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SCIentific RESearch and Information Technology
Ricerca Scientifica e Tecnologie dell'Informazione
Vol 9, Issue 2 (2019), 29-46
e-ISSN 2239-4303, DOI 10.2423/i22394303v9n2p29

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ANIMATION OF TWO-DIMENSIONAL PICTORIAL WORKS INTO MULTIPURPOSE THREE-DIMENSIONAL OBJECTS. THE ATLAS OF THE SHIPS OF THE KNOWN WORLD DEPICTED IN THE 1460 FRA MAURO'S *MAPPA MUNDI* AS A SHOWCASE

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Abstract

This paper reports the preliminary results of an ongoing interdisciplinary research in digital humanities and animation that the authors are undertaking to explore how a new generation of three-dimensional (3D) non-photorealistic animated visualisations can improve upon two-dimensional (2D) visualisation methods. The atlas of the world's ships depicted in the Fra Mauro's *mappa mundi* (Venice, Marciana National Library, dated 1460) has been used to: 1) showcase the design process and techniques of an innovative method through the prototyping of a 3D non-photorealistic-rendering (NPR) model of one ship, and 2) demonstrate the effectiveness of this method through the 3D NPR animation of all Fra Mauro's ships as a contribution to both the advancement of learning in pre-modern maritime history (with a focus on shipping), and the implementation of NPR for the creative industry.

Keywords

Digital Humanities, 3D Animation, Non-Photorealistic Rendering (NPR), Visual knowledge aggregation, Fra Mauro's *mappa mundi*, Atlas of the ships of the pre-modern world, Maritime history

1. *Introduction: Research Background and Hypothesis, Choice of the Case Study, and Structure of the Paper*

Heritage as the science of what might be inherited includes, but is not limited to, conservation. On the contrary, conservation and the resources invested in pursuing it are a consequence of the trust that societies have in preserving human artefacts with high cultural content to treasure and enable the transmission/transfer of the human knowledge and experiences encoded into them. The belief is that knowing from where we come from, we better know who we are, and knowing where we are today, we may influence what we want to become (for a digital-humanities contextualisation of this agenda see Nanetti, Cheong, & Filippov, 2013, heritage and historical sciences; Nanetti & Simpson, 2015, social media; and Nanetti, 2019, Transcultural Human Sciences).

In this prospective cultural context, since the mid-nineteenth century, printed photographic reproductions of pictorial works have been of use in satisfying not only the preservation needs of the artefacts themselves, but also to facilitate the access to and the transmission/transfer of the knowledge embedded in the depictions that were made on different traditional painting supports (e.g., stone, wet plaster, codices, canvas, wood, ceramics) over time and across space; notwithstanding the ongoing issue whether photographs are interpretative "maps" or faithful "duplicates" of the original artefacts (Ivins, 1953, 76; Jussim, 1974, 274; Freitag, 1979, 117).

With the advent of digital capturing, storing, processing, and broadcasting technologies, the former essentially-two-dimensional (2D) field of photographic reproductions can provide data to explore the three-dimensional (3D) information embedded in 2D depictions. Indeed, the digital 3D rendering of 2D data can challenge the very limits and characteristic of 2D human reproductions, because it can bring the user experience of a 2D object in the realm of the 3D one that was conceived by the imagination of the artist who painted it using 2D perspective or non-perspective drawing techniques (Scolari, 2005, 21). The use of Augmented Reality (AR), Virtual Reality (VR), Mixed Reality, and other immersive technologies can open new horizons to the exploration of human imagination. This paper focuses on how to develop, streamline, and test a philologically correct design process able to transfer as much multipurpose raw data as possible from the 2D artefact to 3D user experience.

Efstratios Stylianidis and Fabio Remondino in their editorial preface to *3D Recording, Documentation and Management of Cultural Heritage*, stated that "Recording and documenting cultural heritage is a fundamental part of the process in its protection and sustainable management" (Stylianidis & Remondino, 2016, xi). In particular the photographic reproductions:

1. insure the preservation of content against the degradation and/or loss of the original painting support;
2. contribute to the preservation of the original artefact, because they lower the need of its exhibition, which implies change of microclimate (e.g., from the store room to the exhibition space), exposure to light, and mechanical manipulation by the curators, and eventually the users;
3. allow scholars to remotely access visual contents otherwise available only *in situ* or on display in musealised collections.

Today, worldwide, for the above-mentioned reasons, most of the main cultural institutions have a digital library of 2D facsimile copies. During the last few decades a growing number of scholars is accessing pictorial works online. Digital and web-based technologies have already enormously increased preservation and enhanced accessibility, because, besides the fact of being more accessible, they can usually provide to scholars and professionals even more than what they can experience in front of the original artefact.

In today's museum, library, and archive settings, high-tech digital photographic equipment is commonly used in the conversion of 2D pictorial works into digital data that can be processed by computer software (see Ciagà, 2013, 162-163, for high definition reproductions in the field of cultural heritage). In taking the 2D digital images, the use of different lighting techniques (visible spectrum, ultraviolet, tangential, infrared) provide the data-capturing process with different characteristics of the depicted artefact (for contextualisation, one can refer to the conference papers by Chabries, Booras, & Bearman, 2003; Griffin, 2006; Lettner et al., 2008; Lettner & Sablatnig, 2009; Hollaus, Gau, & Sablatnig, 2012; Valzano, Negro, & Foschi, 2017). However it has to be noticed that these papers focus on non-invasive diagnostics that are instrumental to the conservation and restoration of the artefacts, where the use of high definition photography with different spectra is usually accompanied by X-ray fluorescence (XRF) and other proteomic, elemental, and chemical analyses.

When the focus is the decoding and interpretation of the human knowledge and experiences embedded in depictions, the digital data has been also used to recreate the 3D models of the objects themselves. As an example, one can refer to the 3D rendering of Leonardo da Vinci's mechanical drawings in the web exhibition made by the Galileo Museum (Florence) in 2018 (Galluzzi, 2018). It is a best practice of 3D photorealistic visualisation solutions for the advancement of learning in the history of science and technology. Indeed, the web exhibition fully addresses the interpretation of the functionalities of the mechanical devices. However, in such photorealistic objects, the sketching style and techniques of da Vinci's drawings are disregarded—simply because they are not the aim of this specific visualisation exercise—and consequently the interpretation becomes final. It means that it is not possible to revert the process without going back to the original drawing and making a new 3D model suitable to simulate different interpretations.

To overcome this situation that limits flexibility and might result in misleading user experiences, our research hypothesis is that the use of non-photorealistic-rendering (NPR) could highly enrich in data quality and quantity the 3D digital models provided to scholars and creative artists. And, in the more general perspective already highlighted by Maria Roussou and George Drettakis in reporting the results of the ARCHEOS research experience (Inria Research Centre, Sophia Antipolis, France) in 2003: "using such a non-photorealistic technique has the advantage that the viewer is immediately confronted with an abstraction, thus subconsciously underlining the hypothetical aspect of the reconstruction" (Roussou & Drettakis, 2003, 57).

In Computer Graphics, NPR identifies the creation of computer generated imagery (CGI) that strives against a realistic recreation towards a stylized and expressive depiction, as it has been excellently demonstrated by Santiago Esteban Montesdeoca in his PhD Dissertation successfully defended at NTU, Singapore (Montesdeoca, 2018, 23-26), and exemplified for different painting styles by him and his PhD supervisors (Montesdeoca et al., 2017; Montesdeoca et al., 2018).

The doctoral research resulted, among others, in the development of the Maya NPR (MNPR) system, which is a plugin to create stylized NPR optimised to work in Autodesk® Maya® Viewport 2.0. The MNPR system takes paper scans and replicates the texture overlay in the rendering to get a 2D illustrative look. The system allows a flexible user customization of various features to emulate different painterly styles. Stylisation options range from charcoal to water colour (Chen and MacIntyre, 2008; Montesdeoca, 2018, 131-140). In Virtual Heritage, the application of NPR in animated 3D CGI has been used in creating digital reconstructions of historical or archaeological artefacts and sites (Roussou & Drettakis, 2003, 51), and has very limited applications in films, games, VR and AR, especially when compared to photorealistic rendering.

Thus, in order to provide further evidence related to pictorial works and explore the benefits of MNPR in their 3D visualisation, our research team selected the ships depicted in the Fra Mauro's *mappa mundi* (Venice, Marciana National Library, Inv. 106173, dated 1460, for which one ca refer to Gasparrini Leporace, 1956; Marcon, 2001; Falchetta, 2006; Cattaneo, 2011; Falchetta, 2011; Nanetti et al., 2015; and now the interactive app of the map on EHM, 2019) as a showcase, for the following five consequential reasons:

1. this mid-fifteenth-century map is the earliest known atlas of a large number (fifty three) of detailed depictions of different typologies of ships from the known world (i.e., the Afro-Eurasian *terra continens*);
2. the potential matching of each individual ship depicted on the map with a real historical boat or vessel of the time has not yet been ascertained by scholarship; and as Richard W. Unger pointed out "There are ships of the coasts of Asia and of Africa but they are small and difficult to distinguish" (2010, 57);
3. in such a perspective study, scholars, as discussed above, can highly benefit from 3D digital renderings of the 2D pictorial objects, because research requires accurate investigation of the details and the possibility to make comparisons with other physical or visual materials, possibly online;
4. the use of NPR provides to scholarship a truthful 3D representation of the drawing (i.e., philologically coherent with the pictorial work) that can be used to discuss different interpretative identifications of the ships;
5. the creation of computer-generated models in real time rendering and animation can be used in various display platforms (e.g., smart device, computer screen, large flat screen, holographic pyramid, AR, VR), and also become physical models via 3D printing; thus maximising the user experience in any area of advancement of knowledge and creative industry (Bénard, Bousseau, & Thollot 2009; Akenine-Mo, Haines, & Hoffman 2018).

The present paper is structured in five sections (including this introductory one and the conclusion) followed by acknowledgments (research collaborations and funding), and bibliographical references. Section 2 presents and discusses in a contextualised historical context the ships depicted on the Fra Mauro *mappa mundi*. Section 3 showcases the design process and techniques used by the authors in the prototyping of a 3D NPR model of one selected ship. Section 4 provides the complete atlas of Fra Mauro's ships of the known world complemented with 3D NPR models available on the Internet via active links.

2. *Contextualising and Analysing the Atlas of the Ships depicted in Fra Mauro's* mappa mundi

According to Richard W. Unger, the earliest existing evidence of ships depicted on maps dates back to the fourteenth-century (ca. 1375), to the so-called *Catalan Atlas*, attributed to Abraham Cresques. In fact, besides the six very stylised and identical boats depicted on the copies of Beatus of Liébana's early-medieval map (dated ca. 1060), the *Catalan Atlas* provides the earliest evidence of three typologies of ships, even if very stylised. The map depicts a galley-like ship on the shores of Africa (Fig. 4a), three times the same junk with one mast and a square sail wearing different flags (one in the Caspian sea, one in the Persian gulf (Fig. 4b) with two Caucasian merchants on board of each of them, and one in the sea to the east of India with two Chinese merchants on board), and one boat used by pearl divers in the Persian gulf (Fig. 4b).

Albeit the above-mentioned exceptional examples, "in the mid-fifteenth century putting a ship on a map was a radical act. By the mid-sixteenth century it was still a conscious act but no

Fig. 1: Reduced-size image of the Fra Mauro's *mappa mundi* (Venice, Marciana National Library, Inv. 106173) taken by an unknown photographer before the restoration around 2009. The accomplishment of the artefact is dated 20 August 1460 with an inscription carved on the back (see its reproduction in Falchetta 2015, 21). The map was depicted by inks and colours on sheets of vellum that were glued to a circular revolving wooden platform (diameter of about 196 cm), which is mounted on another wooden frame (almost a square, 223x233 cm) that hosts a further round wooden frame that surrounds the circular platform. The tondo aggregates about 2,800 place names, 200 short texts in vernacular Venetian, and hundreds of iconic representations of, among others, cities, ships, animals, architectural landmarks, mountains, roads, and rivers. The four corner of the squared frame are dedicated to the skies and the astronomical distances (upper left corner), tides and land (upper right corner), Earthly Paradise (lower left corner), theory of elements and southern regions (lower right corner). See Gasparrini Leporace 1956; Marcon 2001; Falchetta 2006; Cattaneo 2011; Falchetta 2011; Nanetti, Cattaneo, Cheong, and Lin 2015.

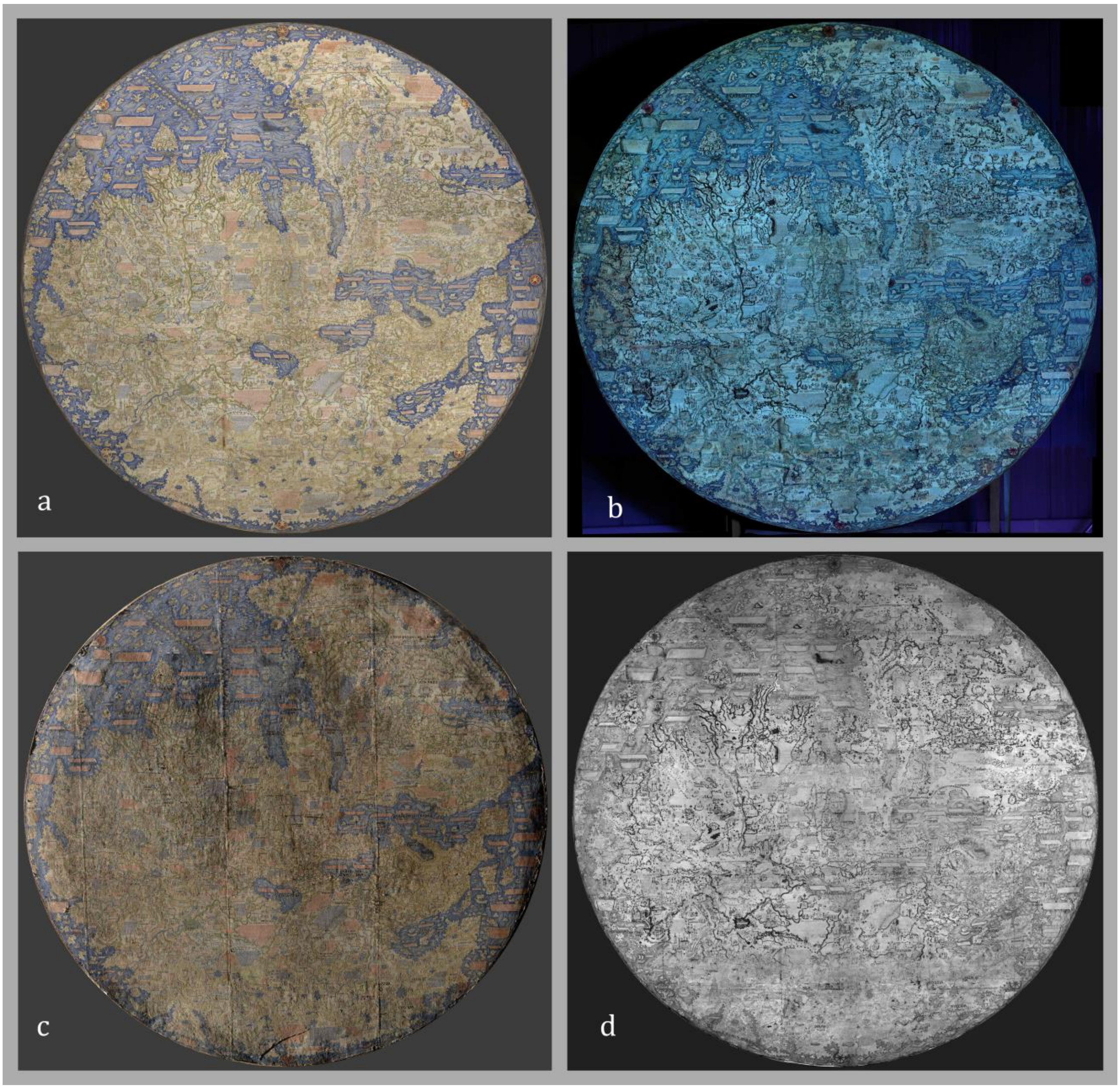


Fig. 2: Reduced-size multispectral images of the central tondo taken by the professional photographer Francesco Mangiaracina, when the Fra Mauro's *mappa mundi* was unmounted before the restoration, in 2009. This photographic documentation (RAW files, in very high and medium resolution, respectively tiff. RGB and jpeg RGB formats) has ensured the recording of data relevant to the investigation of both the techniques used by the artist(s) in the material creation of the artefact and the assessment of the conservation state of the artefact itself, allowing the detection of details otherwise invisible to the naked eye. — Adobe Bridge Camera Data of the original tiff. Files © Francesco Mangiaracina, Padova (Italy): **Fig. 2a visible spectrum** (f/16.0, ISO0,Untagged RGB, 96.43 MB, 300dpi, 7303 x 7087; Data Time Original 10/12/2009, 11:02:38 AM; Focal length 105.0 mm); **Fig. 2b ultraviolet** (f/11.0, 30.0, ISO0,Tag Adobe RGB, 104.63 MB, 300dpi, 7311 x 7087; Data Time Original 10/12/2009, 11:03:26 AM; Focal length 105.0 mm); **Fig. 2c tangential** (f/13.0, 13.0, Tag Adobe RGB, 106.49 MB, 300dpi, 7286 x 7087; Focal length 105.0 mm, Focal length in 35mm 105.0 mm; Max Aperture Value f/2.9, Data Time Original 10/5/2009, 6:23:27 PM; Sensing Method One-chip sensor, Digital Camera, Make NIKON CORPORATION, Model NIKON D3X). **Fig. 2d infrared** (f/13.0, 0.3, Tag Dot gain15% B&W, 37.010 MB, 300dpi, 7315 x 7087; Max Aperture Value f/2.8; Data Time 10/5/2009, 8:19:08 PM; Focal length 60.0 mm, Focal length in 35mm 90.0 mm; Sensing Method One-chip sensor, Digital Camera, Make NIKON Corp., Model NIKON D100).

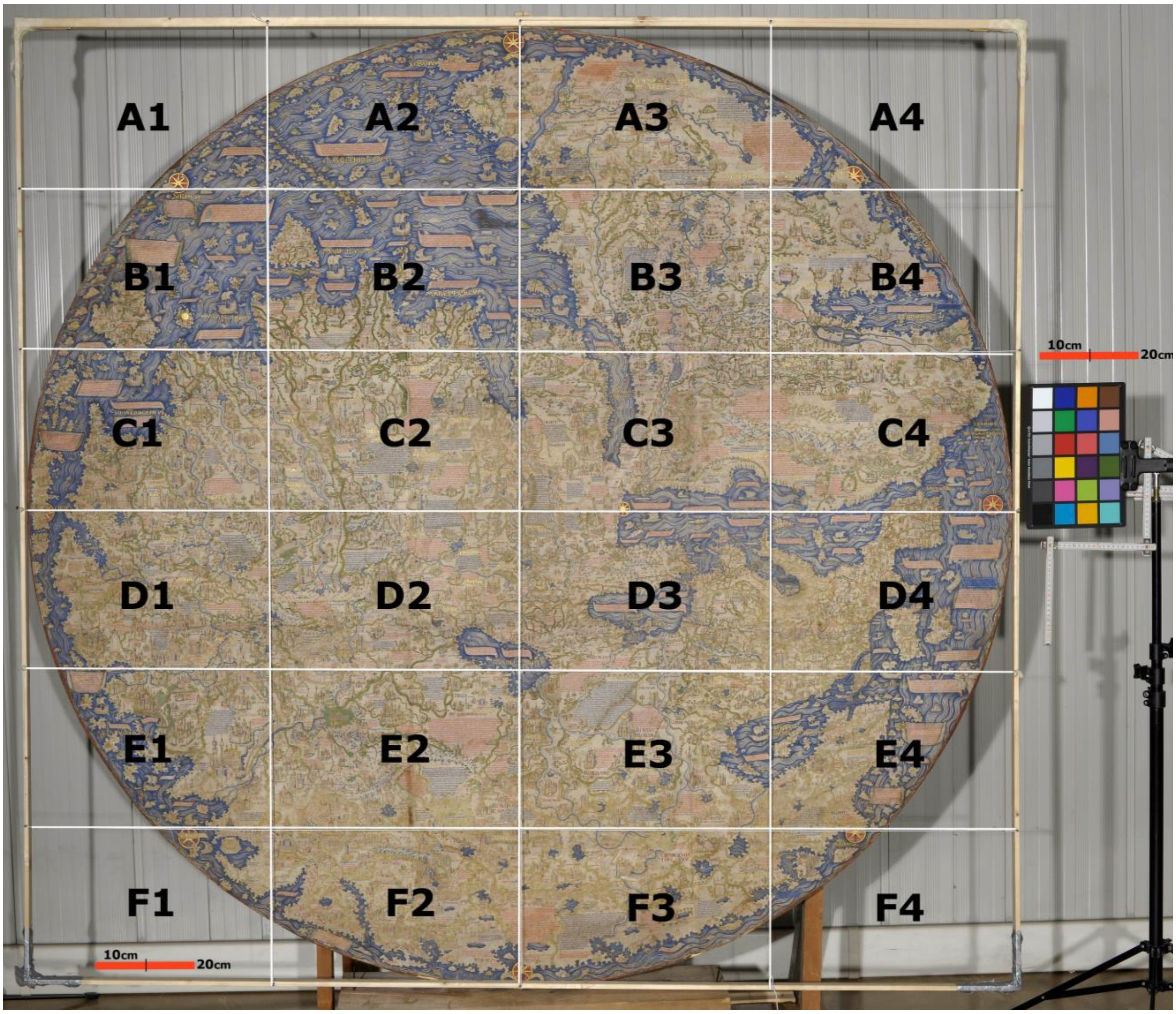


Fig. 3: Reduced-size image of the set up made by the professional photographer Francesco Mangiaracina for the high-resolution photographic campaign of the central tondo before the restoration in 2009. In front of the artefact a grid was mounted to organize the surface in 24 sectors. This facilitated the realization of a higher-definition multispectral images of the entire tondo throughout the aggregation of the highest-possible-definition photographs of the individual sectors realized exposing the artefact to different lights (visible spectrum, ultraviolet, tangential, and infrared) as it was done before the restoration (see Fig. 2). On the right side of the artefact a Colour Rendition Chart (CRC) stands on a tripod to enable the calibration of the colours. A 20-cm scale—digitally incorporated both on the left bottom of the grid and on top of the CRC—provides the ratio between the image and the artefact. - Adobe Bridge Camera Data of the original tiff. file (f/16.0, ISO0, 35.95MB, 300dpi, 5108 x 3684): Data Time Original 10/12/2009, 10:59:58, Focal Length 50.0 mm Nikon D3X, ©Francesco Mangiaracina (Padova, Italy).

longer unusual" (Unger, 2010, 11). Yet the images were mainly ornamental and primarily provided for illustrative purposes. In the overall design, they mainly served the practical need of visually detaching the maritime spaces from the land, and, as argued by John Brian Harley (1932-1991), in "atlases and wall maps decoration serves to symbolyze the acquisition of overseas territory" (Harley, 1988, 298), as seen above in the case of the galley-like ship of the *Catalan Atlas* (Fig. 4a). These may be the two main concurrent reasons why the cartographers usually added to their works only a few iconic images of boats and vessels (Unger, 2010, 13-14).

On the contrary, the Fra Mauro map—through iconographic researches certainly carried out on visual sources, even if it is almost impossible to ascertain them today [1] —supplies the depicted representation of fifty three morphologically-different ships, whose patterns' analysis can classify them in at least eight distinguished groups. Yet it seems practical to refrain from attempting to link each individual image to a specific kind of historical vessel or boat, except for the easily recognizable galley-like long vessels, because the depictions of the ships seem to still have an iconic function, which is instrumental to the visual communication of two main sets of information: 1) the navigable connectivity among all the seas washing the shores of the known world, and 2) the different naval traditions of the peoples of the Afro-Eurasian *terra continens* and the related maritime spaces.

According to Mauro Bondioli, the eight groups in which the ships of the Fra Mauro map can be tentatively classified are the following[2].

Eight drawings can be referred to a Group 1 (see Fig. 5a, nos. 2, 4, 6, 7, 8, 9, 12; and Fig. 5c, no. 36). They are particular and identical in their bow's three-quarter perspective, and with some small variants in the details. This is a model unrelated to the European naval technology. The bow, broad and flat, is more similar to the one of landing military crafts than of offshore ships, and suggests a continuity in its shape along the entire longitudinal section of the bottom of the ship. This is against all the hydrodynamics principles applied to the European ships of the time, whose bows were shaped to cleave the waves and not to face them. The ships are endowed with three to four masts, all supplied with a *coffa* (i.e., crow's nest) on the top.

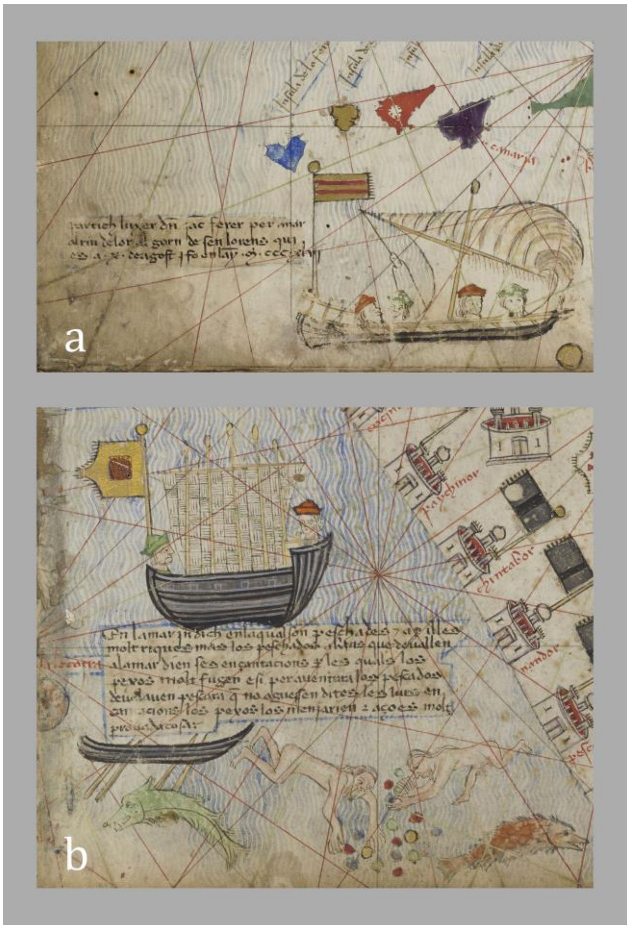


Fig. 4: *Catalan Atlas*, ca. 1375, attributed to Abraham Cresques (Paris, National Library of France, Ms. *Espagnol*, 30; ink and colour on six double leaves of vellum (64.5 x 300 cm) glued on five wooded plates (64.5 x 0.25 cm). © Bibliothèque nationale de France. **(a)** Detail, Leaf 3, left bottom with the stylised depiction of the galley-like ship with which the Catalan Jacome Ferrer set sail for the legendary *Rio de Oro*, River of Gold, in 1346, as written in the cartouche on the left of the ship itself. **(b)** Detail, Leaf 5, central-right bottom with the depiction, among others, of a junk and pearl divers "en la mar Indich" (*in the Indian sea*, cartouche below the junk).

[1] A demonstration of the existence of repetitive and iconic graphic models to represent "a boat" in medieval scriptoria, at least since the twelfth century, as an example one can refer to the illuminated codex "*Queste del saint Graal*" cited by Tangheroni (2003, 199-200: Udine, Biblioteca Arcivescovile, Ms. 117), the "*Roman de Tristan*" (London, British Library, Ms. Harley 4389), the *"Histoire du siège et de la destruction de Troie"* (Paris, Bibliothèque Nationale de France, Ms. Fr. 9603), the Venetian *"Zibaldone da Canal"* (Yale, University Library, Ms. Beinecke 327, published by Stussi, 1967).

[2] This section is based on a series of conversations held between Andrea Nanetti and Mauro Bondioli (world-renowned expert in naval architecture and technology) in Venice in July 2019. It resulted in a tentative classification and historical contextualisation of the fifty three ships depicted in Fra Mauro's map. The research was commissioned by the authors to Mauro Bondioli in early August 2019 and was delivered in Italian by him in September 2019. Mauro Bondioli was provided with the high definition files of all the ships. The files were complemented with a first tentative grouping of the ships made on the basis of visual clues by the 3D artist Gerald Wee Ren Jie (undergraduate student in the School of Art, Design and Media at Nanyang Technological University, Singapore), who worked as Student Training Assistant funded by the Singapore's Ministry of Education TIER 1 research grant on "Data Consolidation for Interactive Global Histories (1205-1533) within the NTU National and International Research Network: Towards an NTU Interdisciplinary Laboratory for Data-Driven Agent-Based Modelling and Simulations for Historical Sciences" (PI Andrea Nanetti and Co-PI Cheong Siew Ann at NTU, Singapore - M4011828).

In all the images the mast that could be identified as the main mast is armed with a square sail, and only in one case also the mast that could be recognised as a foremast. The system of masts and sails, and related rigging, seems to be a false solution of European origin applied to a very different naval typology that did not adopt these specific solutions. All rudders are axial at the stern and there is no sign of Latin or lateral rudders. It is therefore an image certainly of extra-European origin, probably Asian, at least because of the hull's shape. Fra Mauro's source is unknown to us but matches with other coeval information[3].

Group 2, with six ships (see Fig. 5b, nos. 18, 20, 22, 24, 40, 41), showcases the model of typically Mediterranean long ships known as galleys. However, despite of belonging to a naval typology that must have been very familiar to the artist(s) of the map, the ships are stereotyped and lack of technical details. In all images the galleys are represented without oars, from a lateral perspective (three of them have the bow pointing to the right and two to the left). The rudders are axial and the Latin rudders of which they were equipped do not appear. Three galleys have the traditional Latin sail. One of them seems equipped with three masts (see Fig. 5b, no. 18). In fact it is a perspective expedient to represent a small convoy of three galleys without depicting them one by one. All this prevents any possible disambiguation among *galee grosse* (i.e., large, merchant galleys), *galee sottili* (i.e., light, for military activities), and *fuste* (i.e., a galliot, a small galley) that were very common at the time in Venice[4].

As Group 3 (see Fig. 5a, nos. 1, 3, 11, 14; and Fig. 5c, no. 37, 38) we identify six images close to the typology of the Mediterranean round ship of the first half of the fifteenth century with foredeck and quarterdeck. All drawings are almost identical in their stern's three-quarter perspective, even if four of them are oriented more or less to the right and two to the left. The rudders are all axial and the masts vary from two to four, of which the main one is always armed with a square sail. Notwithstanding the excessive emphasis given to the outer wale (i.e., the horizontal wooden strip fitted as strengthening to the boat's side), the uncertainty of the rigging, and the incompleteness of the bow structures, this model is perhaps one of the most successful of the map.

Group 4 (see Fig. 5b, nos. 16, 17, 23, 25, 28, 31, 35) is represented by seven drawings that are technically very close to the previous Group 3, both in the execution and in their relative faithfulness and likelihood. It is a smaller ship, also of Mediterranean tradition, more slender and with an unlikely single mast armed with a square sail. Only once the main mast is accompanied by a mizzen tree. All ships are drawn from a lateral perspective, with axial stern-rudders, forecastle, and quarterdeck. In one case only, the quarterdeck is absent. In five images the bow is oriented to the left and in the remaining three to the right. Two of them are very tilted in an unsuccessful attempt to give the perception of movement to an otherwise static figure. The eighth ship that seems to belong to this typology is the one damaged by the storm.

Group 5 (see Fig. 5a, nos. 13, 42; Fig. 5b, no. 34) has three medium-size boats with a single mast armed with a square sail. They are drawn from a lateral perspective with the bow facing left. One of the boats has the sail folded and the other two unfurled in the wind. The bow is curved and, in two cases, it seems to have a wooden ornament placed on the top, which is difficult to interpret unless assuming a Northern European origin. They have stern-rudders and a quarterdeck. The drawing does not allow any certain identification of the represented typology of boat.

Group 6 (see 5a, nos. 5, 10; Fig. 5b, nos. 19, 21, 29; and Fig. 5c, no. 39) has six boats with the hull's shape very similar to the previous model. The only difference is the single mast, tilted towards the bow, and armed with a typically Mediterranean Latin sail. Even in this case it is difficult to identify any certain typology.

The four ships of Group 7 (see Fig. 5b, nos. 27, 30, 32, 33) are interesting because they recall the naval archetype of round ships belonging to historical periods prior to the time of Fra Mauro. The "banana" profile of these ships is typical of a thirteenth- and fourteenth-century Mediterranean naval architecture, in which the shapes of prows and sterns were curved and the only rudders in use were the lateral ones. The presence, however, in the drawings of the stern-rudder, as well as the absence of the lateral rudders, in combination with

[3] See Keith and Buys 1981, 119-121, and, for further information about archaeological evidence for Asian ships, Kimura 2010, with bibliography.

[4] The main sources are the two manuscript codices known as Michael of Rhodes' Book, and The Book of George "trumpeter" from Modon (see Anderson, 1925, 135-163; Rieth, 2000, 381-393; and Bondioli, 2009, 243-280).

a rounded sternpost not yet evolved into a rectilinear and tilted shape, the so-called stern post, suggests that the visual source of Fra Mauro is an illuminated codex of the first half of the fourteenth century. It is interesting that the monk decided to include in the map a non-contemporary naval model. This may suggest that the purpose was to create naval groups that depicted cultural diversity or perhaps the artist(s) were not aware that that model was not in use at that time any more.

In Group 8 (see Fig. 5a, nos. 2a, 6a, 6b, 7a, 8a, 9a, 11a; Fig. 5b, nos. 15, 26; and Fig. 5c, nos. 36a, 37a, 39a, 39b) there are numerous boats (thirteen), but it is the least significant from a naval architecture point of view. Indeed, it represents a stylisation so naive to become extremely generic. Sometimes it is depicted in combination with larger hulls, like a service boat that the ships used to tie with a top to the stern of the ship and tow. In some other drawings, they seem to sail alone or be anchored with other vessels, and thus indicate a convoy.

In conclusion, the above-identified eight naval groups constitutes a collection of considerable historical value. In fact, Fra Mauro succeeded in making an atlas that, although of modest absolute dimension (fifty three ships), perhaps, represents for its time an absolute primacy in naval iconography. The idea of a naval atlas was indeed taken up by the historians only several centuries later[5]. This merit has to be added to the Fra Mauro's map.

3. *Design process and techniques used in the prototyping of a three-dimensional (3D) Maya Non-Photorealistic-Rendering (MNPR) model of one selected ship (Fig. 5a, no. 4)*[6]

The working hypothesis is that a new generation of 3D NPR animated visualisations can improve upon 2D visualisation methods. This section reports how the research team developed, streamlined, and tested a philologically correct design process able to transfer as much multipurpose raw data as possible from the 2D

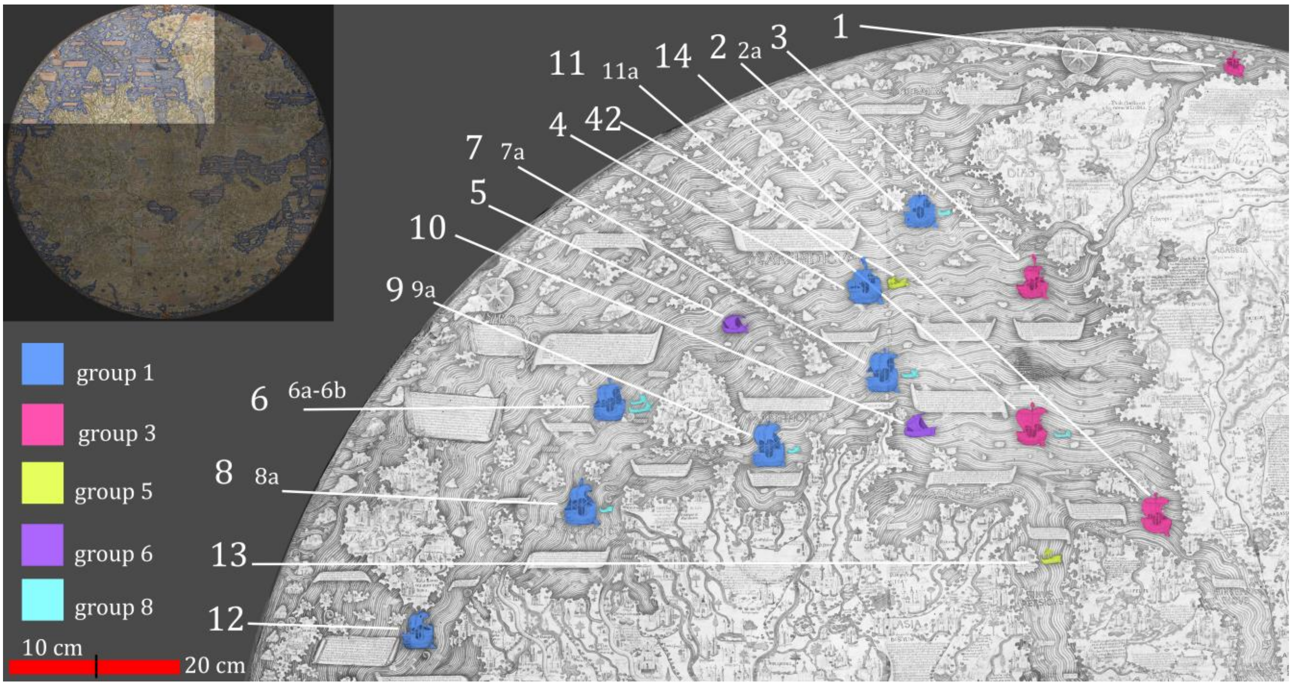
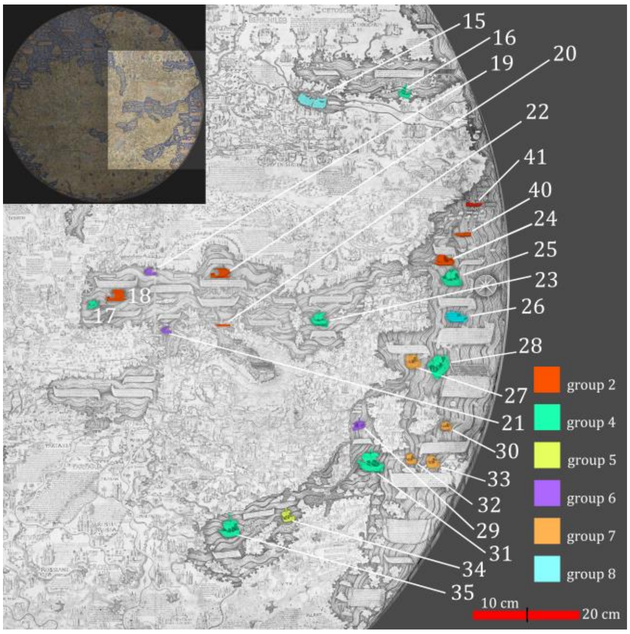


Fig. 5a: Fra Mauro's display of the ships in the Indian Ocean, classified in Group 1, Group 3, Group 5, Group 6, and Group 8.

[5] In general see the monumental work published by Moll (1929). For the Middle Ages, see Villain-Gandossi (1985), and for Classical Antiquity Basch (1987). For the Venetian naval iconography the book of reference is still Levi (1892).

[6] The prototype is one of the results of the internship undertaken by the 3D artist Gerald Wee Ren Jie as undergraduate student in Animation at the School of Art, Design and Media, Nanyang Technological University, Singapore (ADM-NTU), from 3 June to 9 August 2019. Within the framework of the Memorandum of Agreement signed between the Marciana National Library of Venice (Marciana) and ADM-NTU, the internship was supervised by Assistant Professor Davide Benvenuti (ADM-NTU) and Dr Orsola Braides (Marciana).



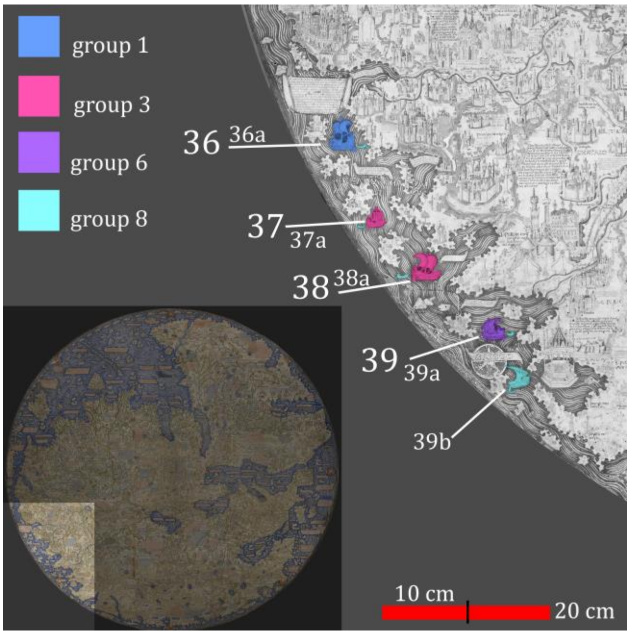


Fig. 5b (left): The Mediterranean Sea and the Atlantic Ocean: Group 2, Group 4, Group 5, Group 6, Group 7, and Group 8.
Fig. 5c (right): Display of ships on Chinese sea in the Fra Mauro's Map, classified in Group 1, Group 3, Group 6, and Group 8.

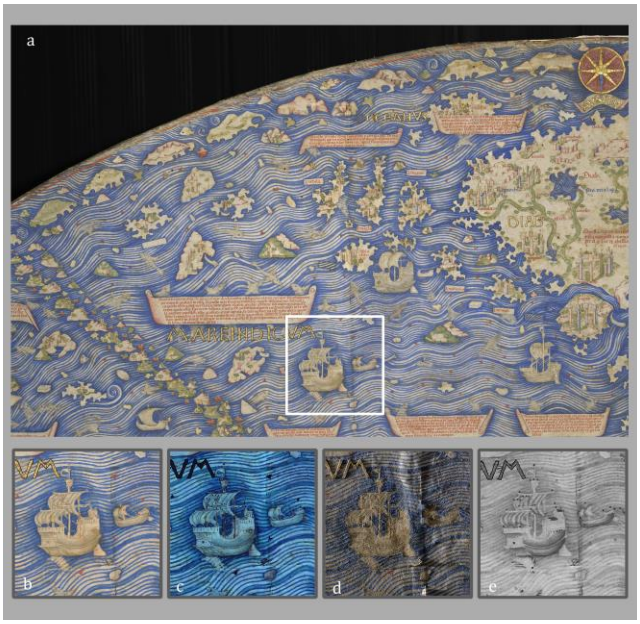


Fig. 6: Reduced-size of the multispectral images of the ship chosen for the prototype. The original digital images were taken by the professional photographer Francesco Mangiaracina in 2009 (see sector A2 of the central tondo in Fig. 3). The images highlight how different details can appear when the texture of the map is analysed under multispectral photography: a) and b) visible spectrum, c) ultraviolet, d) tangential), and e) infrared.

pictorial artefact, making as less assumptions as possible, and still maximise the user experiences into a 3D space. This cultural-heritage-based design process of animated objects for 3D spaces makes reference to the *The London Charter: For The Computer-Based visualisation of Cultural Heritage* (2009).

The starting point is the testing of techniques to model a 3D NPR of one single iconic and very detailed ship as a prototype. The choice is made for a junk represented in the Indian Ocean (Fig. 6a). The data collection for the prototyping was based on images produced by the multispectral and high-resolution photographic campaign of Fra Mauro's central tondo made by the photographer Francesco Mangiaracina in 2009 (Fig. 3). Each of the four different lights (visible spectrum, ultraviolet, tangential, and infrared) emphasises differently the details of the ship (Fig. 6b)

The first challenge being to draw the 3D model keeping a low polygon count (i.e., with less than 30,000 faces) in view of a multiple-purpose use of the asset (e.g., real time performance). An initial modelling technique was to keep the design at a low resolution in order to contain the number of polygons. However this low number of polygons was not satisfactory in reproducing the natural curvature of the shapes of the ship. Thus we had to aim for an intermediate state between the above mentioned conflicting alternatives, and this was reached by compromising to 12,482 polygons. It allows both to collect almost all the texture details of the original depiction and ensure a high performance on real time platforms.

A second challenge was due to the fact that commonly a 3D digital model is created using the default 35-mm camera available in a 3D software viewport. However in using this modelling technique, the 3D artist cannot create anything else than a distorted model (i.e., not faithful to the original pictorial object's isometric perspective), because such a low focal length creates an aberration in the software-generated perspective of the 3D digital space. Hence, we experimented different settings of the software's camera focal length between 200-500 mm looking to achieve a visual experience as close as possible to the original drawing of the ship on the map.

Once solved these initial challenges, the realisation of the prototyping can start with the creation of the model in the 3D software Autodesk® Maya® (Fig. 8) and rendering Maya® Viewport 2.0 (Fig. 9). Our design process can be broken down in seven distinct phases:

1. definition of the basic shapes and the overall silhouette of the ship with basic topology (Fig. 8a);
2. addition of all further available details that can be ascertained from the digital images to improve the topology with an increased number of polygons for an ultimate enhancement of the basic shapes (Fig. 8b);
3. UV ("U" and "V" are used to identify the axes of a 2D texture space where "X", "Y", "Z" are used for the axes of a 3D object in model space) unwrapping of the model (i.e., unfolding the 3D model into a flat surface) in order for the 3D artist to be able to paint the surface textures;
4. enhancement of finer level of details on the surface of the digital object by adding wear, tear, and grunge to the texture painting: the four ovals and grid on the bow; the flag; heavy concentration of grunge (i.e., ink blotches on the stern connecting to the cabin and quarters); roof of the cabin has a slight greenish variation; quarters also have less wear and tear texture, and appears brighter in value; various overlay of grunge paper and leather texture were tried over the base colour; finally, on top of those layers a textured brush was applied to draw the details together with a textured eraser, in order to create some gaps in the line work and thus mimic the natural disparity and ink bleed present in the etching on a weather texture (Fig. 8e, 8f, 8g);
5. Prototype rendering of the chosen ship's model, using the user customization options offered by the MNPR system (Montesdeoca 2018, 131-140), which allows the user to experiment with various options and settings and achieve multiple goals, that is an aged looking paper/leather surface such as the support on which the Fra Mauro's map is painted on and a coloring variation that can approximate the style of the original pictorial representation of the ship (Fig. 9);
6. final 3D turnaround of the ship (Fig. 7, with active link to the EHM website);
7. the asset is exported to Unity Real-Time Development Platform (Fig. 10) to exploit multiple-purpose uses (e.g., VR, AR).

Fig. 7: Screenshot of the final rendering of the prototyped boat in Autodesk® Maya® Viewport 2.0 interface. Link to https://engineeringhistoricalmemory.com/FraMauro.php It is necessary to log in to the web site before being allowed to explore the map and activate the turnarounds of the ships.

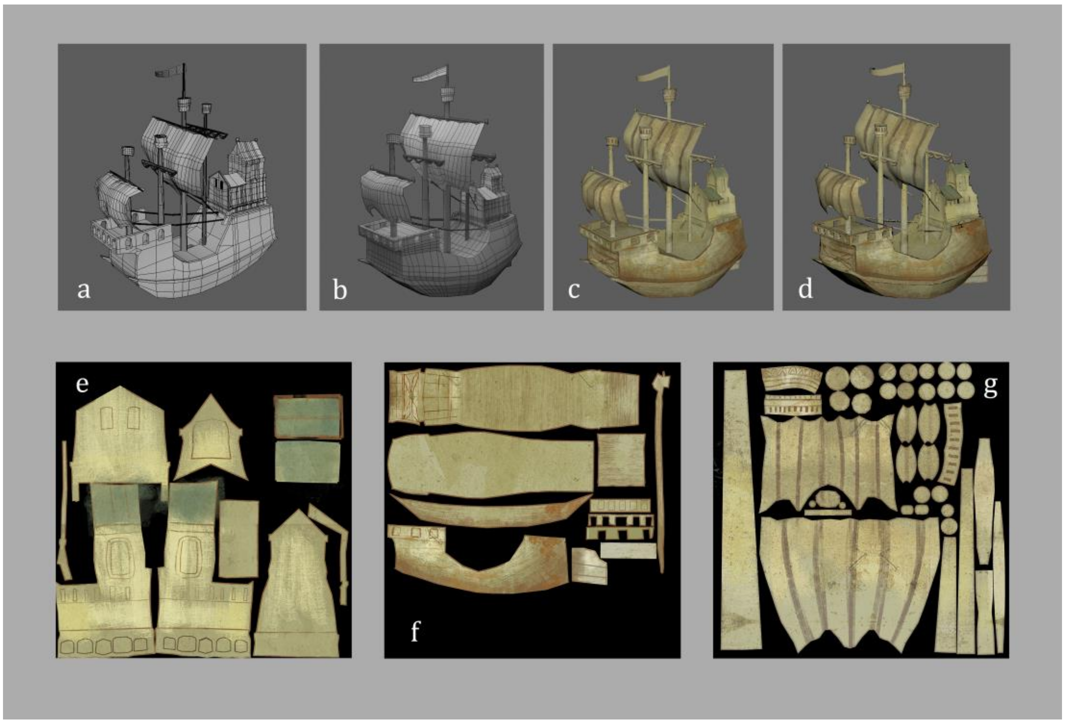


Fig. 8: Progression version (i.e., design process) of the 3D model. From left to right: a) blocking stage, topology is uneven, forms are sketched to capture the basic shape; b) details have been refined and the topology has been corrected to closely resemble the actual image (this is how the model appears with flat shading before the extra level of details is added with textures); c) and d) the 3D models fully textured and ready for rendering (the drawings on the Fra Mauro's map adopt a flat isometric perspective) are presented with different focal length in the viewport; c) standard 35mm length; d) 500mm length; e), f), and g) present the proper unfolded UV colour maps. The final three steps identify a crucial painting process, where most of the tertiary details are added. Here is where the 3D artist establishes some of the illustrative landmarks and the grunge texture to be replicated.

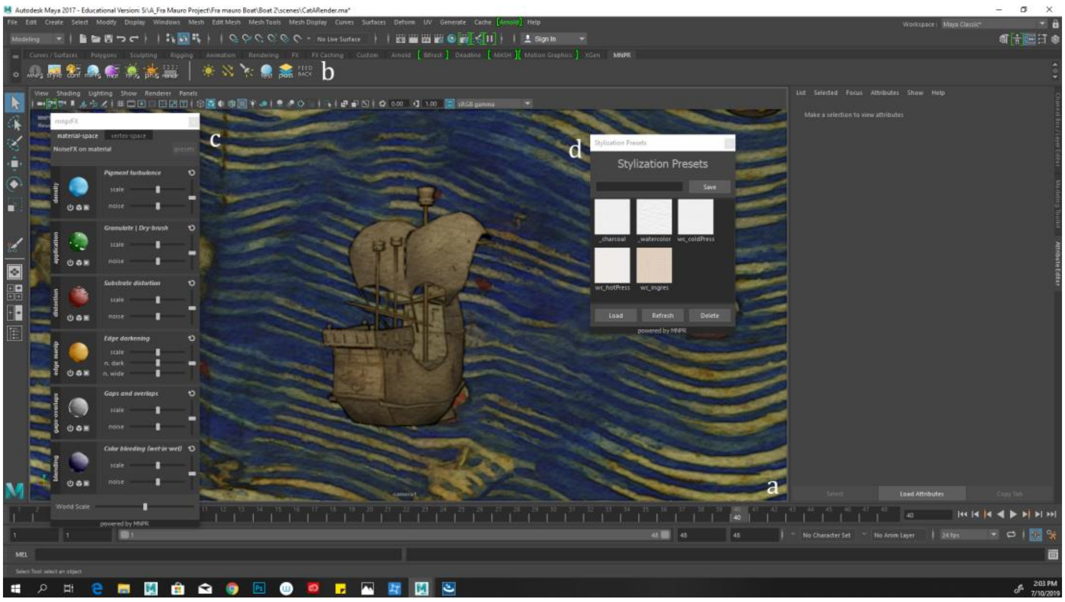


Fig. 9: Screenshot of the Autodesk® Maya® Viewport 2.0 interface **(a)** showing at work the Maya Non-Photorealistic Rendering (MNPR) plug-in developed by Santiago Montesdeoca (Montesdeoca 2018, 131-140) with: **b)** the interface's shelf buttons that give access to different submenus and windows (Montesdeoca 2018, 133, Fig. 6.21); **c)** the 'MNPR Noise FX' interface, in which each slide and icon represents a different kind of simulated watercolor effect that can be applied to the drawing (Montesdeoca 2018, 131, Fig. 6.3); and d) the possibility to create and save stylisation presets. This last tool was extremely useful in our case study to speed up the MNPR of a considerable number of ships.

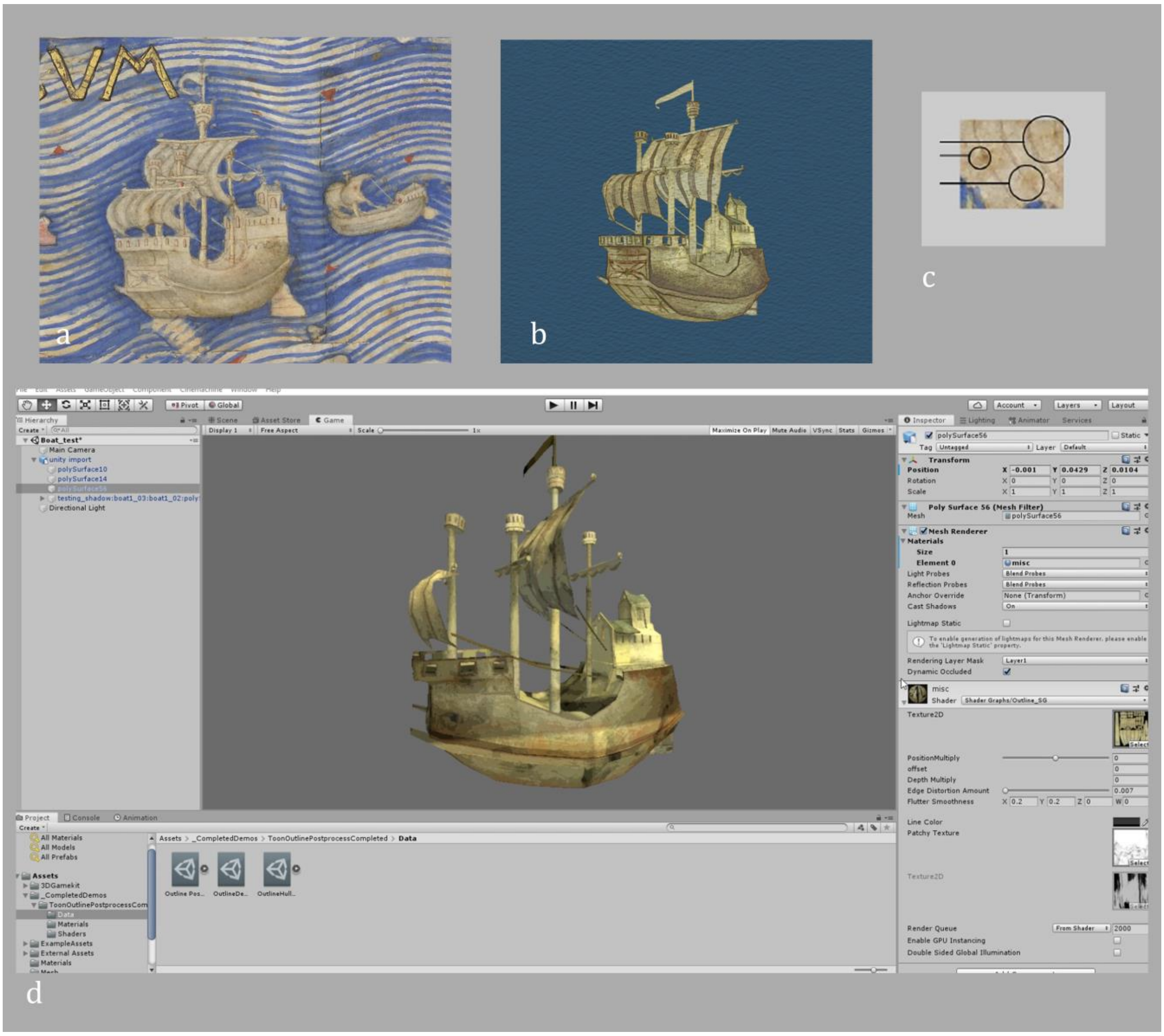


Fig. 10: Display of the design process that starting from the digital image of the artefact ends into the real time platform: **a)** reduced-size of the image of the ship chosen for the prototype taken by the professional photographer Francesco Mangiaracina in 2009 (see sector A2 of the central tondo in Fig. 3).; **b)** 3D MNPR asset created on Autodesk Maya that can be exported on Unity3D Real-Time Development Platform (without the shaders because the plug-in to export the MNPR shaders into Unity does not exist yet); **c)** details of the textures of the painted ship to be replicated in Unity; **d)** 3D model of the ship as it appears in the Unity Viewport.

4. *3D MNPR models of the atlas of the ships of the known world depicted on the Fra Mauro's* mappa mundi, *with active links to turnaround .gif available on the EHM website*

This final section provides the atlas of all the fifty three ships depicted on the Fra Mauro's *mappa mundi*. The ships are organised in a series of images, one for each group as classified by Mauro Bondioli (see Section 2). This comprehensive display provides a first visual interface for the study of pre-modern maritime history (with a focus on shipping). This first interface is linked to a second one online, which provides an ongoing implementation framework of NPR for the creative industry. It is a demonstration that the 3D MNPR models' user experience goes beyond what is visible in the 2D digital images and ultimately complements (improves?) what the user can learn in front of the original artefact. The animated turnarounds available online can be also considered preliminary multiple purpose outputs. They can be later customised in more or less detailed models depending on platform and end-user (e.g., smart device, computer or larger flat screen, holographic pyramid, virtual reality, augmented reality, 3D printing). The following Figures 11-18 display the fifty-three ships, group by group, in scale, and provide their positioning on the Fra Mauro's *mappa mundi*. Each ship has an active link that directs to the 3D MNPR animated turnaround model available on the website of the Engineering Historical Memory (EHM) project, for which see *Acknowledgments*.

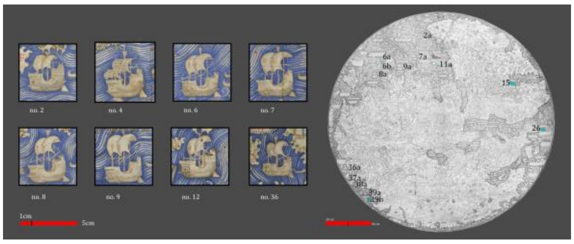


Fig. 11: Group 1 (see Fig. 5a, nos. 2, 4, 6, 7, 8, 9, 12; and Fig. 5c, no. 36).

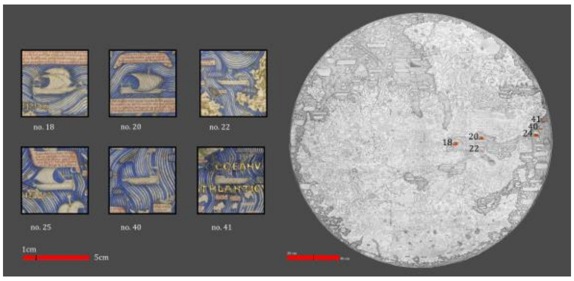


Fig. 12: Group 2 (see Fig. 5b, nos. 18, 20, 22, 24, 40, 41).

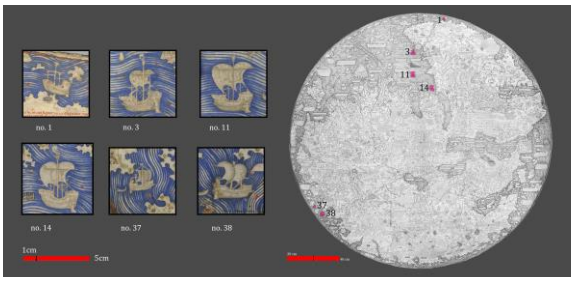


Fig. 13: Group 3 (see Fig 5a, nos. 1, 3, 11, 14; and Fig. 5c, no. 37, 38).

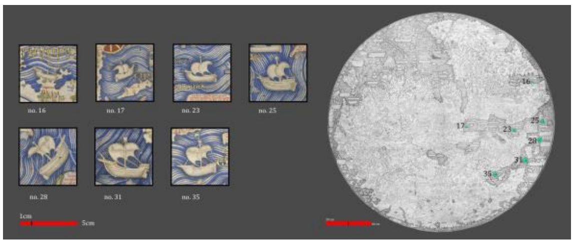


Fig. 14: Group 4 (see Fig. 5b, nos. 16, 17, 23, 25, 28, 31, 35).

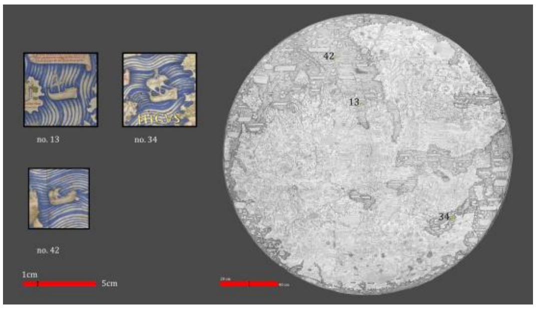


Fig. 15: Group 5 (see Fig. 5a, nos. 13, 42; Fig. 5b, no. 34).

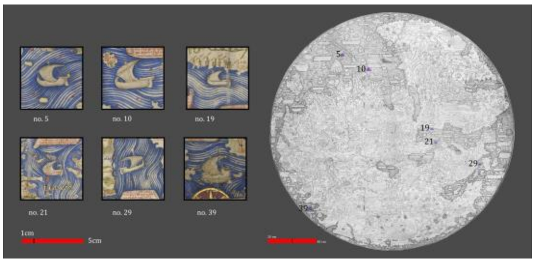


Fig. 16: Group 6 (see Fig. 5a, nos. 5, 10; Fig. 5b, nos. 19, 21, 29; and Fig. 5c, no. 39).

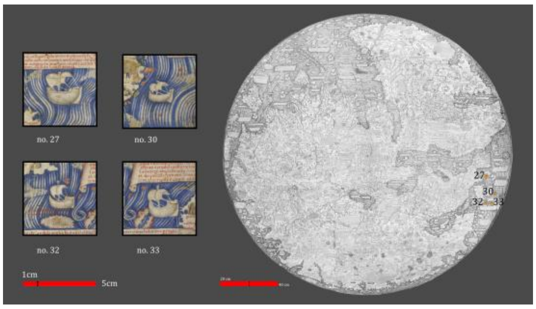


Fig. 17: Group 7 (see Fig. 5b, nos. 27, 30, 32, 33).

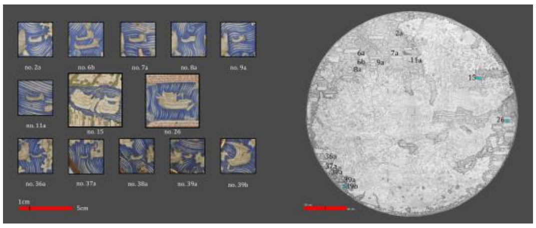


Fig. 18: Group 8 (see Fig. 5a, nos. 2a, 6a, 6b, 7a, 8a, 9a, 11a; Fig. 5b, nos. 15, 26; and Fig. 5c, nos. 36a, 37a, 39a, 39b).

Acknowledgments

The research presented in this paper was carried out by the authors between March and November 2019. It was made possible by the collaboration between the School of Art, Design and Media (ADM) of the Nanyang Technological University (NTU), Singapore and the Marciana National Library of Venice (Italy) within the framework of a Memorandum of Agreement (MoA) signed on 30 March 2018.

The digital images delivered to the authors by the Marciana in March 2019 were taken by the photographer Francesco Mangiaracina (Padova, Italy) in 2009. The 3D artist Gerald Wee Ren Jie worked as Student Training Assistant (Supervision, Assistant Professor Davide Benvenuti) on the high resolution image reconstruction funded by the Singapore's Ministry of Education (MOE) TIER 1 research grant on "Data Consolidation for Interactive Global Histories (1205-1533) within the NTU National and International Research Network: Towards an NTU Interdisciplinary Laboratory for Data-Driven Agent-Based Modelling and Simulations for Historical Sciences" (PI Andrea Nanetti, Co-PI Cheong Siew Ann at NTU, Singapore - M4011828).

The MNPR prototype of the first ship is one of the results of the internship undertaken by the 3D artist Gerald Wee Ren Jie as undergraduate student in Animation at ADM-NTU, from 3 June to 9 August 2019. The internship was supervised by Assistant Professor Davide Benvenuti for ADM-NTU and Dr Orsola Braides for the Digital Library programme of the Marciana, within the framework of the above-mentioned MoA. The authors are particularly grateful to Mauro Bondioli, who provided them with discussions and consultancy that were of essence during the work of classification of the ships in typological groups between August and September 2019.

This research is set in the framework of the Engineering Historical Memory (EHM) project. Andrea Nanetti first theorized EHM as a Visiting Scholar at Princeton University in 2007 to explore new sets of shared conceptualizations, formal specifications, and visualisation solutions for content management systems in the Digital Humanities. From 2012 to 2014 the project was on WordPress, where a first experimental work is still available. Since 2015 it is on Microsoft Azure. In 2018, Ker Min Jie curated a redesign of EHM from a Computer Science perspective as Final Year Project for the Bachelor Degree in Computer Science at NTU (Principal supervisor Gao Cong, Co-Supervisor Andrea Nanetti). Since March 2019, Khoi Nguyen Vu is Research Assistant to the project for web development funded by the above-mentioned Singapore's MOE TIER 1 research grant.

At NTU (2013-2019), the project explored the global scalability of the research. Starting from the world as seen from Venice, the range of the investigation moved to other coeval historiographical traditions in Afro-Eurasia (1205-1433). In practice, the research develops and applies computationally intensive techniques (e.g., pattern recognition, data mining, machine learning algorithms derived from other disciplines, knowledge aggregators, interactive and animated visualization solutions).

The NTU PhD candidate Liu DanYun (Principal supervisor Andrea Nanetti, Co-PI Cheong Siew Ann, Thesis Advisory Committee Member Angelo Cattaneo) is developing her research on the online user experience of fifteenth-century world maps. The Fra Mauro's *mappa mundi* is one of her main research subjects (Content providers and advisors Piero Falchetta and Orsola Braides at the Marciana National Library of Venice). In 2016-2017 Chen Hailin optimised the search using *Microsoft Knowledge Explorer* during his internship at Microsoft Research Beijing as NTU Singapore undergraduate student in Computer Science (Principal supervisor Lin Chin-Yew at Microsoft Research Beijing; Co-Supervisor Andrea Nanetti at NTU). The NTU Singapore MA graduate student Victor Ong collaborated with Liu DanYun in the mapping of the items. Phay Han worked on the website from the Graphic Design and User Experience perspectives. The company of Francesca Pivirotto (Rovigo, Italy) contributed to the database implementation. The 2017-2019 phase of the project was funded by the above-mentioned Singapore's MOE TIER 1 research grant.

On Friday 29 November 2019, this research was presented at the Marciana on the occasion of the event "Digital exploration of Afro-Eurasia in the *mappa mundi* of Fra Mauro" that closed the Study Days on "Venice and the sense of the sea" organized in collaboration with the Veneto Institute of Sciences, Humanities and Arts.

The "Digital Exploration of Afro-Eurasia in the *mappa mundi* of Fra Mauro " is one of the results achieved in the two-year period between November 2017 and November 2019 by the international collaboration of the above-mentioned research team coordinated by Andrea Nanetti at the LIBER Lab of ADM-NTU, in collaboration with researchers from the Marciana (Dr Orsola Braides and Dr Pietro Falchetta), from the Ca' Foscari University of Venice (Prof. Em. Gherardo Ortalli, Prof. Tiziana Lippiello, Prof. Eugenio Burgio), and Microsoft Research (Dr. Lin Chin-Yew, Dr. Winnie Cui, Mr. Xi Chen, Mr. Chen Hailin).

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