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Enhancing Art Accessibility for Visually Impaired Individuals through Multisensory Technologies

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Abstract: This study presents the development of an immersive multisensory system for the artwork *"A Cuca"* by Tarsila do Amaral, designed for visually impaired individuals. The system integrates 3D models, audio descriptions, NFC tags, and an iOS app with native accessibility features, ensuring ease of use, scalability, and applicability in cultural spaces. The development process includes requirement gathering, technology selection, refinement of 3D models, and the integration of NFC tags with the iOS app. The goal is to provide visually impaired individuals with autonomy in interpreting and appreciating art, thereby promoting cultural accessibility. A systematic literature mapping was also conducted to identify existing studies on multisensory technologies for art appreciation by visually impaired audiences. The findings highlight the effectiveness of combining tactile and auditory stimuli, offering guidelines to enhance user experience and autonomy. This approach demonstrates the potential of multisensory technologies to foster inclusion and critical engagement with art.

Keywords: Visual impairment, Accessibility, Inclusion, Artwork, Multisensory Technologies

1 Introduction

Access to artistic elements supports the development of knowledge, critical thinking, and aesthetic sensitivity. Public art exhibition spaces, such as museums and galleries, play a crucial role in this process by democratizing cultural access and fostering exchanges among diverse audiences. However, these spaces often lack accessibility resources that enable visitors with disabilities to explore artworks autonomously and in depth.

The Brazilian Law for the Inclusion of Persons with Disabilities (Law No. 13.146/2015) mandates that "every person with a disability has the right to equal opportunities with others and shall not suffer any kind of discrimination" [Brasil, 2015]. In the context of art appreciation, ensuring equal opportunities requires more than just physical access to exhibition spaces. It is essential to provide resources and tools that enable visitors with disabilities to construct their own interpretation of the artwork, free from third-party mediation or communicational barriers.

For visually impaired individuals, the challenge of achieving immersive interpretation of artworks is even greater. The absence of the primary sense typically used to analyze artworks necessitates the stimulation of other senses simultaneously, aiming to create an experience equivalent to, or even richer than, visual exploration. Consequently, the central problem identified is how to develop an immersive and multisensory system that allows people with visual impairments, ranging from mild to total blindness, to interpret artworks autonomously.

Prior to this project, accessibility requirements were defined to investigate how such experiences could be made more immersive [Andrade and Eliseo, 2022], along with a Systematic Literature Mapping to identify the most explored senses and the solutions already developed for this research problem [Andrade *et al.*, 2025]. The results were satisfactory, as the artwork *"A Cuca"* by Tarsila do Amaral was converted into a three-dimensional version that explored the tactile sense of user. Building on these factors, the present project seeks to incorporate the auditory dimension into the existing model and thereby make the immersion in the artwork multisensory, given that touch and hearing have been identified as the primary multisensory combination in applications with similar objectives.

The general objective of this research is to explore multisensory resources for creating immersive environments in art exhibitions that enable the autonomous interpretation of artworks by visually impaired individuals. The specific objectives are: (a) to analyze, through systematic literature mapping, alternatives for creating multisensory immersive environments; (b) to design and implement an immersive environment using multisensory resources; and (c) to develop an immersive technological system that supports visually impaired individuals in interpreting artworks in exhibition spaces. In addition to promoting equal opportunities for artistic exploration by visually impaired and blind individuals, the research is expected to contribute to advancing studies at the intersection of technology and the arts focused on the development of multisensory immersive environments.

The article is organized as follows. Section 2 presents the theoretical framework, including discussions on the analysis of artworks and assistive technologies in this field. Section 3 reviews related work. Section 4 describes the methodology, outlining the stages of refining the existing 3D elements in the system, identifying functional requirements, functionalities, and integrated technologies, as well as the step-by-step development process. Section 5 reports the results obtained through the methodological steps and discusses their strengths and limitations. Section 6 provides the discussion in light of the research findings. Finally, Section 7 presents the conclusions and directions for future work.

2 Theoretical Reference

2.1 Analysis of Artworks

For artworks to be fully analyzed and interpreted by the observer, they require contextualization that goes beyond what is immediately visible. The use of materials, the artistic movement represented, as well as historical and social data about the author and their work, are also relevant for understanding the artwork. Considering these elements as a basis for interpretation, scholars have developed several categorizations based on different types of art analysis.

One such approach is that of Santoro Junior [1976], which identifies three types of analysis: objective, subjective, and formal. The first encompasses the visual elements of the artwork, combined with interpretations that consider factors associated with its context, including historical, psychological, socioeconomic, and religious aspects. The second is limited to personal interpretations of the observer. Finally, the third refers to the form of the painting, that is, how the artwork is plastically represented based on its mode of expression (for example, Impressionist, Classical, or Modernist visual styles). Furthermore, the content of the artwork is categorized in the same manner: the objective aspect represents the main model of the work, the subjective aspect is personal and associated with the meaning of the title of the artwork, and the formal aspect corresponds to the manner and techniques applied in the painting.

On the other hand, a more recent approach is that of Glass [2017], which divides art into three perspectives: physical object, visual experience, and cultural artifact. The first focuses on materials, applied techniques, and conservation of the artwork. The second addresses formal aspects, describing visual elements (for example, shape, composition, color, light, and texture) and their emotional and aesthetic effects on the observer. The third considers meaning within cultural and historical contexts, including theme, iconography, and the people involved in producing the work.

Art appreciation becomes more complex for visually impaired individuals, particularly regarding visual experience. Understanding how a visually impaired person perceives the environment requires a participatory approach, involving people with disabilities in all stages of design and research, from problem definition to result dissemination [Mankoff *et al*., 2010]. It is essential to observe continuous affective and emotional adjustments during interaction, avoiding non-innocent authorization. Despite well-meaning intentions, interventions may inadvertently reinforce structural norms and biases, framing individuals with disabilities as passive recipients rather than active participants, as noted by Bennett *et al.* [2020]. For example, solutions that filter visual information for blind users may provide incomplete data, even with well-intentioned design [Hickman and Bennett, 2023].

In this context, assistive technologies should not aim to ”correct” individual limitations or treat disability as a physical condition to be fixed. Instead, they should acknowledge complexities of lived experience, giving voice and empowering people with disabilities [Mankoff *et al*., 2010].

2.2 Assistive Technologies in Art

People with visual disabilities, in particular, perceive the world in a significantly different way than sighted individuals. They rely more heavily on their remaining senses, such as touch, smell, and taste, to identify objects and navigate their surroundings. Braille, a system of raised dots read by touch, has long been a primary method of reading for people with visual impairments. However, advances in assistive technologies have introduced alternative methods, such as audio description, which enables a simpler and faster interpretation of information [Kohler and Foerste, 2014].

In the context of artwork analysis, ensuring equal opportunities for people with disabilities that limit their access to or interpretation of artworks requires the implementation of assistive technologies within exhibition spaces. These resources, whether physical or digital, are designed to facilitate daily life in areas such as cognition, communication, mobility, and vision. They have a significant impact on the lives of users, influencing education, employment, leisure, and everyday activities such as self-care and reading [World Health Organization, 2024].

When focusing on assistive technologies to represent visual artworks, their relevance for visually impaired individuals becomes evident, as such applications are the primary means by which users engage in the interpretative process. The challenge for products targeting this audience is not only to convert visual information into non-visual modalities but also to ensure the provision of sufficient data for individuals to construct their own interpretations independently, without external influence.

A study conducted by Fávero [2017], which examined accessibility resources for representing two-dimensional artworks for blind individuals, emphasized the use of 3D printers and scanners to convert artworks into tactile formats. The study also highlighted the role of mobile applications equipped with descriptive tools for visually presented content, citing examples such as *Color ID*, *Be My Eyes*, and *TapTapSee*.

The *Color ID* application uses augmented reality to announce the names of the colors identified by the camera on the device [ColorID, nd]. Be *My Eyes* provides visual assistance through volunteer connections via video calls. Based on language and time zone, the application matches users with available volunteers who can provide support for a variety of daily activities [Be My Eyes, nd]. *TapTapSee* integrates the camera with VoiceOver functions, enabling users to capture photos or videos of objects, which are then identified aloud. The app includes touchscreen commands for capturing media: a double tap on the right side of the screen takes a photo, while a double tap on the left side records a video [TapTapSee, nd].

A more recent study by Guimarães and de Andrade [2024], focusing on the accessibility of two-dimensional artworks for blind students in basic education, underscored the importance of multisensory approaches. The study highlighted the role of teacher mediation in fostering creativity through the integration of tactile and auditory assistive technologies. Regarding tactile accessibility, the use of reliefs and textured representations of artworks, such as tactile and three-dimensional models, was emphasized. In the auditory domain, the study pointed to the effectiveness of poetic audio description, which incorporates literary and stylistic elements, such as rhythm, intonation, and metaphors, into the factual description of the artwork.

2.3 Multisensory experiences

In visual artworks, Souza [2014] employs images, illustrations, and colors to convey sensations and messages to the audience. This transmission, combined with the viewer's interpretation, results in sensory experiences. The degree of immersion in such experiences is directly related to the number of senses engaged: the more senses are stimulated, the more immersive the experience becomes. These interactions, characterized by the integration of multiple senses, are referred to as multisensory experiences. Through stimuli such as sounds, tactile vibrations, and scents that evoke the depicted environment, it is possible to create immersive settings and transmit information in an accessible manner, conveying the intended idea from different sensory perspectives (auditory, tactile, olfactory) [Souza, 2014].

Thus, multisensory experiences "open up opportunities to explore new ways of perceiving one's own body, its interactions with the environment, and the environment itself" [Bandukda *et al*., 2021]. The development of such experiences requires the use of Information and Communication Technologies (ICTs), encompassing both the production and dissemination of information to ensure effective and meaningful communication [Rodrigues, 2016].

2.4 Vision Accessibility Features for iOS Applications

Assistive technologies can be developed through digital products, such as mobile applications. In iOS applications (Apple Inc. mobile operating system), the Swift programming language enables the creation of native, fast, and dynamic interfaces for Apple Inc. devices [Apple Inc., 2024]. To comply with the Web Content Accessibility Guidelines (WCAG) [Henry *et al*., 2016], Apple Inc. iPhone devices incorporate accessibility features designed for different types of disabilities. For visually impaired individuals, features that provide auditory feedback of on-screen content, such as VoiceOver, text-to-speech, and video description, are available. Additionally, users can customize screen presentation through functions such as zoom, text size adjustment, dark mode, color filters, and motion reduction. Finally, features aimed at identifying elements in the surroundings of the user include the magnifier tool, automatic descriptions of detected objects, and text recognition via the camera of the device [Apple Inc., 2024].

Among the native vision accessibility features, VoiceOver operates as an integrated screen reader that audibly describes on-screen content, reading aloud text in documents and windows. Once activated, users can apply specific commands to navigate and interact with screen items. VoiceOver also provides customization options to better address individual user needs [Apple Inc., 2024].

Another recently introduced functionality in mobile applications is interactivity with proximity-identifiable tags, such as NFC (Near Field Communication) tags. These tags allow access to data from the physical environment, enabling the enhancement of assistive applications that rely on spatial interactions.

3 Related Works

Regarding the works related to the proposed theme, it is worth highlighting some found during the Systematic Literature Mapping process conducted in the first stage of this research [Andrade *et al*., 2025]. The projects focus on the same theme, aiming to enable interpretation of artworks by visually impaired individuals.

The work of Ahmetovic *et al*. [2021] employs a touch-screen exploration system and verbal feedback of artworks through a mobile web application, offering two exploration modalities. The first is attribute-based exploration, which covers visual elements of the artwork, and the second is hierarchical exploration, addressing division of the artwork by levels.

The work of Cavazos Quero *et al*. [2021] develops an interactive multimodal guide for blind and visually impaired individuals to explore artworks autonomously. Its structure includes a pseudo-three-dimensional (2.5D) relief model, using touch sensors connected to an Arduino board to capture user interactions and respond with audio feedback.

The work of Bartolome *et al*. [2021] features a color representation system with sound and temperature elements, using a thermal display controlled by Arduino. This display activates devices that release heat on one side and absorb it on the other when an electric current passes through them. The system aims to ensure appreciation of visual arts by visually impaired individuals.

Finally, the work of Rodrigues *et al*. [2025] presents a prototype named "Unseen", which employs binaural audio technology to create an immersive 3D gaming experience, with a central focus on promoting accessibility and digital inclusion. The immersive experience was designed through sound, enabling individuals with visual impairments to access 3D applications.

In comparison with other works, this project also employs an approach that explores tactile sensation, using NFC tags to identify contact with the model, similar to the input sensors used in the study by Cavazos Quero *et al*. [2021]. Additionally, like the work of Ahmetovic *et al*. [2021], it leverages a mobile device to present the solution, ensuring mobility during use. However, this project distinguishes itself by using a tactile representation associated with 3D modeling, unlike the pseudo-three-dimensional 2.5D approach of Cavazos Quero *et al*. [2021]. It combines this with a low-cost hardware maintenance alternative to ensure access to artwork audio description, setting it apart from the approaches of Cavazos Quero *et al*. [2021] and Bartolome *et al*. [2021]. The solution integrates the main positive aspects of the other studies and stands out by incorporating a more recent technology in applications, which remains underexplored in this area. Thus, the primary distinction of this project is integration of a technology using mobile devices, as few works in the field aim to ensure autonomous interpretation with easy navigation through artwork elements while transmitting relevant data for individual subjective analysis, highlighting a significant opportunity in the research area.

4 Methodology

The research methodology is based on an exploratory strategy of an applied technological nature, aimed at the development of a multisensory prototype for immersive appreciation of artworks by visually impaired individuals. To achieve the objectives of this study, a series of activities were systematically conducted. The initial phase involved leveraging elements developed during the Scientific Initiation Program (Brazilian Undergraduate Research Program) [Andrade and Eliseo, 2022] and the Systematic Literature Mapping [Andrade *et al*., 2025]. To identify the most appropriate technology for integrating the 3D models, a comprehensive analysis was performed on the technologies discussed in the articles retrieved through the literature mapping. This analysis was further complemented by an investigation of additional potential technologies. Based on these considerations, the following steps were undertaken:

(a) Systematic Literature Mapping and technology selection;
(b) Definition of application functionalities;
(c) Preparation and printing of 3D models;
(d) Development of the iOS application with NFC tags.

4.1 Systematic Literature Mapping and technology decision

To support the development of this research, a systematic literature mapping was conducted with the aim of identifying studies that explored the use of multisensory technologies in the interpretation of artworks by visually impaired individuals. The search was carried out in the ACM Digital Library, IEEE Xplore Digital Library, and Web of Science, using keyword strings in both English and Portuguese related to accessibility, visual impairment, visual arts, and multisensory experiences. Articles published between 2019 and 2023, in either English or Portuguese, that presented methodological proposals or technological solutions relevant to the field were considered.

The analysis of the selected articles was guided by three research questions:

- Q1: "How can the experience of immersion in the concepts and ideas presented in an artwork be enhanced for individuals with visual impairments?"
- Q2: "Which combinations of non-visual resources would ensure an immersive and multisensory experience rich in information conveyed by two-dimensional artworks?"
- Q3: "What are the limitations in conveying non-visual information for autonomous understanding, without influencing the individual's subjective analysis of the artwork?"

The filtering process involved reading titles, abstracts, and subsequently the full text, considering the relevance of each study to the scope of the research. From this analysis, the technological resources employed, the proposed sensory combinations, and the limitations associated with each approach were extracted.

The results of the mapping played a decisive role in shaping the development of the proposed solution, which integrates 3D models and audio description. The reviewed literature emphasized that multisensory experiences, particularly those combining two or more senses, provide an alternative pathway to visual perception, allowing individuals with visual impairments to engage with pictorial artworks in a more immersive manner. However, a critical analysis revealed that while such approaches broaden sensory access, they also raise concerns regarding the balance between enhancing perception and avoiding interpretative bias.

Among the studies examined, the combination of audio description with tactile models emerged as a recurrent strategy, suggesting a strong consensus on the effectiveness of auditory-tactile integration for conveying structural and contextual elements of artworks. The use of textures to represent colors was also frequently noted. Although they enrich the sensory experience by associating tactile cues with visual attributes, there is a risk of introducing unnecessary information and failing to adequately represent the colors of the artwork. This tension highlights the importance of carefully selecting sensory modalities that add informational value without imposing unintended interpretations.

Based on these findings, the present study adopted the integration of auditory and tactile perceptions as a strategy to enable a multisensory experience. Tactile elements were paired with informational texts about the artwork, triggered by NFC tags and read by the screen reader. Users can freely explore the artwork with their hands while listening to a description of either the touched element or the artwork as a whole.

4.2 Definition of application functionalities

Based on the results of the Systematic Literature Mapping, the functionalities that the system should incorporate were identified and documented. From these, the functional requirements were derived for the development of an optimized application designed to support an immersive experience of autonomous interpretation by the user. The central focus of the requirements listing was not merely to reproduce the artwork through non-visual resources, but to create an immersive experience that would allow the user to interpret and engage with the artwork in a profound and meaningful way.

Although the direct participation of people with disabilities in the design process is both effective and respectful [Mankoff *et al*., 2010], this study could not include individuals with visual impairments. Attempts to collaborate with two organizations supporting blind people in São Paulo were unsuccessful, as they were not available to receive the researchers at that time. Therefore, the functional requirements were identified exclusively through the literature mapping, which prevented the exploration of additional requirements and represents a limitation of this work.

Considering the use of audio description and 3D printing technologies, each aspect was examined to assess the feasibility of prototype implementation. This analysis made it possible to outline the requirements that needed to be addressed, taking into account the defined technology and the objectives of the project. With the listing and identification of functionalities and requirements completed, the process advanced to the refinement of existing 3D models and the development of the iOS application using NFC tags.

4.3 Preparation and printing of 3D models

For the implementation of the prototype, a review and adaptation of the 3D models of the artwork *"A Cuca"* by Tarsila do Amaral was carried out, following the stages of the product development cycle proposed by Noorani [2005] and Omaia *et al*. [2024]: Design Concept, Parametric Design, and Analysis and Optimization. In the Design Concept stage, the general configurations of the product to be developed are defined. The product drawing is specified and described in the Parametric Design stage. The third stage, Analysis and Optimization, consists of analyzing the design and, whenever possible, optimizing it [Noorani, 2005] and [Omaia *et al*., 2024]. According to Omaia *et al*. [2024], these three stages comprise the Product Specification, which culminates in the production of a 3D prototype.

In this study, during the Design Concept stage, parameters for 3D printing, the software to be used in 3D object modeling, the size of the prototype, and the materials to be employed were defined. The product drawing in the Parametric Design stage was implemented using Blender for 3D object and scene modeling. Blender [Blender Foundation, nd] provided meshes and curves that facilitated the efficient creation of components. To generate profile positioning elements, the Monster Mash extension [Monster Mash, nd] was used, enabling the "inflation" of two-dimensional illustrations into three-dimensional forms, which were subsequently exported to Blender for further refinement.

In the Analysis and Optimization stage, the models were reviewed by 3D printing experts to ensure feasibility. As a result, some adjustments were required: the original idea of applying textures to represent colors was abandoned due to fragility concerns, and pins were introduced to reinforce separately printed parts, such as arms and legs.

Given cost and time constraints, and considering the prototype nature of this work, only three elements were selected for printing: the *Cuca*, the frog, and the leaf. A maximum height of 30 centimeters was established to facilitate printing. These elements, positioned on the left side of the painting, were chosen for their representativeness and diversity, combining a folkloric figure with fauna and flora elements. Figure 1 highlights the selected objects in the 3D modeling and compares them with the original artwork.

Although printing only part of the painting may limit the experience and interpretation of visually impaired users [Hickman and Bennett, 2023], the purpose at this stage was to assess the potential of multisensory technology, integrating audio description, tactile objects, and NFC tags, for cultural inclusion and engagement with artworks.

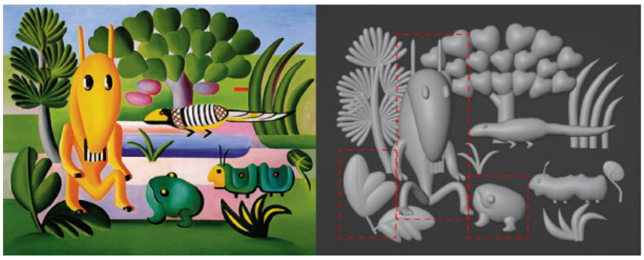

Figure 1. Comparison: Reference of the original artwork (Source: Itaú Cultural [2024]) and 3D modeling of the complete work with the selected elements for printing highlighted in red.

4.4 Development of the iOS application with NFC tags

To provide an immersive user experience through accessible technological resources, an application was developed that presents a brief description of the object, followed by Play/Pause and Reload buttons for audio playback. The audio description is triggered when the phone is brought close to the NFC tag.

The application approach was prioritized due to the integration of native resources already available in the device operating system. Research indicates a significantly higher preference for Apple Inc. devices in terms of accessibility features compared to other products on the market. A WebAIM study reported that, among 248 participants, 64.3% of screen reader users preferred Apple Inc. devices, and 43.6% relied on VoiceOver, reinforcing the choice of iOS for development [WebAIM, 2018].

For development, the SwiftUI framework was selected due to its straightforward interpretability and declarative syntax, which facilitate the creation of accessible interfaces. This choice enables greater focus on application logic, while SwiftUI ensures compatibility with assistive technologies such as VoiceOver and haptic feedback, both integrated to enhance accessibility within the application.

The integration process with 3D models employed Ntag215 NFC tags, which store a URL that directs the user to the corresponding object screen. To enable this, the application allows each page to be associated with a unique URL. Once the application is installed, iOS links these URLs with the developed system based on its metadata.

A logic was implemented for linking the URLs. The screen names were standardized with the name of the corresponding object and the *View* to be loaded. **Figure 2** shows the code linking the URLs to their respective elements. For example, when the URL `tccapp://sapoview` is triggered, the variable `isShowingSapoView` is modified and set to `true`, and the system then displays the corresponding screen. **Figure 3** presents the customization process to direct the system according to the status of the variable `isShowingSapoView`.

To register the generated URL in the application using the

```
.onOpenURL { url in
    if url.scheme == "tccapp", url.host == "sapoview" {
        // Define o estado para mostrar a SecondView
        isShowingSapoView = true
    } else if url.scheme == "tccapp", url.host == "cucaview" {
        isShowingCucaView = true
    } else if url.scheme == "tccapp", url.host == "folhaview"{
        isShowingFolhaView = true
    }
}
```

Figure 2. Example code linking the created URL with access to the desired View.

```
NavigationLink(  ⚠ 'init(destination:is
    destination: SapoView(),
    isActive: $isShowingSapoView,
    label: {
        EmptyView()
    }
)
```

Figure 3. Example code using the variable 'isShowingSapoView' for navigation.

Deep Link concepts, the application *NFC Tools* [WakDev, nd] was used, which allows reading or registering data in NFC tags. The registration process consists of selecting the option to write information to an NFC tag, choosing the option *Custom URL/URI*, and finally inserting the desired address.

Finally, by selecting the option *Scan* and approaching the tag where the URL is to be stored, the process is completed. Thus, every time a device with the application installed approaches the NFC tag, it will receive a notification redirecting the user to the corresponding application screen.

Each screen contains its respective explanatory text with the audio description feature. The transcription was performed using ElevenLabs, an artificial intelligence-based text-to-speech platform that converts written content into realistic audio with natural intonation, appropriate rhythm, and expressive variation [ElevenLabs, 2025].

5 Results

Based on the application of the methodological steps, the results achieved encompassed a multisensory experience, focusing on the main senses explored in immersive representations for visually impaired individuals, namely sound and touch. Through systematic mapping studies, it was possible to analyze the types of technologies that could be utilized, define an advantageous path for this application, and identify the necessary requirements and functionalities to ensure an immersive, multisensory, and accessible experience.

Upon completion of the previous stages, it became possible to develop an optimized experience to achieve the research objectives: an immersive 3D model representing the elements of the artwork, complemented by an application providing audio descriptions, which users can access during tactile exploration. To facilitate access to the audio descriptions, users can bring their mobile devices close to the NFC tags on the artwork, which automatically direct them to the information associated with the touched 3D elements.

5.1 Systematic Literature Mapping and technology decision

The results of the systematic literature mapping were presented in Andrade *et al*. [2025] and proved decisive in defining the non-visual resources adopted to provide an immersive experience in the appreciation of artworks by individuals with visual impairments. It was found that the combination of other human senses, such as touch, hearing, taste, and smell, has the potential to create multisensory experiences that foster a more immersive engagement for visually impaired individuals.

However, the challenge lies in ensuring that the limitations of non-visual information do not lead to misinterpretations or partial representations of the artwork, which could hinder visually impaired individuals from fully experiencing the proposed interaction. The combination of sensory modalities should function as a bridge, where the use of one sense complements the other.

Audio description was conceived as a means of conveying information (such as descriptions of the physical composition, the context of the artwork and its artist, and the represented elements, among others). In synchrony with the tactile exploration of the 3D elements of the artwork, the aim is to foster the perception of the spatial arrangement of components and to enhance the understanding of the structure of the artwork [Ahmetovic *et al*., 2021].

Based on the analysis of the articles collected in the Systematic Literature Mapping, combined with research on techniques for applying auditory and tactile aspects of the project, the following alternatives were identified for use as technological resources:

1. **Audio Description in Response to Tactile Interaction**
   (a) Arduino-based system using an infrared proximity sensor, ultrasonic modules, or RFID (Radio Frequency Identification) tags to identify proximity to the model.
   (b) Arduino-based system using a capacitive sensor connected to a conductive ink base, with sensors embedded beneath the model surface.
   (c) Arduino-based system using a digital base with buttons that trigger audio descriptions.
   (d) Arduino-based system integrated into a glove, capable of identifying the specific element of the artwork being touched.
   (e) Mobile application that interacts with the model through the reading of identifiers such as tactile QR codes or NFC tags.
2. **Color Identification**
   (a) Tactile patterns on the 3D model, accompanied by a tactile plaque serving as a legend with color patterns and Braille text.
   (b) Description of the colors of the artwork elements provided in the audio reproduction.
3. **3D Model Printing**

(a) 3D printing sliced at half height with interlocking components.
(b) Large-scale 3D printing using industrial printers.
(c) Laser cutting of styrofoam, with software used to divide into layers, stack, glue, and refine details.
(d) CNC router with 3D machining for cutting plastic materials.

After a careful analysis of the predefined options, it was decided that the solution would be an iOS application utilizing NFC technology. When the users device comes into contact with the tag positioned in front of the 3D model, VoiceOver is activated, providing instructions and an interactive audio description menu. Regarding the 3D model printing, the decision was to slice the model and use interlocking mechanisms to join the parts. These choices were made considering the following factors:

- Prior knowledge of iOS programming among project participants, which is relevant to ensure a more optimized system result through the use of libraries and extensions capable of creating a more immersive experience, such as native accessibility tools.
- Tactile response that involves easy interaction and processing, avoiding difficulties in its use, as some of the other solutions could generate challenges in the interaction of the model combined with the activation of the audio description. Using the mobile device, the user is more capable of exploring the entire model while listening to the information.
- Project scalability and user autonomy, requiring only the installation of the application for its use. Other alternatives would involve production constraints and resources that are harder to replicate, as well as difficulties in implementing system updates due to the reliance on hardware.
- Cost-effectiveness and development time, since other system and printing options would entail higher expenses for materials and services, in addition to longer production times to achieve the final result.

5.2 Requirements and Functionalities Specifications

After defining the most appropriate technology to ensure immersion and the interpretation of the artwork by individuals with visual impairments, the functionalities and functional requirements of the system were outlined. The prototype implements both a textual description and an audio description of the objective and formal content of the artwork, while fostering the interpretation of its subjective content during tactile interaction with the 3D elements. The audio description is activated when the mobile device is brought close to the NFC tag attached to the artwork. Accordingly, the following functional requirements were elicited:

- **RF1**: The system shall automatically activate the audio description upon detecting the proximity of the mobile device to an NFC tag placed adjacent to the artwork;
- **RF2**: The system shall provide a menu with instructions for controlling the audio description;
- **RF3**: The system shall permit control of audio description playback (start, pause, resume, fast-forward, and rewind);
- **RF4**: The system shall associate different NFC tags with different parts of the 3D model and play the corresponding track when each tag is brought near;
- **RF5**: The 3D model shall feature tactile patterns to represent colors;
- **RF6**: Immersive background music along with the audio description of each element of the artwork, including pause, play, and restart music functions.
- **RF7**: The system shall present a tutorial on how to use the technology in audio, braille, or with support from a mediator;
- **RF8**: The system shall present immersive background music concurrently with the audio description of each element of the artwork;
- **RF9**: The system shall permit control of background-music playback (start, pause, and resume).

It was not feasible to implement all the elicited functional requirements. Due to optimization of the 3D printing process, the tactile patterns for color representation could not be implemented. Accordingly, RF5 and RF6 were not implemented.

5.3 3D models

The 3D model of the artwork *"A Cuca"* was printed in small parts to preserve structural integrity and prevent fractures in the more fragile areas. During the process, body elements such as arms and legs were separated and connected with pins to reinforce these parts. These modifications were intended to optimize the printing process and reduce the risk of damage, resulting in a robust and detailed final model.

For thinner structures, such as the antennas and teeth of the *Cuca*, it was necessary to increase the thickness of the modeling and deepen the connection regions within the body to strengthen the joints. Another critical aspect concerned the tactile color patterns in the Feelipa format previously developed in the modeling. Feelipa is a tactile standardization code that uses geometric shapes and their combinations to represent colors for visually impaired users [Feelipa Color Code, 2014]. For example, a square represents the primary color red, a triangle represents the primary color yellow, and a right trapezoid, a combination of the other two shapes, represents the secondary color orange. Due to the small size of these details, they posed a risk of structural weakening and extended over the entire surface of the objects. Consequently, the tactile representation of colors was replaced with their inclusion in the audio description of the elements.

Following the identification of these adjustments, the pieces were modified using the cutting tool in Blender software [Blender Foundation, nd] to create the pinning structure and improve the fit of the thin parts, as shown in **Figures 4, 5 and 6**. Additional refinements were made to the models to ensure fidelity to the original artwork. Larger and symmetrical pieces, such as the body of the *Cuca*, underwent the slicing process to fit within the available printing area and optimize production time. The 3D model was then exported

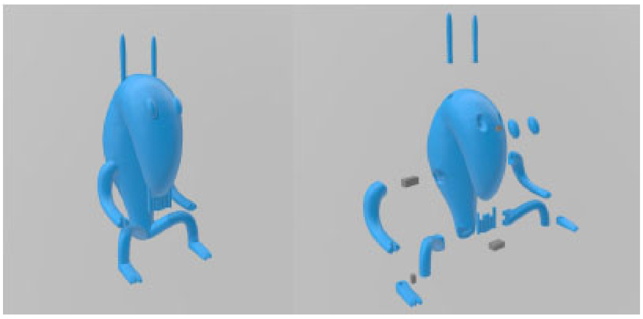

Figure 4. Comparison: Whole 3D Model of *Cuca* vs. Sliced Model with Pinning.

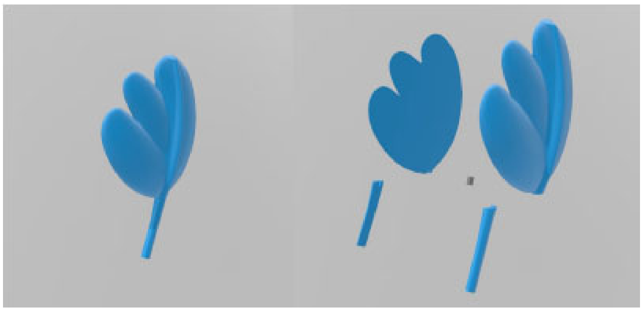

Figure 5. Comparison: Whole 3D Model of the Leaf vs. Sliced Model with Pinning.

and processed in the 3D Builder system [Microsoft, 2024], where the slicing stages were completed, preparing it for configuration in the printing software.

Regarding the printing material, different alternatives were considered: resin or FDM (Fused Deposition Modeling). FDM is the most widely used type of 3D printing, differing from resin in offering a larger printing area, lower cost, and fewer details [ProdutecaLab, 2022]. Among the available filament types, PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene), ABS was selected due to its ability to produce finer refinement of the printed parts.

Figures 4, 5 and 6 illustrate the application of the division and pinning process of the components, as well as the reinforcement of thinner structures.

The finalized 3D model (**Figure 7**) presents a sturdy base, free from fragile or brittle regions, as a result of the structural modifications applied. Since the system is designed to support different degrees of visual impairment, ranging from mild to severe conditions such as total blindness, the models underwent a post-printing stage of detailing and painting, in addition to auditory color references, to visually approximate

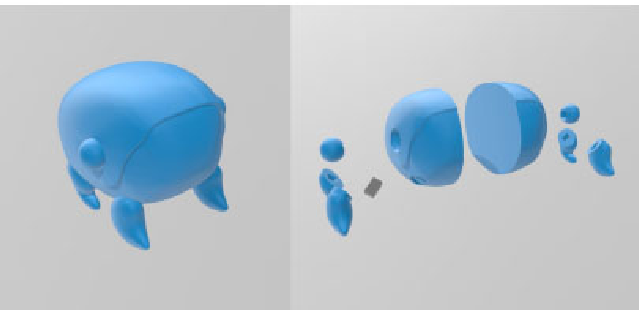

Figure 6. Comparison: Whole 3D Model of the Frog vs. Sliced Model with Pinning.

Figure 7. 3D Printed Models of the Frog, *Cuca*, and Leaf, Positioned Near NFC Tags.

the original artwork as closely as possible.

To integrate the tactile and auditory components, NFC tags were employed. These tags were placed in front of the objects and 3D models, with interaction instructions displayed on the initial screen of the application. Users simply need to bring their iPhone close to the NFC tag to receive a redirection notification. By selecting this notification, the application automatically opens the screen linked to the NFC Deep Link.

5.4 iOS Application with NFC Tags

To complement the tactile interactions with the 3D models of the artwork, an iOS application was implemented to reproduce audio descriptions and provide an immersive experience that enables the user to interpret and engage with the artwork in a meaningful way. Upon launching the application, the system offers a tutorial with audio description for the user, explaining the functionality of the system, the tactile interaction with the 3D model, and the NFC tags, as well as step-by-step instructions for its use and audio controls through screen gestures. The audio description is carried out by the VoiceOver screen reader, and navigation is performed using its features.

The application was designed so that each 3D element of the artwork is associated with an NFC tag and has a unique URL for its identification. When the user touches a 3D element and brings the smartphone close to the corresponding NFC tag, the system identifies the respective URL and automatically triggers the audio description accompanied by background music related to the element being explored.

The application consists of an initial menu screen (**Figure 8**), which provides a brief explanation of its functionality, the arrangement of the objects in front of the user, and their corresponding NFC tags. These tags direct the user to the information screen of the selected artwork element, should

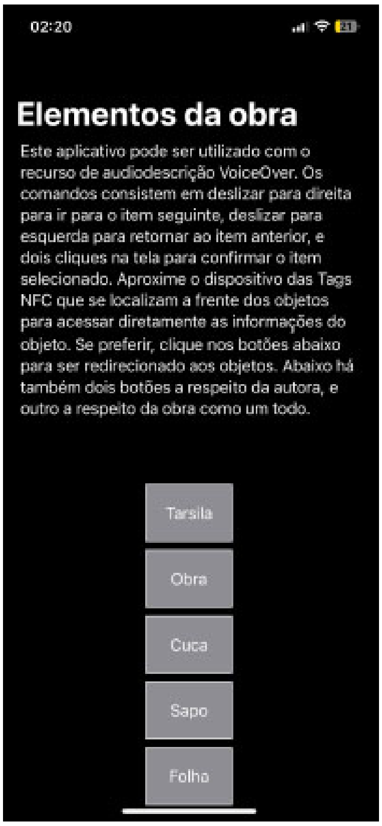

Figure 8. App home screen, with model description selection.

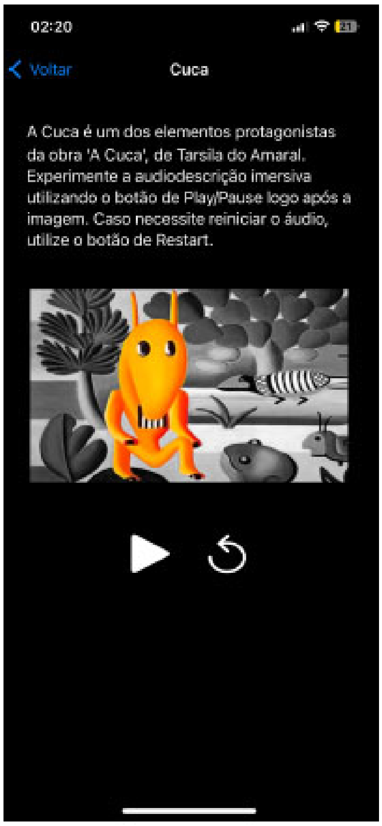

Figure 9. Information screen about the *Cuca* model, with immersive sound and audio description of the model.

the user wish to access them. The screen also includes an audio description of the formal content, that is, the expression of the artwork in its two-dimensional form and the artistic movement explored. Additionally, it contains a button to access further information about the artwork, enabling the user to select the desired information. This additional section includes aspects such as historical, social, and economic context, information about the artist, the technique employed, and other relevant details for subjective interpretation. Furthermore, beneath this section are three buttons that lead to new screens with information on each of the 3D printed objects.

When the smartphone is brought near the NFC tag in front of the currently explored object, the system presents a specific screen with information about the corresponding part of the artwork (**Figure 9**). This screen displays the object's name, a brief objective audio description of the element concerning its concrete structure and colors, an image with description, and buttons to play, pause, or restart the immersive music. The chosen resources were intended to evoke sensations and ambient sounds conveyed by each individual element of the artwork, aiming for greater immersion. Other audio description controls are managed through screen gestures, following the VoiceOver standard. The application also includes haptic feedback to enhance the integration of auditory and tactile senses.

The application source code is available at: `https://github.com/JoaoVictorPimenta/AccessibilityArtTCCII`. As the application was developed for Brazilian users, the screen texts and audio descriptions are provided in Brazilian Portuguese. **Figure 8** presents the initial menu screen with the following text:

Artwork Elements

This application can be used with the VoiceOver audio description feature. The commands consist of swiping right to move to the next item, swiping left to return to the previous item, and double-tapping the screen to confirm the selected item. Bring the device close to the NFC tags located in front of the objects to directly access information about each object. Alternatively, you may tap the buttons below to be redirected to the objects. Additionally, there are two buttons providing information about the artist and another one about the artwork as a whole.

And the buttons: *Tarsila*, *Artwork*, *Cuca*, *Frog*, and *Leaf*.

Figure 9 presents an example of a screen corresponding to *Cuca*, one of the 3D elements of the artwork, with the following text:

Cuca

Cuca is one of the main elements of the artwork "A Cuca" by Tarsila do Amaral. Experience the immersive audio description by using the Play/Pause button located just below the image. If you need to restart the audio, use the Restart button.

6 Discussion and Limitations

Analyzing the obtained results, the implemented application fulfilled the functionality of triggering a description with textual elements and audio description when the user brings the mobile device close to the NFC tag and performs tactile interaction with the 3D elements of the artwork. Considering the challenge of developing a system to ensure an immersive experience in interpreting artworks for visually impaired individuals, the perceptions of touch and hearing were explored in a combined manner, utilizing audio description and haptic feedback in the iOS application, connected to the 3D model for tactile exploration of the artwork through NFC tags.

However, the main limitation of this work was the inability to test the solution with visually impaired individuals due to the lack of access to them, which compromised the evaluation of the multisensory experience. Although the system was tested with sighted individuals to verify the effectiveness of its implemented functionalities, the immersive experience will never be the same as that experienced by visually impaired users. The intention of using tactile and auditory perceptions as an alternative to visual perception was to create an environment in which visually impaired users could appreciate the artwork, in line with the findings of the Systematic Literature Mapping [Andrade *et al.*, 2025]. Perhaps, with the participation of these individuals in the development process, other insights would have emerged. It would have been possible to observe the synchronization of audio description with tactile interaction and verify whether the use of the smartphone to read the NFC tag would interfere with tactile interaction.

Another constraint of the research was the partial implementation of the artwork, which prevented full immersion for users. Although only some elements of the artwork were reproduced in three dimensions, it was possible to verify the technical feasibility of implementing the combination of audio description with tactile interaction.

It is important to highlight that by creating the 3D model of Cuca, another artwork is effectively developed, as the modeling is based on visual reproduction carried out by external observers rather than by the artist or through the use of a direct conversion resource such as a 3D scanner. Thus, despite efforts to create a multisensory immersive environment, the experience does not become equivalent to that of a sighted individual, which may interfere with interpretation when considering the original artwork. As pointed out by Ahmetovic *et al.* [2021], it is challenging to provide an accurate spatial understanding of visual artworks through non-visual channels.

The system does not allow the insertion of a new artwork with its 3D model. To enable this scenario, an interface would need to be developed for registering additional artworks, including integration with an administrator user to insert technical information and contextualization of both the artwork and the author.

Since the application was developed in Swift, its use is limited to iOS devices with models equal to or higher than iPhone 7 that support NFC tag reading. This restriction prevents users of other smartphones from experiencing the application.

Among the positive aspects, the methodology employed involved a Systematic Literature Mapping to identify guidelines for developing a technological solution aimed at fostering the inclusion of individuals with visual impairments in cultural life and art appreciation. Another strength lies in the ease of implementing URLs linked to NFC tags and accessing them via smartphones. Additionally, the maintainability of the application, which can be updated through the App Store, is noteworthy. These factors are particularly relevant for the replicability of the system and its potential adoption in museums and accessible art exhibition spaces.

The results of this research are expected to contribute to promoting inclusion and enhancing the experiences of visually impaired users when interacting with artworks using the developed multisensory system, which combines tactile and auditory resources. The reproduction of artworks as 3D models integrated with auditory feedback enables the creation of an immersive environment, thereby facilitating the inclusion of visually impaired individuals, particularly in museums and art exhibition spaces. Furthermore, this study is expected to inform the development of future technologies that integrate audio description and tactile interaction for the accessible appreciation of artworks.

7 Final Considerations

During this research, multisensory resources were analyzed through a systematic literature mapping to enable immersive and autonomous experiences in art exhibitions for visually impaired individuals. Based on these analyses, a multisensory system was developed, allowing users to explore elements of the artwork through tactile and auditory perceptions. The finalized system has the potential to contribute to studies in the fields of accessible technologies and art, offering new alternatives for interpreting paintings by engaging human senses beyond vision and thereby fostering immersion within artworks.

Although the tactile color patterns intended for the system were not implemented, alternative approaches were identified based on available technologies that rely on auditory and visual perceptions. Notably, the application was developed in Swift, which restricts its use to iPhone users. In addition, an administrative profile was not created, a feature essential for museum curators and art exhibition managers to register new artworks or modify those already present in the system. Although it has not yet been tested with visually impaired individuals, this work has the potential to contribute to the development of technologies integrating audio description, 3D modeling, and tactile interaction to enhance accessibility in museums and art exhibition spaces.

For future work, it is recommended to involve visually impaired users to assess the effectiveness and efficiency of audio description, tactile interactions, and the overall multisensory experience, as well as to identify potential improvements and ensure the system meets user needs and expectations. Further research could explore alternatives for tactile color representation. In addition, the system could be expanded to include an administrative profile, allowing the addition of new artworks and the editing of those already registered. Additionally, considerations for a monetization strategy integrated with museums and art exhibition spaces should be addressed. Finally, extending the application to platforms beyond iOS would enable access for users of other smartphones.

Declarations

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Authors used Generative AI, specifically Copilot and ChatGPT, to improve writing, to perform grammar checks and to generate LaTeX code. In the Systematic Literature Mapping, Atlas.ti was used to assist in the analysis of the selected article.

Authors' Contributions

CFA and JVFP contributed to the conception of this study, software development, data curation, formal analysis, investigation and writing– original draft. MAE performed methodology, supervision, validation, Writing – review & editing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The source code of the application developed during the current study is available in `https://github.com/JoaoVictorPimenta/AccessibilityArtTCCII`.

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