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Original article

# A non-invasive imaging approach for improved assessments on the construction and the condition of historical knotted-pile carpets

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ABSTRACT

The appraisal of the design and the weaving structure of Islamic knotted-pile carpets can tell plenty about the context in which they were produced, and the identification of signs of deterioration can help to establish their condition. These are often somewhat imprecise and laborious examinations, especially when considering carpets of large dimensions. Analytical methods that support these disciplines urge further exploration so that improved interpretations can be obtained.

An interdisciplinary combination of art history, analytical science and textile conservation aimed, on the one hand, to improve the weaving examination of these complex textile objects – by considering the spin of threads and the ply of yarns; the knot count and density; and the weaving structure of warps, wefts and piles – and on the other, to help their condition assessment – by mapping of damaged areas, old repairs and contaminations. For this purpose, the possibilities and limitations of several non-invasive imaging techniques, namely transmitted, raking or incident visible, ultraviolet (UV) and infrared (IR) illumination through Visual Spectral Comparator (VSC), as well as conventional X-radiography, mammography and (micro) CT scanning, were assessed to support the conventional visual examination of the weaving details and present condition of two 17th-century Safavid knotted-pile carpet fragments.

Observation with NUV and NIR imaging with VSC, as well as CT techniques, offered enriching overviews about weaving characteristics, damaged areas or contaminations that were not easily discernible with the naked eye, thus supporting the conventional visual examination. As a result, detailed digital mappings about the technological structure and the condition of the fragments could be obtained in a relatively efficient and accessible way. Moreover, combining art historical identification of the design with the analysis of the weaving structure confirmed that both carpet fragments are border corners that originally belonged to much larger carpets made in the so-called "Indo-Persian" style. The outcome of this interdisciplinary research brings very useful contributions for future art historical and conservation assessments of historical carpets, and it encourages further exploration of imaging techniques in the examination of other textile objects in museums and private collections.



## 1. Introduction

Knotted-pile carpets have been woven for centuries in Islamic territories, and they are today remarkable historical examples of Islamic artistic expression in museums and private collections around the world. Symbols of status and economic prosperity, they ranged from staple floor and wall coverings in peasants' homes, to esteemed furnishing objects in royal palaces, reflecting the artis-

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try and craftsmanship of professional weavers. Their manufacture was always complex and costly, requiring ample expertise in the preparation of high-quality materials (fibrous yarns, metal threads and colourants), the design of intricate motifs, and the painstaking process of adding thousands of individual pile knots of different colours, like pixels in a digital image, on a foundation of warps and wefts [1–6].

Valuable repositories of historical information, knotted-pile carpets can tell plenty about the date, the context and the societies in which they were produced, as their design, weaving structure and materials connect to artistic traditions characteristic of certain periods, regions and workshops of the Islamic world [2–7]. Art historians have majorly focused on the visual examination of the carpets' design and weaving structure, supported by historical written records, Iranian faience or representations of carpets in Iranian and European illuminations and paintings [1–11]. In recent decades, scientific studies have supported art historical interpretations, e.g. through the analytical characterisation of the carpets' fibres, metal threads or colourant materials [5,8,12–18].

Conventional examination of the weaving structure of a carpet is generally made with the naked eye and with the help of a magnifying glass. It focuses on assessing the colour, spinning and plying of the yarns (clockwise – S or counter-clockwise – Z) comprising the warps and wefts of the foundation, and the knots that form the pile surface of the carpet; the warp level in tightly woven carpets, where one warp in each pair is higher or lower than the other (depressed warp); the number of shoots of weft between each row of knots; the height and direction of the pile of knots; the type of knots, such as the asymmetrical to the left or the right, or the symmetrical (Supplemental Online Material – SOM 1); the knot count per 10 cm of warp and weft, which indicates the density ($dm^2$); and the morphology of the selvedges, kilims and fringes at the carpet ends [2,3,5,7].

These features sensibly vary between carpets made throughout the Islamic world, and their conventional examination often entails several problems: it requires the handling of the object, which might be difficult when investigating very fragile carpets; understanding the spin and ply of the yarns might be only possible in damaged zones where they are exposed; knot count can be a laborious task since several counts must be made to achieve acceptable estimations; depressed warps are often difficult to identify and can influence negatively the accuracy of the knot count; weaving irregularities may pass easily unnoticed; and mapping damaged and worn areas, and/or repairs (from re-napping, patching or reweaving) can be a slow and inefficient process. Therefore, the visual examination of knotted-pile carpets remains time-consuming, laborious and imprecise.

Non-invasive imaging techniques can reveal important features in historical textiles that would be secluded, or not easily discernible with the conventional visual examination. These generally involve observation at different levels of energy of the electromagnetic spectrum, other than that visible light.

Techniques employing ultraviolet and infrared radiation, as well as different visible light conditions (e.g. incident, raking or transmitted), have been seldom documented for the investigation of historical textiles. However, they help to characterise different textile materials, weaving structures, dyestuffs, pigments, contaminations like stains, mould growths or adhesives, or locate patches from old repairs [19–23]. Visual Spectral Comparator (VSC) has been widely applied as a forensic tool to examine, compare and authenticate questioned documents [24–27], but only recently has it begun to be explored in the field of cultural heritage [28–30]. This offers live acquisition and comparison of an object while applying different types of illumination covering the visible, near-ultraviolet (NUV) and near-infrared (NIR) regions of the electromagnetic spectrum, and using incident, raking or transmitted light, at variable magnifications. Furthermore, VSC enables the identification of dyes and pigments through multispectral imaging, and in combination with chromatographic and spectroscopic techniques [24,29,30].

With radiographic techniques, beams of X-ray radiation are projected towards an object, and a certain amount is absorbed, depending on the density and composition of its components and materials. The X-rays that are not absorbed and pass through are captured by a detector, creating a radiographic image of the internal structure of the object. This technique has been applied to "deconstruct" complex three-dimensional textile objects, with additional paper, leather, wood or metal components [31–33].

Low X-ray energies, ranging from 15 to 30 keV (kiloelectron volt), and commonly known as "soft" X-rays, have proven suitable for imaging historical textiles since their fibres are made of organic materials (usually wool, silk, cotton or linen), which have a low density, and thus making them transparent to high X-ray energies. This radiation has enabled to assess variations in (single-layered) woven and knitted textile structures and to map worn, damaged or repaired zones and contaminations for the evaluation of the condition of textile objects [32–34]. Mammography, in particular, utilises low energy X-rays and has higher spatial and contrast resolution compared to conventional radiography [31,32].

Three-dimensional renderings can be obtained with computed tomography (CT). With CT, the X-ray generator and detectors rotate around the object, and conical X-ray beams cross from 360°, resulting in volumetric datasets. The result is a set of digital "slices" of the textile object, as well as its complete three-dimensional representation, observable from any angle [31,35]. Recently, micro-CT demonstrated improved spatial resolution than CT in the examination of the needlepoint lace details of one historical textile fragment [36]. This technique has been applied in the field of modern textile technology as well [31,37]. The technical principle of micro-CT is the same as CT, but in this case, the object is rotated 360° and the X-ray tube and detector are stationary [35].

## 2. Research aim chapter

An interdisciplinary pilot study was developed to improve the examination of Islamic knotted-pile carpets, highlight or uncover particular weaving features, and detect and characterise damaged areas, contaminations or repairs that remain unrevealed with visual examination. Two 17th-century Safavid knotted-pile carpet fragments were investigated, complementing the conventional visual examination with the support of an unprecedented combination of advanced non-invasive imaging techniques, i.e. transmitted, raking or incident visible, NUV and NIR illumination with VSC, conventional radiography, mammography, CT, and micro-CT. The resulting imaging data were evaluated to assess the advantages and disadvantages of each technique about the technical study of historical knotted-pile carpets, and thus, to help to determine advisable practices for a better assessment of the carpets' manufacture and their condition for long-term preservation.

## 3. Materials and analytical methods

Two 17th-century Safavid knotted-pile carpet fragments, belonging to the collection of the Rijksmuseum Amsterdam, were selected for this pilot study (Fig. 1). BK-NM-1958-57 (84 × 54 cm), henceforth fragment A, and BK-NM-1958-58 (63 × 57 cm), fragment B, both exhibited comparable designs and similar art historical attributions for place and date of production. Therefore, it was expected that they would show a similar weaving construction as well. Before submitting these valuable historical textiles to handling, packaging and transport that are inherent to examinations with techniques that cannot be carried out in situ, a contemporary


**Fig. 1.** A – carpet fragment BK-NM-1958-57, Iran, 17th century, 84 × 54 cm, source: Rijkstudio, http://hdl.handle.net/10934/RM0001.COLLECT.22450; B – carpet fragment BK-NM-1958-58, Iran, 17th century, 63 × 57 cm, source: Rijkstudio, http://hdl.handle.net/10934/RM0001.COLLECT.22451.

knotted-pile sample (circa 15 × 20 cm) was firstly used to assess the potential of the imaging techniques selected for this study. These techniques were applied on the entirety, or carefully selected parts, of the three textile objects. The most representative imaging data acquired are presented as Supplemental Online Material (SOM). The corresponding raw data are available in the online archive depository DANS [38].

### 3.1. Visual and microscopic examination

Conventional visual examination of the carpet fragments was carried out with visible light, at the front and back of the objects, to characterise their design, colours, and distribution of warps and shoots of wefts. The direction of the pile was assessed by stroking the surface of the pile with one hand. Knot count per decimeter of warp and weft was made at the back, on five random spots, and with a ruler [7]. Major areas of damage and material loss, and the presence of contaminations, were registered.

The number of wefts between knots and the threads and yarns' spin and ply could be observed using a AM413T Dino-Lite Pro digital microscope (AnMo Electronics Corporation, Taiwan). Colour and magnification calibrations were carried out with a colour checker and a calibration target, respectively. The respective microscopic images were acquired with DinoLite 2.0 software (version 1.5.17.B). Representative Dino-Lite microscopic images are displayed in SOM 2, with magnifications set at 95× (5 mm image width) or 200× (2.5 mm image width).

### 3.2. Visual spectral comparator

A VSC 8000 (Foster + Freeman, Evesham, United Kingdom, VSC Suite 7.0 software) was used to acquire digital images of the contemporary knotted-pile sample and the historical carpet fragments under different illumination conditions in the visible part of the spectrum, in near-ultraviolet (NUV 254, 312 and 365 nm) and near-infrared (NIR: from 645 to 925 nm at set intervals), and using incident, raking or transmitted light. The objects were placed in the examination chamber of the benchtop VSC equipment, and a live picture could be transmitted digitally with VSC software, enabling direct examination. Auto-exposure was activated, which means that brightness, gamma, focus, iris and integration time were adapted depending on the image acquisition conditions. To enable direct comparison of images, magnification was set at four specific values: 2.1× (143 mm image width), 7.9× (38.2 mm), 24.3× (12.4 mm), and 31.9× (9.4 mm), and images were taken at VIS, NUV 365 nm and NIR 725 or 925 nm (SOM 3 and 4).

### 3.3. Conventional radiography

Digital X-ray images of the knotted-pile sample were obtained with two X-radiograph instruments from Balteau NDT SA, Hermalle-sous-Argenteau, Belgium: a Baltomatic system, consisting of a Baltograph generator XSD160/4KW, an X-ray tube Baltograph TSD100/0 and a control unit Baltograph LS1; and a Balteau Baltograph system, consisting of a Baltograph generator XSD225, an X-ray tube TSD225/0, a control unit LS1, and a focal spot size of 1 mm (640 W) and 5,5 mm (3000 W). Detection was performed with blue ultra-high imaging plate (UH-IP), utilising a Duerr HD-CR 35 NDT computed radiography scanner. Images were obtained with the Baltomatic system at 15 kV, one-minute acquisition time. With the Baltograph system, images with most detail were obtained at 10 kV (5 min.) or 8 kV (10 min.), using 3 milliamperes (mA), 50 cm exposure. The brightness and contrast of the resulting X-ray images were adjusted, and false-colour was applied (SOM 5).

Digital X-ray images of selected parts of the carpet fragments were captured with a DigitalDiagnost C90 (Phillips Healthcare, Guildford, United Kingdom), equipped with SRO 33,100 high power X-ray tube and a Digital Cesium Iodide flat detector, at the University Medical Centre (UMC), location AMC, Amsterdam. Images showed the most detail when acquisition parameters were set at 40 kV and 201 mA for fragment A and 50 kV and 267 mA for fragment B, and after brightness and contrast were adjusted with MicroDicom viewer software (version 3.1.4) (SOM 6).

### 3.4. Mammography

Mammography and three-dimensional mammography (tomosynthesis) were performed on the knotted-pile sample and selected areas of the carpet fragments, using a Selenia Dimensions™ AWS 9000 (Hologic Inc., Marlborough, United States), at the UMC-AMC, Amsterdam. Scans with most detailed information were obtained with tomosynthesis at 40 kV and 70 mA (SOM 7 and 8). To help contrast, an aluminium filter was used for image acquisition [31]; but silver and rhodium filters were tested as well during the examination of the knotted-pile sample. Brightness and contrast were adjusted with RadiAnt ® DICOM Viewer (version 5.5.1.23267).

### 3.5. Computed tomography

The knotted-pile sample and the carpet fragments were scanned on their entirety (the latter were also partially rolled), using a Dual Source SOMATOM Force CT scanner (Siemens Healthineers, Munich, Germany) at the UMC-AMC, Amsterdam. The scanner was equipped with two Vectron™ X-ray tubes and two StellarInfinity detectors with anti-scatter 3D collimator grid, 0.24 $mm^1$ spatial resolution and a maximum scan speed of 737 $mm/s^1$ with Turbo Flash. Scans with most detailed information were obtained at 100 kV and 150 or 180 mA, at 0.4 mm ultra-high resolution, and containing 571 radiographs for the knotted-pile sample, 2862 radiographs for fragment A, and 2202 radiographs for fragment B (SOM 9 and 10). Reconstruction of the scans was performed with RadiAnt ® DICOM Viewer.

### 3.6. Micro-CT

Tests were carried out with a micro-CT at the FleX-ray Laboratory, at CWI, Amsterdam. This apparatus can perform tailored scans that fit around the object, including spatial tiling for high-resolution scans or unconventional scanning geometries to study fragile or unusually shaped museum objects [35,39].

The knotted-pile sample was mounted with pins on a vertical support of Kapa Line foamboard, whereas fragment A was rolled along its long side, and stabilised with low-density polyethylene foam through the middle and around the bottom of the object. These were mounted onto the rotation stage, standing upright (SOM 11). Acquisition of 1800 radiographs for the knotted-pile sample was carried out over 360°, at a resolution of 37.2 μm (i.e. 2× magnification), and an acquisition time of 21 min. For fragment A, 1800 radiographs were acquired on a selected part of the object, at a resolution of 30 μm (i.e. 2.5× magnification, on a 3 × 1 tiled scan), and an acquisition time of 63 min. The collected data were stitched before reconstructing the volume.

## 4. Results and discussion

### 4.1. Weaving structure

The design, the colours and some structural features of the carpet fragments could be registered with conventional visual examination, namely three shoots of weft after each row of knots, and the asymmetric direction of the pile. With the help of Dino-Lite microscope, it was possible to verify that similar yarns were used to build both carpet fragments, with the warps comprising four Z-spun threads in S-plied yarns (the number of warp threads could only be confirmed in damaged zones, where they were exposed); the wefts, two Z-spun threads in S-plied yarns; and the knots, each wrapped around two warps, comprising two unspun threads in slightly Z-plied yarns, with a short pile height. Both fragments were confirmed to have three shoots of weft per row of knots (Fig. 2 and SOM 2). The white warps are likely cotton, whereas the wefts and the knots, wool. Cotton as part of the foundation is common in this type of carpets [16], but this should be confirmed with higher-magnification microscopy.

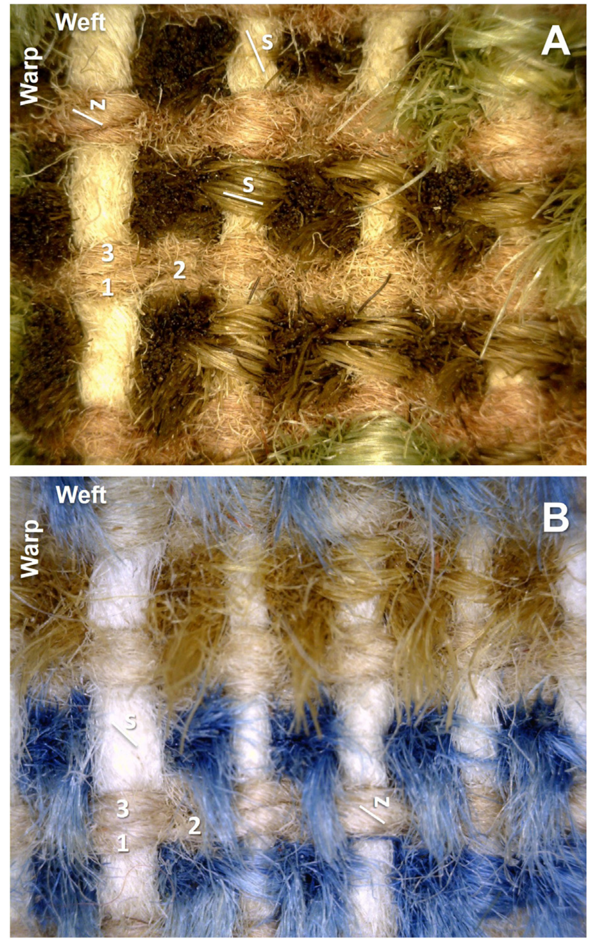


**Fig. 2.** Dino-Lite microscopic details of areas with exposed warps and wefts in carpet fragments A and B (front), at 95× magnification.

VSC imaging was firstly tested on the knotted-pile sample using incident visible-light, NUV and NIR illuminations (SOM 3). Incident NIR, due to the elimination of colour information, enabled an easy distinction between areas with symmetric and asymmetric (open to the right) knots. The latter were also added tighter, as evidenced by the shape of the sample itself (Fig. 3). Zooming in at the back of the sample, it was possible to report three shoots of weft after every row of knots; wefts made of single Z-spun yarns; knots made of two unspun threads in S-plied yarns, with a medium pile height; and warps of six Z-spun threads in S-plied yarns, making plain knotted fringes at each end of the sample.

Interpretations obtained with conventional visual examination and Dino-Lite about the carpet fragments were supported with the VSC, regarding the morphology of the yarns or the number of shoots of weft (SOM 4). Moreover, and as reported by previous studies [21–23], examination in NUV (365 nm) produced an accurate mapping of the colours and the layout of the design in both carpets, especially in cases where their readability was not clear with the naked eye, due to possible colour fading or knot wear – compare A1 with A2, and B1 with B2 in Fig. 4. NUV also highlighted white areas made with undyed woollen knots that show natural luminescence, and the knots in light green and yellow areas, which were

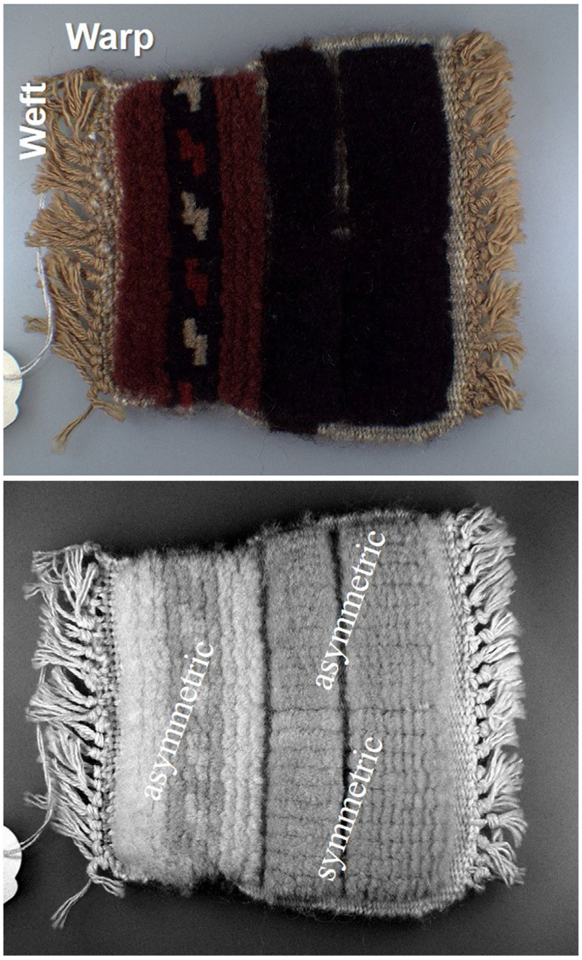


**Fig. 3.** VSC images of the knotted-pile sample (front) under incident visible-light and NIR (725 nm) illumination, at 2.1× magnification. Parameters of acquisition in SOM 3.1 and 3.3.

likely submitted to bleaching treatments before dyeing (Fig. 4 – A2 or SOM 4.8) [40].

Asymmetric knots open to the left and facing downwards could be confirmed on both objects with visual examination and with incident NUV and NIR (Fig. 4 – A2 and B2, or SOM 4.12 and 4.30). Because knots are always added at the top of the warps with the loose ends hanging down in the direction of the starting edge of the carpet [7], and because of the corner design of the fragments, it is possible to conclude that fragment A was the starting edge at the lower right corner of a complete carpet, whereas fragment B, the upper left corner of another carpet.

Examination with micro-CT further confirmed the asymmetric direction of the knots in carpet fragment A (Fig. 5.1). Even though the scan shows them bending towards the right, the sliced imaged of the fragment is shown upside down. If the fragment is positioned according to the direction it was woven, the knots bend towards left. Zoomed details of the scan could also show the shoots of wefts flowing up and down the warps, and the existence of only one warp level, which demonstrates that the carpet was not tightly woven.

More details of a textiles' weaving structure can yet be obtained with micro-CT. Fig. 5.2 shows a sliced image of the knotted-pile sample, which is 12–15 times smaller than the carpet fragments. Because of these dimensions, micro-CT allowed enhanced levels of detail about the morphology of the yarns and the knots, in comparison to those observed in the carpet fragments. Comparable information could be furthermore attained with ultra-high-resolution CT, which uses almost ten times less resolution than micro-CT (Fig. 6S). However, when examining the carpet fragments with similar CT acquisition parameters, an obvious loss of detail was reported since the fragments are much larger than the sample – compare S with A1 or B1 in Fig. 6.

Projecting NIR illumination at the back of the knotted-pile sample and of the carpet fragments revealed the spaces and angles between the knots, as well as the sinuous distribution of the warps and the wefts, which are never completely parallel between each other, as one would expect from handicraft work (Fig. 7-B1 or SOM 3 and 4). These weaving irregularities are more pronounced at the edges where the carpet begins or ends, as highlighted in images obtained with conventional radiography and three-dimensional mammography (Fig. 7-B2 and A1 or SOM 6 and 8).

With these radiographic techniques, images with moderate resolution could be obtained on the knotted-pile sample, permitting to distinguish different knot morphologies, but not the type of knots per se. Moreover, the layout of the foundation was only visible where the pile was not present, indicating that the knots are too dense to allow a glimpse of the underlayer (SOM 5 and 7). Although the carpet fragments are characterised by a short and worn pile, both radiographic techniques only allowed a distinction of the rows of knots covering the shoots of weft and not the individual knots.

An estimation of the knot density could be attained based on the knot count performed with visual examination and then with incident NIR at low magnification (SOM 4): circa 42–44 vertical (warp direction) and 51–56 horizontal (weft direction) knots per one decimetre in fragment A, making 2.142–2.464 knots p/dm$^2$; and

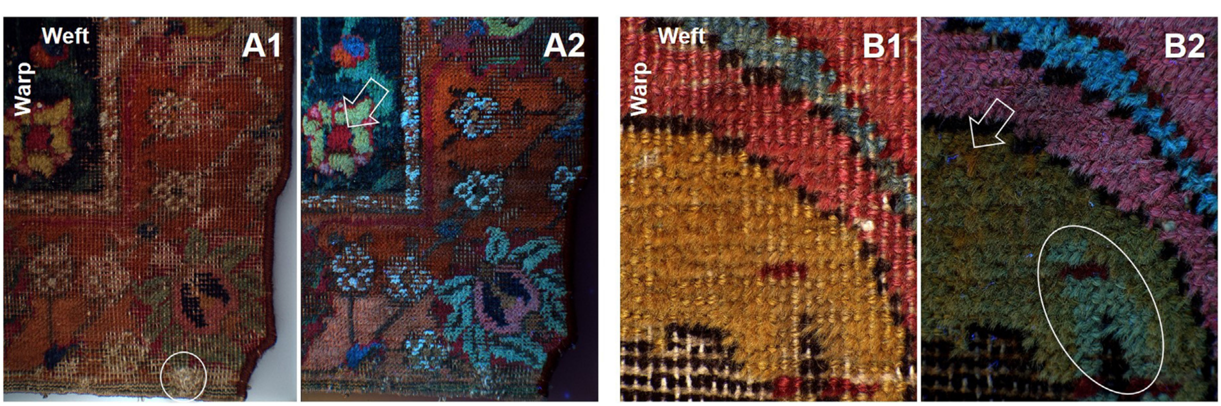


**Fig. 4.** VSC images acquired at the front of carpet fragments A and B, with incident visible-light (A1 and B1) and NUV (365 nm) illumination (A2 and B2). Marked are the colours distribution, the direction of the pile and a repaired area. Parameters of acquisition in SOM 4.1, 4.2, 4.28 and 4.29 (For interpretation of the references to colour in the text, the reader is referred to the web version of this article).

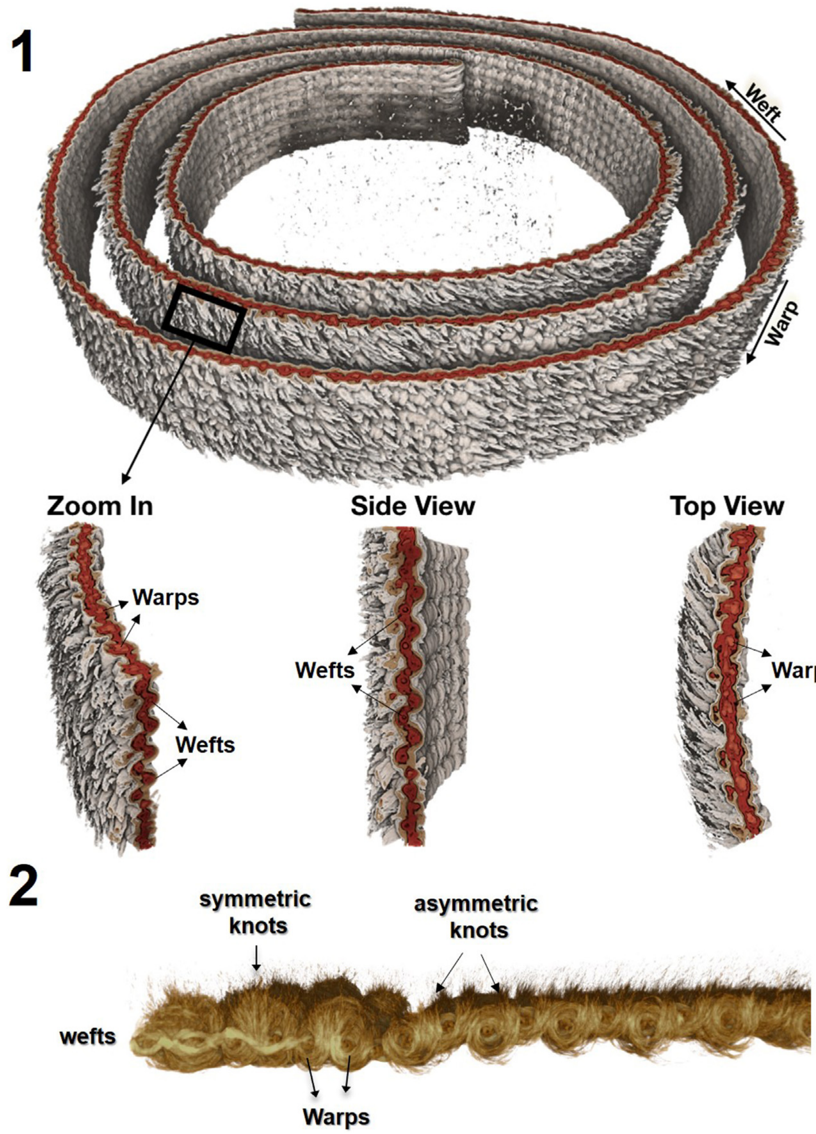


**Fig. 5.** Sliced micro-CT scans of 1. a selected part of rolled carpet fragment A, with details of sliced areas – white corresponding to the knots, orange to the warps, and red to the wefts; and 2. knotted-pile sample, with details on symmetric and asymmetric (to the right) knots (For interpretation of the references to colour in the figure legend, the reader is referred to the web version of this article).

44–46 vertical and 46–48 horizontal knots in fragment B, making 2.024–2.028 knots p/dm$^2$. These numbers indicate that the knot density is somewhat finer in fragment A, as also reflected in its higher design quality, with smoother lines and smaller, more detailed motifs.

### 4.2. Condition assessment

A first visual survey of the carpet fragments appeared to indicate that their condition was relatively stable, with a few evident areas of knot wear, and contaminations at the back of fragment B, but also old repairs of damaged areas and stabilising hems preventing the edges from fraying away. However, more details about the condition of the objects could be uncovered with imaging techniques. For example, CT enabled to map diverse gaps in fragment A that were characterized by considerable material loss of knots and wefts, and which had not been reported with the naked eye (Fig. 8A). These areas were also observed with conventional radiography and three-dimensional mammography (Fig. 7-B2 and A1 and SOM 6), and especially in transmitted visible light (SOM 4.5 and 4.20). Loss of material in fragment B was noted to be somewhat smaller than that from fragment A, showing smaller areas of knot loss (Fig. 9-B1). The morphology of old repairs was also mapped, e.g. fragment A's bottom right corner (Figs. 1A and 4 -A1) or fragment B's upper left corner (Figs. 1B and 7 -B2).

When imaging both carpets with VSC, these displayed many more areas of knot wear than it had been assumed with visual examination. In particular, raking NIR illumination accentuated worn or complete loss of knots belonging to dark brown areas of the design in both carpet fragments (Fig. 9-B2 and SOM 4). In these areas, the remainders of the former brown knots are only held tight in every intersection of warp and weft. These brown knots appear to be more fragile than other coloured knots, such as pink, red, yellow or blue, which remain more or less complete. Although the nature of the dyestuff present in the brown knots was not identified in this study, the dark appearance of these knots in NUV and NIR images (Figs. 4-A2 and B2 or 9 -B2 and B3) suggests that the brown colour could have been achieved with tannins (from oak galls, alder bark or sumac, for example), in combination with iron salts as mordant [21]. This combination would eventually cause the brown wool-

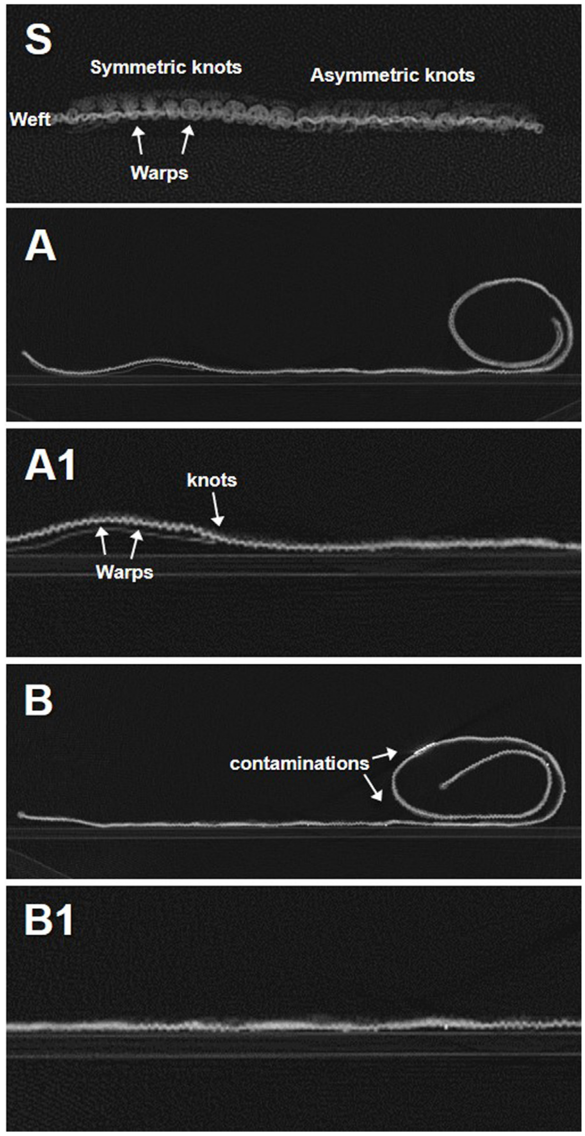


**Fig. 6.** Sliced images obtained with ultra-high resolution CT on the knotted-pile sample (S), the carpet fragment A (and respective detail – A1) and the carpet fragment B (and respective detail – B1). Parameters of acquisition in SOM 9.1, 10.1 and 10.2.

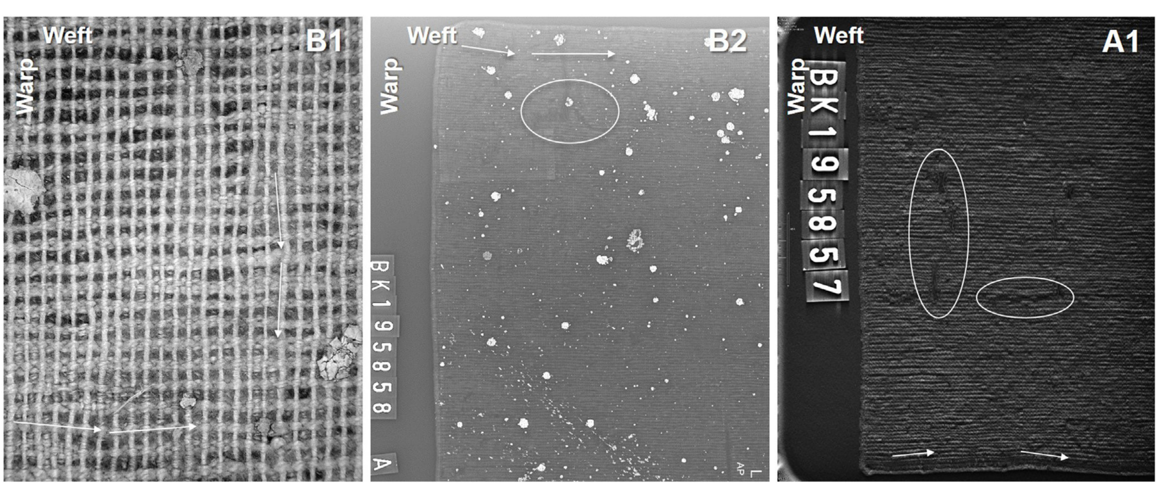


**Fig. 7.** Images of selected parts of carpet fragment B with VSC using incident NIR illumination (back, B1) and conventional radiography (B2), and of carpet fragment A with tomosynthesis (A1), highlighting weaving irregularities and damaged areas. Parameters of acquisition in SOM 4.33, 6.5 and 8.1.

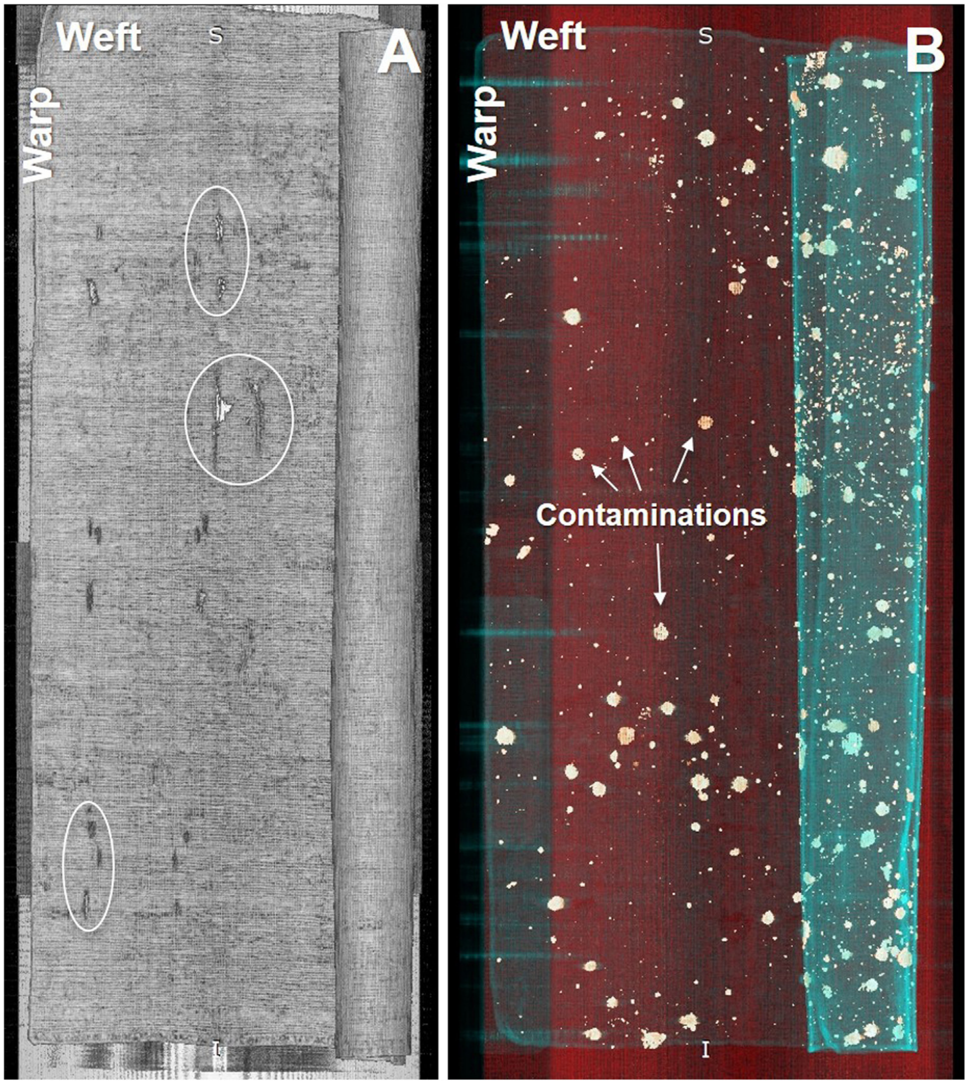


**Fig. 8.** Top view renderings of the complete carpet fragments A (left) and B (right) obtained with ultra-high resolution CT. Mapping of damaged areas on fragment A and contaminations on fragment B. Parameters of acquisition in SOM 10.

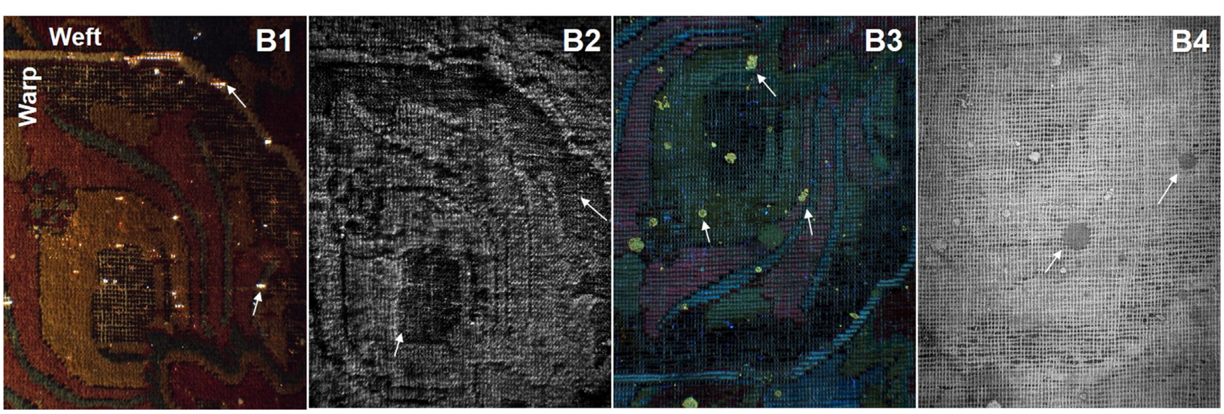


**Fig. 9.** VSC images acquired with transmitted visible-light (B1), raking NIR (725 nm – B2), incident NUV (365 nm – B3) and incident NIR (925 nm – B4) on selected parts of carpet fragment B (front and back). Mapping of areas with material loss, worn knots and contaminations at the back of the object. Parameters of acquisition in SOM 4.20, 4.22, 4.26 and 4.27 (For interpretation of the references to colour in the text, the reader is referred to the web version of this article).

len fibres to become very acidic and brittle, prone to mechanical damage [13,40].

Solid opaque cream and transparent white spatters were found encrusted onto the yarns at the back of fragment B (SOM 4). A sample of one opaque cream spatter could be mechanically removed without compromising the integrity of the object. Elemental analysis with energy-dispersive X-ray spectroscopy revealed that the opaque cream-coloured spatters are lead- and calcium-based;

though further research would be necessary to identify the nature of this contamination. Nonetheless, and for the purposes of this study, X-radiographic techniques (particularly ultra-high-resolution CT – Fig. 8B) and illumination in the NUV helped to map the overall location of the opaque cream contaminations (Fig. 9-B3). The transparent white spatters were highlighted with incident NIR (Fig. 9-B4).

### 4.3. Advantages and limitations of imaging techniques

Of all techniques tested here, VSC has shown to be the most versatile, offering variable illumination conditions and magnifications for characterising the carpet fragments and their condition. Handling of a VSC instrument can be learnt by any textile researcher: the object is placed horizontally in a chamber, illumination and magnification are directly adjusted, the examination is followed on a screen, images are acquired immediately, and the parameters of acquisition are recorded directly. The potential of VSC in historical textile research is enormous and deserves further comparative studies with conventional photographic techniques [30]. Even so, VSC remains a rather costly instrument, and it is not portable, thus requiring the objects to be transported for examination in specialised facilities. Recently developed hand-held, high-resolution digital cameras from the same supplier of the VSC can be a suitable alternative. These can be used in situ and also provide imaging in visible, NUV (365 nm) and NIR (780 nm) illuminations, in combination with bandpass- and longpass-filter systems.

Dino-Lite digital microscope is more accessible than VSC, it is portable and often employed in the field of textile conservation. Although the model selected for this study could not offer improved spatial resolution nor extended depth-of-field, a wide range of state-of-the-art Dino-Lite and other magnification tools, such as Hirox or Keyence microscopes, are currently available on the market. More recent versions of Dino-Lite offer improved microscopic resolution, long working distance, extended depth-of-field and additional ultraviolet and infrared illuminations. However, even though Dino-Lite enables live examinations, it requires prior calibration and acquisition parameters are added manually.

Micro-CT provided high levels of resolution that resulted in sliced scans of elaborate detail, disclosing the warp level and the spacing between warps, and showing high potential for the visualisation of individual knots and the morphology of the yarns in the knotted-pile sample. However, the acquisition of these data can be rather slow, ranging from minutes to hours. Also, preparing and fitting the objects inside the instrument for examination can be rather challenging. Fragment A had to be rolled and mounted vertically onto the stage of the instrument, something that is not feasible with more fragile textiles. The instrument itself has its space limitations, as fragment B was a few centimetres too long to fit in it vertically, making it impossible to be examined. Newly emerging micro-CT instruments might be more suitable for the examination of larger and frailer textile objects.

Previous X-radiography studies of textile objects with single, consistent thickness, like the carpets assessed here, have demonstrated that mammography can provide higher spatial and contrast resolution than conventional radiography [19–22]. In this study, three-dimensional mammography offered more detailed renderings than conventional mammography, while applying voltages of 40 kV, which are above the "soft" X-ray range (SOM 7 and 8). Images showed the most detail when acquired with an aluminium filter; though a rhodium filter had a noticeable impact on the contrast as well.

"Soft" X-ray conditions during examination with conventional radiography on the knotted-pile sample helped to achieve a good level of detail, although the small radiographed area also contributed significantly (SOM 5). In contrast, the radiographed area of the carpet fragments was wider and imaging was more suitable at voltages that fall outside the "soft" X-ray range (SOM 6). However, the density of the pile appears to be a major obstacle in conventional radiography and mammography, since the output data do not allow distinguishing the pile from the foundation. Relevant information can still be obtained about the weaving irregularities or the level of material loss and contaminations.

Differentiation between the pile and the foundation was possible on sliced images obtained with ultra-high resolution CT on the knotted-pile sample. Although this technique offers somewhat less resolution than micro-CT, it permitted a fast examination of the complete carpet fragments, as well as a detailed mapping of their damaged areas and contaminations. Furthermore, the objects were partly rolled during scanning to explore the possibility of examining larger carpets or other three-dimensional textiles. Post-processing of the renderings should allow their digital unfold for more visual details in future research. Even so, a major drawback of considering scans of large objects is that resolution will proportionally decrease, and information about their weaving structure will reduce accordingly.

In contrast to CT, all other imaging techniques tested here only allow fragmentary examinations on selected parts of the objects. Images can still be collected with conventional radiography or VSC throughout the objects' full length and width (with some overlap between them), and all the acquired data can be "stitched" together to form a complete image of the whole object [19]. However, this task is laborious and time-consuming, especially when considering sizeable carpets. It is also impossible when considering mammography or micro-CT, due to physical constraints. Mammography, for example, can only accommodate small textile objects or the edges of larger ones.

Finally, handling state-of-the-art X-radiographic equipment requires expertise, and it may be dependent on availability. Therefore, it is important to evaluate beforehand the need for radiographing a whole object, or only representative areas that provide equally insightful information. Besides, radiographic imaging of historical textiles should be always re-considered when other materials, particularly of inorganic nature, are present. Indeed, due to the contaminations at the back of fragment B, higher energy beams were required to improve the overall radiographic image, which somewhat hindered the level of detail of the weaving structure (SOM 6) [19,21].

## 5. Conclusions

The interdisciplinary combination of conventional visual examination with non-invasive imaging techniques brought comprehensive details about the weaving features of the carpet fragments selected for this study. These features were found to be characteristic of one type of large 17th-century carpets, the so-called "Indo-Persian", which not only share similar weaving structures but are also characterised by designs with large palmettes, lotus flowers and other motifs intertwined by vine-scrolls in red fields, surrounded by blue or green borders with palmettes facing inwards and outwards [5,16]. Hence, fragments A and B are border corners of much larger objects, likely produced in well-organised urban 17th-century Persian textile centres, and probably meant for export to Europe, as often suggested by their depictions in European paintings of this period [5,11,16].

Microscopy (Dino-Lite) and imaging under variable illuminations (VSC) provided complementing information that could not be achieved with the conventional visual examination, namely the yarns' morphology or the mapping of colours. Non-invasive imaging with VSC also permitted to avoid touching the objects to determine the direction of the pile; the knot count was more efficient when colour was eliminated with NIR and the studied areas were zoomed in; and the digital mapping of areas of material loss, repairs and contaminations was essential to appraise the overall condition of the carpet fragments and define proper guidelines for their treatment, storage or exhibition at the museum.

Micro-CT and CT revealed to be useful techniques to support interpretations obtained with VSC and Dino-lite. Micro-CT highlighted details that would be difficult to characterise with any other techniques (e.g. warp level), whereas CT provided an efficient recognition of the condition of the complete objects.

In conclusion, this study demonstrates that non-invasive imaging techniques can support conventional visual examination, by offering deeper insights into the objects, as well as more efficient and accessible examinations. Further exploration of machine learning techniques to support this type of study should be highly encouraged, as it may help complex knot and thread counts, discriminate irregularities characteristic of handwoven work, and eventually, contribute to assessing the context in which objects were made.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.culher.2020.09.012.

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