. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472))	Posição a barbeta, composta de um muro de baixa altura, tendo na entrada um cone de granito lacrado, onde se encontra placa de inauguração 1900. (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro)
Bateria Mallet	
final do século XIX: a Fortaleza de São João recebe armamento moderníssimo a época. Dois canhões de calibre 95mm (dos que pertenceram ao cruzador “Tamandaré”), um de 120mm e dois Krupp de 150mm c 40, todos constituindo uma bateria mista a “Marque Porto” e mais a “Bateria Mallet”, inaugurada a 02 de dezembro de 1901, com 02 canhões e completada no ano seguinte com dois outros idênticos , também Krupp 150mm cq40, modelo 1893-5. A ocasião do documento elaborado pelo Exército Brasileiro, essas duas baterias continuavam em serviço com canhões de 150mm, constituindo o artilhamento costeiro com que conta a Unidade para desempenhar sua missão. Suas peças embasadas em concreto e instaladas nas cotas médias de 42m (Marques Porto) e 72m (Mallet), não mais visam somente o canal da Barra. (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado - Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472))	Posição a barbeta, sem canhões ou estruturas fixas para a instalação dos mesmos, a não ser um possível embasamento de pesa, mas sem indicativos de ter recebido canhão. Na entrada há um arco com o nome da posição e uma guarita (portão com pórtico), placa alusiva da inauguração (marco ou obelisco) No local ainda há um paiol de munições moderno, do tipo feito depois da 2 Guerra Mundial, um paiol mais antigo, provavelmente da época da construção da bateria 1900, um posto de observação de dois andares, padrão Pratti Aguiar, e duas estruturas mais recentes sem funções defensivas. Na casamata há um telêmetro DFV Vasconcellos modelo 1943, fora de sua base e sem a luneta de observação. O Registro fotográfico evidencia a bateria, os paiois existentes, o posto de observação e telêmetro DFV Vasconcellos. (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro). Registro Fotográfico 2018 IPHAN, de autoria da Arquiteta Regina Prado Lima de Souza e Adler Homero Fonseca de Castro
Praia de Fora	
1559: chega a esquadra sob comando de Bartolomeu Vasconcelos da Cunha à Salvador com ordem real ao 3 Governador Geral Mem de Sá para expulsar os franceses do Rio de Janeiro. Com a participação e apoio de outras Capitanias para à ação, pode ser considerada a primeira batalha para a Defesa da integridade do território (Fonte: Projeto Tombamento do Conjunto da Fortaleza São João, elaborado pelo Exercito Brasileiro, autoria Cel Arthur Telles Cramer Ribeiro. Processo Digitalizado -	Faixa de areia. Registro fotográfico mais exíguo. (PARECER N 236 2014 COTEC RJ, 28 de novembro de 2014, Arquiteta Claudia Maria Girão Barroso, referente à Praia de Fora) e (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro.) Registro Fotográfico 2018 IPHAN, de autoria da Arquiteta Regina Prado Lima de Souza e Adler Homero Fonseca de Castro

Volume Vol 1 Parte 1.1 - Resumo HIstórico (0314472)) 1769-1778 : “Luís de Almeida Portugal, 3 vice rei e marques de Lavradio (1769-1778), relata: ‘Reedifiquei as defesas da fortaleza de S. João: fiz-lhe algumas de novo, e pus-lhe mais francas as suas comunicações, e projetei uma obra semelhante à da Praia de Fora na praia que fica encostada ao Pão de Açúcar, e encostada à fortaleza. (...)’ Segundo Pizarro, essa fortificação da Praia de Fora ‘se ultimou fabricada de faxina’ (Pizarro-v5). (Fonte: PARECER N 236 2014 COTEC RJ, 28 de novembro de 2014, Arq Claudia Maria Girão Barroso, da referente à Praia de Fora)	
Praia de Dentro	
1649: A Praia de Dentro (Santa Luzia) recebeu uma trincheira de pedra e cal que os engenheiros Quintam e Lescolles, durante uma vistoria, julgaram ser pouco útil e mal defendida, por se localizar fora da fortificação. (Fonte: Parecer 2018 IPHAN-RJ. 28 de dezembro de 2018. Autoria: Arquiteta Regina Prado Lima de Souza)	Faixa de areia Registro fotográfico mais exíguo. (PARECER N 236 2014 COTEC RJ, 28 de novembro de 2014, Arquiteta Claudia Maria Girão Barroso, referente à Praia de Fora) e (Laudo nº 31 2017, de 14 de julho de 2017, autoria do Historiador Adler Homero Fonseca de Castro.)

Nota 6: Conforme informado pelo Historiador Adler Homero Fonseca de Castro, na década de 60, o forte recebeu quatro canhões Vickers-Armstrong de 152,4mm Mk XIX, que foram instalados na bateria Mallet, saindo de serviço na década de 1980. O forte hoje encontra-se desativado como fortificação.

2.4. **Proposta para tombamento pela Superintendência do Rio de Janeiro**

O Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza, recomenda que o “Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas” seja tombado em âmbito federal e inscrito:

a) Livro do Tombo Histórico;

b) Livro do Tombo de Belas Artes; e

c) Livro do Tombo Arqueológico, Etnográfico e Paisagístico (pelo valor paisagístico).

2.5. **Poligonal da área que compõe o Conjunto a ser tombado pela Superintendência do Rio de Janeiro e Diretrizes de gestão para a área**

O Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza, apresenta as coordenadas geográficas que delimitam uma única área, que corresponde a proposta para tombamento e compreende o Conjunto Arquitetônico e Paisagístico da Fortaleza de São João e as Praias de Dentro e de Fora. Como parâmetro de ocupação dessa área têm-se que a mesma deve ser ocupada somente com as edificações existentes e equipamentos que se façam essenciais, desde que devidamente justificados e submetidos à análise deste IPHAN.

2.6. **Poligonal da área de entorno e Diretrizes de tombamento para a área**

O Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza, apresenta as coordenadas geográficas que delimitam uma única área correspondente a proposta da área de entorno do bem tombado e para ela apresenta diretrizes de gestão.

2.7. **Acervo de Artilharia**

Apesar de levantamentos e inventários do material de artilharia (realizados em 1998 e 2017 pelo Historiador Adler Homero Fonseca de Castro) constantes no processo, a Arquiteta Regina Prado Lima de Souza explicitou em seu Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, a importância que um servidor do IPHAN da área de bens móveis se manifeste sobre o tombamento dos elementos de artilharia da Fortaleza de São João, em virtude de ir além do que cabe à sua área de formação profissional.

Ressalta-se que ela citou canhões, nas Casamatas do Forte São José, bastante danificados pela ação da corrosão e o Canhão Vovô posicionado na Bateria Pau da Bandeira.

3. **ANÁLISE E SUGESTÕES**

Assim como observado por demais técnicos do IPHAN que analisaram o processo, não há dúvidas quanto ao valor histórico do bem para o Brasil, como elemento que marca a retomada do território por Portugal, do domínio francês; e como berço da cidade do Rio de Janeiro, capital do Brasil até 1960. O levantamento histórico apresentado no processo está bem detalhado.

No entanto, por se tratar de um bem complexo, pois na área do tombamento há elementos considerados com valor para proteção e outros não, além de elementos destacados cujos atributos podem caracterizar diferentes valores do Conjunto, é necessário clareza de como será gerido.

Confrontando os dados do processo, juntamente com as informações trocadas a partir das reuniões de meados de 2020, percebe-se a necessidade de detalhamentos de algumas informações no que diz respeito a descrição dos elementos de destaques no Conjunto e das estruturas defesa que o compõe e de esclarecimento sobre a correspondência de seus atributos e os valores indicados e como deverão ser preservados. Ademais, propõe-se discutir ajustes em relação ao nome, a relevância de manter a réplica marco da Fundação da Cidade do Rio de Janeiro e a inserção de alguns elementos que podem agregar valor cultural ao Conjunto da Fortaleza de São João.

Considera-se importante explicitar a decisão de não estender a proposta de proteção do conjunto ao Forte da Laje, apesar de sua importância na história da Fortaleza e da narrativa apresentada em diversos documentos do processo, em virtude das dificuldades de sua preservação, fruição e uso. Trata-se de estrutura parcialmente submersa nas águas da Baía de Guanabara, sofrendo a imprevisível ação das marés, o que torna a sua apropriação inviável em condições seguras.

3.1. **Sobre o nome proposto para o bem:**

“Conjunto Arquitetônico e Paisagístico da Fortaleza de São João, incluindo os seguintes elementos: Praia de Fora, Praia de Dentro, Marco de Fundação da Cidade, Forte São José, Reduto São Teodósio, Bateria do Pau do Bandeira, remanescente das muralhas do Forte São Diogo, Ponte da Praia de Dentro, posto de comando da região leste, Bateria Marques Porto e Bateria Mallet, com as estruturas anexas”

Considera-se bastante extenso e ainda assim impreciso, pela necessidade de esclarecimento sobre o que seriam consideradas as estruturas anexas. Sugere-se refletir, sobre a possibilidade de restringir-se a Conjunto Arquitetônico, Histórico e Paisagístico da Fortaleza de São João, Praia de Fora e Praia de Dentro, ou simplesmente a Conjunto Arquitetônico, Histórico e Paisagístico da Fortaleza de São João.

Os elementos de destaque podem ser propostos na descrição dos bens, indicando-os atributos de cada um deles que correspondem a valores específicos entre àqueles atribuídos ao bem.

Durante a discussão da equipe presente na reunião de meados de 2020, essa é uma questão que ficou de ser detalhada a partir de vistoria futura com equipe interdisciplinar, pois a partir dessa decisão cabe indicar como tais elementos deverão ser preservados.

3.2. **Sobre os elementos destacados e suas narrativas:**

O Marco de Fundação da Cidade na praça entre a Praia de Fora e a Fortaleza São João é uma réplica. O marco original foi transferido para a Igreja dos Capuchinhos, na Tijuca, e seu tombamento está sendo analisado no âmbito do Processo 1380-T-87, referente ao acervo remanescente da antiga Igreja de São Sebastião. Considera-se que não cabe incluir o marco que se encontra no local no âmbito da proteção que está sendo proposta para a Fortaleza de São João. A proposta de proteção da praia de Fora e da Fortaleza de São João fomentam a preservação e a memória do local, e sua correspondência com a fundação da cidade do Rio de Janeiro.

A maioria dos elementos que constituem a Fortaleza de São João encontram-se citados na sua narrativa histórica, que justifica o destaque que lhes estão sendo atribuídos. No entanto, observou-se uma lacuna sobre a importância da Ponte da Praia de Dentro, denominada de Ponte de desembarque pelo Historiador Adler na reunião de meados de 2020. Nessa ocasião, Historiador informou ter citações da sua relevância para a Fortaleza e dispôs-se a colaborar disponibilizando essas informações, requerendo a formalização para tal.

Entre os diversos documentos do processo, os nomes dos elementos destacados (**Nota 7**) no Conjunto da Fortaleza de São João podem gerar dúvidas sobre o que estão se referindo.

Nota (7): É desejável o georreferenciamento dos elementos de destaque do bem.

É importante identificar junto ao(s) Comando(s), gestores do Bem, qual a melhor designação para identificar cada elemento ou estrutura de defesa, sem gerar futuros equívocos sobre o que foi tombado e destacado em função dos atributos e valores identificados, tanto por fiscais do IPHAN, quanto pelo Exército Brasileiro.

Por exemplo, utilizar a designação Forte da Entrada para o elemento em que se encontra o Portão da Fortaleza São João permite incluir em sua descrição, por exemplo: uma bateria baixa, com dois meio baluartes – redutos São Martinho e São Diogo – e uma linha de tenalhas, que vai da Praia de Fora até a de Dentro, interrompida por uma ponte de acesso de construção mais nova; e entre os elementos externos à cortina, têm-se o fosso - criado a partir dos vestígios de uma esplanada - a ponte de acesso ao portão, e os remanescentes da citada contra-escarpa. (Figura 8)

A denominação Bateria Pau da Bandeira que aparece no Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza não foi encontrada nos outros documentos. Neles não há diferença entre o Reduto São Teodósio e a Bateria do Pau da Bandeira.

Na reunião de meados de 2020, foi aventada a possibilidade de destacar pelo menos duas edificações pela sua importância dentro do uso militar, incluindo as entre os elementos defensivos: (a) Prédio do Comando de artilharia da Costa do Brasil e o Edifício que serviu de prisioneiros de guerra em 1867 (identificados pelos números 29 e 33 na Figura 9).

Considera-se que agregaria valor cultural incluir nos elementos de destaque a rota que interliga os demais elementos com o Forte da Entrada e vestígios da rota identificados, caso existam, na face do morro Cara de Cão voltado para o mar aberto. Essa rota ficou evidenciada no registro histórico que consta do processo de tombamento (Figura 10). Conforme informou-se o Historiador Adler Homero Fonseca de Castro, em comunicação com o Comando da Fortaleza São João, posterior a reunião de meados de 2020, o caminho existe, mas está coberto de mato. Há uma arqueóloga trabalhando no forte, com pesquisa autorizada pelo IPHAN e que, segundo informado, delimitou o caminho.

Cabe ainda ressaltar, que se considera importante que elementos em destaque estejam em consonância com aqueles que estão sendo selecionado pelo Comitê Técnico para a Candidatura das Fortificações Brasileiras a Patrimônio Mundial, considerando que as duas atividades de identificação e reconhecimento ocorrem em paralelo dentro da mesma instituição.

3.3. **Sobre a descrição dos elementos que constituem o bem e o estado de conservação:**

O Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018 apresenta descrição para o Forte São José, ao Reduto São Teodósio e o Pau da Bandeira. Ainda que se observe a descrição dos demais elementos destacados em outros documentos do processo, é necessário complementá-la.

Sugere-se que a descrição dos elementos que constituem o bem ou as estruturas anexas limite-se àquelas que serão objeto de proteção, contendo explícitos os atributos que devem ser preservados. Em especial, incluir a descrição da estrutura semi-enterrada do Posto de Comando da região leste (Coronel Pratti de Aguiar); detalhar as características da Ponte de Embarque (ou Ponte da Praia de Dentro); e precisar as descrições das Baterias Porto Marques e Mallet. A descrição dos elementos e de suas estruturas devem ser complementadas e relacionadas ao registro fotografico com imagens atualizadas.

Quando consultados pelo Historiador Adler, o Comando da Fortaleza de São João informou que o acesso a estrutura do Posto de Comando poderá ser viabilizado com agendamento da vistoria com antecedência.

É importante esclarecer por meio de imagens e textos complementares, por exemplo, se a casamata da Bateria Mallet é o Posto de observação.

Sugere-se, portanto, para cada elemento destacado indicar: Designação, imagens e descrição geral, atributos e valores correspondentes, estruturas de defesa relevantes para compreenção do uso militar com descrição e fotografias específicas, características a serem preservadas (técnicas construtivas, acabamentos, características da vegetação, etc.)

Quando se tratarem de elementos destacados por valor histórico, sugere-se associar a descrição de sua estrutura de defesa com a da proposta de operação (uso militar), considerando o número de militares, onde estariam locados em contexto de guerra, como se daria a proteção desses soldados, etc.

Sugere-se refletir sobre a relevância de proteger estruturas de apoio à defesa, que não correspondem a época das baterias e, evidenciar a decisão; também refletir e evidenciar quando relevantes placas integradas (inaugurais), pináculos, portais, etc.

Propõe-se esclarecer quando as características de piso existentes são relevantes para a compreensão e interpretação do bem, enquanto elementos de defesa e engenharia militar, assim como luminárias, e outros acabamentos e acessórios.

É recomendável complementar o Registro Fotográfico, por vezes com imagens panorâmicas dos elementos destacados (por exemplo, Bateria Porto Marques e Ponte da praia de Dentro), outras vezes por imagens de detalhes das estruturas de defesa (Túneis e áreas internas do Posto de Comando, detalhes construtivos da Ponte da praia de dentro), preferencialmente, relacionadas com os atributos e características a serem preservadas.

Em função de recursos disponíveis, fotografias aéreas com imagens panorâmicas podem ser reunidas entre acervo existente no IPHAN e no Exército Brasileiro.

São desejáveis imagens recentes tomadas durante vistoria, sobretudo no que se refere à Bateria Marques Porto, ao Posto de Comando da região leste (Coronale Pratti Aguiar), à Ponte de embarque (ou Ponte da Praia de Dentro), além de vistas a partir do mar tanto da Praia de Dentro, quanto da praia de fora; e incluir fotografias a partir do alto do Pão de Açúcar, pois a Fortaleza de São João e a Praia de Fora estão no pé do morro, sendo um referencial paisagístico importante para visitantes desse ponto turístico.

As imagens da Praia de Dentro e da Praia de Fora, a partir do mar, devem evidenciar sua ambientação e características do entorno imediato, uma vez que está sendo atribuído a elas valor paisagístico. Cabe lembrar que as imagens que têm no processo e em que se pode observar esse aspecto são muito antigas.

Sugere-se atualizar o estado de conservação, que deverá subsidiar algumas propostas de diretrizes de gestão do bem, em especial para: o Reduto São Teodósio (em função do estado de conservação relatado pela Arquiteta Regina em 2018), a Ponte da Praia de Dentro, o Posto de Comando da região leste, a Bateria Marques Porto e a Bateria Mallet.

O Forte da Entrada, o Forte São José, a Bateria do Pau do Bandeira, Praia de Fora e a Praia de Dentro, em função das frequentes atividades de visitação por público externo e uso para as atividades de rotina das instituições militares instaladas encontram-se geralmente bem conservadas, como observados nos registros constantes dos documentos do processo. No entanto, também podem ser objeto de diretrizes de gestão, em função, da interpretação como estruturas de defesa.

É interessante, retomar com os Comandos das unidades militares, instaladas no bem, discussões no âmbito de Plano Diretor de Intervenção.

3.4. **Sobre a Proposta para tombamento pela Superintendência do Rio de Janeiro**

Considera-se pertinente que o “Conjunto Arquitetônico, Histórico e Paisagístico da Fortaleza de São João", seja tombado em âmbito federal e inscrito em:

a) Livro do Tombo Histórico;

b) Livro do Tombo de Belas Artes; e

c) Livro do Tombo Arqueológico, Etnográfico e Paisagístico (pelo valor paisagístico).

Os valores paisagísticos e históricos podem ser observados nas características e atributos de praticamente todos os elementos destacados da Fortaleza São João, no Parecer 2018 IPHAN-RJ de 28 de dezembro de

2018, de autoria da Arquiteta Regina Prado Lima de Souza. Exceto na réplica do marco de fundação da cidade do Rio de Janeiro (conforme já mencionado, sugere-se não fazer parte do bem).

A Fortaleza São João, as Praias de Dentro e De Fora, juntamente com o Morro Cara de Cão permitem rememorar a consolidação dessa fortificação ao longo da história, bem como constituem parte da Paisagem Cultural do Rio de Janeiro (entre o mar e a montanha) como Patrimônio Mundial, reconhecida pela Unesco.

Recomenda-se discutir e esclarecer que elementos de destaques possuem atributos que sugerem a inscrição do bem no Livro do Tombo de Belas Artes. Para esta Parecerista, as características observadas no Forte da Entrada e no Forte São José podem ser facilmente associadas aos valores arquitetônico e da engenharia militar. O mesmo não está explícito para os demais elementos de destaque. Os atributos devem ser relacionados com propostas de preservação para as estruturas.

Cabe ainda ressaltar, que se considera importante que os valores atribuídos a Fortaleza São João e aos elementos em destaque estejam em consonância com aqueles que estão sendo atribuídos a esse bem pelo Comitê Técnico para a Candidatura das Fortificações Brasileiras a Patrimônio Mundial, considerando que são trabalhos que ocorrem em paralelo dentro da mesma instituição.

3.5. **Sobre a área de tombamento e suas respectivas diretrizes**

A área do bem tombado está georreferenciada, no entanto a proposta de gestão está muito suscinta. Sugere-se detalhar as diretrizes ou apresentar proposta para sua elaboração a partir de ações integradas entre IPHAN e gestores do bem em função dos atributos e valores correspondentes identificados no “Conjunto Arquitetônico, Histórico e Paisagístico da Fortaleza de São João". Cabe reiterar a importância de convergir para a elaboração de planos de gestão e conservação, em construção em função da Candidatura das Fortificações Brasileiras a Patrimônio Mundial.

3.6. **Sobre a área de entorno e suas respectivas diretrizes**

A área de entorno está descrita e georreferenciada, com proposta de gestão. Cabe reiterar que se tem conhecimento o trabalho da Conservação Geral de Normatização do DEPAM junto à Superintendência do IPHAN no Rio de Janeiro de uma proposta única para bens tombados na região que inclui o bairro da Urca e o entorno do Conjunto da Fortaleza de São João.

3.7. **Sobre o acervo de artilharia (móvel):**

Observa-se que muitas vezes a compreensão das estruturas das baterias e redutos é facilitada, ou requer a presença de elementos de artilharia. Para esta Parecerista, no caso em questão esse acervo torna-se ainda mais relevante para compreender o Reduto São Teodósio (canhão Vovô), a Bateria Marques Porto e a Bateria Mallet (atualmente sem acervo de artilharia).

Sugere-se que o Processo seja encaminhado para tombamento com indicação dos bens imóveis juntamente com a do acervo de artilharia, e eventualmente alguns outros instrumentos de apoio as ações de defesa que foram instaladas naqueles locais. O Laudo 31 2017, de 14 de julho de 2017, de autoria do Historiador Adler Homero Fonseca de Castro aponta a presença de telêmetro DFC Vasconcellos modelo 1943, fora de sua base e sem a luneta de observação na casamata da Bateria Mallet.

Na reunião de meados de 2020, quando consultado pela Parecerista, o Historiador expressou a possibilidade de auxiliar nessa etapa após formalização junto ao Centro Lúcio Costa. O grupo ali reunido considerou importante a participação de um servidor da área de bens móveis da Superintendência do Rio de Janeiro.

Ficou proposto identificar entre o acervo de artilharia relacionados à Fortaleza São João, aquelas peças que estão guardadas no Museu da Fortaleza; e as que estão expostas em estruturas de defesa.

4. **CONCLUSÃO**

Após análise do Processo de Tombamento e do Parecer 2018 IPHAN-RJ de 28 de dezembro de 2018, de autoria da Arquiteta Regina Prado Lima de Souza, recomendamos que o Processo deve retornar para Superintendência do IPHAN no Rio de Janeiro para os ajustes sugeridos ao longo do item 3 deste Parecer, e para emissão de Parecer(es) Técnico(s) referente(s) ao bem, que contemple(m) o patrimônio imóvel e móvel, em especial o acervo de artilharia.

Reiteramos a importância de equipe interdisciplinar para finalização dessa instrução, que a discussão *in loco* de pormenores referentes à identificação e reconhecimento do bem dialogue com os gestores da Fortaleza São João e com o Comitê Gestor para elaboração do Dossiê de Candidatura das Fortificações Brasileiras à Patrimônio

Mundial, que os elementos destacados no “Conjunto Arquitetônico, Histórico e Paisagístico da Fortaleza de São João" e as estruturas de defesas estejam, preferencialmente georeferenciados, e relacionados ao que se deseja preservar para transmitir os valores atribuídos pelo tombamento federal.

A complementação de informações requer a participação de servidor da Superintendência do IPHAN no Rio de Janeiro da área de bens móveis e, se possível, da arqueologia.

Agrega considerável valor cultural para a proposta de tombamento estendê-la ao acervo de artilharia; e, se possível, incluir vestígios de rota e caminho que interligam os elementos destacados e que evidenciam, a operação de defesa conforme foi pensada para a Fortaleza em épocas remotas.

A complementação da instrução deve propiciar dados relevantes a ações de gestão, fiscalização e conservação do tombado em âmbito federal. Portanto, designação dos elementos destacados e estruturas de defesa que não gerem dúvidas, mapas, relatório fotográfico do sítio e de suas estruturas históricas com imagens atuais viabilizam e promovem a adequada preservação do bem cultural.

Adicionalmente, recomendamos: esclarecimento junto à Procuradoria Federal sobre a possibilidade de notificar o tombamento provisório, por meio de edital, ou considerando o DECRETO nº 77.180 de 17 de fevereiro de 1976 folhas 342 e 343 do Processo SEI nº 01458.001154/2012-55; e que essa Coordenação Geral intermedie a formalização da solicitação junto ao Centro Lúcio Costa da participação do Historiador Adler Homero Fonseca de Castro ao longo das etapas futuras, até a conclusão deste processo de tombamento.

Documento assinado eletronicamente por **Claudia Bastos do Nascimento**, **Técnico I – Área: Engenharia Civil**, em 18/05/2021, às 13:50, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

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Referência: Processo nº 01458.001154/2012-55 SEI nº 2672680

B.2 UNESCO Tentative List

Brazilian Fortresses Ensemble

Brazil
Date of Submission: 30/01/2015
Criteria: (ii)(iv)
Category: Cultural
Submitted by:
Permanent Delegation of Brazil to UNESCO
State, Province or Region:
States of Santa Catarina, São Paulo, Rio de Janeiro, Bahia, Pernambuco, Rio Grande do Norte, Paraíba, Amapá, Rondônia, and Mato Grosso do Sul
Ref.: 5997

Description

Categorization: Serial monuments; Military architecture; Sixteenth to the nineteenth centuries; nationwide coverage.

The set of fortresses installed by Europeans in Brazil originated in a territory occupation process, different to those found in other colonial powers. It was based on a decentralized effort, arising from the actions of inhabitants of the different captaincies that formed Brazil, without further intervention from the mother country. This resulted in the construction of hundreds of fortresses, scattered throughout the country, built to cater more to local interests than the motherland. The fortresses not only marked the presence of towns and cities of Lusitanian origin, but also the contact between different cultures. Many of the defensive buildings and settlements were set up where there were already indigenous settlements, while French, English, Dutch and Spanish forts were destroyed by forces that were not sent from the mother countries, but by residents in Brazil. These were mobilized without further directive from Europe, marking the formation of a territory with its own language and identity, different from all the other existing territories in the New World and a territory that would have a greater geographic extension than the European continent. Due to the nature of the decentralized efforts coming out of small community actions without greater support from the Portuguese government, the result was a variety of works, with different strokes, styles and construction techniques that served to demarcate the ingenuity and creativity of the people in coming upon unique solutions to address ecological and cultural conditions that were very different from those existing in the Old World. Even today, there are dozens of these Luso-Brazilian fortresses pointing out its activities in establishing a unique culture. The purpose of this application is to present a set of fortresses that includes a selection of 19 (nineteen) monuments representing the formidable defenses deployed in Brazil, the points that served to define the sea and river borders that resulted in the largest Latin American country: Brazil. The selection of monuments fell on the following works:

1864. São Antônio de Ratones Fort (Florianópolis/SC, 27º 28’ 21” S, 48º 33’ 41” W): Built in 1740 during the implementation of the captaincy (state) of Santa Catarina to support the struggles in the southern part of the continent against the Spanish. The conquest of the island of Santa Catarina by the Spanish in 1777 and the island’s exchange for the *Colônia de Sacramento* (Uruguay) temporarily interrupted the cycle of clashes in the south. These would be rekindled with the independence of Brazil and the last Brazilian military action in Uruguay, supported by the forts in Santa Catarina, taking place in 1864. Leveraging the insularity, the position of the fort is formed by curtain curve, a proper construction of precarious resources available then. The Federal University of Santa Catarina maintains a site visitation program. Federal protection of 1938.

1865. Santa Cruz de Anhatomirim Fort (Governador Celso Ramos/SC, 27º 25’ 36” S, 48º 33’ 51” W): Built in 1740, it was the main defense of the captaincy of Santa Catarina and, over the centuries, served other functions such as a hospital and even a hostel for foreign travelers who might have been infected by contagious diseases. The fort was kept operational and in constant expansion until the 1950s. With an irregular shape, the fortress consists of a series of interconnected batteries, each of rugged and very simple design. The set is completed by the large barracks, which was once the residence of the governor, and a monumental gate in an oriental style. Administered by the Federal University of Santa Catarina, it is Santo Amaro da Barra Grande Fortress (Guarujá/SP): With its initial construction starting from open to visitations. Federal protection of 1938.

1866. Santo Amaro da Barra Grande Fortress (Guarujá/SP, 23º 59’ 40” S, 46º 18’ 25” W): Built from 1584 when Portugal and Brazil were part of the Iberian Union (1580-1640), it was designed by the Italian architect Bautista Antonelli in response to an attack by the English privateer George Fenton carried out the previous year. The Fortress, however, was not yet ready when another Englishman, Thomas Cavendish, sacked the town of Santos in 1588. The fort, the main defense of Santos, was kept in operation until 1908. Its format is of two overlapping rectangular batteries with a long curtain defending the coast and an auxiliary battery on top of the elevation where it is located. Currently, it operates as a municipal museum. Federal protection of 1964.

1867. São João Fort (Bertioga/SP, 23º 51’ 18” S, 46º 08’ 04”W): Originally built in 1532 to prevent the indigenous peoples from using the Bertioga channel to attack the towns of Santos, was the military post in which the German gunner Hans Staden, author of one of the first accounts of the conquest of America, served. Therefrom, residents of St. Vincent used it to expel the French Calvinists who had found a settlement in Rio de Janeiro in 1555. The current fort was erected in 1750 in the context of fixing the borders with Spanish America, with a very narrow rectangular battery format, and in the back a railing in the form of a tenaille. It is a local municipal government museum. Federal protection of 1940.

1868. Santa Cruz da Barra Fortress (Niterói/RJ, 22° 56' 16"S, 43° 8' 3"W): The Fort began to be raised in 1578 as the main defense of the city of Rio de Janeiro, and it has been kept in operations and constantly expansion for three hundred years. In the early eighteenth century, it became the largest fort of Portuguese America, its irregular construction being a testimony to different styles and defensive programs. Even considering its importance, it could not prevent the French privateer René Duguay-Trouin from invading Guanabara Bay in 1711, and sacking the city. The fortress is still in use by the army, which has its own tourist visitation program. Federal protection of 1939.

1869. São João Fortress (Rio de Janeiro/RJ, 22° 56' 36" S, 43° 9' 25" W): erected in the location where the settlers from São Vicente founded the city of Rio de Janeiro in 1565 to fight the French Calvinists who had settled in the Bay of Guanabara ten years earlier. Attacked several times by the French and indigenous, the fort served as a base of operations for the conquest of the region. The present work, built over nearly three hundred years from 1602 to 1864, the cluster is formed by three different forts, one of trace italienne , an irregular battery and another casemated on the navigation channel. Still in use by the Army, it is a museum. Federal protection of 1938.

1870. Nossa Senhora de Monte Serrat Fort (Salvador/BA,12° 55' 47"S, 38° 31' 3" W): Built in 1582, it's a transition fort with some characteristics of a medieval castle, with its large turrets in salient angles, but with a *terre-plein* already adapted to the use of cannons and an exposed quarter on the back of the walls. It took part in combats against English and Dutch privateers in 1587, 1599, 1604, and 1627. It was taken by the Dutch West Indies Company's fleet in 1624, serving as the Dutch resistance point against the locals in a siege by the residents of Salvador. Taken up in 1625, it was again raided by the Dutch in 1638, also taking part in the encounter against the West India Company fleet in 1647. In these times of conflict, it has had always been garrisoned by Bahia militia residents. It is currently managed by the Army. Federal protection of 1957.

1871. Santo Antônio da Barra Fort (Salvador/BA, 13° 0' 36"S, 38° 31' 58"W): The fort is shaped in an irregular decagon in tenaille, with large barracks on its ramparts. Built in the place of the second Lusitanian town of Salvador (1534), it had to be evacuated because of the native resistance and was rebuilt during 1582, just after the Union of the Crowns of Portugal and Spain (1580-1640), with the increasing risk of attacks by European powers. The fort was part of the additional defenses of Salvador and it took place in combats against English and Dutch privateers, which mark the history of the city in the late sixteenth and early seventeenth centuries. It currently serves as a Naval museum. Federal protection of 1938.

1872. Santa Maria Fort (Salvador/BA, 13° 0' 16"S, 38° 32' 2" W): The first Santa Maria Fort has been erected soon after the reconquest of Bahia, in 1652, when a fleet with more than ten thousand troops (Spanish, Italian and Portuguese) came to Salvador to retake the city, occupied by the forces of the Dutch West Indies Company. It served to defend the small harbor, where the Dutch had landed the previous year and which was

once more used to attack the city in 1625. The current work is the result of a reconstruction in 1694, shaped like a rectangle with walls in a very smooth line of tenailles, with an elevated hood on the walls, as is typical of the Bahia military architecture. It belongs to the Army, responsible for its maintenance. Federal protection of 1938.

1873. São Diogo Fort (Salvador/BA, 13°0'6.89"S, 38°31'58.03"W): The Fort is part of the Barra de Salvador complex, along with the Santo Antônio and Santa Maria Forts. Along with Santa Maria Fort, São Diogo Fort was built in 1625, and rebuilt in 1694 in the form of a semicircular battery, with its headquarters on the hillside where it is centered and where the first Portuguese settlement of Bahia was founded. The Fort had to be abandoned in 1534 because of the native resistance. In the small inlet at São Diogo's fort front, the Dutch landed in 1624, with the Spanish-Italian-Lusitanian forces driving the Dutch the following year. It is owned by the Army. Federal protection of 1954.

1874. Forte São Marcelo (Salvador/BA): known as Nossa Senhora do Pópulo and São Marcelo Fort or as "Forte do Mar", Sea Fort, it has been built away from the coast for fear of the Portuguese of new Dutch invasions. Its function was to impede the entrance to the Salvador Port, crossing fire with the Forts of São Franciso, São Felipe and São Paulo de Gamboa. Influenced by the design of Fort Bugio, in the backshore of Tejo, its construction stretched until the 18th century, with participation of the French engineer Felipe Guiton, and his compatriot the engineer Pedro Garcin. The circular design is constituted of a main tower involved by a ring of equal height, formed by the perimeter embankment and barracks. In sandstone stonemasonry, it possess a barrel vaulting, and is the only still existing example of circular shaped forts in the country. It belongs to IPHAN and is under federal protection since 1938.

1875. São Tiago das Cinco Pontas Fort (Recife/RE, 8° 4' 18"S, 34° 52' 51"W): Originally built as a Italian traced pentagonal fort by the Dutch West India Company in 1630 , it was a key element for the Dutch defenses of the city of Recife, being kept under siege by the residents of Pernambuco during the sieges from 1630 to 1635, and ensuing sieges of 1645 to 1654. It was rebuilt by Pernambuco residents in the late seventeenth century, adopting a rectangular layout. However, the name of the fort kept the same name of the fort as during the episode of the Dutch occupation of Pernambuco. It now operates as the Museu da Cidade do Recife. Federal protection of 1938.

1876. São João Batista do Brum Fort (Recife/PE, 8° 3' 10"S, 34° 52' 15"W): The Fort's origins date back to 1595, when English privateers, under James Lancaster's command, erected the fort. Later, the fort would undergo various expansions and modifications. One modification that has marked its history was the construction of Schans de Bruyne, by the Dutch in 1630, one of the main points of resistance for the siege of the Luso-Brazilian forces, which occurred between 1630 and 1635. The Fort was rebuilt in brick and stone with the same layout of the Dutch in 1690, a straight curtain to the sea with bastions and half-bastions to land, maintaining the Portuguese version of the Dutch name, Brum. It belongs to the Army, housing a museum. Federal protection of 1938.

1877. Santa Cruz de Itamaracá Fort (Itamaracá/PE): known as Fort *Orange*, it is one of the testimonies of both the Portuguese and the Dutch action in Pernambuco during the colonial period. The monument was built in the 1630's by Dutch military serving the East India Company and has been undergone several changes in its structure since the Portuguese restauration of 1654, changing its name to Fort *Santa Cruz de Itamacará*. In limestone and lime masonry, the current fort presents a regular quadrangular polygon design, with pentagonal bastions at the vertices in the Vauban system, stonemasonry sentry-boxes, escutcheoned gates, as well as barracks for the troops, Command House, bunkers under the walls, involving the embankement. Federal protection of 1938.

1878. Santa Catarina Fort (Cabedelo/PB, 6°58'8.51"S, 34°50'24.80"W): Dated from 1590, the fort was built after a long campaign to subdue the native inhabitants who, together with the French, contested the occupation of their territories. Attacked in 1596 by thirteen French ships, the Fort was renovated by locals in 1603. In 1631, the position withstood a Dutch West Indies Company attack before being taken in 1634. Rebuilt by the Dutch two years later, the current work is from 1700, following parts of the reaces of the Dutch Fort, a tenailles line to the river, with bastions defending the side of land. It is

administered by the State Government of Paraíba today, which maintains a museum on the site. Federal protection of 1938.

1879. Reis Magos Fort (Natal/RN, 5° 45' 22 "S, 35° 11' 41"W): Built in accordance with the 1597 project of the Spanish Jesuit priest Gaspar Samperes, the fort is the first of the Lusitanian America to follow the trace italienne, with a unique architecture in Brazil, with a tenaille line to the side of the river and half bastions with orillons to the side of land. Built as part of the campaign by Pernambuco residents to oust French traders who worked with indigenous populations, it was attacked by a French and Indian force in the same year of its construction. Later, in 1634, the fort was taken by the Dutch, remaining under its administration for twenty years. Administered by IPHAN, it is the largest cultural attraction in the city of Natal/RN. Federal protection of 1943.

1880. São José Fortress (Macapá/AP, 0° 1'50.60"N e 51° 2'57.77"W): The square fortification of italienne trace according to the French school was built on the north bank of the Amazon River, where the Irish and then British had established trading posts and settlements to trade with the natives in the early seventeenth century. After the destruction of these occupations, and the construction of a Portuguese fort in the same location, it was destroyed by the French in 1697 as a result of claimed ownership of the north bank of the Amazon River mouth. The current work was erected in 1764 by Portuguese settlers who, coming from the evacuated village of El Jadida, Morocco, participated in the formation of the established colony in the region. The area protected by the fortress was later occupied by the French in 1838 and 1895, but the situation was resolved through diplomatic means. Administered by the Government of the State of Amapá, the building is open to visitors, with cultural activities taking place within it and its surroundings. Federal protection of 1943.

1881. Príncipe da Beira Fort (Costa Marques/RO, 12° 25' 40"S, 64° 25' 22"W): Built according to the trace italienne in 1776 in a failed attempt to establish a trading post with Spanish America, it is located in an area long occupied by indigenous peoples, region in which the Spanish had established the Jesuit mission of Santa Rosa. The Portuguese presence in the area, which guaranteed river communication between the modern states of Pará and the Mato Grosso mining region, led to two attacks by Spanish troops coming from the Andes, both repelled, consolidating possession of that border. Currently, it is owned by the Army, open to visitations. Federal protection of 1950.

1882. Coimbra Fort (Corumbá/MS, 19º 55’ 12” S, 57º 47’ 31” W): Installed on the East bank of the Paraguay River, as a way to claim ownership of this communication route for Portugal, the primitive fort, built in 1777, was attacked and destroyed by the native inhabitants, leading to the fort’s reconstruction in stone masonry in the late eighteenth century with a stroke in tenailles, with bastions in the back. This site was attacked unsuccessfully by the Spanish in 1802, and the fort was taken by Paraguay in 1864. Disabled as a fortress in 1998, it is maintained today by the Army and it is open to visitations. Federal protection of 1974.

Justification of Outstanding Universal Value

Justification for the selection of components

The continental dimensions of Brazil are the result of a slow process of expansion, occurring over four centuries. The construction of fortresses functioned largely to consolidate future occupation strategies of these vast geographical areas. Based on this criterion, the set of locations was delimited by Fortes Príncipe da Beira/RO and Coimbra/MS, as landmarks on the western border; the São José do Macapá/AP, as a mark of the northern border settings; the set of fortresses on the island of Santa Catarina (Ratones and Anhatomirim), marking the southern division; and marking the extreme eastern borders, the Fort of Reis Magos, in Natal/RN, and Santa Catarina Fort, in Cabedelo/PB. The strongholds of Pernambuco (Cinco Pontas and Brum) mark the struggles against the India Company. In turn, the strongholds of the Baía de Todos os Santos (Monte Serrat, Santa Maria, São Diogo and Santo Antônio da Barra) and Baía da Guanabara (Santa Cruz and São João) marks the defenses of the two capitals of colonial Brazil, Salvador and Rio de Janeiro. Finally, the fortresses of Barra de Santos, including the Canal de Bertioga forts (Barra Grande and São João), point to the defense of the port that drained most of the wealth produced in Brazil and, therefore, endowed with a fortresses system built from the fifteenth century to the early nineteenth century, forming one of the largest defensive sets in the world, with continental dimensions.

The artillery forts chosen represent, therefore, a decentralized effort associated with local interests of different captaincies for the occupation of Brazil and are representative of the diversity of the architectural solutions with different traces, styles and construction techniques. They are significant influences of classical architectural proposals, as the trace italienne forts of the French schools (Príncipe da Beira and Macapá forts), Dutch style (Bum and Cinco Pontas), Spanish (Barra Grande and Reis Magos) and Portuguese (São João/RJ and Coimbra), as well as local solutions, exemplified by the forts of Salvador and the fortresses of Santa Cruz/RJ and Anhatomirim.

The motivation for building these forts were linked to the principal factors of defense and territory demarcation, in different situations of local threats such as the Dutch (PE and BA), English (EP, BA, AP), French (SP, RJ, PB , RN and AP), Spanish (MS, RO, SC), and indigenous (PB, RN, SP and RJ).

Lastly, the management conditions and the state of conservation of the forts were relevant to their selection.

Criterion (ii): Brazil's complex of fortresses is a remnant of a single contact produced between different cultures from the Old and the New World, beginning with the establishment of European villages in the territory previously occupied by natives, passing through a long period of conflict between the powers of the Old World, like the French in Rio de Janeiro, Paraíba and Rio Grande do Norte, the English and Irish in Amapá, Pernambuco and Sao Paulo, and the 55 years of war against the Dutch, in a geographical area of thousands of kilometers, that extends from the Equator to the Tropic of Capricorn. Finally, the conflict with the Spanish in Prato resulted in the formation of two Brazilian states (Santa Catarina and Rio Grande do Sul), with a great influence on the formation of Uruguay, originally a Portuguese colony. The victory of the Luso-Brazilians in these conflicts resulted in the emergence of a country whose conformation, still maintained today, has mainly been defined by the third quarter of the eighteenth century with the construction of establishments on the western border. The strongholds, built in response to these contacts, marked the success of a unique formula of occupation in the territory, where Brazilian residents played a more important role than the actions of the governments of the Old World cities, contrary to what occurred in other European colonies around the world. Thus, the constructions were made in order to ensure ownership and the safety of new territories, forming a complex that bears no resemblance to other fortified systems built in the same period elsewhere in the world, playing an important role in territorial occupation in South America.

Criterion (iv): The Brazilian fortresses ensemble is the result of influences of classical architectural proposals, as seen in the Italian forts trace of the French schools (Príncipe da Beira Fort and Macapá Fort), as well as Dutch architecture (Bum and Cinco Pontas forts), Spanish (Barra Grande and Reis Magos forts), Portuguese (São João/RJ and Coimbra forts), as well as local solutions, exemplified by the forts of Salvador. The forts don’t have a more elaborate technical quality, compared to the European standard, but were still very effective, given external and internal threats existent in America, which were minor considering the difficulty of existing communications. Thus, the specific type for defensive constructions erected with strictly local resources are characterized by local solutions, many of them improvised due to the little technical training of most of its designers and builders, as seen in the cases of the Santa Cruz/RJ and Anhatomirim fortresses. However, it is precisely this lack of a "classical" unifying standard, established in adverse circumstances and against great opposition of the natives and rival powers, as well as the success of the proposal to establish limits through fortified works, that makes this fortresses ensemble worthy of being highlighted, especially considering the large number of surviving works to this day. It should also be emphasized the unique aspect of maintaining a continuous and stable geographical boundary of continental dimensions, from the mid-eighteenth century through fortresses, which resulted in a country with distinct cultural characteristics then of Brazil’s South American neighbors, a situation without equal to the observed dissolution of colonial territories in the South American continent, or even in Africa and Asia.

Statements of authenticity and/or integrity

Authenticity

The fortresses that were chosen, all characterized as eminently utilitarian works, remained in constant improvement and evolution throughout the period of Portuguese rule, maintaining a continued use until the twentieth century, which ensured their preservation. In this sense, all the forts selected to represent the ensemble are intact as fortresses, allowing its understanding as such and the understanding of different times and historical facts that they represent, ensuring its authenticity in the aspects of form and design, materials and substance. Although none of the forts have maintained their original use as defensive constructions, this function can be easily perceived by the observer, a fact reinforced by the military use and/or cultural use of various constructions. The location and the environment of the selected forts are still enough preserved to allow the assessment of the works as defensive buildings, making it clear that the

spirit imbued in these assets is preserved. The selection, addressing forts in all regions of Brazil in an exemplary and representative character, demonstrates the Luso-Brazilian solution imprint to occupy a vast territory that, in general, remains to the present day.

The choice for nomination as an ensemble series of only a portion of the over the hundreds of forts that still remain in the country was based on the assembly of the most representative examples that still exist and formed the basis for the country`s occupation. With the exception of the river border and São Paulo forts, all the others were built in towns that became capitals of current states of Brazil, always aiming to establish ownership in areas militarily disputed by other European powers.

Integrity

1. The set is complete, the selection criterion prioritizes the main elements of the defensive systems established in each region of Brazil, being a representative group with the necessary elements to express the proposed Outstanding Universal Value.
2. The selection of the sites was made considering places that point the Brazilian river and sea borders, and that represents different architectural works that marked different moments of history, both in the technical and construction styles, as well as the events that led to the formation of a continental sized territory, as Brazil has.
3. The outline of the chosen works allows a complete representation of the historical processes that underlies the importance of the forts for the South American continent history, and of the continent for the world history;
4. In its entirety, the sites have a use compatible with the preservation and cultural function, with visitors welcome to all selected locations, with agencies responsible for the management and maintenance of buildings, considering their educational and cultural use.
5. All elements of the complexes are protected at the federal level, and some of them fall under other jurisdictions, such as state and municipal. All are publicly owned, without major problems in management. There is also no threat to any of the elements of the ensembles.

Comparison with other similar properties

The World Heritage List contains at least three other discontinued fortress complexes. The most similar is formed by the fortresses on the Caribbean side of Panama: Portobelo-San Lorenzo, composed of fourteen distinct works, selected as unique assets of the Spanish military architecture of the seventeenth and eighteenth centuries. Located in geo-cultural areas of Central and South America, there are notable distinctions between Brazil and Panama, such as geographical and chronological dimensions of the two fortification groups, much more restricted in the case of Portobelo-San Lorenzo and broader in Brazil. Most notably are the cultural inferences present in the Brazilian fortresses selected, that is, the contacts between different cultures resulting in a particular way of defense, in a country with environmental and territorial characteristics of continental dimensions that shows no parallel.

With greater geographical coverage, there is also the case for the twelve sets of fortresses in Vauban, France. The unifying element of this set is the work of Sébastien Le Prestre, Lord of Vauban, the French military engineer of the seventeenth century and the first years of the eighteenth. In this case, the comparison is valid for the border demarcation point, although in the French case the defensive works were made in areas already consolidated and belonging to the country. Furthermore, in Brazil, most of the fortresses are not exemplary of classical architecture such as Vauban’s, presented more relevantly as works that express representations of the different cultural groups that were established at that time, precisely with the building of defensive works, which delimited the scope and extent of the Portuguese occupation in the New World in the face of different neighboring cultures (Indigenous, Spanish, French, English and Dutch).

In none of these cases there is a direct comparison with a similar reality, usually being limited by geographic extension and narrower chronological outline of the works already included in the World Heritage List of UNESCO. In the case of the fortresses in Brazil, what is being proposed is a representative set with conceptual unity based on the principles that guided the initiative of local residents, covering an area of 8,500,000 square kilometers and 23,000 km of borders. The distinguished character of the Brazilian set of fortresses should also be emphasized, which was formed by the activities of the residents of the country local administration, and not as a result of a central government project, as was the case in the examples mentioned.