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ORIGINAL PAPER

New applications of 3D modeling in artefact analysis: three case studies of Viking Age brooches

Michael Neiß · Sabrina B. Sholts · Sebastian K. T. S. Wärmländer

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Abstract Three-dimensional (3D) laser scanning is a nondestructive and versatile technique that provides archaeologists with 3D models of archaeological and ethnographic objects. We have previously shown that 3D models facilitate shape analysis of archaeological bones and stone tools, due to the high measurement accuracy inherent in the latest generation of 3D laser scanners. Here, we explore the utility of 3D modeling as a tool for analyzing Viking Age metal artefacts with complex morphologies. Four highly ornate Viking Age brooches from Scandinavia and Russia were digitized with a portable laser scanner, and the resulting 3D models were used in three case studies of (a) artefact reconstruction, (b) tool mark analysis, and (c) motif documentation. The results revealed both strengths and limitations of the employed techniques. 3D modeling proved to be very well suited for artefact reconstruction and was helpful also in the stylistic and motif analysis. The tool mark analysis was only partially successful, due to the resolution limits of the laser scanner used. 3D-based motif analysis of a grandiose Scandinavian-style brooch from Yelets, Russia, identified an anthropomorphic figure with a bird-like body that previously has been overlooked. This figure may be a Rurikid coat of arms, possibly linking the object to a princely household and providing further evidence for a connection between Scandinavia and the Rurikids. As 3D technology keeps improving, we expect that additional applications for 3D modeling in archaeology will be developed, likely leading to many new findings when old objects are re-analyzed with modern techniques. However, our results indicate that 3D modeling cannot completely replace traditional artefact analysis—instead, we argue that the two approaches are best used in combination.

Keywords 3D laser scanner · Archaeometry · Artefact autopsy · Digital reconstruction · Scandinavian studies

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M. Neiß
Department of Archaeology and Ancient History, Uppsala University, 751 05 Uppsala, Sweden
e-mail: michaelneiss@hotmail.com

S. B. Sholts
Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington, DC 20013, USA
e-mail: SholtsS@si.edu

S. K. T. S. Wärmländer (✉)
Division of Biophysics, Stockholm University, 106 91 Stockholm, Sweden
e-mail: seb@dbb.su.se

S. K. T. S. Wärmländer
Cotsen Institute of Archaeology, UCLA/Getty Conservation Program, University of California, Los Angeles, Los Angeles, CA, USA
e-mail: warmland@ucla.edu

Abbreviations

NM	The National Museum, Copenhagen, Denmark
GE	The State Hermitage Museum, Saint Petersburg, Russia
SHM	The Swedish Historical Museum, Stockholm, Sweden

Introduction

As scanners for three-dimensional (3D) modeling are becoming increasingly more affordable and user-friendly, they are also becoming more widely available to archaeologists and anthropologists. Creating 3D models allows for spectacular

3D visualization of archaeological and ethnographic objects, buildings, and landscapes. 3D modeling is also an ideal documentation technique for fragile and rare objects, as researchers and museum visitors then can study the 3D images rather than the physical objects (Hermon 2008; Wachowiak and Vicky Karas 2009). Recent work has shown that 3D laser scanners of the latest generation are suitable instruments for shape analysis of archaeological bones and stone tools (Gingerich et al. 2014; Petaros et al. n.d.; Shearer et al. 2012; Sholts et al. 2010, 2011a, b, 2012; Sholts and Wärmländer 2012). In this study, we investigate the usefulness of 3D modeling as a tool for addressing questions encountered in traditional artefact analysis of cast metal objects.

To explore the limits of 3D laser scanning, we chose to study artefacts with very complex morphologies that are nearly impossible to capture with traditional 2D images recorded from a fixed viewpoint (e.g., photographs). Suitable objects were found in the form of baroque-shaped brooches from Viking Age Scandinavia, renowned for their highly ornate and intricate décor: one recently excavated brooch from Denmark and three Russian brooches with nearly iconic status in the field of Viking Age studies. In three separate case studies, we present possible uses of 3D modeling for (a) artefact analysis, (b) artefact reconstruction, and (c) tool mark and motif analysis. The results of the case studies are discussed and presented in detail to allow evaluation of the pros and cons of 3D modeling and to provide suggestions for how to best incorporate 3D modeling in future artefact studies. In addition, the case studies provided new insights about the baroque-shaped brooches and their uses during and after the Viking Age.

Viking Age baroque brooches

Baroque-shaped brooches constitute a group of dress ornaments mainly encountered in eastern Viking Age Scandinavia. Their name derives from the characteristic large cast and/or attached bosses, which give them an almost baroque appearance (cf. Jansson 1984, p. 81), even though these objects appeared during the tenth century and have nothing to do with the baroque style that evolved in late sixteenth century Italy. The baroque brooches are cast in either silver- or copper-based alloys and come in two design versions: circular or equal-armed. Because of the positions in which copper alloy brooches have been encountered in burial contexts, it appears that they were used to fasten the cape or shawl in the female Viking Age dress (Aagård 1984, 96 ff.; Capelle 1962, p. 106; cf. Jansson 1984, 75 ff.; Neiß 2007, fig. 3). When Eastern Scandinavia embraced Christianity in the eleventh to the twelfth century, the baroque brooches gradually went out of fashion.

The morphology of baroque-shaped brooches is typically very complex. This complexity probably stems from tenth century technological advances allowing casting with elaborate 3D designs, in combination with the constant ambition of luxury-object craftsmen to fill the object's surface with as much imagery as possible. This desire often prompted casters to create puzzle pictures in the brooch design, i.e., ambiguous pictures containing two or more motifs. Due to limits in human perception, such motifs cannot be viewed simultaneously; instead the viewer's consciousness oscillates between two or more alternative readings (cf. Neiß 2011, 2012 and references therein). When executed in three dimensions, the puzzle pictures are sometimes composed of elements located far apart that only interact when viewed from a certain angle. Thus, the most complex of the tenth century brooches constitute a form of sculpture, changing their shape as the observer changes his or her viewpoint. When the brooch is turned, some figures in the motif slowly appear, while others change their character.

3D scanning

The 3D surface models were recorded with a NextEngine desktop 3D laser scanner operated with the ScanStudio HD v.1.3.2 software from NextEngine Inc. With this instrument, the target object is positioned on an automated rotating platform and scanned from different angles. The automated mode allows for between 5 and 16 angles per turn and automatically aligns each scan with the previous one(s), thus building a 3D model step by step. The auto-alignment algorithm is however not flawless, and it has problems with thin objects like the studied circular brooches. Consequently, scans sometimes have to be aligned manually. To prevent misalignment, we recommend the following measures: (i) Place the scanner and the platform on the same solid support (e.g., a robust table). (ii) A chemically neutral wax or similar material can be used to hold the object and loose parts in place during scanning. The clay that comes with the scanner is not neutral but might corrode metal objects. The wax should have a different color than the object being scanned. (iii) Eight scans or more per rotation usually provide the auto-alignment with enough common reference points between scans for proper functioning. (iv) Terminating the scanning before the ScanStudio software passes into the "Global alignment" phase will prevent the software from displacing the different scans.

A general problem with metal objects is their often shiny metallic surface, which spreads light in various directions. The NextEngine scanner performs best for opaque objects with a matte surface, wherefore it is often recommended to coat translucent or shiny objects with a matting agent such as talcum powder. Although such powder can conveniently be washed away with alcohol—not water as it might induce corrosion—it is often not permissible to powder rare museum objects. In these cases, the best approach is to block all external light sources by covering the entire scanner/object setup with a plastic or cardboard box, ideally black on the inside, and scan the object using the “normal” surface setting in the ScanStudio software. In general, we have not found conditions where the scanning has been improved by using the “light” or “dark” surface settings. Each scan is then manually checked for reflection-induced errors, and bad scans are redone. This approach is somewhat time-consuming but usually ends up producing high-quality 3D models. In addition to light and shiny surfaces, also very dark (black) surfaces pose a problem as they reflect very little light. This causes the NextEngine scanner to erroneously interpret black spots as surface indentations. For our studied objects, this was a problem for patches of black surface corrosion (due to silver sulfides) and when ID numbers had been written on the objects with black ink. Currently, our only remedy for this problem is to cover the dark/black areas with, e.g., talcum powder. On the other hand, these indentations may not always pose a major problem, depending on the purpose of the 3D model, and having the ID number digitally engraved in the 3D model surface can help avoid confusion about an object’s identity.

As the platform rotates only horizontally, a single rotation scan will not capture the whole object. Sometimes re-orienting the object and executing another rotation scan is sufficient for obtaining a complete 3D model, but often additional single scans have to be made manually from various angles. When scanning human crania for example, which have a complicated shape, we have developed a suitable scanning sequence that includes both rotation scans and single scans with particular orientations of the cranium (Sholts et al. 2010). When scanning is completed, all scans are cleaned using ScanStudio’s cropping tool and manually assembled with the ScanStudio aligning tool. For complicated cases, we sometimes export the models to the Rapidworks v.2.3.5 software (INUS Technology Inc.), which has more advanced functions for cleaning and improving the scanned data, including “hole-filling” for parts where scan data is missing. After alignment, the scans are fused into a single 3D surface model using the ScanStudio software at a 0.5 resolution ratio. Resolution rates of 0.2 to 0.5 are recommended for objects that are thin and/or have sharp edges, such as the studied circular brooches. For 3D models of human crania, which are generally rounder and thicker, we typically use a resolution ratio of 0.7. When scans are fused in the Rapidworks software, we typically use the “medium” mesh density setting.

In the final step, the fused 3D models were saved as *.ply files and exported into MeshLab v.1.3.2 (freeware from the Visual Computing Lab at ISTI-CNR), which has a wide repertoire of tools for 3D model analysis. After the model surfaces had been reconstructed with a Poisson filter, we considered the 3D models complete. They were then visually examined in the MeshLab environment and also converted into the 3D pdf format using the Tetra4D converter from Tech Soft 3D Inc.

Case study 1. 3D reconstruction of the brooch from Vestervang, Denmark

In 2007, the Roskilde Museum conducted a rescue excavation at the Vestervang farm in the parish of Kirke Hyllinge, on the Danish island of Sjælland (Zealand). Metal detector surveying yielded a number of interesting small finds, including a disc-shaped brooch (NM inventory number 2010-015766-C38040) with a diameter of 73 mm and a weight of 132.7 g (Fig. 1). The find place is located about 10 km from the Viking Age central place of Lejre (Neiß 2011; Thirup Kastholm 2009, p. 34, fig. 1).

Some parts are missing from the plate, making it difficult to unambiguously ascertain its function. The most plausible interpretation of the plate, however, is that it constitutes the frontal shell of a circular brooch of baroque type. In order to reconstruct the original design of this brooch, we have employed both a traditional approach, i.e., a comparison of artefact types, and a more modern approach where we extract information from 3D modeling analysis.

We assume that the brooch follows the typical symmetry rules for its time period (cf. the baroque-shaped brooches in Neiß 2007, 2010), which implies that it consisted of a vaulted frontal shell and a more or less flat back plate. The frontal shell displays a tripartite design dividing the front into three ornate fields (Fig. 1b). Originally, these three ornate fields would each have had a proximal boss. Today, only one of these bosses remains, although the original presence of the other two bosses can be concluded from the rivet holes in the two empty fields. As the remaining boss illustrates, the bosses were rather bulbous and added extra volume to the brooch. In the center of the front unit, a small and partially corroded pit can be discerned, the function of which is unclear. The pit might be an additional rivet hole, but there is no clear evidence that a central boss ever existed. Another possibility is that the pit was used to fit a precious or semiprecious stone to the center of the brooch (cf. Thunmark-Nylén 2006, 393 f.). A framing recess running along the inside of the frontal shell testifies to the existence of a now-lost back plate (Fig. 1a). In order to fulfill its function in the brooch, this lower shell must have featured a pin, a pinholder, a pincatch, and a chainholder. The two shells were most likely held together by the same rivets that fastened the bosses. Hence, no additional rivets were required, which demonstrates the well-planned manufacturing of the brooch.

From the above description, it is clear that the original design of the Vestervang brooch is not easily reconstructed with traditional techniques. Hence, we decided to investigate whether 3D modeling could help answer some of the

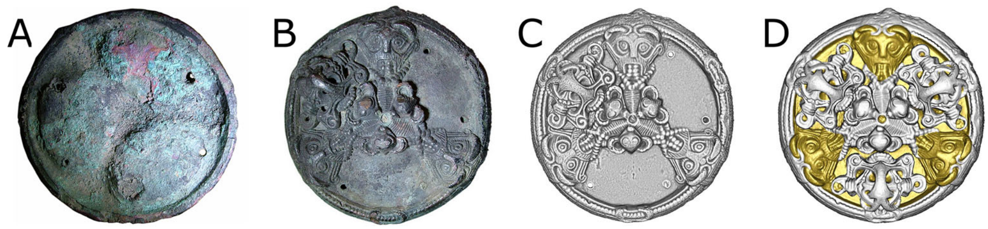

Fig. 1 Circular baroque-shaped brooch from Vestervang, Kirke Hyllinge, Sjælland, Denmark (The National Museum of Denmark, deposited at Roskilde Museum; NM 2010-015766-C38040). **a** Photograph, *back view* with framed recess visible. Large amounts of purple and turquoise corrosion products are present. **b** Photograph, *front view*. **c** 3D model of the brooch. **d** 3D model reconstruction with possible color scheme. Photos and 3D models After Neiß (2012)

questions regarding the brooch, such as the possible existence of a central boss, the nature of the décor, the design of the back plate, and the material composition of the object.

The tenth century baroque-shaped brooches often display a very complex décor (see above), with imagery and figures that are difficult to capture with traditional drawings and photographs. Because these figures can be difficult to detect, it is desirable to reconstruct the complete design of the Vestervang brooch before beginning the iconographic analysis. As it turned out, conducting such a reconstruction via 3D modeling offers certain advantages.

The starting point for the 3D reconstruction was a 3D model of the front part of the brooch, created with the NextEngine laser scanner (Fig. 1c). This model was duplicated in the MeshLab software. From the duplicate model, the proximal boss was isolated, duplicated, and attached at two places on the virtual brooch front (Fig. 1d). The perfect fit of the added proximal bosses confirms that the brooch was designed around a tripartite construction, where the voluminous bosses interact with the cast details to form an intricate pattern. It has earlier been argued that the brooch contains up to 36 puzzle pictures (Neiß 2011), all of which cannot be elaborated upon in this work. Instead, in Fig. 2, we give an example of an anthropomorphic figure present in the design pattern of the reconstructed 3D model, as well as another pattern, evoking the design of a Viking Age trefoil brooch (Fig. 1d).

The brooch displays detailed animal-style ornamentation and has obviously been crafted with great skill and care. The piece displays a dramatic composition with a sharp relief contrasting against a flat surface. Some of the flat areas seem to contain traces of niello, suggesting that the original artwork contained alternating areas of gold and silver. The material composition, and corresponding coloration, might be of great importance for understanding the visual expression of the brooch (Neiß 2011, p. 61, 2012, p. 44). With this in mind, a major advantage with digital 3D reconstruction is that different coloration alternatives and their visual effects on the overall brooch design can easily be investigated on the computer screen (Fig. 1d). The 3D modeling software furthermore allows the model to be illuminated from any given direction, allowing the observer to investigate the effects of interplay between light and shadow, which together with the surface colors arguably affected how the brooch was perceived in its original Viking Age context.

Another advantage with digital reconstruction of this brooch is the improved time efficiency compared to traditional reconstruction methods. The work involved in the 3D model reconstruction, i.e., 3D scanning, post-scanning processing, 3D model editing, and computer-based drawing, amounted to four full work days. An earlier reconstruction of the same object based on traditional photography amounted to 3 weeks of work (Neiß 2011). These 3 weeks included a museum visit to photograph the details of the brooch from similar angles using similar lighting, converting the photographs to analytical drawings, combining these hand drawings into a coherent

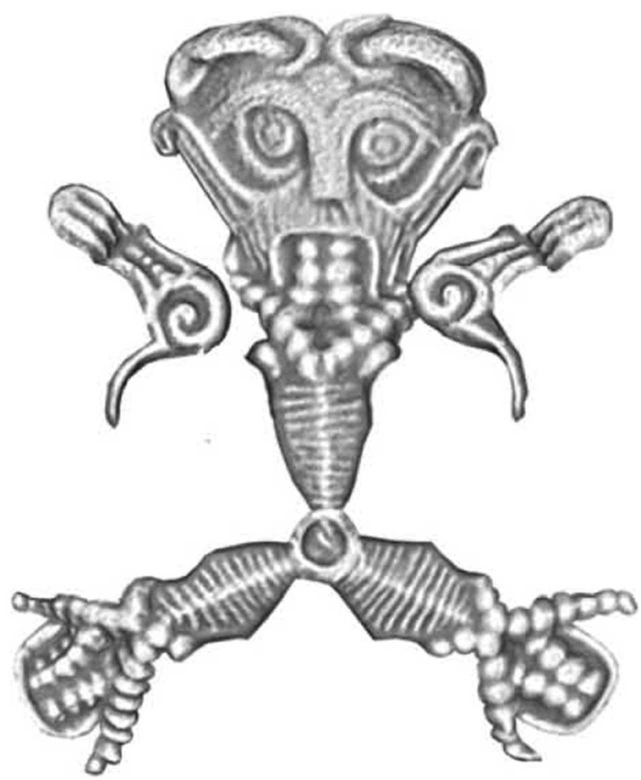

Fig. 2 Anthropomorphic figure present in the Vestervang brooch ornamentation. 3D model after Neiß 2012

representation of the object, and then traveling back to the museum in order to match the final drawings to the original object.

Unfortunately, material analysis has so far not been carried out for the brooch. The back unit exhibits large amounts of purple and turquoise surface corrosion products, indicating that the bulk material is a copper/zinc alloy (Scott 2002). The front side displays a matte silver-gray finish, which may originate from a coating with a white metal such as silver or tin, or from some kind of treatment of the copper alloy surface (cf. Wolters 2006a, b). As far as we can tell, similar Swedish brooches from the same time period were predominantly cast in high-grade silver alloys. Based on the mending patterns and deposition contexts of these silver brooches, it appears that the surviving brooches were in most cases treated as prestige objects and may possibly have constituted important heirlooms (Neiß 2007, p. 143, cf. 2009, pp. 125–129).

Interestingly, the Swedish silver brooches closest to Vestervang each weigh around one mark, suggesting that the clients did not miss on weighing their silver before commissioning the brooch with the caster (cf. Neiß 2007, p. 143, 2009, p. 113, 2010 and references therein). Even though the bulk material of the brooch appears to be a copper alloy, Vestervang displays many qualities typically found in high-end silver brooches, such as an intricate décor with multiple puzzle pictures (iconographic relevance), a clever construction (functional value), and great attention to details (craftsmanship, cf. Neiß 2007, 131 f., 2010). Moreover, a detached boss with a similar appearance to the Vestervang boss has previously been found in the central place of Tissø, Denmark (NM inventory number FB1166). Overlaying the 3D models of the two bosses demonstrates that they are virtually identical in shape (Fig. 3a–c and Supplementary Fig. 1), suggesting that this brooch type may have been produced in multiple editions. This raises the question whether the design concept behind Vestervang and Tissø was developed for a cheaper metal. An alternative hypothesis is that the Vestervang and Tissø brooches were modeled after a corresponding silver brooch, or after a hard model primarily developed for silver brooches.

In order to estimate the weight of such a template silver brooch, we followed a multistep 3D model analysis. First, the proximal boss was erased from the 3D model in order to estimate the volume of the frontal shell (=16.5 cm^3). Second, the volumes of the three proximal bosses were estimated based on the almost identical (yet completely detached) Tissø boss (=3×0.96 cm^3; Fig. 3). As a result, the reconstructed 3D model featuring three bosses and a back plate has a total volume of 19.38 cm^3. If this volume were filled with a high-grade silver alloy, such as 90/10 Ag/Cu with a density of 10.33 g/cm^3 (a reasonable estimate if high-grade Arabic silver coins are used as the raw material, cf. Eniosova and Mitoyan 2011), the Vestervang brooch would turn out to weigh about 200.2 g. This can be compared to the 200.4 g for the richly decorated Jämjö brooch (brooch "B", SHM inventory number 13534) from Gärdslösa parish in Öland, Sweden, which is the brooch with the closest resemblance to Vestervang still in existence. Although not of a generic Gotlandic type, ornamental details indicate that the "Jämjö B" brooch might have been produced in accordance with a certain Gotlandic workshop standard (Neiß 2007, 2010, pp. 143–155). But what about the back plate of the brooch? In principle, the surface area of the back plate can be estimated from the brooch radius, and the thickness can be estimated from the framing recess on the reverse side, even though these estimates will suffer from some uncertainty. On the other hand, the hypothetical silver model for the Vestervang brooch may not have had a back plate, as some brooches were manufactured without such a part. In the "Jämjö B" brooch, for example, the pin arrangements are attached directly to the reverse side of the frontal shell, which provides some justification for excluding the volume of a back plate from the above calculations. If a few grams of silver are added to our hypothetical brooch for a pinholder, a pincatch, and a chainholder, the final weight comes close to the Gotlandic mark unit of 204 g (cf. Wiechmann 2001; Thunmark-Nylén 2006, p. 345). The 3D model volume analysis could therefore provide support for the hypothesis that the Vestervang and the Tissø brooches were modeled after a corresponding silver brooch, weighing around one mark, or at least after a hard model that had been primarily designed for such a silver brooch.

Together with the other results, this case study demonstrates the effectiveness of 3D modeling for both artefact reconstruction and volume analysis. Future material analysis of the object, in combination with the 3D reconstruction, is

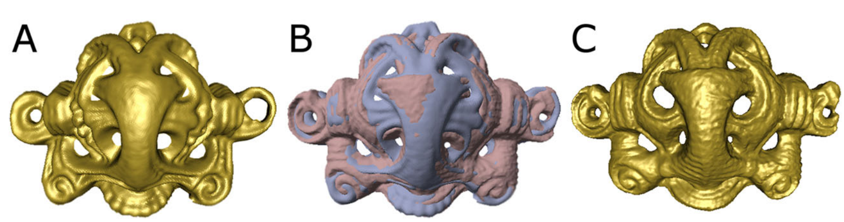

Fig. 3 3D models of **a** a boss from the Vestervang brooch and **c** a detached boss found at the central place of Tissø in Sjælland, Denmark (The National Museum of Denmark; NM FB1166). Overlaying the two 3D models, **b** demonstrates that the two bosses are virtually identical in shape and size. 3D models after Neiß et al. (2012)

expected to give us valuable information about the brooch in terms of stylistic design, material composition, and artefact biography.

Case study 2. Production marks in the two exquisite brooches from Gnëzdovo, Russia

The Gnëzdovo hoard was discovered AD 1867 in Gnëzdovo (Russian: Гнёздово, aka Gnyozdovo) outside Smolensk, Russia. An analysis of its objects dates the hoard to the late tenth century (Puškina 1998). Although its original composition is still under debate, the hoard undisputedly contained two elaborate baroque-shaped brooches, which are of interest for this paper. Whether it also contained two Arabic coin fragments *terminus post quem* AD 950/51 is less certain. The two brooches, "Gnëzdovo A" and "B" (GE inventory numbers 994-92 and 994-93), are made from solid silver and differ from similar baroque-shaped brooches by lacking cast animal protomes at the edge. This distinction has been taken as evidence that the brooches might stem from a different workshop tradition than their Scandinavian counterparts (Capelle 1962, p. 104). Here, we will present additional evidence for this idea, as we find that the deviating design patterns of both brooches seem to result from later repair work.

Gnëzdovo "A"

A detailed artefact autopsy conducted on brooch "A" (Fig. 4) revealed that the piece is a patchwork, consisting of parts from between three and five different brooches (Neiß et al. 2012). The bottom plate is a partially gilded circular brooch of the Toftegård type (Kleingärtner 2007, Tafel 15.2e). Use-wear analysis revealed that this bottom plate has been subjected to extensive wear. The central part has been modified to harbor a secondary medial boss, now lost, which was secured with a rivet that has left a marked hole in the plate. The current and final medial boss is fastened with a double rivet and has a visual appearance identical to those of other baroque-shaped brooches (cf. Neiß 2009). Around the central boss, six proximal bosses of silver have been mounted in the form of quadruped animals, three smaller and three larger, all of them gazing forward toward the central boss. It is difficult to determine whether these small animals constitute later additions to the plate. Given that Toftegård type brooches typically lack animal figures, and that the brooch has been modified a number of times, we believe that the three smaller quadrupeds were added at the same time as the now-lost secondary medial boss. The three larger quadrupeds, on the other hand, are less harmoniously integrated in the design: they are disproportionally large and obscure the design pattern on the plate, and only two of the larger animals constitute a matching couple—the third one is clearly dissimilar. The two matching animals display signs of extensive wear, both on their tops and their sides. As animal-shaped bosses on circular brooches typically only display wear on their top ends and their behinds, we conclude that this animal pair most likely originally decorated an equal-armed brooch before it was moved to the present object. The third animal boss is crafted with different details and displays only top wear.

Fig. 4 Circular baroque-shaped brooch from Gnëzdovo, Smolensk oblast, Russia ("Gnëzdovo A"; The State Hermitage Museum, Russia; GE 994-92). Photos by MN, with kind permission from GE

The notion that some brooch elements are later additions is supported by elemental composition analysis via X-ray fluorescence (XRF) measurements (by Natalia Eniosova and Tamara Puškina, Moscow State University, in close collaboration with Rafael Minasyan, The State Hermitage Museum), which revealed that the circular plate and the larger quadrupeds are made from Ag/Cu alloys with different compositions (personal communication from Natalia Eniosova).

The eyes of the two matching quadrupeds have been stamped with a circular punch. Using measurement tools in the 3D modeling software, the punch mark diameters of the "Gnëzdovo A" brooch were found to be circa 1.7 mm, which is quite similar to corresponding punch marks in an equal-armed brooch from Varvboholm in the parish of Varv, Västergötland, Sweden (SHM inventory number 16334; Fig. 5). This could be taken as evidence that the two Gnëzdovo quadrupeds have been stamped with the same punch and, consequently, derive from the same workshop as the Swedish brooches. However, the evidence is rather weak as standard punch marks are rather generic. In order to be diagnostic, punch marks typically need to display some kind of imperfection alongside the identical dimensions (cf. Andersson 1995, p. 206; Thunmark 1974, p. 17). Nevertheless, our analysis revealed that 3D modeling is a better technique for tool mark analysis than 2D photography, because measurements from photographs suffer from geometric distortions when photos are taken from different angles. Photographs, on the other hand, have higher resolution than our laser scanner and will therefore perform better for the analysis of minute details. As a solution for future punch mark comparisons, we suggest a mixed approach containing both 2D and 3D analysis, perhaps using the TexAlign function in the MeshLab software which allows the user to project a 2D photo onto a 3D model with great accuracy (cf. Dellepiane 2009, pp. 24–33).

Gnëzdovo “B”

Brooch “B” also displays heterogeneous features, indicating that a number of details have been replaced during repairs (Fig. 6). Because of these repairs, the brooch may be viewed as a Viking Age reconstruction of an older baroque-shaped brooch. The brooch consists of six parts: the bottom plate, a center boss, and four proximal bosses in the shape of quadruped animals. The central boss was originally fastened with a single central rivet, parts of which still remain. Presently, however, the central boss is held in place by two internal rivets. It is unclear if this constitutes a prehistoric repair or a modern addition of a new boss (Figs. 6 and 7). Use-wear analysis reveals that the different parts were added at different times. The bottom plate and the central boss appear to be relatively new and are decorated with niello. The four animals display heavy wear, indicating that they are older. The animals are secondarily gilded without traces of niello, and remains of an older bottom plate are still attached to their feet (Fig. 7). Instead of removing these remains during the remake of the brooch, the caster chose to manufacture the new bottom plate with large holes to accommodate the animals with their “enlarged” feet. The holes are gilded on the inside, which shows that they represent a primary feature. The use of niello on the bottom plate clearly demonstrates that the caster could have closed the holes with a silver alloy had that been desired. Instead, the caster’s chosen approach seems to mirror an almost antiquarian sentiment, in the modern sense of the word.

In terms of décor, the Gnëzdovo B brooch is closely related to a brooch from Torsta in Hälsingtuna, Sweden (Neiß 2009), although the bottom plate of “Gnëzdovo B” lacks a couple of animal heads. As a result, the whole ornament has been transformed iconographically, resulting in a Terslev-like pattern (Figs. 8 and 9a). Interestingly enough, in its original context, the Terslev motif *might* include a Christian connotation (cf. Kleingärtner 2007, especially Tafel 15.2e). The Torsta brooch was furthermore produced with more advanced technology than the Gnëzdovo brooch: the pinholder and pincatch of the Torsta brooch have been reinforced to make them more durable (Neiß 2010), and the back of the Torsta brooch displays a textile imprint, showing that the casting mold was manufactured with the aid of a (probably waxed) textile. This allowed the caster to reduce the material for the bottom plate to a minimum, while at the same time maintaining an even thickness (Fig. 9c). The 3D modeling results reveal that the “Gnëzdovo B” brooch lacks this production mark, indicating that it was cast without any use of textile. As a consequence, the bottom plate turned out uneven and rather thick (Fig. 9b). Hence, none of the technical solutions that are common in later baroque-shaped brooches from Scandinavia are present in the “Gnëzdovo B” brooch. Moreover, the iconographic message at the bottom of the brooch appears to be altered (Fig. 9a). It therefore seems highly likely that the bottom plate and the proximal animals of “Gnëzdovo B” were crafted according to different workshop traditions. This result is further supported by an independent XRF analysis (by Natalia Eniosova and Tamara Puškina, Moscow State University, in close collaboration with Rafael Minasyan, The State Hermitage Museum) revealing differential elemental composition between the bottom plate and the quadrupeds (personal communication from Natalia Eniosova).

Taken together, the repairs and modifications of the two Gnëzdovo brooches are unexpected and require an explanation. No stylistically corresponding brooches from mainland

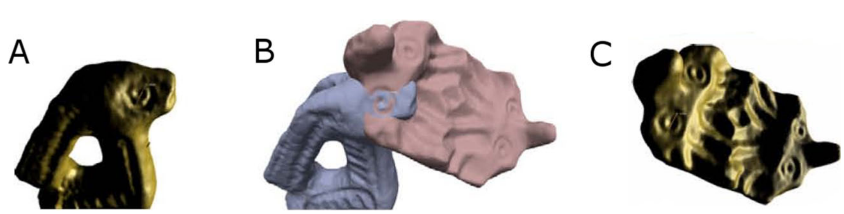

Fig. 5 **a** 3D model of detail from the “Gnëzdovo A” brooch, including a circular punch mark. **c** 3D model of detail from an equal-armed brooch from Varvboholm, Varv, Östergötland (The Swedish History Museum; SHM 16334), including a circular punch mark. **b** Overlaid 3D models showing the two punch marks to be nearly identical in shape and size. 3D models after Neiß et al. (2012)

Fig. 6 Circular baroque-shaped brooch from Gnëzdovo, Smolensk oblast ("Gnëzdovo B"; The State Hermitage Museum, Russia; GE 994-93). Photo by MN, with kind permission from GE

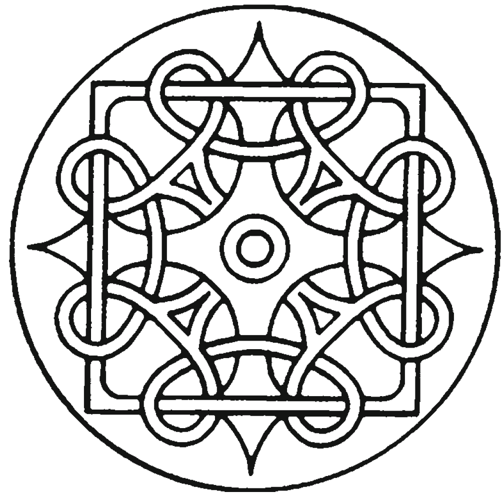

Fig. 8 Terslev motif, type 1. After Kleingärtner (2007)

Scandinavia display similar amounts of antiquarian sentiment. Why was so much effort put into restoring the Gnëzdovo brooches? One intriguing possibility is that these brooches represented valuable heirlooms for Scandinavian settlers in the lands east of the Baltic Sea. Examples from the Viking colonies in the North Atlantic and the Danelaw illustrate how inherited dress fittings contributed to the cultivation of local upper class identities, based on the principle of ethnicity (Hayeur Smith 2004, pp. 75–81; Kershaw 2009; Wärmländer et al. 2010). This may explain why the brooches were maintained and re-created over a long period of time, while corresponding items in the Scandinavian motherlands were replaced by new fashions. Such a scenario could also explain the somewhat unexpected stylistic features on the Gnëzdovo brooches, such as the unusual metal finish with both niello and gilding, and the way the different brooch elements display iconographical disharmony. It becomes tempting to propose that the metal workers responsible for the later modifications operated under a local rather than a Scandinavian workshop tradition (cf. Duczko 2004, p. 184). Hence, they may not have been familiar with the iconography of Scandinavian brooch design. Alternatively, a conscious decision might have been made to alter the pictorial message, in accordance with a more contemporary ideal (cf. Neiß 2011, p. 62). Further research is expected to clarify the sociocultural significance of the Gnëzdovo brooches among the local populations.

Fig. 7 Details of the "Gnëzdovo B" brooch: medial boss with secondary rivet; proximal boss with gilded wear traces and remains from an earlier bottom plate; bottom plate with both primary and "blind" holes. Photo by by MN, with kind permission from GE

In summary, the results of this case study confirm the presence of design patterns in the Gnëzdovo brooches that deviate from similar brooches from Scandinavia. These differences are most likely the product of later repair work. The 3D modeling techniques employed in our investigation have been demonstrated as excellent tools for studying production marks on a macroscale, while studying production marks on a microscale might require a combination of different techniques.

Case study 3. Décor analysis of the famous brooch from Yelets, Russia

The third case study concerns a majestic equal-armed brooch found in Yelets (Russian: Елéц, aka Jelec, Elec), Oblast Voronez, Russia (Fig. 10; GE inventory number 997-1). There is a general agreement that the brooch displays an overall Scandinavian style (Stenberger 1959, p. 195), although some researchers have suggested that it contains elements untypical for Scandinavia that may reflect an Eastern origin (e.g., Arbman 1960, p. 120; cf. Duczko 2004, p. 185). Overlooked

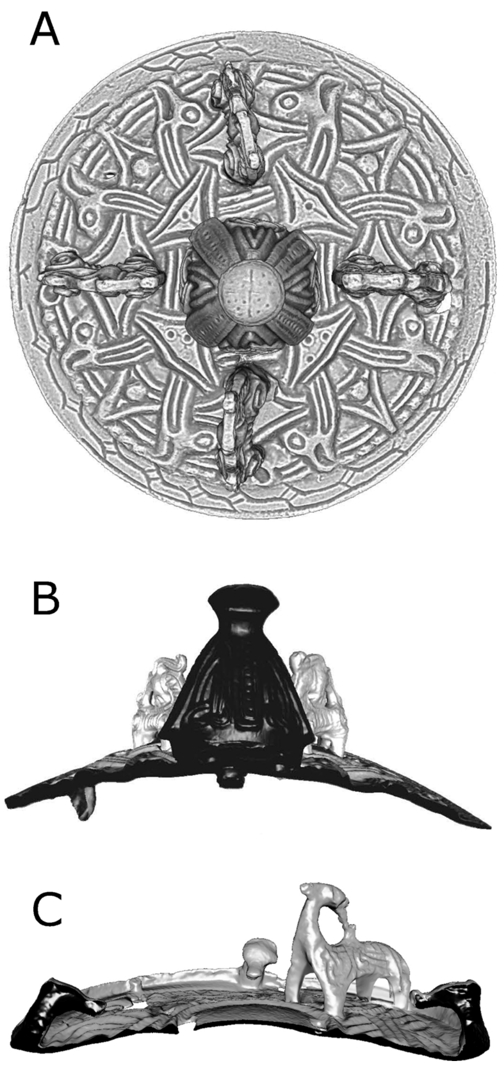

Fig. 9 **a** 3D model of the "Gnezdovo B" brooch, front view. **b** Digital cross section of the 3D model of the "Gnëzdovo B" brooch, revealing an uneven and thick bottom plate. **c** Digital cross section of the 3D model of a circular baroque-shaped brooch from Ekeskogs, Hejde, Gotland, Sweden (Swedish History Museum of Sweden; SHM 26697). Note the thin and even bottom plate. 3D models after Neiß et al. (2012)

Fig. 10 3D model of an equal-armed baroque-style brooch from Yelets, Voronez oblast, Russia (GE 997-1), front/side view. 3D model after Neißet al. (2012)

until now is however the rope-cord pattern ending in a triquetra knot, a feature diagnostic for artefacts produced in a Gotlandic workshop tradition (Fig. 11a; e.g., Klindt-Jensen and Wilson 1965, plansch 46, 47a, 30 h; Neiß 2007, 153 f., 2010, 133 f.; Thunmark-Nylén 1998, Tafel 8.2, 46–47, 168.1, 163.6). The Yelets brooch displays a fair amount of niello décor, a decorative technique that gained popularity in Gotland during the tenth century—sometimes at the expense of the relief ornamentation. Thus, this niello may indicate a connection to a Gotlandic workshop, even though dating and provenancing based only on décor is a notoriously difficult task. In addition to the niello, the Yelets brooch exhibits numerous bosses and rich relief. The use-wear and repairs indicate that the brooch probably was in use for an extended period of time. With the abundance of relief and bosses, it is not an easy task to detect, document, or decode the imagery of the object—especially since many of the details obscure each other (which maybe was exactly what the caster intended). These problems can be remedied with 3D modeling tools, which allow individual details of the brooch to be cut out from the digital model and analyzed in isolation. Due to its unusual complexity, the Yelets brooch turned out to be the most labor-consuming artefact we so far have encountered—it required three working days for scanning and six working days for processing with a high-end laptop computer.

By isolating and studying features of the high-quality 3D model, we were able to identify many figures and hidden images in the Yelets brooch, and two of these are presented here. The first is an anthropomorphic head (Fig. 11b) from the inside of the proximal boss, and the other is a chimera at the bottom plate consisting of a bird-like body adorned with a human head (at the medial boss; Fig. 11c). To go from the general to the specific, chimeras with body parts from different species constitute a contemporaneous phenomenon in Scandinavian art (cf. Klindt-Jensen and Wilson 1965). However, the combination of a bird-like body and an anthropomorphic head with a Napoleon-like headgear further links this object to a Gotlandic crafting tradition (e.g., Thunmark-Nylén 1998, Tafel 2.8.a–e). On the other hand, a detailed analysis reveals that the closest iconographic parallels to the Yelets "bird" are to be found in Russia. For example, a pendant from a kurgan at Chilovo shows an almost identical pattern (Fig. 12). Scholars have argued that these bird-like representations were a key element in the coat of arms of the Rurikids, only to be used by the inner circle of the princely household (Duczko 2004, p. 233). According to one suggestion, the coat of arms consisted of a basic pattern to be personalized by every regent, by adding and subtracting certain elements

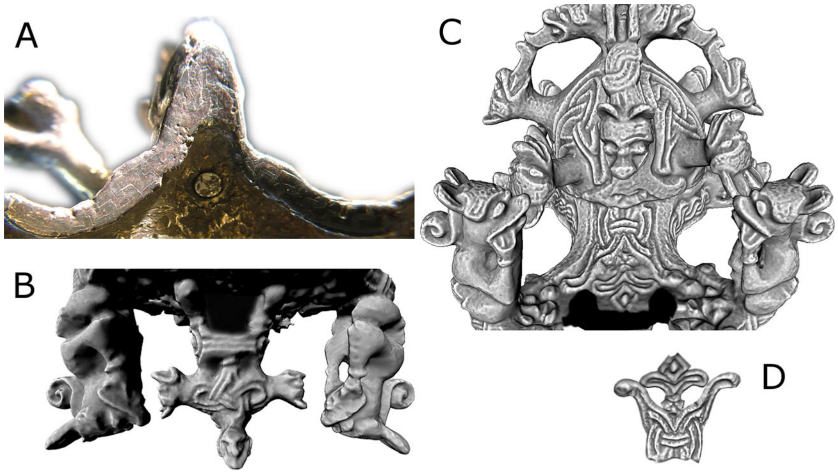

Fig. 11 Details of the brooch from Yelets. **a** Photograph of back-side detail, showing a Gotlandic rope-cord pattern with a triquetra knot. **b** 3D model of brooch detail depicting an anthropomorphic head on the inner side of the proximal boss. The image was created by digitally cross-sectioning the 3D model, allowing a viewpoint of the motif from inside the brooch "space." **c** 3D model of brooch detail revealing a being with an anthropomorphic head and a bird-like body. Image created by digital cross-sectioning of the 3D model. **d** Turned upside-down, the bird-like body in **c** turns into a "Rurikid trident." Photo and 3D models after Neiß et al. (2012)

(Bjeletskij 1998, 200 ff.; Edberg 2001, pp. 6–9, referring to: Sotnikova and Spasskij 1982, p. 109). In the case of the Yelets brooch, the silver caster chose to put this potentially Rurikid emblem next to a couple of triquetras that are at the central boss of the brooch (Fig. 10). Interestingly enough, a recent work concerning decorated bricks from the church of the Tithes in Kiev points toward the possibility that the triquetra sign has been used for similar purposes as the Rurikid emblem (cf. Jolshin 2012). A detailed discussion on the symbolism of these signs and their historic relation to the Rurikid dynasty is presented in Neiß et al. (2012). Because of the exquisite quality of the Yelets brooch, and because it was encountered outside of Rus in what used to be Pecheneg territory, it is tempting to associate the Yelets brooch with persons and events in the Russian Primary Chronicle (Neiß 2005). Future research will hopefully show whether these associations are founded on fact or fiction. For now, it suffices to point out that that the combination of Scandinavian design elements and plausible Rurikid symbols in this majestic brooch seems to corroborate the Rurikids' proposed Scandinavian connection. Furthermore, the results of this case study show that 3D laser scanning is a useful, albeit sometimes time-consuming, tool for décor analysis.

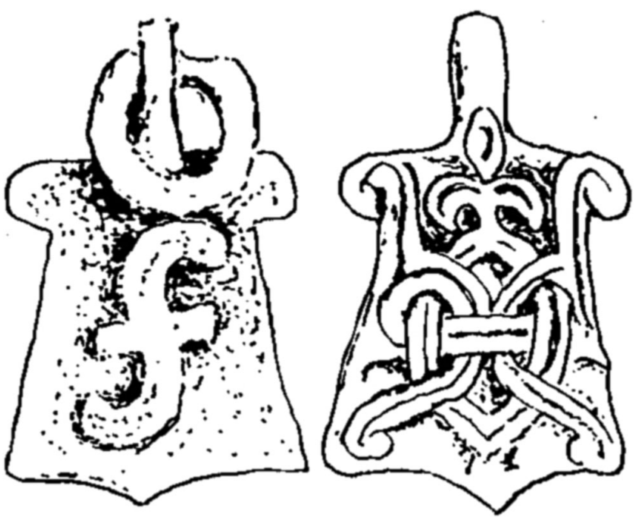

Fig. 12 Pendant from Chilovo, Tver oblast, Kurgan 60(19), with a Rurikid trident; front (left) and back (right) sides. After Paulsen (1953)

Conclusions

The three case studies presented in this paper reveal both strengths and limitations of 3D imaging and the portable laser scanner technology employed. 3D modeling was found to be very well suited for artefact reconstruction, but only partially suited for tool mark analysis, due to the resolution limits of the laser scanner used. 3D modeling was also a very useful technique for stylistic and motif analysis. Interestingly, analysis of a grandiose rooch from Yelets, Russia, identified an anthropomorphic figure with a bird-like body, probably linking the object to a princely household. Given the overall Scandinavian style of the brooch, this observation might provide further evidence for a connection between Scandinavia and the Rurikids. As 3D technology keeps improving, novel findings like this are likely to result from 3D model-based analysis (Hermon 2008). However, the study shows that 3D modeling cannot completely replace traditional artefact analysis. Instead, the two approaches appear to be best used in combination.

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