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Cartografia Histórica em 3D e Realidade Virtual: uma metodologia de baixo custo

3D Historical Cartography and Virtual Reality: a low-cost methodology

Bernardo da Cunha Carvalho de Mello [1], Juliana Moulin Fosse [2], Alan José Salomão Graça [3], Luís Augusto Koenig Veiga [4]

1 Universidade Federal Rural do Rio de Janeiro, Seropédica, Brasil. bernardo.dacunhacm@gmail.com. ORCID: https://orcid.org/0000-0001-9138-8255
2 Universidade Federal Rural do Rio de Janeiro, Seropédica, Brasil. jumoulin@ufrrj.br. ORCID: https://orcid.org/0000-0002-4221-781X
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brasil. alan.salomao@eng.uerj.br. ORCID: https://orcid.org/0000-0002-0580-6746
4 Universidade Federal do Paraná, Curitiba, Brasil. kngveiga@ufpr.br. ORCID: https://orcid.org/0000-0003-4026-5372

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Abstract: The purpose of this article is to develop a methodological workflow, using low-cost solutions to carry out parametric three-dimensional modeling of buildings and objects belonging to historical-cultural and material heritage. In the context of Historical Cartography, the objective of this work is to promote the dissemination and preservation of Historical Heritage through the use of Virtual Reality, thus providing an interactive, immersive and dynamic approach. As an example, a military building was used, which was built in the 19th century. This building was modeled in 3D based on its original topographic plant and implemented in Virtual Reality for visualization. The applied methodology used cartographic data obtained from the original topographic plant of the building and current scenario photographs, to respectively generate the parametric three-dimensional model and its texturing, in order to resemble the original structure. From the 3D model of the building, a Virtual Reality application was created for the Android system, using the Unity graphics engine and programming tools from the Google API console. The obtained results were adapted for visualization and navigation with the aid of a low-cost virtual reality glasses solution.
Keywords: 3D Modelling. 3D Cartography. Virtual Reality. Cultural Heritage.

Resumo: O propósito do presente artigo é o desenvolvimento de um fluxo de trabalho metodológico, empregando soluções de baixo custo para a realização da modelagem tridimensional paramétrica de edificações e objetos pertencentes ao patrimônio histórico-cultural e material. No contexto da Cartografia Histórica, o objetivo deste trabalho é promover a divulgação e preservação do Patrimônio Histórico com o uso da Realidade Virtual, proporcionando uma abordagem interativa, imersiva e dinâmica. Como exemplo, foi usada uma edificação militar, que foi construída no século XIX. Esta edificação foi modelada em 3D a partir de sua planta topográfica original e implementada em Realidade Virtual para a sua visualização. A metodologia usada empregou dados cartográficos obtidos a partir da planta topográfica original da edificação e de fotografias de campo atuais, para gerar respectivamente o modelo tridimensional paramétrico e sua texturização, de forma a se assemelhar à estrutura original. A partir do modelo 3D da edificação, criou-se um aplicativo de Realidade Virtual para o sistema Android, por meio do motor gráfico Unity e ferramentas de programação do console Google API. Os resultados obtidos, foram adaptados para visualização e navegação com o auxílio de uma solução de óculos de realidade virtual de baixo custo.
Palavras-chave: Modelagem Tridimensional. Cartografia 3D. Realidade Virtual. Patrimônio Histórico-Cultural.

1 INTRODUCTION

At the beginning of this decade, travel restrictions, lockdowns (either total or partial), and absenteeism due to illness emerged as significant effects of the COVID-19 pandemic, with substantial social and economic impacts. The adoption of social distancing measures in Brazilian states and municipalities had repercussions on access to cultural heritage, education, tourism, leisure, and in-person forms of cultural interaction (Brito et al., 2023; Botto et al., 2022; GaBERLI, 2022; Nascimento, 2020; Neca; Rechia, 2020). Like other countries, these sectors had to find new ways to engage the public, as travel and mobility were largely restricted (Botto et al., 2022; Theodoropoulos; Antoniou, 2022).

Reflecting on this problem imposed by the "stay at home" (Brito et al., 2023; Neca; Rechia, 2020), Virtual Reality (VR) represents one of the alternatives that enables users to be virtually transported to these spaces, generating digital environments that provide both specialists and non-specialists with the experience of interactivity and immersion in spaces similar to perceived reality (Bagher et al., 2023; Botto et al., 2023; Cheng et al., 2022; Pinto; Centeno, 2012; Fosse; Veiga, 2006). In recent years, with the Industry 4.0, VR technologies have become cheaper and powerful enough to reach a much wider audience (Graça et al., 2021; Walmsley; Kersten, 2019). This development presents new and exciting opportunities for institutions responsible for cultural heritage, such as museums, archaeological sites, and historical buildings, which seek to engage new audiences through their collections, historical artifacts, architectural particularities, and archives (Ackerman et al., 2023; Chong et al., 2022; Theodoropoulos; Antoniou, 2022; Walmsley; Kersten, 2019; Fritsch; Klein, 2017; Remondino, 2011).

Combined with 3D modeling, VR presents itself as a tool with great potential for understanding Cartography and its applications, providing efficient solutions for handling complex scenes, through new tools and new data sources to represent realistic models, or extensions of reality with digital data or the reconstruction of past landscapes (Bagher et al., 2023; Tsou; Mejia, 2023; Chong et al., 2022; Gatta; Arioti; Bitelli, 2017; Fosse; Veiga, 2006). The digital reconstruction of historical sites has become a relevant application for Geomatics, which provides inputs for the conservation of cultural heritage, through surveys, modeling, and three-dimensional imaging of objects (Ackerman et al., 2023; Graça et al., 2021; Walmsley; Kersten, 2019; Gatta; Arioti; Bitelli, 2017; Remondino, 2011). This reconstruction can result in photorealistic virtual models, as well as non-photorealistic parametric models (Ackerman et al., 2023; Günay, 2019; Gavette; Page-Schmit, 2018; Döllner, 2007).

In both perspectives, more advanced studies (which are beyond the scope of the present research) theoretically mention or propose practical experiments for cartographers to use new "visual cues" in the representation of dynamic virtual environments supported by immersive technologies (Bagher et al., 2023; Limberger et al., 2023; Tsou; Mejia, 2023; Cheng et al., 2022; Halik, 2012). These scientific researches deal with cartographic representations in augmented realities, working with 3D/4D mapping, exploration of spatio-temporal patterns and associations between objects, the use of the "Metaverse" as a scientific inspiration/metaphor to create web GIS applications, and user-centered design (UCD) aimed at capturing users' experiences in immersive environments (Bagher et al., 2023; Tsou; Mejia, 2023; Chong et al., 2022; Herman; Kvarda; Stachoň, 2018). On the other hand, the analysis of historical maps and plans allows the reconstruction and understanding of the current configuration of cultural landscapes, revealing the marks and nuances left in the past (Ackerman et al., 2023; Zawadzki, 2022). This allows for a critical assessment of its evolutionary dynamics based on the cultural artifacts contained in these documents (Balletti; Guerra, 2016; Lafreniere; Rivet, 2010). Historical Cartography brings with it valuable information about geographical arrangements, cultures, and the landscapes of past eras, which often cannot be found in other written sources, such as toponyms, boundaries, and physical characteristics of features that have been altered or completely erased by time (Fiorini; Friso; Balletti, 2022; Gavette; Page-Schmit 2018; Balletti; Guerra, 2016; Hájek et al., 2013). In the field of historical cartography research, cartographic products such as maps, charts, plans, and diagrams (where they exist) constitute a factual basis for a diachronic analysis of a city (LAFRENIERE; RIVET, 2010). These can make cartographic information more accessible and geographic environments more intuitively understandable (Balletti; Guerra, 2016).

This article presents a process of 3D cartographic visualization of spatial data in historical maps, in order to reconstruct a lost architectural heritage, employing the use of different digital technologies. Its scientific domain at the interface with Historical Cartography was based on the works of Tytarenko, Pavlenko and Dreval (2023), Fiorini, Friso and Balletti (2022), Janovský, Tobiáš and Cehák (2022), Morlighem, Labetski and Ledoux (2022), Günay (2019), Gavette and Page-Schmit (2018), Herman, Kvarda and Stachoň (2018) Fritsch and Klein (2017), Gatta, Arioti and Bitelli (2017), Hájek et al. (2013). The objective of this article was to generate a reusable three-dimensional modeling methodology, showing how low-cost technologies can be used to create an interactive and immersive virtual reality environment. The 3D visualization was obtained using non-photorealistic parametric modeling in CAD (Computer Aided Design) adopting mainly data from historical cartographic documents with immersive VR technologies for smartphones (Bagher et al., 2023; Tytarenko; Pavlenko; Dreval, 2023; Herman; Kvarda; Stachoň, 2018; Döllner, 2007). To obtain a low-cost product, technological alternatives such as free and/or commercial software with educational licenses, low-cost VR glasses on e-commerce sites, and free programming solutions for Android operating system applications were explored. As a test area for the experiments proposed in this article, Forte do Raio was chosen, an important fortification during the period of Imperial Brazil, which served to protect the land route between the villages of Mangaratiba and Itaguaí, and the coastal region of Rio de Janeiro (De Souza, 1885). In 2018, the fort was rediscovered by researchers, and a process was initiated, together with the Institute of National Historical and Artistic Heritage (IPHAN), for it to become an archaeological site, given its historical importance in the regional context (Mello, 2018). The cartographic product generated for this fortification made it possible to recognize past forms and features, digitally reconstructed and accessible to people remotely.

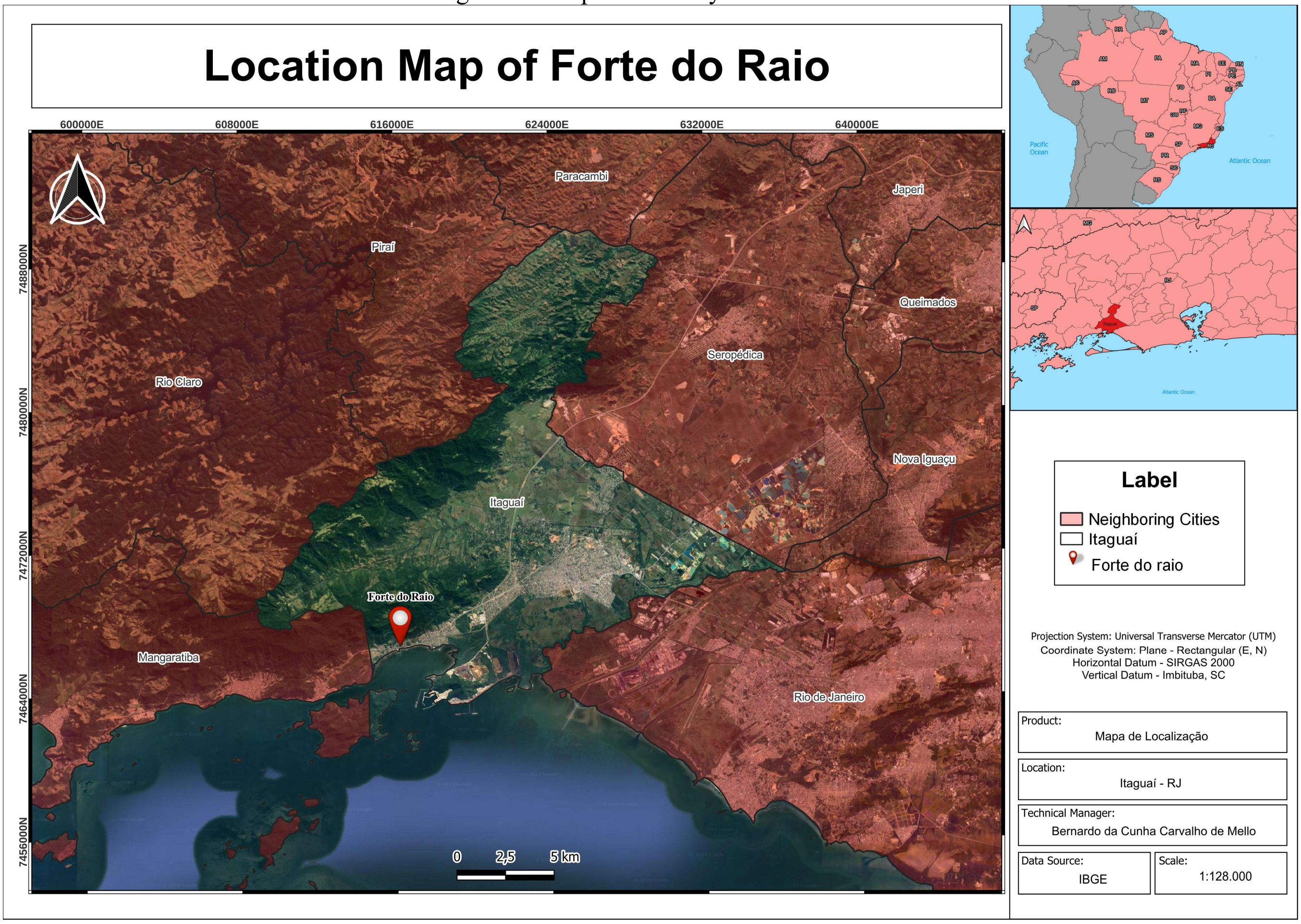
2 MATERIALS AND METHODS

In order to achieve the proposed objectives, the methodology was structured so that users could have access to a cartographic product that could be operated on Android smartphones available on the market. The aim is to promote material historical heritage through a high-quality virtual tour, which is academically reusable and accessible to the general public (Ackerman et al., 2023; Fiorini; Friso; Balletti, 2022; Janovský; Tobiáš; Cehák, 2022; Luo et al., 2018; Fritsch; Klein, 2017; Pinto; Centeno, 2012; Fosse; Veiga, 2006).

2.1 Study Area

The Forte do Raio was chosen as the building, located in the Coroa Grande neighborhood, in the municipality of Itaguaí, in the state of Rio de Janeiro, in the region known as Costa Verde, which encompasses the Sepetiba Bay (Figure 1). A three-dimensional version of the forte was modeling in Sketchup. According to Mello (2018), it is estimated that the construction of the fortification was around the year 1822. During the Imperial period of Brazil, it played a crucial role as a defensive structure in the outskirts of its capital. The main function of this fortification was to protect the connecting route between the village of São Francisco Xavier de Itaguaí and the region of Nossa Senhora da Guia de Mangaratiba, which today correspond to the cities of Itaguaí and Mangaratiba, respectively, as well as the coast of Rio de Janeiro (De Souza, 1885). In a lamentable state of conservation, the fort was rediscovered in 2018, with only ruins remaining of what was once an imposing fortress (Mello, 2018).

Figure 1 – Map of the study area location.

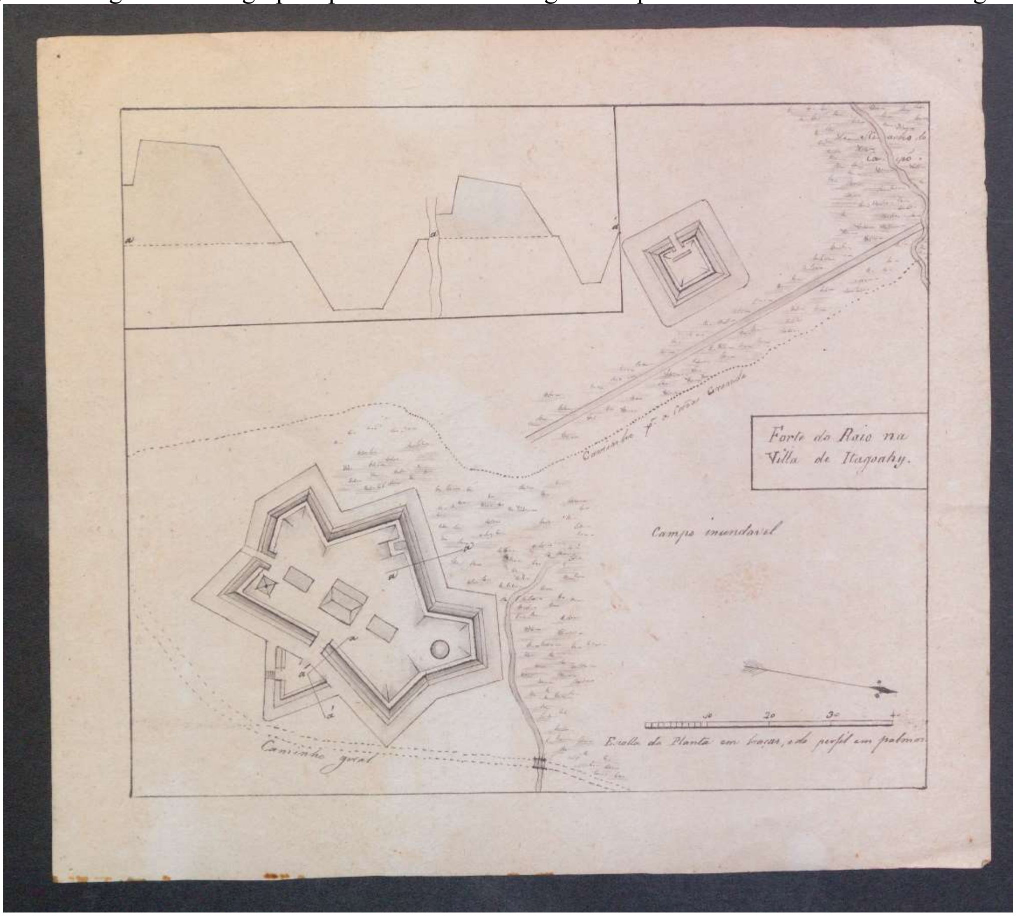


Source: The authors (2024).

2.2 Materials Used

As the primary documentary source of spatial data, the original topographic map of Forte do Raio (Figure 2) was used, owned by the Portuguese Military Historical Archive (record code PT/AHM/DIV/3/47/AV2/3563). Titled "Forte do Raio na Villa de Itagoahy," this cartographic product presents, along with its scale, the information "Scale of the Plan in fathoms (braças in portuguese), and of the profile in palms," since Portugal only adopted the metric system in 1852, and even then, gradually (Marques, 2001). With the digitized image in TIFF format (2823 x 2541 pixels), it was possible to obtain the dimensions of the geometry of the external and internal features of the fortification, its shapes, and the geographical accidents present in the site's surroundings, as well as the height of the buildings in relation to the terrain, provided by the elevation profile contained in Figure 2.

Figure 2 – Digitized cartographic product from the original map "Forte do Raio na Villa de Itagoahy"



Source: Portuguese Military Historical Archive (2022).

With the purpose of recognizing the structure of the building and verifying the real dimensions with the graphic scale on which the fortification was represented (in units of fathoms), including the vertical scale adopted (in units of palms), a field research was carried out at the ruins of Forte do Raio in 2022. A photographic record was taken at the site and manual measurements were made with a tape measure, for comparison with the original topographic map, as well as to assist in 3D modeling. The purpose of the photographic record was to assist in the reconstruction of textures and geometric shapes peculiar to the building under investigation, similar to the research of Zawadzki (2022) and Hájek et al. (2013). The elevation profile of the terrain does not clearly show the height of the wall; therefore, a simple arithmetic mean of the heights found was taken, obtaining a value of 4 meters in height. Through the photographic record, it was possible to formulate approximate conjectures to detail the structure and facades of the fortification (Zawadzki, 2022). Given the advanced stage of deterioration of the ruins, these photographs do not make it possible to reconstruct specific ornaments. Combined with the information from the field and the topographic map, secondary sources of readings on Brazilian fortifications were adopted, such as De Souza (1885) and the registration of the designation of the Forte do Raio by Mello (2018).

The cartographic base of the municipality of Itaguaí, whose altimetry is represented by contour lines with an equidistance of 5 meters, was collected from the National Spatial Data Infrastructure (INDE) in the IBGE database, and cropped for the region around the fortification. Information regarding the planimetric features of the surroundings was collected using Google Earth Pro software (Luo et al., 2018). These images were discussed in an interview with historian Eduardo Vieira, discoverer of the archaeological site of the fortification, in order to obtain greater conjectural knowledge about the terrain at the time. One of the contributions of the interview with the historian was the remodeling of the region due to the carrying out of several landfills in the region over the years. Regarding the technological solutions used, in addition to the Google Earth Pro software, the following were used:

a) The open-source QGIS software, version 3.20, for carrying out cartometric analyzes on the fortification plan, together with the visualization of features using the Google Earth base map (openlayer) (Lafreniere; Rivet, 2010);

b) Autodesk AutoCAD Civil 3D 2019, educational version, for generating vectors of contour lines, digital plan and insertion of linear dimensions obtained in the field plan (Tytarenko; Pavlenko; Dreval, 2023; Günay, 2019);

c) Blender software, student version 2.93, for parametric modeling of the fortification (Herman; Kvarda; Stachoň, 2018);

d) Trimble Sketchup Pro 2019 firmware, adopted to build the digital terrain model and texture both the DTM and the 3D model of the building, finally creating the cartographic representation of the region (Zawadzki, 2022; Günay, 2019; Gavette; Page-Schmit, 2018);

e) Unity game engine, version 2018.3.3f1, available for free on its own website for building the VR navigation environment (Bagher et al., 2023); mapa base (*openlayer*) do *Google Earth* (Lafreniere; Rivet, 2010);

f) Microsoft Visual Studio 2019 free software, which contains adaptable programming codes for navigation with the smartphone's motion sensors (gyroscopes and accelerometers) (Sampaio; Veiga; Alves, 2023);

g) Android Support plugin, which makes it possible to create an application for smartphones with the Android operating system (Kanchana; Sindhya, 2021);

h) a smartphone in versions 11 and 12 of the Android system, used for testing the VR application;

i) and a low-cost VR headset with a joystick, from the VR BOX brand (Herman; Kvarda; Stachoň, 2018; Coburn; Freeman; Salmon, 2017).

2.3 Generation of Cartographic Representations

2.3.1 REPRESENTATION OF PLANIMETRIC INFORMATION

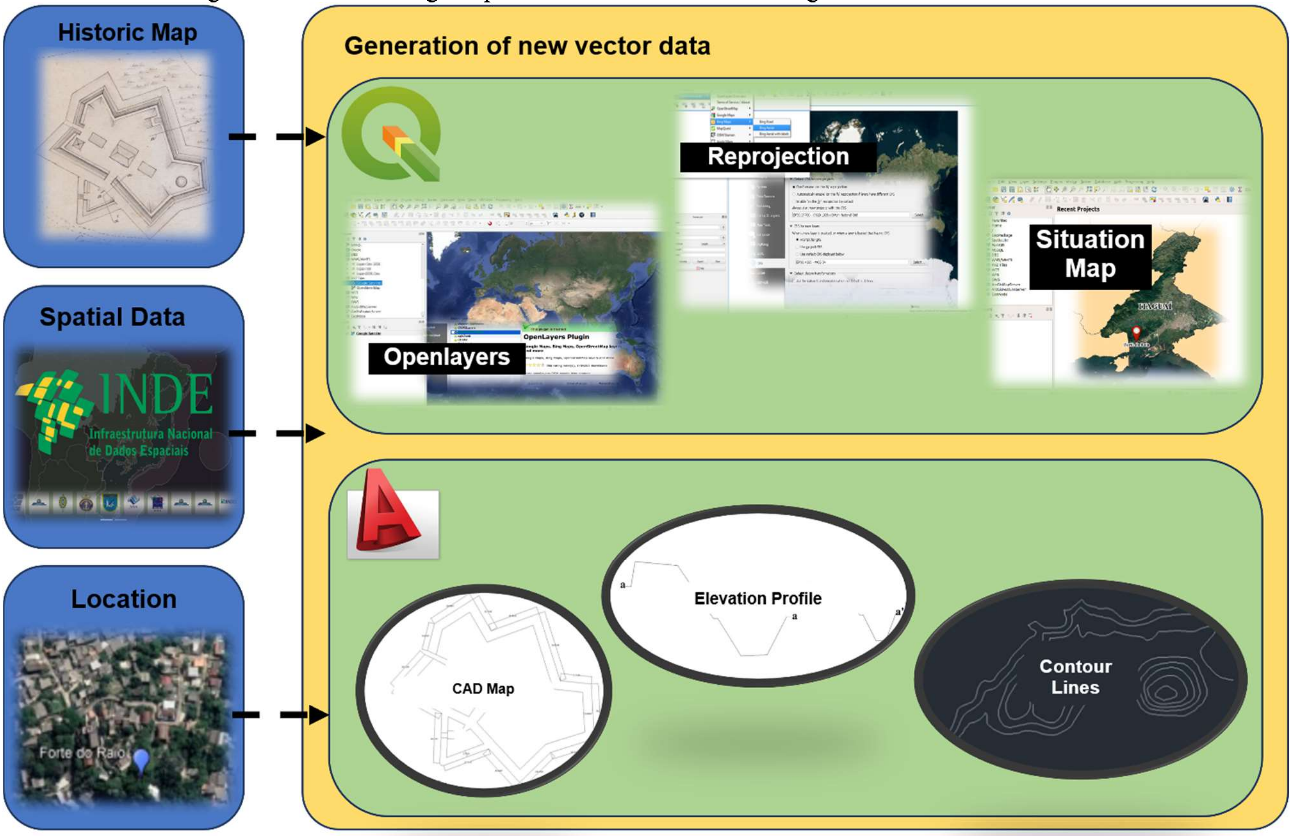
The measurements of the fortification's topographic map were analyzed using GIS and CAD software, respecting the scale obtained in the field (Janovský; Tobiáš; Cehák, 2022). The creation of the situation map used the municipal base in vector format available on the INDE geoportal, together with the Google Earth Satellite open layer base map. The coordinates of the fortification were obtained indirectly, using Google Earth Pro software, with the UTM coordinate system option (Luo et al., 2018). These coordinates were inserted as a new point layer in QGIS, version 3.20, together with the aforementioned layers, all reprojected to the EPSG:3857 encoding ellipsoid (very close to SIRGAS2000), focused on spherical Mercator projection systems, known as Web Mercator Projection, adopted in Google's web mapping geoservices (Kessler; Battersby, 2019). Other cartometric procedures that are not part of the objectives of this article, adopted for the extraction of historical features contained in this map, are available in Mello et al. (2023). The conversion of the original measurements of the cartographic document to the international metric system could be performed simply by applying data from the conversion table of measures brought by Marques (2001). Braças and Palmos are old measurement units used in Brazil, the value of Braça (approximately 2.2 m) and Palmos 0.222 m. Equation 1 and Equation 2 show respectively, that:

$$valorembraças * 2{,}22\left(ou2\frac{1}{5}\right) = valoremmetros \quad (1)$$

$$\vee\ valorempalmos * 0{,}222 = valoremmetros \quad (2)$$

For this cartometry stage, the map was scaled in the Autodesk AutoCAD Civil 3D 2019 software, educational version. The zoom on the screen was increased by 70% with the topographic map layer activated, in order to measure the graphic scale with the aid of a graduated ruler, and to measure the linear dimensions of the fortification. It was measured that 10 braças are equivalent to 3 cm on the topographic map of Forte do Raio, therefore each 1 cm on the map is equivalent to 7.4 m in ground measurements. And for the profile present in the document, it was measured that 10 palmos are equivalent to 3 cm, that is, each centimeter on paper represents 0.73 m on the ground. From the dimensions identified on the topographic map, it was possible not only to measure the dimensions of the structure of Forte do Raio but also to create a digital topographic representation of the site. Similarly, the elevation profile of the building was created. In this analysis of the dimensions, it was identified that Forte do Raio had a built-up area of approximately 6,620.55 square meters and a perimeter of 372.84 meters. These cartometric procedures are excessively limited, given that: since it is a building plan, the curvature of the Earth was considered negligible, working only with the conversion of units of measure (Lafreniere; Rivet, 2010); in order to minimize uncertainties for cartometry and perform more robust spatial analyzes in a GIS (Fiorini; Friso; Balletti, 2022); some recommendations were pointed out in the conclusions. Continuing with the methodological procedures, the digital file of the altimetry of the municipality of Itaguaí was imported into Autodesk Autocad Civil 3D, limited (layer clipping) to the contour lines only to the region of interest of the study, which correspond to the limits of the historical map. This vector file in DWG format was edited automatically to correct the geometries of the polylines, thus ensuring the absence of duplicate vertices and disconnected points in the same. Figure 3 illustrates the methodological procedures carried out in this stage of the work.

Figura 3 – Methodological procedures carried out for the generation of the 3D model.

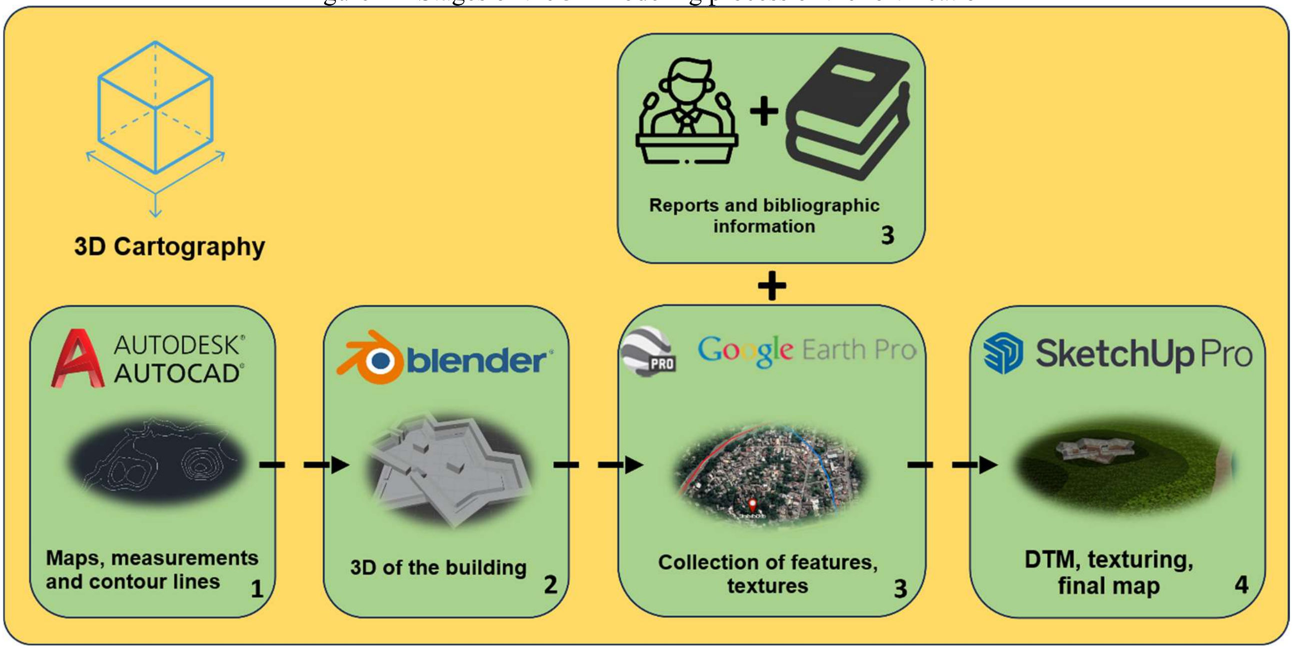


Source: The authors (2024).

2.3.2 3D CARTOGRAPHY

Simultaneously, a three-dimensional model was constructed to highlight the material heritage and enable better understanding by users. For this purpose, the information was input into applications commonly used to generate products in CAD and BIM (Building Information Modeling), as shown in Figure 4. Its adoption is possible because it offers many intuitively usable tools for modeling 3D objects, compared to the tools available in GIS software (Janovský; Tobiáš; Cehák, 2022; Günay, 2019; Hájek et al., 2013).

Figure 4 – Stages of the 3D modeling process of the fortification

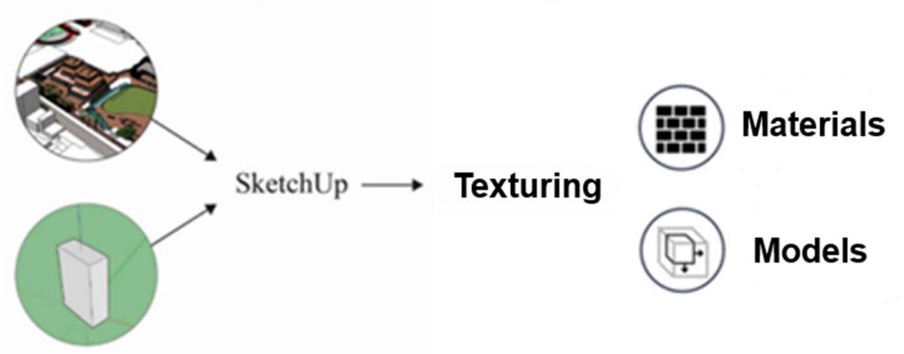


Source: The authors (2024).

Subsequently, the updated contour line file was imported into Trimble Sketchup Pro, version 2019, a trial version, with the aim of creating a non-photorealistic DTM (Digital Terrain Model) (Tytarenko; Pavlenko; Dreval, 2023; Hájek et al., 2013; Döllner, 2007). Using the "Sandbox" tool, a parameterized 3D model of the area around Forte do Raio was created based on the measurements of the contour lines in the .DWG file. Based on information collected from Google Earth Pro and oral history accounts from researcher Eduardo Vieira, Sketchup editing tools were used to adjust the DTM to resemble the terrain at the time.

By correlating these bibliographic sources on other contemporary fortifications with photographic records of the ruins, it was possible to interpret that its structure was made of ashlar limestone masonry. These structures of the fortification were similar to others from the time of its construction, defining the textures, which could not be interpreted in the original topographic map. There are pre-defined models of textures for facades and walls of buildings in Sketchup similar to the textual information described, and they offer a good contrast for this visual variable with the 3D representation scenario (Günay, 2019; Gavette; Page-Schmit, 2018; Halik, 2012). These textures were combined in the software with the textures observed in the photographs, thus better reconstructing the building. These procedures are outlined in Figure 5.

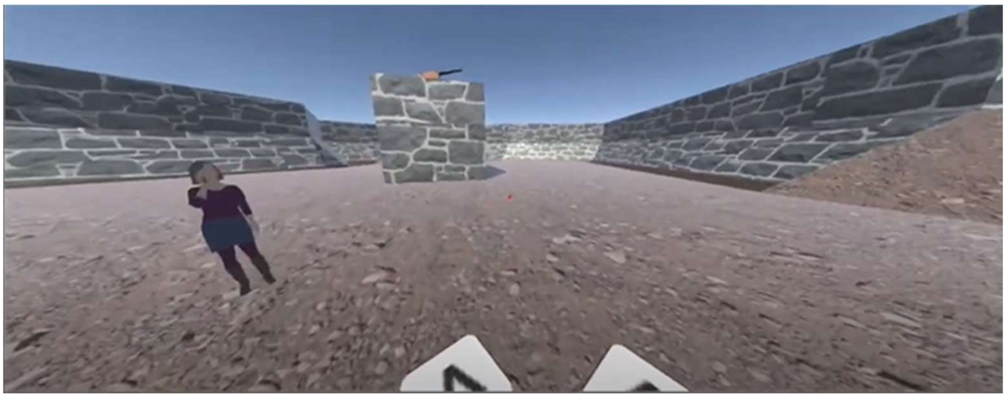
Figure 5 – Process of texturing the 3D models.



Source: The Authors (2024).

In addition to applying the texture to the 3D model, a person approximately 1.80 m tall was added to illustrate the dimension of Forte do Raio at the time. This additional element is an inference resource so that the user can have a scale assessment of the model (Morlighem; Labetski; Ledoux, 2022), as can be seen in Figure 6.

Figure 6 – Reference model of a person added to the 3D model.



Source: The Authors (2024).

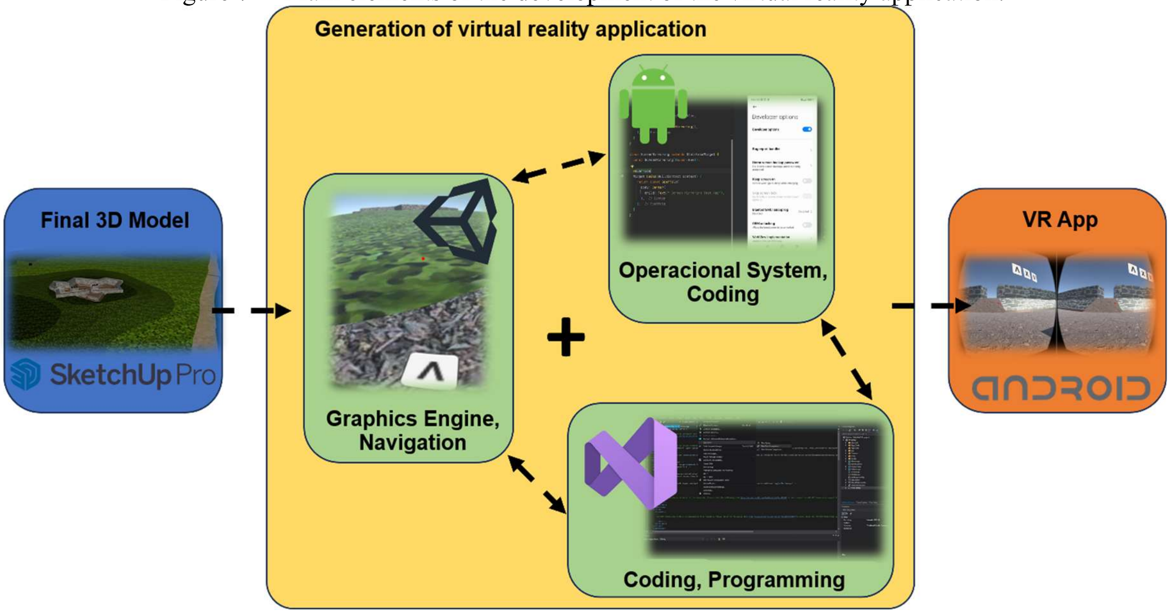
In addition, lighting features available in Sketchup were adopted to facilitate users' visualization of volumetric features, including elements such as the object's shadow projected onto the ground (HALIK, 2012). The position of other objects, such as the cavalier battery, for example, can be interpreted from the iconography of the Forte do Raio model derived from the historical map.

The next step was to combine the 3D model of Forte do Raio with the DTM of the surrounding region. Using Sketchup Pro, the two models were integrated, resulting in the final 3D model, which represents the highest level of detail achieved in this research (Hájek et al., 2013). By positioning the three-dimensional model of the fortification on the current ruins, the user can visualize the orientation of the fort's batteries, gaining an understanding of coastal defense and surrounding paths.

2.4 Navigation in VR

The procedure for creating the VR navigation environment was carried out using the Unity game engine, version 2018.3.3f1, available for free on the company's website, along with the Microsoft Visual Studio Community 2017 and Android Support plugins (Walmsley; Kersten, 2019). In Unity, the free Google developer tool package was used, which offers components for building VR experiences. In addition to the Google package, other tool sets provided by Unity were incorporated into the project, including the "Environment" and "Characters" packages (Kanchana; Sindhya, 2021; Coburn; Freeman; Salmon, 2017). Subsequently, the 3D model of Forte do Raio was imported into Unity in DAE (COLLADA) format, a format capable of transporting textures to the graphics engine without loss of visual quality of the graphic elements. Figure 7 presents a methodological scheme of how the VR application was structured.

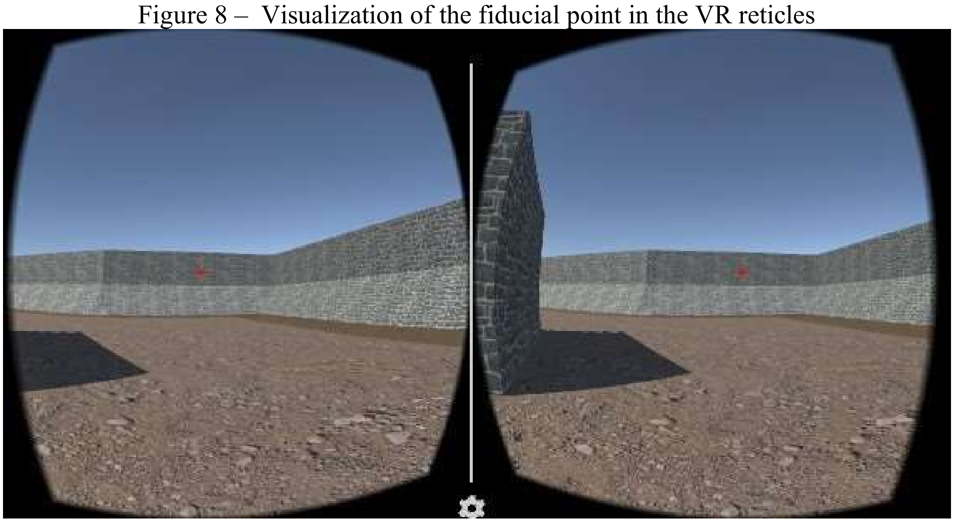
Figure 7 – Main elements of the development of the virtual reality application.



Source: The Authors (2024).

The Google VR components: "GvrViewerMain" and "GvrEventSystem", imported from Android Support, made it possible to split the viewing screen so that each user's eye sees a part of the image with overlap, enabling stereoscopy (KANCHANA; SINDHYA, 2021). In the project environment, a folder called "Head" was generated to represent the "user" within the project, and a main camera was imported into this folder. In VR, it is important that the main camera of the graphics engine is positioned appropriately to simulate human vision within the 3D model. Therefore, the main camera was positioned in the 3D model of the structure of Forte do Raio at a height corresponding to the simulation of human vision. For this purpose, the human scale of 1.80 m was positioned inside the model of the fortification. In addition, the use of the "GvrReticlePointer" component from the Google package was incorporated into the camera (KANCHANA; SINDHYA, 2021). This component enables the creation of a homologous focal point in VR vision, allowing the user to interact with the immersive environment in a manner similar to a mouse cursor on both screens. Initially, the created point has a white color; however, to avoid conflicts with the lighter colors of the 3D model textures, the color of the point was changed to red, as exemplified in Figure 8.

Figure 8 – Visualization of the fiducial point in the VR reticles



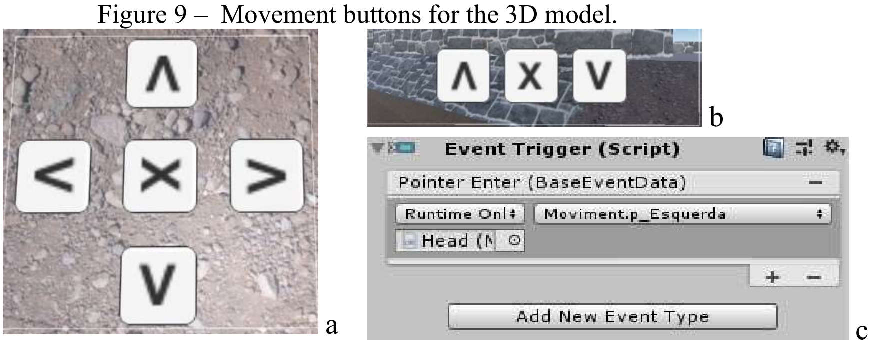
Source: The Authors (2024).

One of the most challenging parts of VR implementation was developing the ability for the user to move within the 3D model, which required the use of specific programming codes. The code responsible for this movement, called "Movement", was developed using Microsoft Visual Studio 2019, a free programming tool. Subsequently, the code was incorporated into the "Head" folder in the graphics engine.

During the process, it became evident that it was necessary to allow the user to move on the Y axis in the immersive environment, that is, to move closer or farther away from the 3D model of the fortification (Coburn; Freeman; Salmon, 2017). To meet this need, an additional code was developed for movement on the Y axis, also using Microsoft Visual Studio 2019, with a programming approach similar to the locomotion code.

To make the newly implemented codes accessible to the user, navigation buttons were created using the "Canvas" object in Unity (Figures 9a and 9b). For their design in the "Canvas," the fundamentals of digital visual variables were employed (Limberger et al., 2023; MacEachren, 1994), based on practical experiments that indicate satisfactory contrast results between navigation elements and immersive environments on smartphones (Halik, 2012; Pinto; Centeno, 2012). Buttons with a white background and black movement symbols were adopted, arranged in the center of the background, with a focus effect smoothing the vertices of the graphic rectangles (Halik, 2012; MacEachren, 1994). These buttons provide directional movement, as well as a stop button, identified by the letter "X". The movement buttons were positioned below the main camera to avoid obstructing the user's field of view in the 3D model (Halik, 2012). Additionally, using the "Canvas" object, additional buttons were created for movement on the Y axis, placed in the upper right corner of the main VR view. Being small, these buttons do not interfere with the user's immersive visual experience. The next step was to give movement functionality to each button: initially inserting the movement codes into the "Head"; followed by the individual addition of the "Event Trigger" component; where the "Point Enter" function was defined so that each button is activated by clicking. Thus, the functionality was chosen for each button, as shown in the screenshot in Figure 9c.

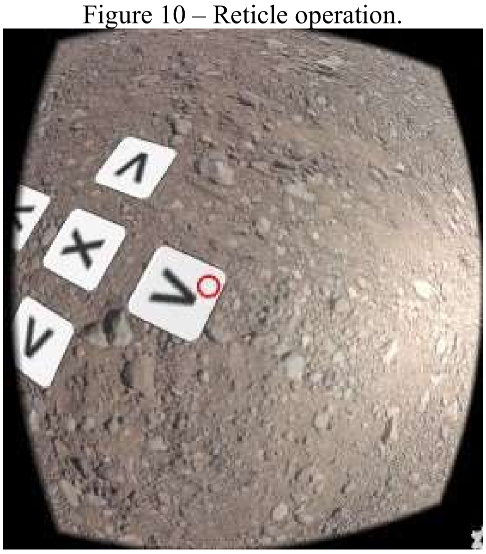
Figure 9 – Movement buttons for the 3D model.



Source: The Authors (2024).

It became possible to move around the 3D model simply by positioning the cursor over the button. In this way, the circular reticle increases in size, indicating that it is being used, as shown in Figure 10.

Figure 10 – Reticle operation.



Source: The Authors (2024).

The center of the Forte do Raio structure was chosen as the starting point of the immersive experience, as it provides a broad view of the building, making it an interesting location to start the navigation experience. It was necessary to modify the application's use platform from computer to the Android system in the "Build Settings" window, changing the option "PC, Mac & Linux Standalone" to "Android". In this way, it was possible to create an application for smartphones with the Android operating system, as the graphics engine is conditioned to create applications for personal computers.

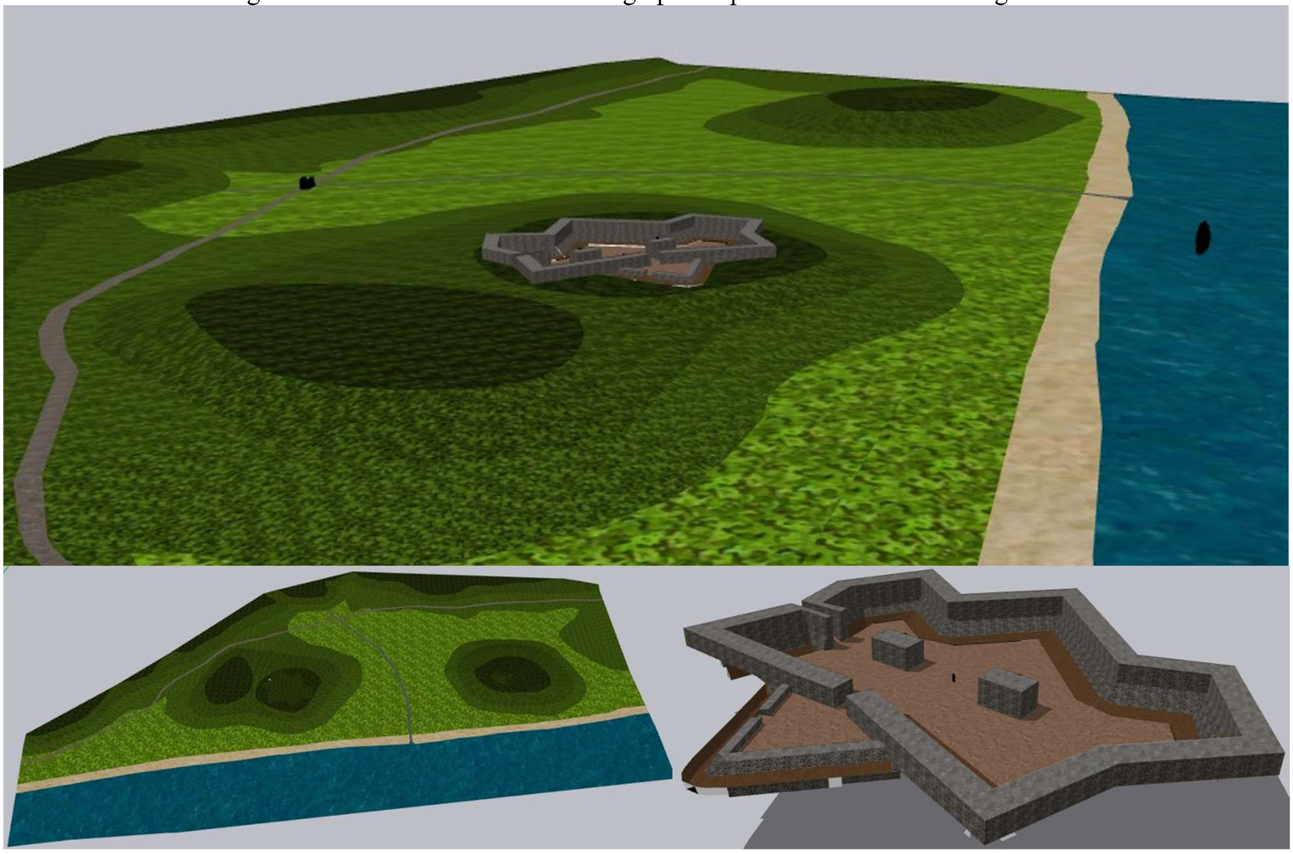
After this procedure, it was necessary to make customizations to the application settings in the "Player Settings" window, such as name, description, logo, and others, and in the "XR Settings" tab, choose the "Virtual Reality Supported" function and opt for "Cardboard". Before creating the application, it was necessary to locate the folder designated to host the Android application in the computer's operating system. To locate the folder for creating the Android application, Android Studio version 2021 was used, and the path to the aforementioned folder was indicated in Unity (Walmsley; Kersten, 2019).

Finally, after making the necessary corrections to the application, such as the initial location and scale of the 3D model, the VR associated with this application was ready. In the "Build Settings" window, the "Build" button was clicked to create the application in .apk format, and after a few minutes, the VR application was created. The application can be transferred to the smartphone of interest as long as it supports the use of VR technology for the 3D model of Forte do Raio.

3 RESULTS AND DISCUSSIONS

The first result generated was the parametric three-dimensional model of the fortification, inserted into a digital terrain model of the surrounding area (Figure 11). Both were textured conjecturally, using bibliographic sources and information from oral history accounts, and compatible with the marginal information of the topographic map "Forte do Raio na Villa de Itagoahy" and the field photographs presented earlier in the methodology.

Figure 11 – Three-dimensional cartographic representation for VR navigation.

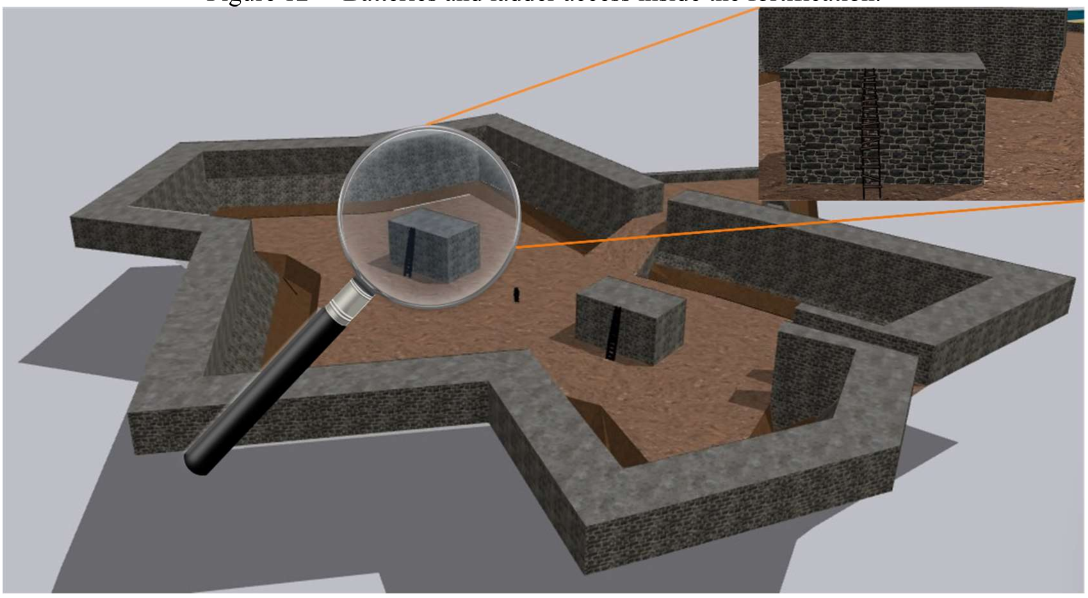


Source: The Authors (2024).

The texturing process of the 3D model of the building was created artificially, finding elements close to the patterns of colors, shapes, and textures similar to the information collected throughout the research process. Based on the current conditions of the ruins and the soil on which the fortification stands, a non-photorealistic three-dimensional cartographic product was generated that enables visualization inside and outside the building. Inside, the wall and access to the battery were intentionally highlighted, as they are the most notable features of the historical map.

The "cavalier" batteries of Forte do Raio were at a higher elevation than the surface of the fortification (De Souza, 1885). There are no records about the height of these batteries, nor indications on the map about the range of the artillery, which would allow obtaining these measurements indirectly through trigonometry. Access to the batteries was represented by a ladder made of wood. This is because, in the original map and in the additional data, a ladder made of stone (the same material as the structure) or even beaten earth was not identified. Therefore, these stairs were conjectured in a plausible position and compatible with the use of artillery pieces described by Lyra (2019) for Portuguese fortifications, as illustrated in Figure 12.

Figure 12 – Batteries and ladder access inside the fortification.



Source: The Authors (2024).

The immersive navigation environment was developed for Android smartphones with gyroscope and accelerometer sensors, compatible with low-cost VR Headset (VR Box) (Sampaio; Veiga; Alves, 2023; Herman; Kvarda; Stachoň, 2018; Coburn; Freeman; Salmon, 2017). In most cases, the smartphone's protection system will not allow the application to be installed directly, so the user needs to enable permissions in the operating system through the smartphone's settings.

After installing the application on different smartphone models and different versions of the Android operating system, an execution error involving the Unity Game Engine and the Android system in version 12 was noticed. This problem was reported in several international forums on VR, and possibly occurs due to issues with updating component drivers in the operating system. Thus, it prevents the use of the application on smartphones with some versions of the operating system, which did not occur on smartphones with version 11 of the Android system.

After installation, the application will be in the smartphone's app list with the name "Forte do Raio", and by clicking on the logo, the user will access the initial screen shown in Figure 13.

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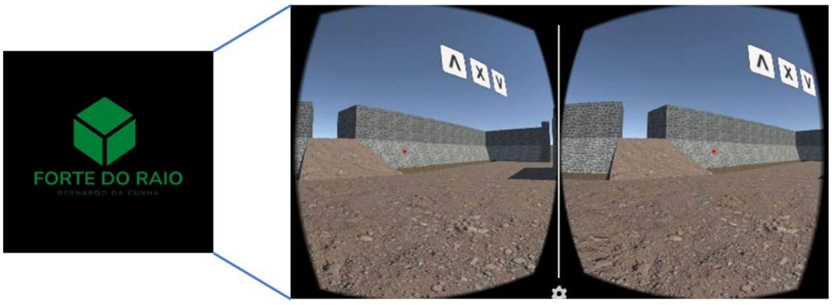
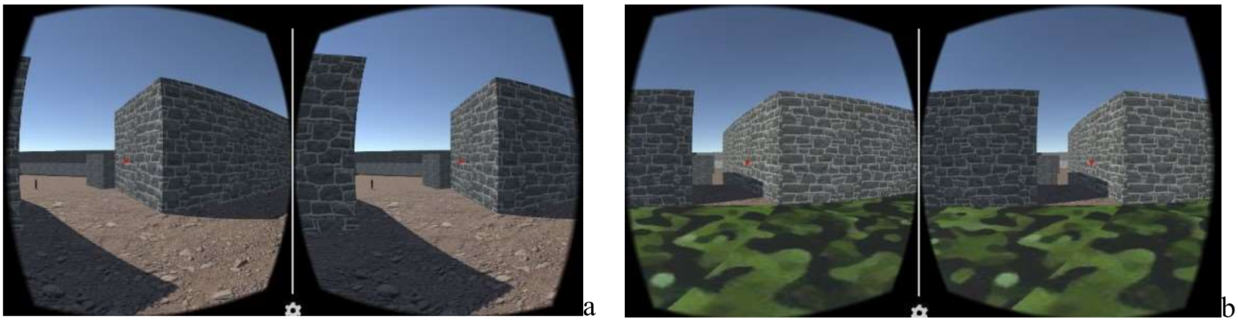
Figure 13 – Initial view of the user when opening the VR app.



Source: The Authors (2024).

Aiming to meet one of the proposed objectives of creating an immersive tool to disseminate and promote historical and material heritage buildings, the following results explore navigation through features in the three-dimensional model. Figure 14 illustrates the user's view when entering the fortification through its different accesses. Forte do Raio had two entrances; it is believed that the side entrance was the main entrance, as the other entrance was located at the tenailles - an external military protection instrument (Mello, 2018).

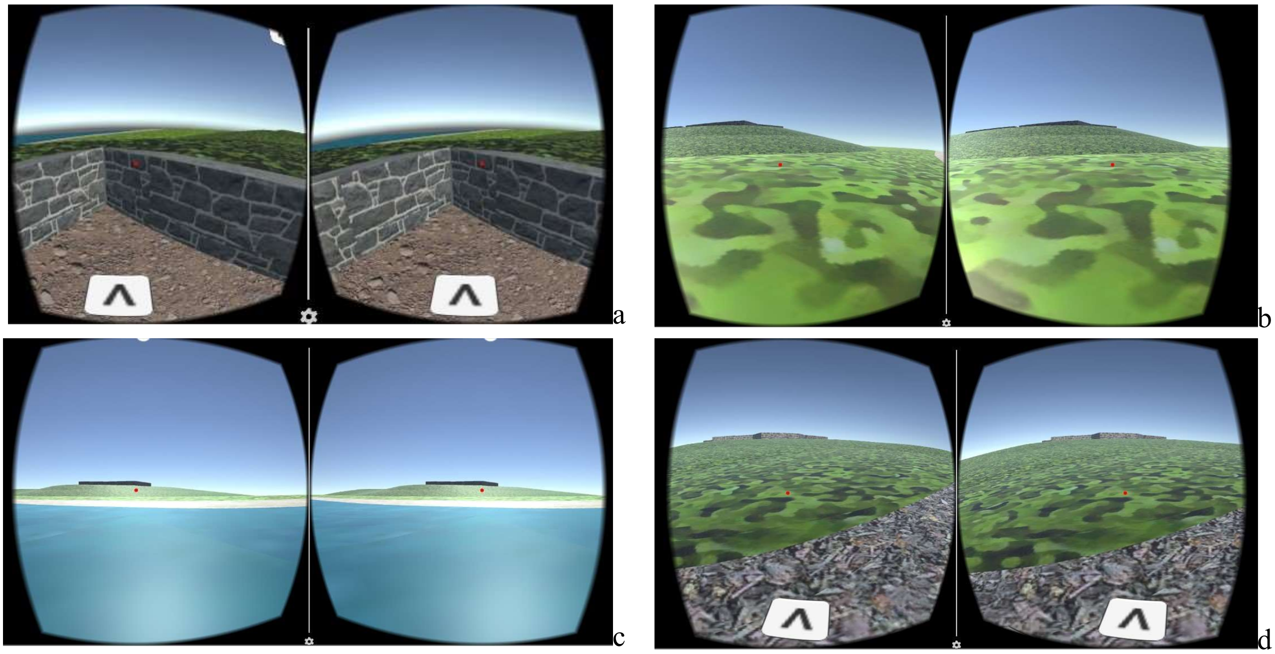
Figure 14 – View of the tenailles into the fortification in a VR environment: (a) view of the tenailles; (b) view of the side door.



Source: The Authors (2024).

Continuing with the navigation, Figure 15a shows the view oriented towards the sea from the tenailles. After leaving the tenailles, there is a view of Forte do Raio from the beach, illustrated in Figure 15b, and the imposing nature of Forte do Raio becomes evident when turning the camera back towards it. Despite all its imposingness, it could easily be camouflaged due to the large number of trees in the area. Just as an illustration, a caravel was added to the model, and Figure 15c shows the view that an enemy ship would have of Forte do Raio, showing that even from the sea, the fortification could go unnoticed by enemies. On the opposite side of the beach, on the interior of the continent, there is the path to Coroa Grande, which has a wide view of Forte do Raio, as illustrated in Figure 15d. As a demonstration of this experience, the following link opens a video of the navigation inside the 3D model of Forte do Raio in a VR environment: https://youtu.be/gZTm1TXgSJ4.

Figure 15 – Shows: (a) the view from the tenailles to the sea; (b) view of the beach to Forte do Raio; (c) view of an enemy ship to the fortification; (d) view of the path to Coroa Grande to the fort.



Source: The Authors (2024).

4 FINALS CONSIDERATIONS

This study sought to demonstrate in a practical way that low-cost VR technologies, combined with Historical Cartography, reveal an immersive, dynamic, and interactive way of learning about our country's history and maintaining and preserving Historical and Cultural Heritage (CHONG et al., 2022). In this way, it enables the digital reconstruction of monuments or even entire cities based on three-dimensional models generated from geospatial data contained in historical maps. The metric recovery and processing of past data contained in historical maps, in addition to preserving the historical geographic and cultural heritage, opens up new possibilities for the use of this digitized geoinformation, unattainable with only analog support. The historical map served as a source for the generation of a parametric model, complemented by other data sources that enabled VR navigation.

The development and adoption of virtual tourism practices is an example of how access to cultural assets, existing or reconstructed, as is the case in this work, can be made available to the population (Theodoropoulos; Antoniou, 2022; Remondino, 2011). The so-called Internet of Things (IoT) has enabled museums, historical buildings, archaeological sites, or even places that no longer exist today to be visited virtually (Gaberli, 2022; Graça et al., 2021). Regarding access to cultural heritage during the lockdown period, the use of 3D modeling combined with the use of VR and AR technologies became popularized with the flow of data managed by APIs available for smartphones.

3D modeling in Sketchup proved consistent with the article's objective, where the three-dimensional parametric model of the fortification is metricated as best as possible within the measurement possibilities of the available topographic map: the model is accurate enough for visualization and low-cost navigation similar to good results obtained in the literature as in Tytarenko, Pavlenko and Dreval (2023). The texturing of the model is conjectural and not photorealistic, but in this approximation, no filling failures of the model were identified in the navigation process. The three-dimensional cartographic representation generated in this research provides subsidies for future work in the area of Historic Building Information Modeling (HBIM), which will enable more effective planning actions in the conservation and restoration processes of the ruins, as well as the management of the archaeological site itself (Tytarenko; Pavlenko; Dreval, 2023; Dore; Murphy, 2012; Remondino, 2011).

The Unity game engine showed good results in creating the VR cartographic visualization application for Android smartphones. However, it is not without limitations. Unity presented an error with version 12 of the Android SDK system, through discussions in online forums such as GitHub (https://github.com/) and in Kanchana and Sindhya (2021) it was identified that this problem was faced by several developers around the world. Compatibility solutions were sought within the graphics engine, but without success, and thus the application is limited to version 11 of the Android system that was used in this work. To correct the error presented by version 12 of the Android system, it is necessary to perform tests with other graphics engines, such as Unreal Engine (Walmsley; Kersten, 2019), to find out if the error occurs only in Unity or is related to version 12 of the Android system. Another solution would be to update the Android system by the developer to fix this problem.

For future work, it is suggested to conduct a qualitative test based on ergonomic parameters, in order to evaluate users' experience of navigating the model. It will be sought to explore in other successful experiments, possible paths for improvements in the methodology of this work, such as: changing the functionalities of the VR application for other operating systems and new alternatives for the texture of the 3D model in search of maximum realism. It also foresees the use of other methods for obtaining information, such as close-range photogrammetry. To continue the work, it is intended to improve the immersion experiments, with a technology that is more responsive to the user's body movements in a VR environment, providing a more intuitive visualization with less dependence on auxiliary peripherals (Theodoropoulos; Antoniou, 2022; Coburn; Freeman; Salmon, 2017).

Finally, the work concludes the possibility of representing Historical Heritage through VR, in conjunction with Historical Cartography. The experiment carried out at Forte do Raio shows how reconstruction in a VR environment provides users with knowledge of an important unknown historical element, in order to disseminate and preserve it. In this way, VR helps in the dissemination and preservation of Historical Heritage, as it allows its representation even if it no longer exists, or is in ruins.

Author Contributions

Bernardo da Cunha Carvalho de Mello contributed to the conceptualization, methodology, and writing - first draft. Juliana Moulin Fosse contributed to the supervision and writing - revision and editing. Alan José Salomão Graça contributed to the writing - revision and editing. Luís Augusto Koenig Veiga contributed to the writing - revision and editing.

Conflicts of Interest

We declare that there are no conflicts of interest.

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Main Author Biography

Bernardo da Cunha Carvalho de Mello, born on March 22, 1999, in Rio de Janeiro, currently resides in Itaguaí-RJ. He holds a bachelor's degree in Surveying and Cartographic Engineering from the Federal Rural University of Rio de Janeiro, Seropédica campus. He is an engineering partner in the Itaguaí Banana Geographic Identity project at the Municipal Secretariat of Agriculture and Fisheries of Itaguaí, and currently coordinates Geotechnologies at the DRONE & GIS company, where he works with aerial photogrammetry and geoprocessing. His research area is Historical Cartography and 3D Cartography, but he is open to working on new research lines.