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Flexible, Integrable and Accessible Digital Tools for a Dynamic and Adaptive Experience of Museum Environments. The CHAMELEON project

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Abstract

The project CHAMELEON - Adaptable, integrable and accessible digital tools for a dynamic and adaptive use of museum environments*, is focused on the Piero Leonardi Museum of Palaeontology and Prehistory, part of the Museum System of the University of Ferrara. The aim is to develop a set of digital tools for documenting, enhancing, sharing and narrating the museum palaeontological and anthropological collections. Starting with the conceptualization of a new digital exhibition system, the accurate 3D digital acquisition of more than thirty objects have been performed. The fossils were selected considering their state of preservation, relevance and scientific representativeness, and the need to be linked to an augmented set of information. The survey, carried out through structured-light handheld 3D scanner and digital photogrammetry, is the result of a methodological assessment highlighting the critical-interpretative and documentation opportunities that digitisation offers. The application design and development includes IT configurations aimed at managing content and virtual experiences. Responsive design, standard metadata, and open APIs support an inclusive user experience embedded in the IT architecture through applications for Semantic XR Museum, Semantic XR Avatar, 360° AR Experiences, frontside AR Experiences, and VR Experiences in specific settings. The overall outcome is a "chameleonic" repository able to manage on-line all the multimedia contents associated with the fruition and storytelling of tangible and intangible information.*

CCS Concepts
• ***Computing methodologies*** → *Computer Graphics;* • ***Information Systems*** → *Data Management Systems; Information Storage Systems;*

1. Introduction

CHAMELEON aims to develop digital tools for documenting, enhancing, sharing and narrating museum heritage, with a particular focus on science and natural history museums. The project is grafted into Spoke 4 of the CHANGES project [BBB*24], and focuses on one of the case studies identified as "core" for its importance within palaeontological and anthropological collections: the Piero Leonardi Museum of Palaeontology and Prehistory, part of the University of Ferrara's Museum System (hence SMA). Since 2013, the Museum has launched a digitisation campaign experimenting with different ways of acquiring the collections to create educational pathways and modernise exhibition content [FBT*13; TPT*21; PT24]. Digitisation was mainly aimed at non-displayed and medium-sized exhibits, leaving out more composite specimens such as complete large vertebrate skeletons and complex fossils. CHAMELEON's main objectives are based on the use of digital tools to enhance the museum and its collection, addressing different needs and users. The first objective is to increase accessibility and knowledge (both onsite and remotely), maximising the openness to the general public. The project will also enable the museum's managers and curators to update the information system related to the fossil collections and to create adaptable visits and exhibitions. In order to achieve these goals, the project started with the accurate digital acquisitions of more than 30 objects selected on the basis of a preliminary educational and communicative design of the Museum. The palaeontological remains were carefully selected, taking into account their state of preservation, their scientific relevance and representativeness, as well as the need to link them to an augmented set of information.

The survey, carried out using a handheld structured-light 3D scanner and digital photogrammetry, is the result of a methodological assessment that highlights the critical interpretation and documentation possibilities offered by digitisation. The collaboration of the two Departments of Architecture and Humanities and the Piero Leonardi Museum of Palaeontology and Prehistory of the University of Ferrara, together with the technical partner Inception has been crucial in this respect. In fact, the aim is indeed to obtain semantically enriched 3D models, enhancing the levels of information linked to the metric-morphological data, according to current standards and Open Data, pursuing inclusion and accessibility.

The application design and development, led by technical partner MediaSoft, includes a back-end configuration module that allows exhibitors to define the content and behaviour of both the visitor experience and the virtual experience. MediaSoft is also designing and developing the Digital Asset Management module, Augmented Reality (AR) applications, and the scalable local cloud infrastructure hosting the entire system. The software platform is based on responsive design, standard metadata, and open APIs. The user experience design, by No Real Interactive, is embedded in the IT architecture of applications, and includes five main tools:

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Semantic XR Museum, Semantic XR Avatar, 360° AR Experiences, frontside AR Experiences, and Virtual Reality (VR) Experiences in specific settings. The overall outcome is a "chameleonic" repository able to manage online all the multimedia contents associated with the fruition and storytelling of tangible and intangible information. Dynamic digital paths are based on semantic associations and can be reconfigured by the end user, increasing engagement and interactivity with the Museum heritage [DFC23]. The repository is accessible from different interfaces to allow multiple digital fruitions, and applications are adaptable and integrable, exploiting the potential of virtual paths to create new forms of knowledge narration and to broaden critical-interpretative analyses of cultural heritage.

2. The research context

The context of the CHAMELON project is the Piero Leonardi Museum of Palaeontology and Prehistory (hence MPPPL). It is part of the SMA of the University of Ferrara, founded in 2007, which brings together the University's museums and historical-scientific collections. It is located at Palazzo Turchi di Bagno (Fig. 1), which houses the MPPPL, the Exhibition Hall, and the Botanical Garden and Herbarium. It also includes the "Giovanni Tumiati" Anatomical Museum, and the scientific collections of historical interest located in the Departments (CISFIS and the Ancient Navarra Pharmacy). The richness of the SMA represents a great potential as it is an archive of knowledge and historical-naturalistic evidence to be exploited [Lor01]. This heritage, spread over several historic-architectural sites and only partially accessible today, fits well into an overall project of new and renewed accessibility of exhibition spaces and collections.

Figure 1: *Main facade of Palazzo Turchi di Bagno, entrance to the Piero Leonardi Museum of Palaeontology and Prehistory*.

The MPPPL was founded in 1964 by Professor Piero Leonardi, the first Chair of Geology at the University of Ferrara. The materials that make up the museum are the result of an intense activity of collection, acquisition and exchange that has continued over time. In addition, staff and students brought rocks and fossils to the Institute on every excursion and their return from conferences. Professor Leonardi himself donated his private collection to the museum when he retired. The exhibition section is entirely housed in the rooms of the *piano nobile* of the Palazzo Turchi di Bagno, along Corso Ercole I d'Este. The exhibition is divided into four main sections: Palaeontology of Vertebrates (Fig. 2), Human Palaeontology and Prehistory (Fig. 3), Palaeontology of Invertebrates, and Historical Geology.

The initial exhibition was mainly intended for university teaching, but since the late 1970s, the growing interest in natural sciences in compulsory education has led to a constant and increasing demand for the use of the museum. The building is currently used by the staff of the University of Ferrara and for temporary exhibitions on the ground floor, while the permanent exhibition is temporarily closed to the public, following the earthquakes that hit Emilia in 2012. However, it is possible to study the museum's collections by appointment or visit the exhibition rooms for small groups.

Figure 2: *View of the room housing the Vertebrate Palaeontology section*.

Figure 3: *View of the room showing the Human Palaeontology and Prehistory section*.

As a result, the museum has had to rely heavily on digital strategies [BTPP19; SBT21]. These current limitations on the permanent exhibition accessibility make it even more relevant to design a digital repository enhancing the collection through a reorganisation of the information and documentary sources and creating a set of digital interfaces for different uses, associating in-depth information content with the digital replicas of the exhibits.

2.1. The Museum and the deposited collections

Palaeontological and archaeological excavations carried out by the University of Ferrara have significantly increased the quantity and the scientific value of the museum's objects.
Concerning the invertebrate collections, the most important

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[PB01] are: holotypes and paratypes of new species of foraminifers, molluscs, brachiopods from the Permian, Triassic, Lower Jurassic and Palaeogene of the Southern Alps; a collection of bivalves from the Lithothis facies, unique in the world for the wealth of specimens isolated from the rock, some of which exceptionally also show the original microstructures of the shells (Lower Jurassic); a rich collection of Triassic molluscs from the Dolomites and Hungary; a collection of ammonites from the Lower Jurassic and Lower Cretaceous of the Meridional Alps; calcareous coralline algae from the Paleogene and Neogene of Veneto and other Italian and foreign localities.

Among the most important vertebrate collections are:

- the fossil fish from the Pesciaia di Bolca, the famous Tertiary deposit in the Lessini Mountains (VR), known since the 16th century for the extraordinary preservation and abundance of its remains;
- the holotype of a large marine reptile from the Middle Jurassic-Early Cretaceous of Italy, in particular the largest specimen so far preserved from the metriorincoid group;
- two original skulls of *Lystrosaurus*, perhaps the only ones in Italy, from the Triassic period in South Africa;
- the Pleistocene collection of remains from the Settepolesini di Bondeno deposit (Ferrara), the study of which has made it possible to document, for the first time in Italy, the faunal population and fossil biocenosis of the mammoth steppe-taiga and woolly rhinoceros of the Po Valley during the last glaciation;
- the palaeontological and archaeological collections of several Pleistocene deposits in caves or rockshelters (i.e. Grotta del Broion, Riparo Tagliente, Riparo Villabruna, and others), which represent the most significant archaeological deposits for the chrono-stratigraphic reconstruction of the Recent Quaternary in northern Italy;
- a large batch of faunal remains from several Pleistocene deposits in Sicily, which document the evolutionary phenomenon of insular dwarfism and gigantism.

3. Methodological framework for the creation of digital exhibitions and applications

The objectives of the core case study on the Leonardi Museum are multiple, and can be summarised as follows:

- To increase accessibility (physical and virtual) through virtual routes, maximising openness to the public for different users through an inclusive approach;
- To activate a 3D digitisation process systematising what already digitised and focusing on exhibition and critical-interpretative opportunities that digitisation can offer;
- To apply a semantic approach to the models [MDM*20], enriching the levels of information associated with the metric-morphological data, according to current standards and with a view to Open Data / Semantic Web;
- To set up a platform and related VR and AR applications to make museum contents explorable;
- To activate a network with other Museum Systems or places of interest (e.g. archaeological excavations) for digital content sharing;
- To update the ICCD catalogue, in line with the ArCo project, and the Italian Ministry of Culture (MiC) Digital Library, including 3D and 4D (spatial-temporal) models.

3.1. User Experiences and target users

Starting from these purposes, the design process was divided into four main actions: application design, digital use design, inclusive use design, and gamified use design. The applications setting up started from the semantic mapping and identification of the objects to be digitised, describing the IT architecture (Fig. 4) for managing the flow of data to/from the central repository (e.g. client-server), defining the hardware required for the creation and use of the prototypes being developed, and considering the quantity and quality of the data to be managed. The hardware included all identified devices that could be used by each target user. A major part was the design of the software 'layer' (middleware) to connect the repository with the application prototypes, and the design of a 'chameleon-like' repository, able to:

- manage online all the multimedia assets that can be associated with a tangible or intangible museum object, including 3D replicas, audio-video clips, dialogues with avatars, information for users with different types of disabilities, etc.;
- enable to design dynamic digital visitor paths, i.e. based on semantic associations configurable by museum curators (e.g. to support temporary physical exhibitions or to create temporary online virtual exhibitions);
- allow the reconfiguration of the created itineraries by the end users (oriented and facilitated action), in order to adapt visits and increase their involvement.

The aim is to create a single repository accessible from "n" interfaces, different in form and function, allowing multiple digital uses supported by semantics that can be reconfigured at will [MMF21]. Such a repository fully meets the need to include not only the fruition of 3D models but of any other multimedia asset; and to create WebXR applications for exhibited objects, as a container for the virtual replicas [FDB*22], and related data and metadata, accessible through effective interfaces in the exploration of the 3D models via web browser. The identification of target users (curator, general user, specific user, disabled user, etc.) and expectations from the proposed experiences, and the analysis of the User Journey led to development of the User Experience (UX), described by means of graphical schematisations highlighting possible actions, criticalities (such as over-inoculation, loops, etc.), limits and freedoms granted to the user by correlating them with the combinatory potential offered by the "chameleon-like" repository.

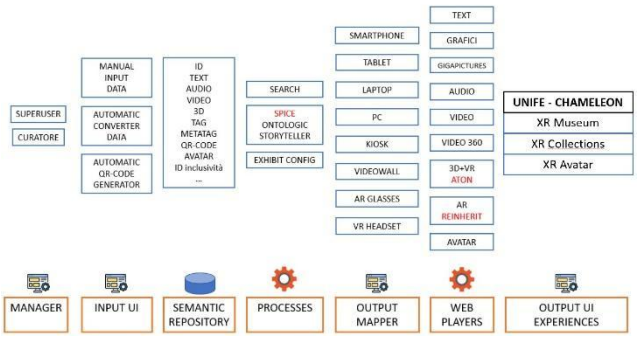

Figure 4: *CHAMELEON IT architecture*.

The user interface is designed specifically for each prototype, including functionality, graphical appearance, multi-device responsiveness, and accessibility. The design of an inclusive

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digital use is necessary both when the digital is considered to support a visit to a real museum, and when the museum (with its multiple declinations) is virtual. The "chameleon-like" repository will also allow disadvantaged users to configure their own path. Considering the game as a mode of cultural access not exclusively for children, a specific task to plan how to introduce 'gamified' logics in the production of digital fruition paths was introduced. Starting from the analysis of gaming best practices for museum context (style, time, rewards, correlation with the objects on display, etc.), the aim is to describe at least a gamified application to be structured on the semantic repository and applied in the different prototypes. This task is also in line with the Spoke 4 partnership willingness to develop a gaming activity that includes all the core case studies.

3.2. The semantic repository

The semantic repository allows the online management of all multimedia assets, the design of new experience paths by the curator, and their reconfigurability. It includes:

- The "semantic editor", an intuitive configuration back end based on a drag and drop interface that allows the curator to create experiences, and user interfaces. Content is managed by populating the repository.
- The "Semantic XR Museum" prototype for browser-based use of digital experiences through the user's own device, remote use of AR and VR, generic, gamified and inclusive paths. In addition to applications for exploring object models with augmented content, two immersive environments are also included.
- The "Semantic AR Collections" prototype enables the marker-based AR experience on the display case, which can be activated by QR code. This application is realised through the creation of thirty prehistoric animals.
- The "Semantic XR Avatar" prototype enables the experience of dialogue with a conversational AI avatar that can be accessed via a web browser with a smartphone connected to the Internet.

3.3. Semantic XR Museum and Avatar

Digital use is via the web and focuses on the "Leonardi collection", which contains all the digital objects in the repository. It will be accessed via an online web browser so that digital itineraries can be realised in situ or anywhere in the world via the users' mobile devices (Fig. 5).

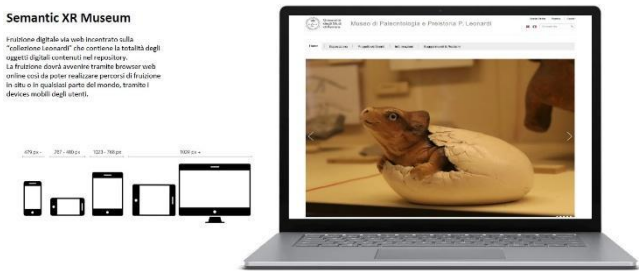

Figure 5: *CHAMELEON responsive fruition via mobile devices*.

The avatar is the museum guide, more targeted to children or a young audience. Three dialogues are planned, one for each of the two permanent rooms on the first floor and one in anticipation of the temporary exhibition to be set up on the ground floor. Each dialogue can be activated with a QR code. On the screen of the smartphone, in portrait position, the avatar will appear in the upper part (Fig. 6), while the lower part will host the initial instructions, the written answers, the suggestions to the questions (which can also be clicked on for maximum inclusiveness), and the button to activate the microphone.

Figure 6: *View of a possible Avatar prototype*.

3.4. AR experiences

A 360-degree AR experience is designed for exhibits in individual showcases. Thanks to a maximum of four QR codes of approximately 15x15 cm placed on the four sides of the showcases, it will be possible to activate the AR exploration of the selected animals (Fig. 7). Scanning the QR code, the system launches the 3D reconstruction of the animated animal's body. At the bottom of the screen there will be the name of the animal and the button to activate the Information Tab, which will switch to the consultation mode of the digital object. The Information Tab will allow to read info and to explore the animal in real time in 3D. The Navigation Menu allows to close the tab, select the language and accessibility options, and come back to the AR view.

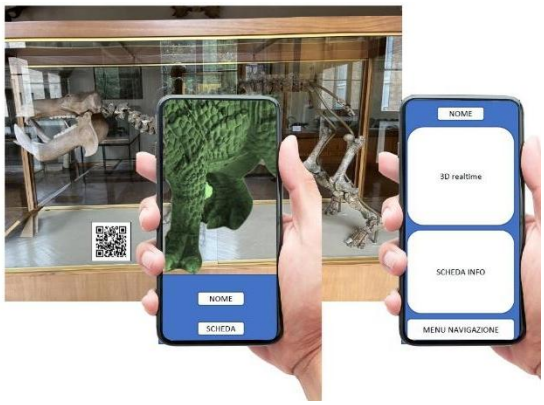

Figure 7: *Sample visualisation of a 360° AR experience*.

The frontal AR experience is provided for artefacts in wall cases. By framing the QR code of about 5x5 cm placed near the object, it will be possible to access the information of the corresponding digital object (Fig. 8) and in particular:

- Common name and Scientific name,
- Curiosity,
- Narrative Text 1,
- Narrative Text 2 (Fact Sheet),
- Alternative Text (e.g. for children),
- Interactive 3D model (if available),
- QR code for vocal readers (inclusivity).

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At the bottom, the Navigation Menu will allow to close the tab (for another scan), choose the language and select accessibility options.

Figure 8: *Sample view of a frontal AR experience*.

3.5. VR experience in settings

The VR experience in settings is designed for at least two locations: one in the offshore, deep-water setting of a Jurassic sea (Tethys Ocean), mainly represented by deposits from the province of Verona and the Asiago Plateau, (Vicenza), and one for the setting called Settepolesini (Fig. 9), taking its name from the location near Bondeno, in the province of Ferrara. This experience can be enjoyed by smartphones tablets, and VR by scanning a QR code located in one of the exhibition rooms (or on the web or on external signage). The user will be able to explore in 360° the changing natural environment and the fauna that lived there by scanning three historical periods in the Settepolesini area: the Last Glacial, the Late Glacial, and the Contemporary (Roman era). The Jurassic marine environments, on the other hand, present extinct pelagic fauna in an underwater environment, with the possibility of accessing details and insights on the selected animals. The technology will be chosen when the first tests can be carried out using a smartphone. Possible choices are Play 3D real-time, and Play of a video generated from the 3D scenario. The Play 3D real-time function includes an ATON scenario (or similar) in which the following will be played: spherical/cubic image of the historical period; animation loop of the animals that will be arranged all around the user (so as to reduce the computational burden); audio of the narrated voice and subtitles; accompanying graphics (timeline).

Figure 9: *Sample view of a VR experience in a 360° setting (Last Glacial Fauna found in the excavations at Settepolesini di Bondeno, drawn by Busetto)*.

Moreover, temporary exhibitions will be able to benefit from the outputs of the CHAMELEON project thanks to the use of the Avatar with the display of the QR code at the entrance; the use of a Digital Web Exhibition created with the exhibition configurator, accessible via browser (PC, laptop, smartphone) at the http address generated by the system, where the user can navigate through the digital objects and interact with the available 3D models.

4. Semantic mapping and 3D digitisation of museum objects

The development of the project action related to the digitisation of museum exhibits to obtain 3D models was anticipated by a careful analysis of the methodological approach and semantic mapping for the enrichment of models with information content. The careful analysis of the needs for narration through digital applications was developed according to the semantic-informative approach, while semantic mapping allowed the preparation of models for information enrichment.

The first phase involved the analysis of the museum context, both in terms of the characteristics of the exhibition halls and of the displayed objects. The University of Ferrara, through the joint work of the two departments (Architecture and Humanities), developed the overall methodological framework, defining the objectives for the different users and analysing the best reference practices. The joint work between the partners made it possible to define survey methodologies, enhancing the museum's needs.

The selection of exhibits to be digitised was guided by criteria of scientific, historical and narrative relevance, in line with the project's objectives. Firstly, specimens of central importance to the museum were selected as representatives of a collection able to tell the story of the area studied and its natural context. Secondly, special attention was paid to specimens with taphonomic characteristics and fossilisation or conservation processes of exceptional interest, which offer an important opportunity for study and valorisation through digitisation. The selection was also guided by the narrative purpose of the project: the specimens were identified to reconstruct significant thematic environments, such as the landscape of Settepolesini or deep-sea ecosystems, in order to create immersive and informative paths that make complex and scientifically relevant content accessible to the public. More than 30 specimens have been collected according to these criteria, with the possibility of adding other objects from the collection to the Museum's digital assets in the future.

4.1. 3D digitisation procedures

The digital acquisition of the specimens (34 objects) focused on the most representative and relevant items. The use of advanced digitisation techniques made it possible to fulfil the need for high-quality and accurate 3D models, but also to open up new interpretative and documentation opportunities, enriching the information levels associated with each object. Two three-dimensional survey methods were selected: structured light scanning and photogrammetry [AFGG21].

The handheld structured light scanner, which uses projections of light patterns onto the surface to be scanned, is a 3D scanning technology that combines the principle of triangulation with light projection, allowing precise and detailed measurement of surfaces. It is therefore particularly effective in gathering qualitative and quantitative information about the geometry of the object, making it ideal for surveying complex shapes. The decision to use a handheld scanner, i.e. a portable scanner, lies

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precisely in its mobility, which allows the operator to move freely around the object to be scanned, unlike fixed scanners that require a stable support. In addition to ease of use and, consequently, reduced scanning times, its freedom of movement offers greater possibilities for detecting objects that, due to their size or fragility, cannot be moved from their original location.

The laser scanner used is the Einscan PRO HD with 0.2 mm resolution. The surveyed objects were scanned by rotating the instrument around them, starting from the front and proceeding to the back, when possible (Fig. 9). Afterwards, with the use of the EXscan software, a complete textured model was processed using the scanner's onboard camera. The final result was an .OBJ file with textures in .JPEG format.

Despite the freedom of movement given by its portability, the use of the laser scanner was not very effective for some artefacts due to the small size of the object combined with the very complex geometric characteristics. For this reason, and to capture textures as best as possible, the digital photogrammetry (or Structure from Motion - SfM) was chosen for a set of objects [KMR21]. Photogrammetry is a surveying technique based on the analysis of photographs taken from different angles, which is significant in capturing information on the colours and textures of surfaces, which can be used to improve the visual appearance of 3D models [FMR*22].

Figure 9: *3D survey phases by structured light laser scanner*.

Although laser scanner surveying can provide much higher accuracy in terms of geometry and a higher point density, photogrammetry has the advantage that the camera can be moved more freely and does not necessarily require the use of a fixed support [FMG*22]. The camera used for photogrammetry is the Sony A7 r5 full frame 60 megapixel model with fixed 50mm macro lens and ring flash. The objects to be surveyed were photographed starting from the front and progressing with several shots along the main axes, thus making a rotating movement with the camera around the object (Fig. 10).

Figure 10: *Views of the set for photogrammetric survey*.

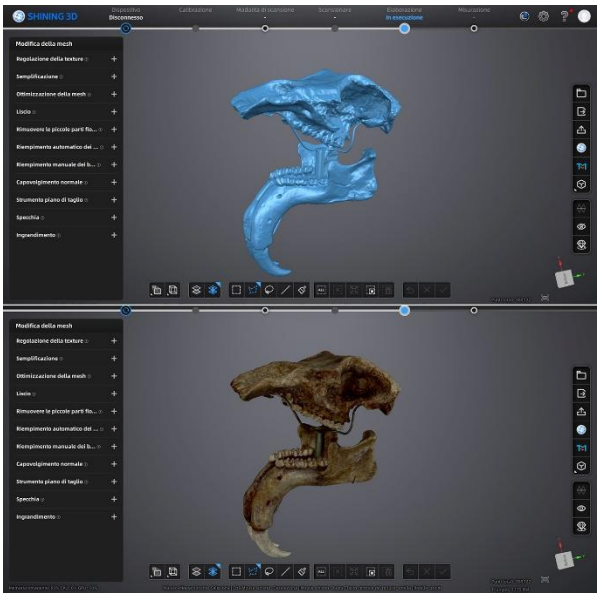

Figure 11: *Steps in the processing of the 3D model of the Deinotherium. Top, solid model, above, textured model*.

It was then possible to scale it using GCPs (Ground Control Points) of known coordinates. The four viewpoints - front, side and front - (two for objects with simpler geometry) made it possible to completely cover the surface of the object in order to obtain 3D models without gaps.

The controlled light of the flash and the fixed lighting set allowed the creation of a complete texture without chromatic aberrations (Figg. 11-12). The software used for the photogrammetric project is Agisoft Metashape with final outputs in .OBJ format and texture in .JPEG format.

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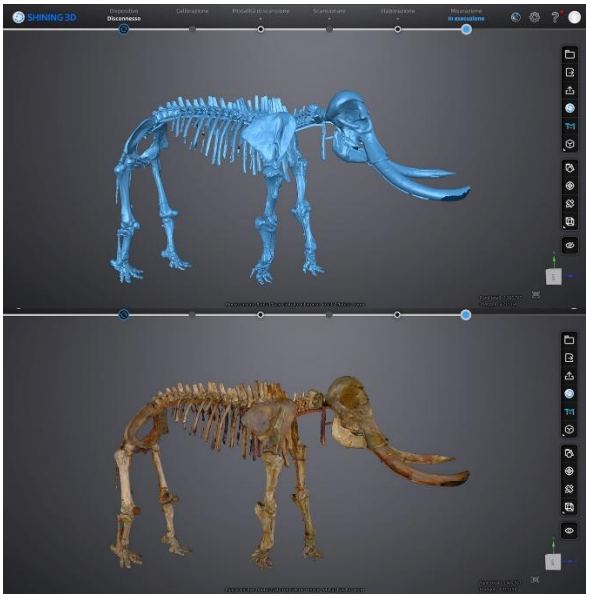

Figure 12: *Sicilian elephant 3D model processing*.

The 3D digitisation through digital photogrammetry has been performed by arranging a specific set. Objects were placed on a support within a fixed lighting set. In order to obtain the complete digital object, some photos were taken by rotating around the object, placed on a target, allowing easier recognition and merging of the different parts of the object during the data.

Wherever possible, a combination of the two methods was chosen as the surveying method (Fig. 13), combining the geometric accuracy of the laser survey with the quality of the photogrammetric textures of the SfM models (Figg. 14-15).

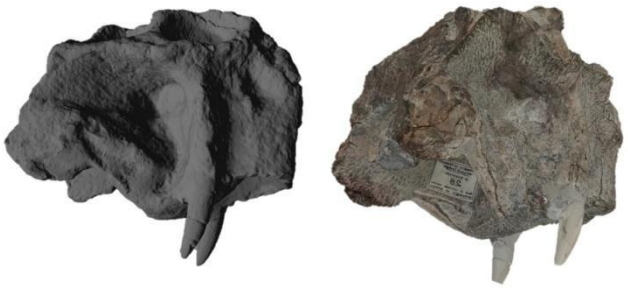

Figure 13: *3D model of the therapsid* Lystrosaurus. *On the left, the laser scanner model, on the right, the textured model.*

5. The cataloguing of the museum specimens

For each specimen selected for digitisation, a dedicated repository of cataloguing details has been created. Access to these datasheets integrates the digital enhancement of the museum's exhibit, allowing visitors to gain insights and more detailed information about the selected specimens.

Each datasheet has been divided into three macro-sections based on the nature and use of the specimens it contains:

- SIGEC analytical fields, including the data reported in the SIGEC sheets of the specimens, together with the catalogue information.
- Additional fields, including information such as the scientific name, informative texts, data on the characteristics of the fossil organism in life as reported in the scientific literature, the place where the specimen was recovered, the method of its acquisition by the MPPPL, and its location in the exhibition room.
- Each specimen datasheet is also accompanied by a text transcribed into spoken audio for the visually impaired and neurodivergent people, using inclusive and accessible language. These texts have been written according to the principles of accessibility and inclusion, in particular by adopting the European "Easy-to-Read" guidelines [Inc09] to ensure that the information is easy to read and understand for all users.
- Particular attention has been paid to linguistic clarity, readability (including for users with dyslexia), and the removal of cognitive barriers, aimed at enabling independent and equal access to the Museum's information content. The descriptions simplify complex concepts without compromising scientific accuracy, and include detailed accounts of the physical characteristics of the objects, their position within the exhibition space, and their historical and scientific significance. Although intended for a non-specialist public, these fields provide bibliographic references for academic users.
- Functional fields and taxonomy, including the data useful for indexing the specimen in the database and in search engines.

This repository has a dual function: a purely cataloguing function for the museum's users, and a didactic function for visitors who are interested in more detailed information about the specimens on display.

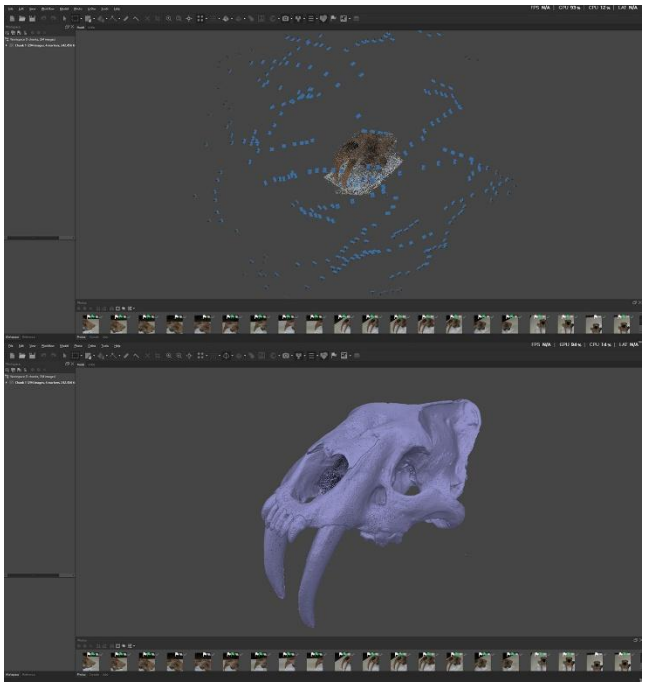

Figure 14: *Above, development of the 3D model of the Smilodon by positioning the photos through tie points in Agisoft Metashape software. Below, wireframe model.*

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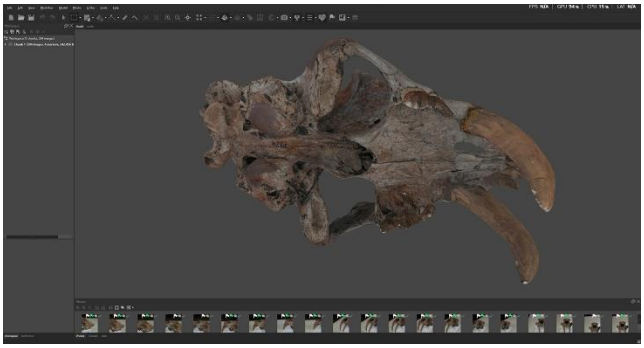

Figure 15: *Processing of the 3D textured model of the Smilodon via Metashape through 294 photos by a full-frame camera.*

The specimens' classification follows the most updated palaeontological and zoological studies, thus providing the reader with a modern and accurate understanding of the material on display. The scientific information is made accessible to the public using a simplified, yet specific and technical language, so as not to detract from the learning experience. Narrative text sections offer more informative insights and curiosities about the selected specimen, such as details of its anatomy, of its original time period and its kin. Among the additional fields, one will document the object's history from its recovery to its acquisition by the museum, depending on the availability of relevant information. This addition will promote virtual links with other museums, collections, individuals, and archives that have direct or indirect links with the artefact, thus fostering a network of relationships and information that will clarify its historical narrative, encompassing both its formation and acquisition up to the present day. Furthermore, linking the datasheet to the corresponding 3D model will facilitate the integration of various materials of historical and cultural significance, including the museum's archival documentation. The use of digital tools will not only enhance and display the museum's heritage but will also create new opportunities for research and development in a dynamic and interdisciplinary framework. Therefore, the selection of the fossil specimens to be analysed and the development of a specific cataloguing of the associated data were guided by an overall methodological approach aimed at enhancing not only the individual find, but the entire historical and cultural heritage of the MPPPL. The data thus collected, selected, and edited in this way, once digitised, will form the semantic backbone of the 3D models, leading to the creation of an implementable digital system for different users, linking different levels of information to specific IT applications.

6. Fruition design for an interactive museum

Within the framework of CHAMELEON, prototypes of 'Semantic XR Museum' [PCd*23], 'Semantic AR Collections', and 'Semantic XR Avatar' are being developed, including the IT architectures composed of the semantic repository and user interfaces, usable with different devices depending on the specific objective (virtual exhibitions, AR, conversational avatars).

6.1. State of the Art and best practices

The design of the applications started with a state-of-the-art analysis of the system infrastructure for interactive museum applications [MSR*25], based on the integration of technologies such as Artificial Intelligence (AI), AR, VR, and digital asset management systems. These solutions are designed to enhance the visitor experience [AZF*25], support the preservation of cultural heritage, and increase overall accessibility. In particular, the main components of a typical infrastructure were analysed, i.e. digital asset management, solutions that allow organising, describing and storing content in a scalable way, supporting metadata customisation and access control, and improving the user experience [APM*21]. AR and VR applications and interactive tours explore artefacts and historical environments [BPP*23], making the museum experience more engaging and educational. AI can analyse large amounts of data and enrich visitor interaction. Multi-channel experiences, thanks to digital platforms combining physical and virtual, enable hybrid activities that engage both on-site and remote visitors, increasing the educational and cultural reach.

Best practices for the system architecture of interactive museum applications [PPFd21] aim to ensure scalability, efficiency, accessibility, and an engaging user experience. The main guidelines include: a scalable and modular architecture through cloud services, separate microservices for content management, data analysis, and interactive rendering; integration with immersive technologies (AR/VR) with support for devices such as viewers and smartphones; multi-sensory interactivity combining audio, video, and haptic feedback to make the visit more immersive. In addition, responsive interfaces work on desktops, mobile devices, museum kiosks and viewers to create applications that allow virtual access to museums [PPBF21], with online guided tours and 3D explorations of collections ensuring maximum accessibility and inclusiveness. Systems for archiving, cataloguing and disseminate digital resources such as high-resolution images and 3D reconstructions, through standards such as IIIF (International Image Interoperability Framework) and the integration of APIs (for collaboration between museums and with external developers) ensure standardised metadata sharing. In addition, sustainability principles are considered through measures to minimise energy consumption, and aspects of security and maintenance.

6.2. The architecture of the CHAMELEON project

Based on the requirements of the project, the infrastructure (system and physical) already available, and the goal of open-source, it was decided to implement a client-server infrastructure that does not rely on a cloud but on a single server installed locally and with the possibility of being reached from the outside through devices, applying secure and efficient communication protocols such as REST APIs, and open-source frameworks and libraries, to allow for future scalability. The choice was made to develop the applications in Node.js, taking advantage of its large community of developers and its extensive open-source library [FG24]. For authentication, the JWT Token authorisation protocol was chosen. The main components of the system infrastructure are the Frontend Configurator, i.e. the interface for the administrator user or designer who configures content and templates, which dialogues with the Backend Configurator to manage the data saved in the database and any connected devices through HTTP protocols for fast data transfers. The Database contains the configured data and makes it accessible to the backend, using a document database (such as MongoDB) for flexible management of multimedia data or configurations. The output devices are AR/VR visualisers for immersive experiences. The connection to the backend allows configurations or interactive settings to be uploaded for display in VR or AR viewers, while QR Codes enable fast interaction between mobile devices and the platform. In terms of visualisation, the VR visualiser is managed by an API backend via Aton, a framework for VR experiences, connected to

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3D objects and advanced configurations; the AR visualiser is based on AR.js, a JavaScript framework accessible via browser and used on mobile devices for experiences connected to 3D objects or other configured content.

6.3. Semantic repository and configurations

Within the scope of the project, it was decided to use a NoSQL database, which does not require a rigid schema like relational databases, allowing different types of data (structured, semi-structured and unstructured) to be managed in the same database. Document-based databases represent documents in JSON format. Each document can have different fields without the need for structural changes, data can be added or modified quickly, complex data can be represented and documents can be accessed and written quickly. Furthermore, the use of a NoSQL database offers advantages in the programming workflow, especially for applications that require scalability, flexibility and high performance. It can have a natural integration with REST APIs since the JSON format integrates directly with APIs and frameworks; it also provides a natural mapping of objects that, in applications, can be saved directly without complicated conversions. By filling in an Excel file containing information required to populate the database, the data can be automatically imported into the web application. The curator's configuration, to create and manage the museum exhibits, and the visualisations for visitors have been designed considering all relevant aspects for museum applications, including the use of Aton [FFD*21], an open source framework based on Node.js and Three.js designed, developed and co-ordinated by VHLab, CNR ISPC to create Web3D/WebXR apps interacting with cultural heritage objects and 3D scenes on the Web. Aton adopts a 'develop once, deploy everywhere' approach, requiring no installation for end users, with its front-end automatically adapting to the device (mobile, desktop/kiosk or immersive XR). This modular framework offers a simple yet powerful API to manipulate graphics, customise event management for rich interactions and much more, along with a scalable rendering system with responsive interfaces [MMB*22]. Regarding the AR framework, considering the search for primarily open source solutions, it was decided to use the AR.js library, which is particularly suitable for mobile devices and works on both desktops and smartphones.

7. Conclusions

The expected impacts of the project concern, in particular, the increase of the knowledge of the important heritage preserved in the Leonardi Museum, the increase of the visibility of the collections both for scientists and for citizens, young people, schools, and the involvement of the widest number of categories of users. The applications will lead to a consequent increase in the number of physical visitors who go to the museum spaces, also through the organisation of specific visits and special openings, with the possibility of using digital applications designed for greater "on-the-spot" fruition. Another important expected result concerns digital access to the museum's collections through digital storytelling paths. A key role is played by the increase in knowledge of the Ferrara SMA and its collections, a reorganisation of the preserved objects, the definition of a database consisting of a set of digitised objects, expandable and integrable, with semantic features to enrich the information level in addition to the geometric-formal data. It is therefore expected that the digital applications developed by the project will increase public participation, make the exhibition more visible and sustainable, encourage a critical approach to knowledge both by curators and experts who can use the scientific content, and by citizens and specific users such as young people, schools, scientists, etc., increasing accessibility, inclusiveness and participation. The creation of the repository of digital models and data configured to integrate different interfaces allows multiple digital uses supported by semantics that can be reconfigured at will, according to its adaptive nature and the creation of multiple user interfaces. The project is indeed designed to be shareable and replicable, providing for the systematisation of digital contents (3D models of objects, ICCD data sheets where available, internal database developed by the Department of Humanities on the information content of the objects preserved at the Leonardi Museum, etc.), and the use of open formats and open platforms/repositories, through a replicable workflow, optimised for natural history and scientific museums, providing a data aggregation tool for research/in-depth analysis that can constitute a best practice at national level, providing for the creation of a set of technologies reusable in similar contexts.

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