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DISPLAYING DANTE'S DIVINE COMEDY MINIATED MANUSCRIPTS IN EXHIBITIONS

Marco Gaiani, Simone Garagnani*, Michele Zannoni**

*Alma Mater Studiorum, University of Bologna – Bologna, Italy.

Abstract

Ancient manuscripts are part of many collections belonging to historic libraries and museums: due to their fragile nature and to the difficulties to display most of their contents during exhibitions, their study is often complicated for scholars who also need generally special permissions to examine them, mostly for a limited time window. Beginning from these premises, this paper introduces the outcomes of the digital replication and presentation of three manuscripts related to Dante's Divine Comedy, as proposed on a real exhibition, "*Dall'Alma Mater al Mondo. Dante at the University of Bologna*", held in 2021. Some of the principles related to the production of their replicas and the fruition of their contents through dedicated applications targeted to visitors and scholars are presented, with care to the reproduction of details such as the ability to explore 3D replicas of detailed elected pages or to browse many of them on dedicated touch screens.

Keywords

Digital heritage, manuscript digitization, digital artefacts for museums, real time rendering

1. *Introduction and general background*

In 2021, the 700th anniversary of Dante Alighieri's death was celebrated, with a series of events dedicated to the author of one of the greatest works of medieval poetry, the *Divine Comedy*. This epic poem, written in Italian and known all over the world, narrates the poet's spiritual journey from the depths of hell to the heights of heaven, while exploring spiritual themes such as sin, virtue, and transcendent love.

To take active part in these celebrations, the Alma Mater Studiorum University of Bologna inaugurated the exhibition "*From the Alma Mater to the World. Dante at the University of Bologna*" (October 25 to December 17, 2021), aiming to present the contribution of its professors to Dante's study, not only in the field of research, but also in the teaching one (Figure 1).

The exhibition path began in the anteroom of the Aula Magna of the BUB University Library of the *Biblioteca Universitaria di Bologna* (BUB) where three ancient original manuscripts from BUB collections were placed, both in their real presence and in their digital replicas (Figure 2):

- the manuscript catalogued as no. 589, which dates to the XIV century, and concerning the Divine Comedy with gloss in the vernacular language (Dante Lambertino),
- the manuscript catalogued as no. 590 (Divine Comedy with Latin glosses taken from the commentary by Benvenuto da Imola, from the Convent of S. Paolo in Monte, Bologna, second half of the XV century),
- the manuscript catalogued as no. 591 (Divine Comedy, some songs with Latin glosses and commentary in the vernacular, from: Amadei, Giovanni Giacomo, second half of the XV century).

Digital surrogates were presented exploiting three multimedia touch screen monitors, to navigate within some of the oldest Dante's codices of the BUB, exploring the relationships between the text, the gloss system, and the images.

Their exploration was completed at the end of the exhibition, in the Aula Magna, where two more touch tables let visitors leaf through the manuscripts (Figure 3).

Showing the true value and the complexity of a manuscript in an exhibition is a complex task, mainly because they are usually bound in books who compel curators to choose which pages to show in recto or verso, leaving the other ones covered by remaining pages. Also, the delicate nature of parchments and inks let the manuscripts be displayed with care and low lights, preventing visitors to touch them and explore their full contents and their chromatic features when miniatures are in the pages.

Fig. 1: The Aula Magna at the *Biblioteca Universitaria di Bologna* (BUB), during the exhibition

To overcome these issues and to make manuscripts understandable to different kinds of possible end-users (from the simple visitor to the acclaimed scholar), after a safe and accurate acquisition, our team developed two different applications for the exhibition: one (called *ISLe* after the original application's name *InSight Leonardo*) meant to explore interactive digital reproductions for three pages of the manuscript n. 589 in their recto and verso, related to Dante's Hell, Purgatory and Heaven, and another one dedicated to a flip-through reproduction of whole manuscripts no. 590 and no. 591. Both the applications run on five dedicated touch screens appositely located at the beginning and the end of the visitors' route during the exhibit visit. The two touch screens at the end of the exhibition proposed a guided exploration of all the structure of manuscripts and allow the visitors, flipping page by page or following an automatic navigation mode, to understand the real consistency of all the parts that compose the book. The users that browse the interactive version of the manuscript on the touch screen could perceive the quality of the writing technique and the parts that are more defined or incomplete.

The possibility to access high-quality visualization manuscript reproductions is usual in digital archives also through the network with any common browser, but the full reproduction of the book in an interactive fruition permits to understand and access an ancient manuscript without any limits and precautions. This experience proposed on a large touch screen changes the relationship between visitors and the artifacts and it opens to many possible interactions and narrations on the contents.

This paper will introduce processes and methods applied to devise these applications, as tailored on the display of the Divine Comedy's manuscripts during "*Dall'Alma Mater al Mondo. Dante at the University of Bologna*".

The first section (*The exhibition and the dedicated applications*) delves into the exhibit and how the two applications were developed for the three manuscripts and prepared for the venue. In *An*

Fig. 2: The three touch screens dedicated to Ms. no.589 placed in front to the original manuscript

application to browse manuscripts section, the software developed for the flip-through replicas of manuscripts no. 590 and 591 is introduced, while in *the ISLe application* section a detailed description of the pipeline adopted to produce 3D accurate digital replicas of three pages in the manuscript no. 589 is presented.
The section is divided into two paragraphs, to better explain the safe acquisition techniques adopted to digitize the original manuscript, and the graphic application to interactively visualize the digital replicas during the exhibit.
Then a *Conclusion* section is added to sum results up and propose possible perspectives.

2. *The exhibition and the digitized manuscripts*

The University of Bologna has built over the last one hundred and fifty years a very deep tradition in Dante studies, which has offered a multiple and decisive contribution to the development of modern philology and criticism but also to the reception of the artistic and scholastic perspectives on Dante and his works, especially the Comedy.

The connection between Dante and the University of Bologna is a close, deep, and ancient relationship, which has its roots in the Poet's biography and then in the very first reception of his works. The traces of his presence in the city are numerous and date back to the first attestation of one of his works, the sonnet of the Garisenda, transcribed in 1287 on a page of the Bolognesi Memoriali by Enrichetto delle Querce (Delle Querce, 1287).

"*Based upon such an important and profound relationship with Dante, the University of Bologna has built over the last one hundred and fifty years a very high tradition of Dante studies which has offered a multiple and decisive contribution to the development of modern Dante's philology and criticism but also to the reception of artistic, scholastic and popular measure of Dante and his works*", as Giuseppe Ledda wrote in the introduction to the catalogue for the exhibition (Ledda and Zironi, 2022).

Opening the celebrations, a recently passed away professor of the Alma Mater, Andrea Battistini, recalled how the Divine Comedy not only touches the emotions of its readers, but it asks for a 'response' from them: one might even think that "*Dante has foreseen from the beginning the necessary presence of commentators, immediately starting to disseminate enigmatic figures such as the three fairs, which arouse not only suspense and the need to continue in the hope of finding some explanation, but also stimulate those who they believe they have deciphered the meaning to affix to his text glosses which, once settled, have given life to the age-old comments*" (Citti, 2021).

The exhibition aimed to enhance the contribution of the Bolognese professors to Dante's study, which is characterized by a profound multidisciplinary nature. The exhibit collected some of the readings of Dante at the University of Bologna which, starting with Carducci and Pascoli, reaches the present day, involving different disciplines and points of view.

The variety of materials exhibited culminated in some ancient commentaries, in Latin and vernacular, among which the names of Benvenuto da Imola, Pietro di Dante, Iacomo della Lana and, later, Cristoforo Landino stand out.

To enhance this approach from different points of view, our team began to work on customised solutions to allow a focused and easy in-depth analysis directly on accurate manuscripts' digital replicas displayed on touch screens, to let scholars and visitors investigate around the "*glosse*", the written text, the remarks annotated over the centuries, the materials, and decorations, without any damage to the original copies. Basically, the focus was on the mentioned three manuscripts.

The manuscript no. 589, written in the XIV century, is titled *Dante Alighieri, Commedia con rubriche volgari brevi e glosse dal Lana per le prime due cantiche*. It measures mm 273x187 (173x84) and it was originally collected in 1755 by the Library

Fig. 3: Digital reproduction of manuscripts no. 590 and 591, as exhibited through touch screens

of the Institute of Sciences together with the entire library belonged to Pope Benedict XIV, born Prospero Lambertini (1675-1758), hence the name of *Codex Lambertino*. The manuscript is made of parchment, written with iron gallic ink with miniatures. In its f. 1r (Hell) representing a canticle, a foliate and framed capital letter introduces a text surrounded by four circles at the corners, depicting Dante in various attitudes with a cap on his head and a red cloak, alluding to the first triplets of Canto I; in f. 69r (Purgatory) a starting foliated and framed capital letter again on the left side is miniated, while at the lower margin, immediately below the written text, two two-toned rectangles of different sizes frame Cato with a white beard and hands raised in a greeting gesture, with the Purgatory mountain as a background (on the left), then Virgil and Dante are aboard of the two-sails "*navicella*" that moves towards Cato (in the low right frame, Figure 4); f. 137r (Heaven) is the initial page of a figurative canticle (God with rayed halo and raised right hand) with a frieze that runs around the text with the image of St. Peter with the Heaven's keys (in the centre of the left side) and two "tondi" in the lower margin (on the left Dante and Beatrice, on the right three winged angels playing trumpets and other musical instruments). The starting letters of the canticle are filigreed in red with purple arabesques, and in blue with red arabesques. The rubrics at the beginning of each song are written in red colour. On the upper margin of the cover, it is still readable the ancient location handwritten in ink: *"Reponatur versus occidentem bench. xiiij °. loco sexto"* probably referring to an ancient monastic library to which the codex may have belonged. There follows another hand note by Lodovico Maria Montefani Caprara, librarian from 1747 to 1785: "*Cod. num° 134 Classroom. II. To Dante Comedia. Codex. Ms. Saec. XIIII Ex Bibliotheca Benedicti XIV P.M.*". In the lower left corner, there is the manuscript number: "19". A f. IV manuscript number: "431", perhaps an ancient signature. At the beginning of the XX century on the front plate of the binding "*in tutta bazzana*" was a label with the number "194", probably dating back to the catalogue for the Dante exhibition in 1865 (Frati, 1923; summary by G. Flamma and S. Mantovani on Ms. 589 (134 Aula II A))

The manuscript no. 590 was written in the second half of the XV century and is titled *Divina Commedia con chiose latine tratte dal commento di Benvenuto da Imola*. It measures mm 292x212 (183x72) and it is made of paper prepared with dry ruling and written with iron gallic ink. The manuscript is in *littera antiqua* language, written by one writer only as one hand only is recognizable, and the font has different size for the text and for the

Fig. 4: The manuscript no. 589, as displayed at Canto I, f. 69r during the exhibition

glosses. It consists of 211 pages, containing the Comedy with rubrics in vernacular and a compendium of the *Comentum* by Benvenuto from Imola to Hell and Purgatory, all expressed in Latin. The *Comentum* had a comparable success with that by Iacopo della Lana, it was very extensive, and it can hardly be found collected into a single volume. Benvenuto da Imola (approx. 1336 - approx. 1388), reader of the classics, had also epistolary exchanges with Francesco Petrarca and Coluccio Salutati. His fame as a Dante's interpreter grew due to at least two courses on the Comedy, held in Bologna and Ferrara.

The manuscript no. 591 was written in the second half of the XV century too, and it is titled *Divina Commedia, alcuni canti con chiose latine e commento in volgare.* It measures mm 180x130 (140x88) and it is made again of paper prepared with dry ruling and written with iron gallic ink. It is a composite manuscript, assembled by at least three copyists. The manuscript does not contain illustrations, although the copyists left some spaces which, in the original project, should have been used to host miniatures. The materials related to Dante are collected in the first part of this codex (cc. 1-54), which includes fragments in the vernacular commentary of the Commedia by the pseudo-Boccaccio, with frequent presence of Dante's triplets. The glosses in vernacular by the Falso or Pseudo Boccaccio in part traditionally attributed to the tradition and in part by some nineteenth-century critics, to Giovanni Boccaccio, are due to the hand of an unknown commentator, probably from Florence. Written around the year 1375, they spread with some success among the Tuscan merchant class, with some northern exceptions, as for the sample preserved at the BUB (Bologna, Biblioteca Universitaria, Ms. no. 591, 242 Aula II A).

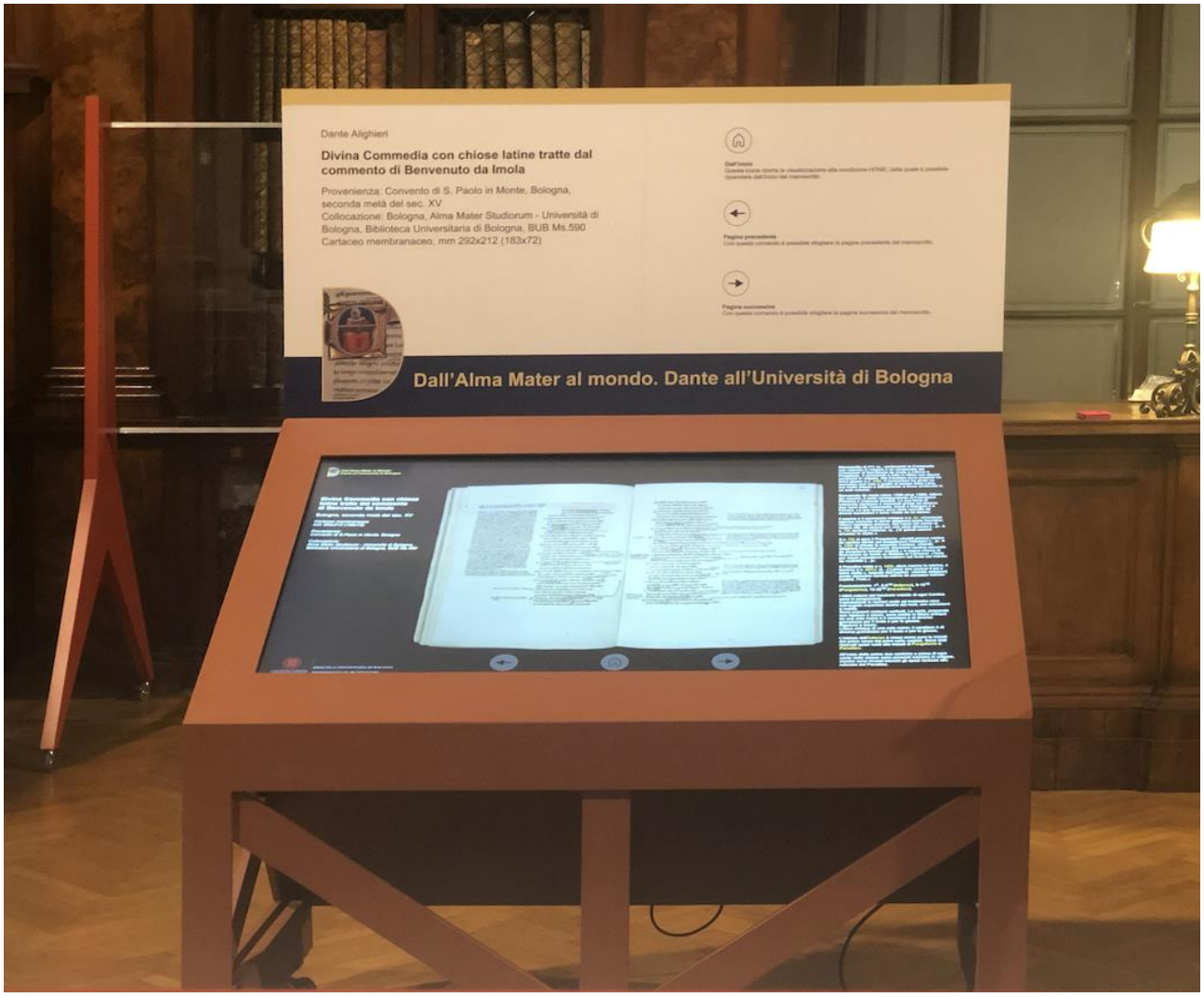
3. The application to browse manuscripts

Applications for browsing digital books are currently very common in stand-alone executable or web-based solutions over the network. Different kinds of these software solutions were released in open source by the developers in the first decade of this century and the standard features of many of these libraries are now sufficiently articulate to create complete interactive artifacts with a good user experience on any platform or website.

In the development process of the touchscreen for the manuscripts no. 590 and 591, we used the *turn.js* Javascript library (TurnJS) developed by Emmanuel Garcia. The choice to use this software solution to code a web-based app in html5, Javascript, and CSS is encouraged by the performance of this library released in 2012 and until now has been perfectly compatible with the most popular browsers on the network. Moreover, this configuration will allow in the future to scale the product to new supports or devices.

The touch screen application (Figure 5) was organized into three parts: the area on the left was dedicated to basic information relating to the title of the manuscript and the description of the physical characteristics and the archival location; the central area is dedicated to the visualization of the pages with the main navigation controls (home, forward and back) in the bottom; on the right side there is a text about scientific description of the manuscript with links to the pages of the book. Each interactive association refers in some cases to a recto or verso page and allows the user to directly access part of the manuscript (Figure 6).

The pages visualization solution supports raster images with the alpha channel to reproduce the exact shape of the paper with all the imperfections and contours of the pages. In the turning page animation, the image is deforming and rotated to simulate the movement of paper. In this effect, the contour of the page overlaps the others below. In this phase of the animation, the quality of the visualization is very important for the user experience of the fruition of the digital version of the book. Every single imperfection in the file outline is highlighted by the contrast during the page movement. The digital images of the manuscripts no. 590 and 591 were provided



Fig, 5: The touch screen dedicated to manuscript n. 590 during the exhibition

already scanned because they were the result of a cataloging flow defined before the exhibition.

The standard used in the photographic acquisition was not adapted to design and develop an interactive book because there were not a correct alignment and proportion between the pages of the manuscript.

The inevitable deformations consequence of the geometric form of the manuscript and its arrangement on the photographic plane create many issues in the preparation of the single pages that were post-processed to adapt for three-dimensional visualization of the book.

Every single image was processed to be used in the application to browse the manuscript. In this process, the image background of the plane was the book posed during the acquisition process was removed and left transparent.

The inner border of the page towards the bookbinding was different on every single page and was normalized on a fixed alignment guide with a manual process through a deformation by points that allowed to achieve a realistic visual effect when the page is turning in the application.

Preventing this manual processing is not easily solved because the different behavior of each book that is placed on the plane behaves randomly every time a page is turned.

4. The ISLe application

To provide a disposable tool beyond today's limits in the conservation and communication of ancient drawings and manuscripts, starting from 2010 the University of Bologna has developed a solution that has reached maturity with the current version, which provides different actors

Fig. 6: The interaction between the text in right area and the interactive visualization of the manuscript

with a software tool covering the entire process of communication of the original manuscript: *ISLe*, a digital communicative artifact developed to surrogate, investigate, describe, and communicate ancient drawings and manuscripts, their methods of representation and their contents, accurately reproduces their shape, characters, and appearance in a digital domain (Gaiani et al., 2015; Gaiani et al., 2015; Gaiani et al., 2019; Apollonio et al., 2019; Apollonio et al., 2021).

This solution proved to be more than effective for museums, having been tested by many visitors in previous different exhibitions, as recorded by the affluence and the average consultation time spent on each touch screen as *Perfecto e virtuale – l'Uomo Vitruviano di Leonardo*, at Centro Studi Vitruviani in Fano (Italy) 24 October 2014 - 6 January 2015, counting more than 10,000 visitors, without any original material; *Leonardo in Vinci, at the origin of the genius*, at Museo Leonardiano in Vinci (Italy) from 15 April 2019 to 6 January 2020, counting more than 140,000 visitors; and *Leonardo, drawing anatomy*, at Museo Leonardiano in Vinci (Italy) from 8 May 2021 to 1 September 2021 counting more than 150,000 visitors. *ISLe* proposes the transposition of the manuscript no. 589 into a digital form as an interactive 3D photorealistic replica that uses two paradigms: "the manuscript as if it is in your hands" and "showing what you cannot see with the naked eye". *ISLe* can be used both by the curator on a desktop or tablet PC, and by visitors to an exhibition via a high-definition monitor and touch interactions based on the same gestures used with common smartphones.

ISLe aims to provide a unified solution to two distinct and complementary issues. The first one is the constitution of archives of drawings and manuscripts that faithfully describe the information offered by the original analogue physical system. This is a conceptually simple problem - the faithfully replication of an object to itself – whose solution does not necessarily involve the use of the best available technology or the most innovative one, but rather the most appropriate and easy to use.

The second issue is related to the methods adopted for the acquisition and the graphic visualization of the manuscript, that is the systems and techniques that allow to reproduce and analytically show the three-dimensionality of the graphic sign in a perceptive form, to guarantee a credible visual evaluation of the preservation state of parchments and inks, the superimposed sedimentations and the interventions received over time. Among these techniques, the best known is certainly the photographic shooting with grazing light.

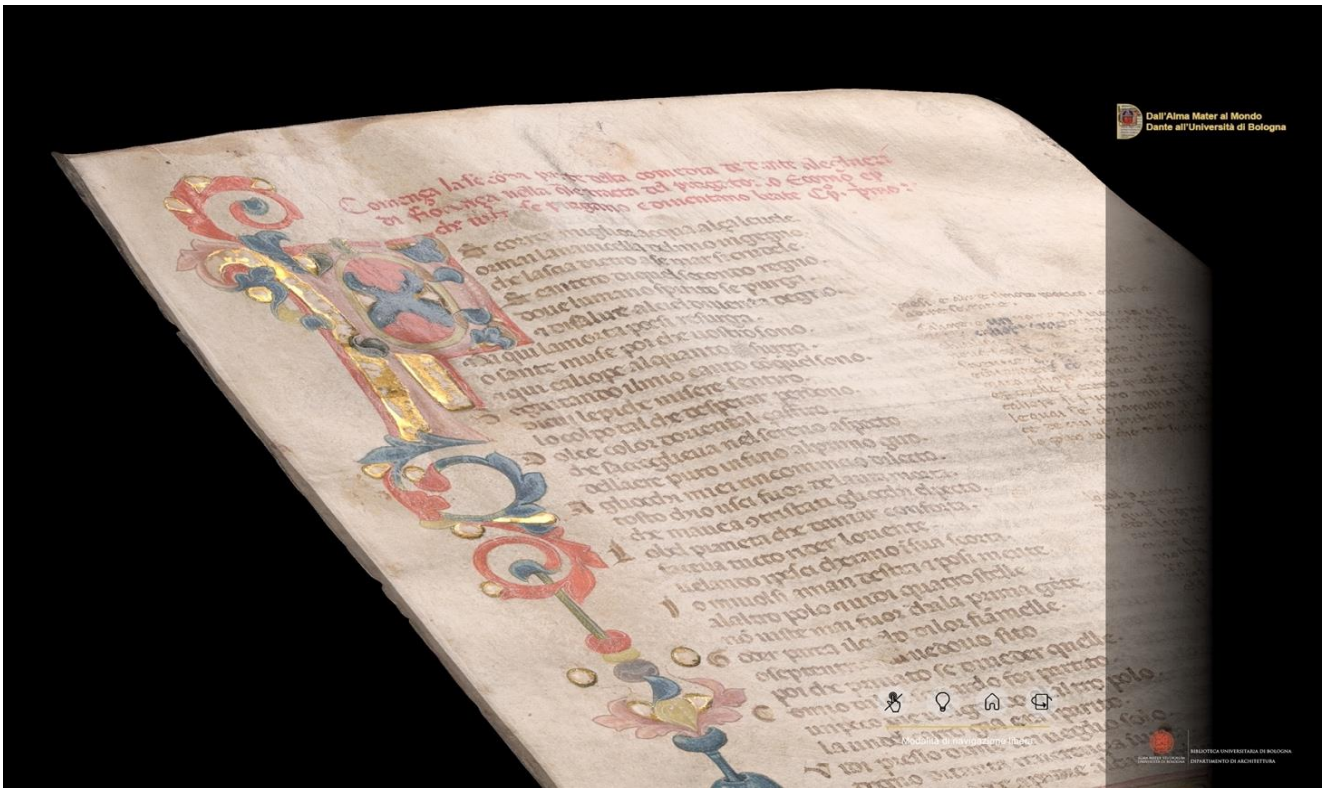


Fig. 7: The digital reproduction in ISLe for the manuscript no.589, Canto I, f. 69r, with the parchment undulations, the inks' specular reflections and the gilding as in the original sample

In recent times, several solutions have been developed involving digital techniques to show the characters of materials' micro-surface, such as the *Reflectance Transformation Imaging* (RTI, Malzbender et al. 2001), which basically consists of a computational photographic method that acquires the shape and colour of the surface of an object, returns it in two dimensions and make it possible interactive re-lighting from almost any direction. This is a very appropriate visualization technique to inspect fine surface details, like the traditional physical inspection with grazing light, which however applies to selected points of view only (which usually prevents users from being able to view both front and back of a manuscript at the same time). RTI is effective at the level of the meso-structure only, and it is complex to produce since it requires countless images with different illuminations and non-trivial equipment.

Other solutions, such as the web-based viewer developed by the Center de Recherche et de Restauration des Musées de France starting from the open-source software IIPImage, or the one proposed by Google (Google Arts & Culture), also applied by the Rijksmuseum in the recent and highly successful project on Rembrandt's Night Watch (Operation Night Watch), simply offer ultra-high-resolution images in number of pixels (gigapixel images) and colour depth. Super-resolution means that they can be used for a qualitative visual assessment but also for quantitative measurements on works of art. However, the absence of a third scale dimension of the meso-structure, the need to generate large files difficult to manage by a non-expert, as well as the great efforts necessary for the acquisition of images in terms of hardware costs and image processing, make Gigapixel images unsuitable for manuscripts.

To faithfully reproduce the three-dimensional shape of the original manuscript, instead of adopting these essentially 2D (very high-resolution images) or 2D and a half (the RTI) solution, a completely 3D solution was developed with *ISLe*, relying on the concept of "total appearence", a sort of extension of photography resulting from the generation of digital synthesis images that are perceptually correct. Overall, the solution guarantees the necessary perceived fidelity rather than a metric accuracy of the returned artefacts, and it uses an acquisition scheme that is much simpler and less harmful to the manuscript than other workflows, though producing excellent results such as the one

described precisely for manuscripts by Gardner et al. (2003), later perfected by the same and by other researchers (Meseth et al., 2012).

ISLe aims to reconstruct the entire spatial reflectance of the artifacts in three dimensions to ensure high-fidelity multiscale dynamic visualization, to make not only the graphic characters of the elaborate appreciable, but also the undulations and movements of the parchment, the specular reflections of inks, pencils, and gilding, in addition to the conservation criticalities of the surface such as corrosion due to acid phenomena (Figure 7).

The system is in the same line of other solutions addressing the same problems and approach, e.g., Ferwerda et al. (2013) and Watteeuw et al. (2016). With the first one it shares the main two properties of the images produced by the system:

- *realistic*, accurately representing the shapes and material properties of surfaces
- *responsive*, changing appearance suitably with direct manipulation and changes in observer viewpoint.

The main advantage of *ISLe* compared to existing solutions resides in a visualization that is not limited to a simple orthogonal view, but provides the ability to document, visualize, and analyze the fine details of the surface. Users can zoom into high-resolution pictures, measure the features of an image, change the visible dynamic range, compare, and overlap front and back or various parts of the manuscript with different shaders or lighting techniques. In addition, analysis visualization can be easily implemented exploiting the shader arrangement (e.g., emphasis on the details), and/or moving the lights sources (e.g., grazing light analysis). Finally, the system integrates semantic and historical-critical annotation to the 3D model through the multimedia environment, so that both the simple visitor and the scholar can observe the details of the manuscript in connection with the studies already existing or discover features still unknown because hardly visible in the original (Apollonio et al., 2021).

From a technical point of view *ISLe* consists of five sub-systems:

- an accurate and safe on-site 48-bit color acquisition at each pixel location image capture, supported by a precise fully automated CC from RAW images based on our software SHAFT (SAT & HUE Adaptive Fine Tuning) allowing a very wide tonal and color range (Gaiani & Ballabeni, 2018)
- a LED-based lighting system that avoids the typical problems of fluorescent illuminators that prevent the acquisition of information reflected at certain light wavelengths and at the same time it ensures safety conditions for the manuscript preservation (Gaiani et al., 2020)
- a solution developed to replicate the original surface with micro and macroscopic fidelity (Apollonio et al., 2021)
- a solution to display the communication artifact in high fidelity using a low-cost rendering engine that is portable to multiple devices (PC monitors, touch tables, tablets, smartphones)
- a kiosk visualization interface for visitors to museums and exhibitions based on touch and usual gestures.

These five subsystems corresponds to the development of three modules: the first, starting

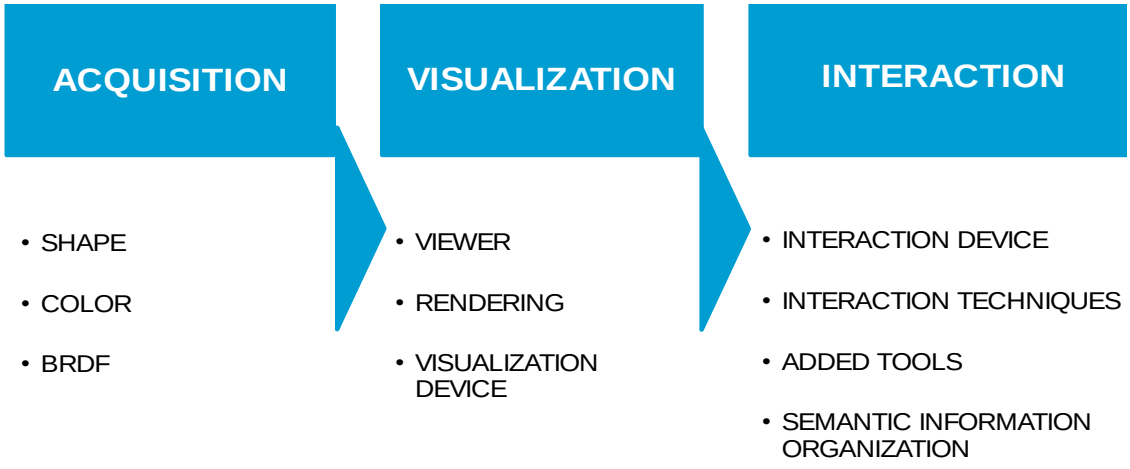


Fig. 8: The ISLe working pipeline

from five photographs of the original, reconstructs and digitally restores the three-dimensionality of analog manuscripts by reproducing their entire formal quality and surface reflectance; the second renders color and reflectance with imperceptible difference to the expert observer, and the texture at a resolution of 50 μm., the third consists in an adaptation of the traditional multitouch interaction paradigm to fit the exploration of 2D-3D contents to minimize uncommon gestures (Figure 8).

The main advantage of our *ISLe* system in its visualization stage is a faithful replication not limited to a simple rendering view, but able to replicate the fine details of the surface at any angle of observation and under different kind of lights instead. Users can zoom in high-resolution images to evaluate characteristics of a chosen view, edit the light behavior, explore various parts of the manuscript with different lighting techniques, to isolate fine details, notes, or remarks.

Activating the different illuminating sources by touching virtual buttons in the *ISLe* interface, is possible to outputs a very realistic visualization under direct and raked lights. The model can also be freely rotated and enlarged to better estimate from different perspectives these changes in light as documented in Figure 9.

The digital pages of the manuscript could be enjoyed through the developed navigation interface, based on an adaptation of the traditional multi-touch interaction paradigm to fit the exploration of 2D-3D contents and to minimize uncommon gestures.

ISLe is built into a graphical environment that can be run on a multitude of different devices, from desktop computers to mobile smartphones or tablets. Due to this versatility, during the exhibit in Bologna pages 1, 69 and 137 belonging to the manuscript no. 589 run on three different, 55 inches wide touch screens, with 12 points projected capacitive grid and a supported 3840x2160 px max resolution, connected to workstations equipped with Core i7 9700 at 3 GHz CPUs and 8 GB RAM, implemented with a graphic card ASUS Phoenix Radeon RX 550 and GDDR5 4GB video memory.

Finally, to understand the meaning of *ISLe* in a real exhibition context, it is necessary to get back to 1998, when Werner Schweibenz (Schweibenz, 1998) dealing with the concept of "virtual museum" was the first to introduce a theme that appeared in the mid-1980s but then forgotten.

He wrote: "*museums were no longer thought of as being repositories of objects only but as storehouses of knowledge as well as storehouses of objects*".

He then tackles the theme of contextualization which is the second cornerstone of *ISLe*: "*the myth that "objects speak for themselves" forgets that the meaning of an object is learned and established by the context. ... Instead of only presenting objects, museums must create meaning and establish context. This shows that an important aspect of the museum is to connect visitors, objects, and information...*".

Just like reading the warning by Roberto Longhi against the contemplative absolutization of works of art as a condition capable of denying the understanding of the work of art itself: "*the work of art is always an exquisitely relative work [...] the work does not stand alone; it is always a relationship [...] a single work in the world would not even be understood as a human production, but viewed with reverence or horror, as magic, as taboo*" (Longhi, 1950).

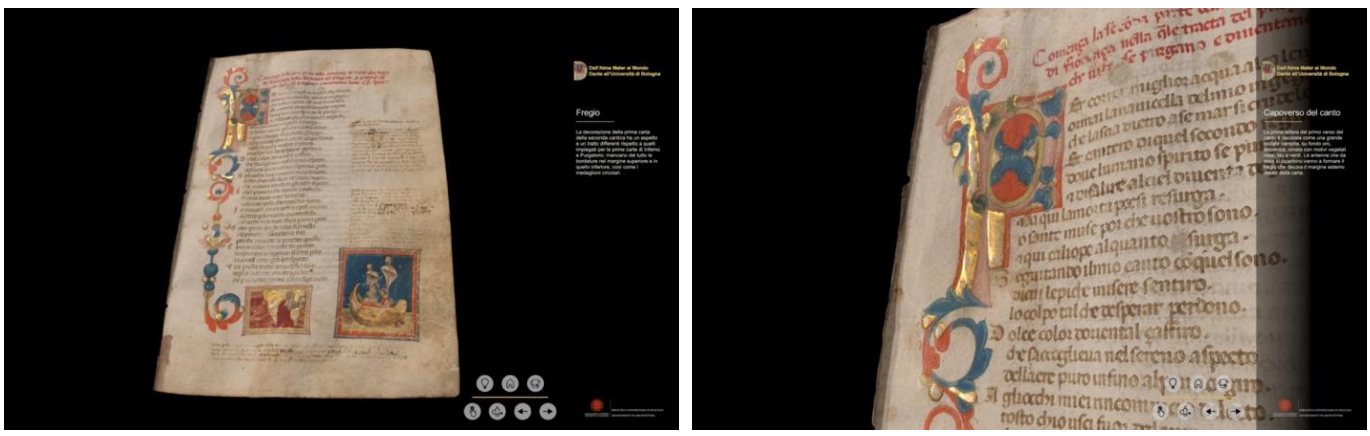


Fig. 9: The *ISLe* interface, in which the digital representation of manuscripts

5. *Acquiring and visualizing the high specular gold leaf in the miniatures*

One of the main goals of *ISLe* is an accurate physically based visualization of material appearance (Dorsey et al., 2007). This is noticeable in manuscript no. 589, where the initial letters of each Comedy's canto are filigree in red colour with purple arabesques, alternating with those in blue with red arabesques. The parchment of each page is mostly well preserved, but it is the gold leaf used to enrich some of the miniatures that introduces a remarkable challenge in the *ISLe* replication system. This problem requires to integrate all the previous studies carried out to acquire and replicate old paper or parchment and iron gallic inks (Guarnera et al., 2016). To solve this issue the acquired artefacts had to be precisely replicated in a comprehensive visual framework, meant to mimic real behaviours toward light of parchments and its handwritten decorations.

The fundamental problem in the digital acquisition and reproduction of manuscripts and drawings is the chromatic and tonal definition of the graphic work which must be framed within the more general theme of the complete definition for the material properties, or rather the *Bidirectional Reflectance Distribution Function* (BRDF), a function that describes, in a quantitative way, the real light reflection considering the entire hemisphere surrounding the light/surface collision point (Nicodemus, 1965). To correctly model the BRDF, we used the types of light interactions described in Westin et al., where they are roughly grouped by the size of the geometric structures in three different levels: a *macrostructure* (used to define general shape and geometry), a *mesostructure* (that includes elements still visible to the naked eye, but which are usually not considered constitutive of the overall shape of an object), and a *microstructure* (given by microscopic facets of orders of magnitude below the resolution of the human eye which, however, contribute significantly to the appearance of the material).

The whole solution to the accurate BRDF acquisition and rendering presents two sides:

- colour and surface structure acquisition,
- colour and surface structure visualization.

A key step concerns the Color Correction (CC) of the acquired images, i.e., the stage in which colour signals detected by the sensor of the camera are translated into the corresponding pixel values of a digital image. The objective of the CC is therefore to correct the colour measurements of the camera towards colour spaces related to the human visual system. For digital cameras, the most common solution to achieve CC is to use tables of reference colour patches with known spectral reflectance, usually measured with a spectrophotometer. In fact, following a theoretical approach, CC can be seen as finding a unique shift in a well-ordered series of colour differences among patches on a colour target. Real implementations are very far from this ideal situation (Simone et al., 2021).

5.1 Color and surface structure acquisition

Manuscripts were acquired taking pictures under a specific light set, designed to be as safe as possible to parchment and inks. High Flux LED white lighting technology was used, which consists of light diodes on a single chip providing a very bright source with a primary heat dissipation device integrated into its case, with no UV and IR emitted radiations. An 'ad hoc' lighting system was built including sixteen Relio[2] (Relio) single LED lights, having four of them on each side of the acquisition table, integrated with 3D printed angled holders. These illuminators emit continuous spectrum light at a CCT of 4000°K, with 40,000 lux at 0.25m in brightness of a CRI>95%. Their SPD shows a high chromatic reliability at all wavelengths and an excellent yield of color rendering. Each Relio[2] is individually calibrated, and the light emitted is certified through spectrophotometry to mathematically calculate, with no empirical outcomes, the white balance. Geometric features of the manuscript surfaces were acquired using images, according to Photometric Stereo principles as introduced around the 1980s by R. J. Woodham (1980).

In fact, color corrected images previously produced in SHAFT were edited using *nLights*, a MATLAB-based software (Xiong, 2022) we authored to produce maps to be later adopted in the production of the final shader:

- an albedo map, estimating lighting matrix by solving a nonlinear least squares problem
- a normal map, inferred by the different light directions to define the materials microstructure
- a depth map recovered from estimated normal vector field
- a reflection map, later detailed also for gold leaf parts simulations

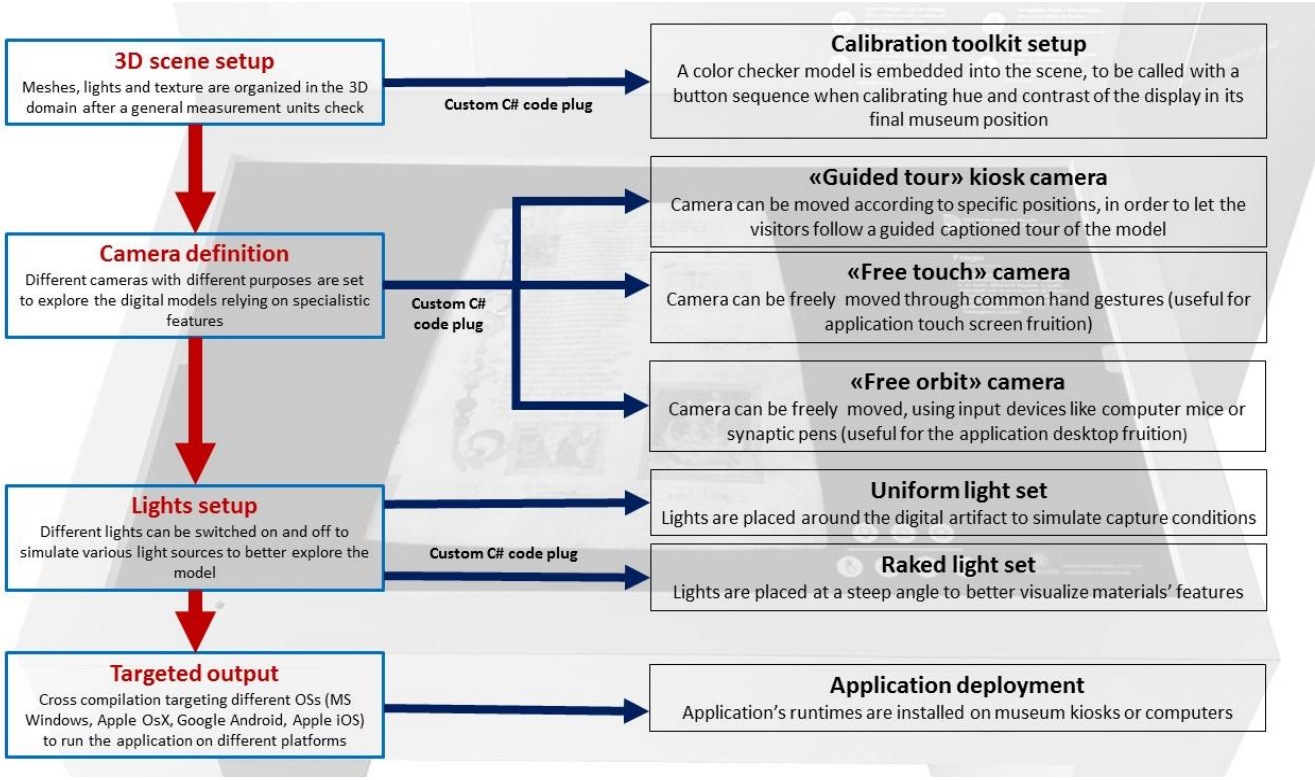


Fig. 10: General scheme of the *ISLe* visualization system with the custom shader production steps (on the left) and all the features developed to explore the digital manuscript

- a geometric 3D representation of the manuscript shape, in form of STL or OBJ file, to define the macrostructure.

nLights exploits the simple stationery zenithal acquisition of 9 images with different light directions.

The typical solution includes one single image to capture the diffuse reflection, while three of them allow to solve the photometric problems and the last one allows to handle outliers generated by many causes: self-shadowing, interreflections, non-Lambertian behavior, etc. (Ackermann & Gosele, 2015).

However, this solution does not allow to model correctly specular reflections for the limited angle used to get the maps (i.e., in our case appearing at gaze angle of 30-35°) and we implemented a new solution with 4 lights placed at 45° and 4 lights placed at 30°. This allows a correct evaluation of the specular component.

5.2 Color and surface structure visualization

From a technical point of view, the developed solution for color and surface structure visualization aims to match two main divergent requirements:

- a physically based light transport and material modelling solution aiming at an accurate visualization
- an interactive rendering system allowing frame rates of 60-100 Hz to easily interact with the manuscript visualization.

Over the last decade, there has been significant progress in the real-time rendering (RTR) visualization quality (Akenine-Möller, 2018), and many applications were developed upon existing graphic game engines with progressive improvement of the rendering results (Eberly, 2015; Salama and ElSayed, 2018; Zarrad, 2018).

To express the best visualization environment fitting our needs, in terms of graphic quality, cost and accuracy for the geometric model definition, we started the development of a custom 3D visualization application by investigating the state of the art for existing gaming rendering platforms.

After extensive investigations on existing software implementations, in fact, we opted to test a custom-made render sequence developed into the High-Definition Render Pipeline (HDRP), a rendering framework tailored on C# scripts and easily customizable on top of Unity 3D RTR graphic engine (Unity 3D). Unity is a videogame development platform, originally released in 2005,

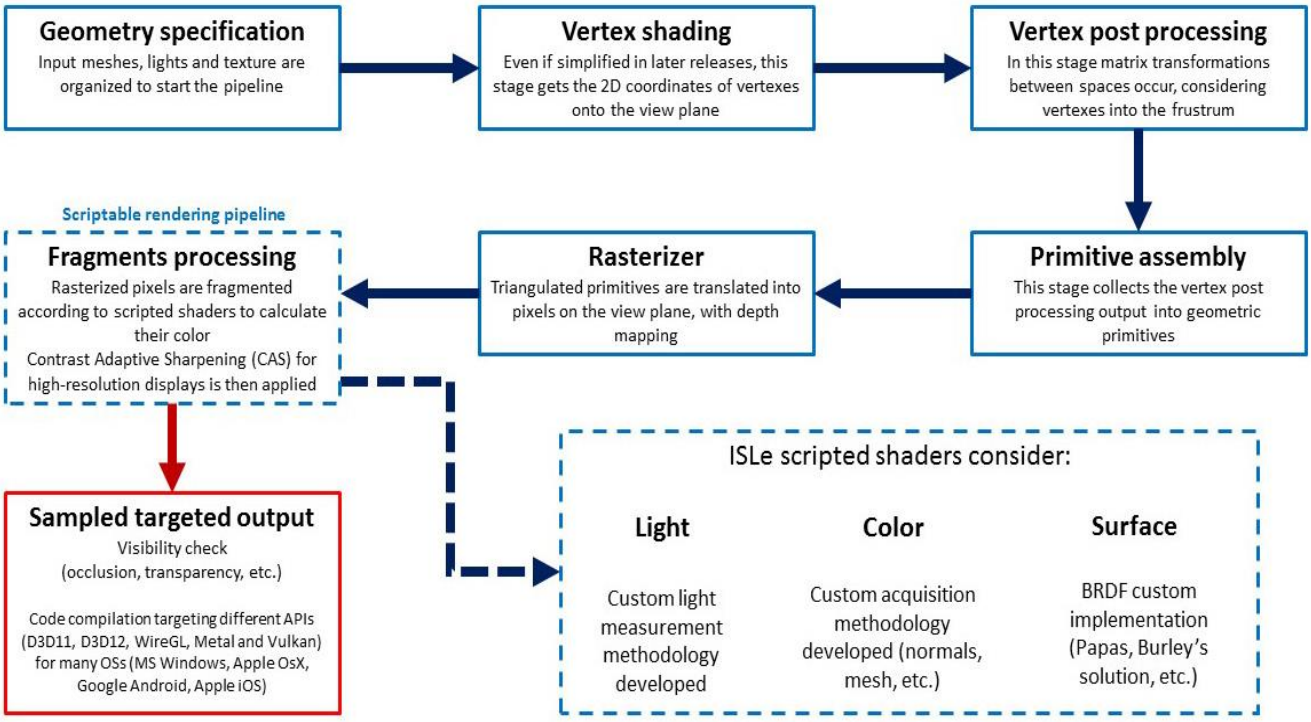


Fig. 11: A schematic view of our rendering pipeline, with stages referred to the final visualization in *ISLe*

which consists of a graphical user interface (GUI) and a game render engine. A large community of developers uses this piece of software to author interactive simulations, ranging from small mobile and browser-based games to high-budget console games and AR/VR experiences.

This general-purpose approach supports a variety of software platforms, making the Unity engine an ideal development platform for our visualization purposes in *ISLe*, since our visualization software need to be scalable and versatile to meet both museums and scholars' requirements (Figure 10).

The exploitation of the traditional GPU-accelerated graphic pipeline (Toledo and Levy, 2004; Korunoski et al., 2019) led to necessary requirements in customization for manuscripts' translucence and gold leaf reflectivity, two traits that our visualization app replicates in any light and any visual angle condition.

Basically, we applied principles inferred by the physically based rendering (PBR) techniques (i.e., scripted shaders to represent complex micro-faceted models in which glazing angles and backscattering issues deeply influence resulting spectral behaviors) (Figure 11).

In practice, we appropriately implemented for each material the Torrance-Sparrow theory for off-specular reflections on micro faceted surfaces (Torrance and Sparrow, 1967), as modified by Burley (Burley, 2010).

5.2.1. Parchment

Real parchment has a predominantly organic composition, based on protein collagen in association with small quantities of elastin, globular proteins, and fats. It is generally prepared from an animal skin that has been wetted, immersed in lime water, dehaired, scraped, then left to dry under tension on a wooden frame. The stretching of the soaked pelt has the effect of reorganizing the collagen fiber network into a laminate structure, resulting in a stiff sheet that is durable and can last for centuries if kept cool and dry (Larsen, 2007).

The parchment was found to be an optically thick material that entails light behaviors given by the combination of many effects: subsurface dispersion, mirror reflection, retro-reflection, surface glossiness, and transmission. The effect of the subsurface dispersion was modeled extending the BRDF to the BSDF (*Bidirectional Scattering Distribution Function*), a quantity that consists of the sum of the BRDF and the *Bidirectional Transmittance Distribution Function* (BTDF). The latter function expresses how much light passes through a (semi)transparent surface. Starting from Papas et al. (Papas et al., 2014), who

introduced an accurate model of paper's BRDF, transmission and diffusion of light were modeled from observations on parchment dispersity (Bartell et al., 1980).

Thus, parchment behavior in *ISLe* is reconstructed using a BSDF representation exploiting three components:

- a reduced version of the multi/layered model of Donner and Jensen (2005)
- the single dispersion theory model (Hanrahan & Krueger, 1993)
- the microfacets model for surface reflections and refractions as in Walter et al., 2007.

The Fresnel refraction calculation is done twice, both for incoming and outgoing light that scatters from the paper's surface, to preserve Helmholtz's principle of reciprocity exploiting the Schlick approximation (Schlick, 1994), which expresses the grazing retro-reflection response by passing to a specific value determined by the roughness instead of a null value.

The error introduced by this approximation is smaller than that due to other factors, allowing to consider Fresnel deficiencies in presence of opaque paper (Papas et al., 2014), improving the overall original non-natural response to grazing light.

5.2.2. Gold leaf

In manuscript no. 589 decorations and initial letters aside of the digitized pages were featuring gold leaf layers presenting a metallic behavior, that reflect the energy differently from the parchment's one. To display with significant realism this kind of behavior proper of gilding, we extracted at first the specular properties and the material portions of the manuscript where the gold leaf was layered exploiting the photometric stereo technique adopted as in Walter et al., 2007. To successfully replicate the gold leaf portions, we filtered the reflection map generated in *nLights* to isolate all the pixels resulting in a high albedo value (i.e., metallic behavior). This way the parchment and ink's albedo and the specular gold components were separated, generating a mask map to be later used in the production of the visualization shader. Operationally, we implemented, at the top of our RTR *ISLe* system, a custom shader able to replicate inks, parchment, and gold leaf behaviors to light.

The shader was written starting from what is reported in Doppioslash (2018), introducing as missing coefficients evaluations achieved from measurements made during previous experiences and on a literary basis.

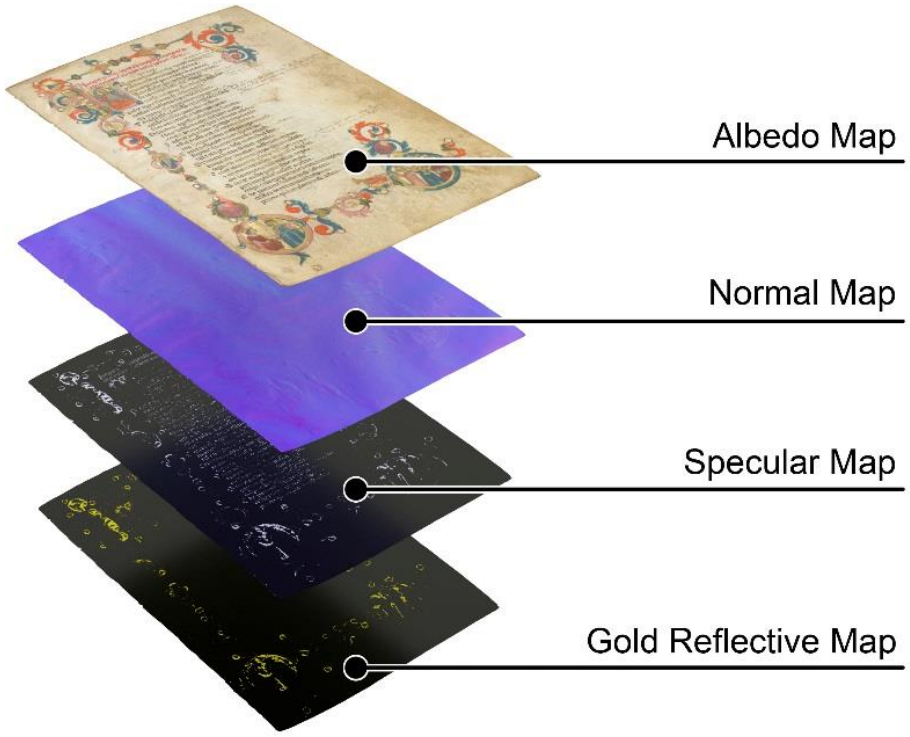


Fig. 12: The general shader structure, in which maps produced by our custom application *nLights* are overlaid to mimic realistic behaviors of materials

Finally, to render the iron gallic ink and the gold leaf, maps with dedicated alpha channels were added to activate portions of the page influenced by the Fresnel effect and the filtered specular maps (Figure 12).

6. Conclusion

Through the development of the applications introduced with this work, we described a series of multimedia solutions that were designed to improve the knowledge on manuscripts of the Dante's Divine Comedy at different levels, with particular care to display them in an exhibition. In particular, the presence alongside the digital representations of the originals made it possible to achieve a sort of increased knowledge on the original artifacts, with a direct experience based on the digital replicas whose peculiarities enhanced their fruition and possibilities without any damage to the originals.

The proposed pipeline begins from the digital acquisition to get the faithful replication of all the peculiarities in the real manuscripts, bringing to a complete solution for museums and cultural institutions.

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