Three-Dimensional Digital Recording and Modelling Methodologies for Documentation and Reconstruction of the Newport Medieval Ship

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Abstract:

The following thesis presents the three-dimensional digital documentation methods and modelling approaches used during the excavation and post-excavation research phases of the Newport Medieval Ship Project. The primary case study is the Newport Medieval Ship, a large clinker-built merchant vessel discovered in 2002 in Newport, Wales, United Kingdom. The use of accurate and efficient three-dimensional digital recording methodologies has allowed for the development of innovative approaches to organising, analysing, modelling and disseminating data about the individual timbers and the overall original hull form. The utilisation of advanced digital technology and engineering, in the form of Rhinoceros3D modelling software, contact digitising and rapid prototyping has enabled the project to develop and test a variety of new methodologies for documenting and reconstructing ancient vessels. Results of the individual ship timber documentation and modelling methodologies are presented, along with analysis and comparison to more traditional documentation and reconstruction approaches. Additionally, the thesis examines the changing philosophical or conceptual approaches to hull form recording and reconstruction research over the last 200 years, and focuses in detail on the last 20 years of the rapidly evolving field of digital documentation in nautical archaeology.

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File Name	File Format	File Size
001_P16_S16_interior_hull_planking_final.pdf	PDF	44.5 MB
001_P16_S16_interior_hull_planking_final.wrp	WRP	133.0 MB
002_full_interior_hull.pdf	PDF	66.2 MB
002_full_interior_hull.wrp	WRP	177.0 MB
003_full_exterior_hull.pdf	PDF	40.0 MB
003_full_exterior_hull.wrp	WRP	81.2 MB
004_bow_decimated.pdf	PDF	7.9 MB
004_bow_decimated.wrp	WRP	95.6 MB
005_Total_Hull.3dm	3DM	79.7 MB
005_Total_Hull.pdf	PDF	44.4 MB
005_Total_Hull.stl	STL	100.0 MB
005_Total_Hull.wrp	WRP	94.2 MB
NMS_Scale_Model_Doc_WF_Data _Meshes.3dm	3DM	63.2 MB

Note: Files with the same numerical prefix (i.e. 001) all contain the same data, albeit in different formats. The PDF version is typically cited in the text, as it is the most readily accessible format. The DVD can be found in the inside of the back cover of Volume 1.

Acknowledgements

Since its inception, the Newport Medieval Ship Project has relied on a multidisciplinary approach to achieve the numerous archaeological research and conservation goals. The complexity and scale of the post-excavation research project has necessitated the use of a variety of specialists, too numerous to individually name. However, several people have been instrumental in enabling the project to succeed by securing funding or providing expert guidance. These include Nigel Nayling at the University of Wales Trinity Saint David, Fred Hocker at the Vasa Museum, and Pat Tanner at the University of Southampton. Special mention goes to Kate Hunter, the initial Newport Ship Project leader, for her vision and drive, which allowed the project to flourish.

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Funding for the ship project (and this thesis) has been provided by Newport City Council through the Newport Museums and Heritage Service, along with numerous

grants from public bodies and charities and private individuals. The Welsh Government provided substantial funding for the excavation and initial storage of the vessel remains. A generous grant from the Heritage Lottery Fund (HLF) provided funding for the purchase of three contact digitisers and the appointment and training of a sizeable team of archaeologists. The HLF funding also provided support for a substantial education and outreach programme. Grants from the Arts and Humanities Research Council (AHRC) facilitated the digital solid modelling and physical solid modelling phases of the project, while grants from CyMAL (Welsh Museums, Archives and Libraries) and underpinned the successful efforts to create digital minimum and capital reconstructions of the vessel by Pat Tanner.

Additional support, advice and constructive criticism has been provided by the Faro-Rhino Archaeological Users Group (FRAUG) network of marine archaeological researchers. Colleagues from around Europe, including Mike Belasus, Holger Schweitzer, Jens Auer, Nicolas Ranchin-Dundas, Tom Lenaerts, Tori Falck, Alexandra Grille, Alice Overmeer, Frank Dallmeijer, Christian Thomsen, Johan van Laecke, Morten Ravn, and Vibeke Bischoff, have provided useful feedback in the development of digital recording and modelling. Mark Starr kindly provided detailed information regarding the early history of contact digitising at Mystic Seaport in Connecticut.

I would like to thank several members of the Nautical Archaeology Programme faculty at Texas A&M University (TAMU) for their long-standing support and encouragement. Professors Kevin Crisman and Filipe Castro have provided valuable advice over the years. Fellow students (and friends) from TAMU, Justin Leidwanger and Troy Nowak, have also offered encouragement and advice. Thanks are also due to Rod Bale, Jemma Bezant, Colin Green, Anaïs Pajot and Chuck Meide.

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The author's role in the Newport Medieval Ship Project

The following section briefly describes my role in the Newport Ship Project, as well as detailing the different research phases, funding sources and publication outputs that have occurred over the duration of the project. It is hoped that this will provide the reader with a better understanding of the scale and complexity of the project, and my changing role within it.

The Newport Ship is owned by Newport City Council, with the Newport Museum having archaeological and curatorial responsibility for the find. The ship project was originally led by Kate Hunter, an archaeological conservator, with Nigel Nayling serving as the project's archaeological consultant. I began working for the Newport Medieval Ship Project in November 2004. I was hired as an archaeological Project Officer to help develop and refine a methodology for efficiently cleaning and accurately recording the sizeable ship timber assemblage.

I was initially hired on a one-year fixed term contract in order to take part in a pilot study exploring the application of digital documentation technology to archaeological ship timber recording (I had recently graduated from Texas A&M University with an MA in Anthropology and a specialisation in Nautical Archaeology). I was trained in contact digitising by Ivan Conrad Hansen at the Viking Ship Museum in Roskilde, Denmark, in November 2004. After this training period in Denmark, the remainder of the first year was spent systematically cleaning and recording timbers from the Newport Ship. At the end of the pilot study, the results and methods were analysed and many of the successful procedures codified into a comprehensive work plan and timber recording manual (Jones, 2005: 12-15, Jones, 2013).

The results of this pilot study were used in an application to the Heritage Lottery Fund in 2005. The grant application was successful, with the HLF providing substantial funding for an expanded programme of cleaning and recording, set to run between April 2006 and March 2008. During this phase of the project, a large team was assembled to undertake the cleaning and recording work. In September 2006, I was promoted to recording coordinator, with a range of responsibilities, including training and supervising the archaeological team. I was responsible for maintaining quality control over the recording process and liaising with the archaeological consultant (Jones, 2009a: 36-41, Jones, 2008: 85-88).

In January 2008, I started to work on a PhD in Archaeology at the University of Wales in Lampeter, under the supervision of Professor Nigel Nayling (who remained the Newport Ship Project archaeological consultant). This PhD research was supported by the Newport Museum and Newport City Council, who covered the tuition fees. The research I was undertaking was seen as relevant and valuable to Newport City Council, as it furthered understanding of the archaeological material. I have continued to work in my dual roles as a full-time employee of Newport Museum and student at the University of Wales from 2008 to the present (June 2014).

In April 2008, I was promoted to Curator of the Newport Medieval Ship Project. In this new role, I was responsible for all aspects of the project, including organising the archive, preparing artefactual and environmental material for specialist analysis, and promoting the ship project through the dissemination of archaeological information through popular and academic publications, on public open days, and at community lectures and academic conferences. During this period, I worked on the development of digital and physical modelling methodologies, looking specifically at the creation of a 3D physical scale model of the remains of the Newport Ship. This innovative research into 3D digital and physical solid modelling became one of the main subjects of my PhD research.

The digital and physical modelling methodologies used in the Newport Ship Project were developed with support from an Arts and Humanities Research Council Large Research Grant called ShipShape 3D. The principal investigator for the grant was Nigel Nayling. In my role as Curator of the ship project, I was seconded to the AHRC ShipShape 3D research grant. Around 30% of my time was made available for the duration of the multi-year AHRC project. The physical manufacturing costs and assembly of the 3D model were some of the research objectives financed by the AHRC grant. I played a key role in this research, which was documented with several articles outlining the project methodology and results (Jones, 2009b: 111-116, Jones and Nayling, 2011: 54-60, Nayling and Jones, 2012: 319-324, Soe et al., 2011: 757-762, and Soe et al., 2012: 443-450).

The AHRC-funded research culminated in the creation of a physical scaled model of the hull remains as well as a series of CAD files containing digital models of all of the structural hull timbers, called master composites. The physical hull form was digitally documented, using laser scanning and contact digitising technology. These hull form shape state data sets, along with the master composites, represent the culmination of my PhD research.

These data sets are now being used as a starting point for minimum and capital reconstruction research. Much of this subsequent research is currently being carried out by Pat Tanner at the University of Southampton, as part of his PhD research into digital hull form analysis. The advanced digital modelling research has been funded by a CyMAL grant and by Newport City Council (Jones, Nayling & Tanner, 2013: 123-130, Jones, Nayling & Tanner, Forthcoming).

The archaeological consultant, Nigel Nayling, and I have recently completed a comprehensive summary of the research results from the Newport Medieval Ship Project (Nayling and Jones, 2013). An online archive, hosted by the Archaeology Data Service, has also been deposited and is now publically accessible (Nayling and Jones, 2014a). It is envisioned that these resources will be used as definitive sources of primary information relating to the ship project. A further article explaining the structure and function of the online archive, as well as a book about the Newport Ship, are planned.

Online Digital Archive and Appended Digital Data

The text of this thesis occasionally makes reference to digital files, which the reader may wish to download and view while reading through the text. Selected files are available by accessing an online archive hosted by the Archaeology Data Service (ADS) (http://archaeologydataservice.ac.uk/archives/view/newportship_2013/index.cfm, with a DOI: 10.5284/1020898), while other files are available on a digital video disc (DVD) inserted in the back cover of the first volume of the thesis. The location of each file (whether online or on enclosed disc) is noted at each relevant point in the text. Further information about the digital archive and associated digital file formats can be found in the section on Archiving in Chapter 3.

A note about terminology

The terminology used in nautical archaeology to describe aspects of wooden shipbuilding is quite specialised and the use of certain words instead of others still generates debate within the field. This thesis generally follows the terminology (and illustrated glossary) used by J. Richard Steffy in his book *Wooden Ship Building and the Interpretation of Shipwrecks* (Steffy, 1994). The text, although 20 years old, remains a standard reference in the field and the reader may wish to consult it for further information. Other specialised terms are defined in the text.

Chapter 1: Introduction to the Newport Medieval Ship Project

Introduction

The Newport Medieval Ship Project has provided a rare opportunity to base the reconstruction of a large medieval merchant vessel on archaeological remains, as opposed to relying solely on written historical sources or contemporary medieval imagery and iconography. The use of accurate and efficient three-dimensional digital recording methodologies has allowed for the development of innovative approaches to organising, analysing, modelling and disseminating data about the individual timbers and the overall original hull form. The meticulously documented remains of the vessel have provided the basis for further hull form research, including the creation of a convincing and accurate minimum reconstruction and a well-supported capital reconstruction. The utilisation of advanced technology and engineering, in the form of Rhinoceros3D modelling software, contact digitising and rapid prototyping has enabled the project to develop and test a variety of new methodologies for documenting and reconstructing ancient vessels. The abovementioned areas of research and methodological development will be explored in greater detail below.

The following thesis provides a brief overview of the Newport Medieval Ship, including a description of the site and detailed construction information about the vessel itself. A review of the *in situ* archaeological documentation approaches has been included, helping to place the recording methods used on the Newport Ship excavation into context. The development, use and spread of contact digitising in nautical archaeology is presented in detail. The thesis goes on to cover the recording and reconstruction processes used to document individual timbers through to the creation of a series of master composites showing all of the digitally recorded and modelled articulated hull timbers in their right relative positions. Full-size digital solid models of each individual hull timber have been created from the digital records. These digital solid models were, in turn, scaled down to 1:10 and manufactured using an additive manufacturing technology known as selective laser sintering. The resulting scaled physical model pieces, made from a strong and flexible nylon plastic called polyamide-12, were fastened together to create a 3D scaled physical model of the recovered hull elements.

The scaled physical model of the hull form, representing the post-depositional shape state of the vessel was digitised and used as a basis for further reconstruction efforts, both physically and digitally. As more elements were added, the changing shape of the physical model was captured using contact digitising and laser scanning technology. A basic preliminary set of lines was digitally extracted from the model using the abovementioned technology.

The physical model was then used as a foundation to which plastic fairing ribbands were attached in order to ghost-in missing areas and reveal localised and global damage and distortion. The hull remains had been subjected to damage and distortion during the use life, deposition, excavation, storage and subsequent conservation of the vessel. The areas and degrees of this damage and distortion were identified, recorded, analysed and later accommodated/rectified in the reconstruction efforts.

At this point in the research process, the model and ribbands were physically manipulated (i.e. forced) into a fairer hull form. The new shape state data, captured with the contact digitiser and point clouds created by the laser scanner, served as the building blocks for creating idealised surfaces and hull forms for use in hydrostatic and hydrodynamic modelling and advanced reconstruction efforts. This data is currently being utilised in a forthcoming PhD thesis by Pat Tanner at the University of Southampton, who is using the final digital models and 3D point data presented here as a starting point for creating construction drawings, sail plans, and a detailed set of sailing characteristics, including comprehensive hydrostatic and hydrodynamic calculations.

The Newport Ship has not yet been directly identified in the historical record, however, it should be possible, through continued careful archaeological and historical research, to identify its role in wider European social, political, and economic history. While these areas of research are beyond the scope of this thesis, it is hoped that the hull form documentation and research presented here will provide, to interested scholars, a valuable and definitive resource about the physical nature of the ship and the processes used to uncover that information. The detailed digital records created for each timber, as well as the scaled models and digital reconstructions, will ideally be used as blueprints by those tasked with reassembling the conserved remains of the vessel in the future.

Background – Discovery and Description

The Newport Medieval Ship was discovered during the construction of the Riverfront Theatre and Arts Centre, immediately adjacent to the River Usk in Newport, Wales. The ship was found inside of a sheet pile coffer dam which was inserted around the planned area of the theatre's orchestra pit excavations (Figure 1). The first articulated hull remains were discovered in June 2002, and the hull was subsequently uncovered over the next 12 weeks. The ship was then documented, disassembled and raised, with the last timbers being removed from the main site in December 2002. The bow of the ship, lying just outside the main coffer dam, was excavated separately in April 2003 (Nayling and Jones, 2013).

The hull remains (26m x 8m) were buried under several metres of alluvial clay, which helped preserve the timbers, but also caused some distortion due to the immense overlying weight. In addition to damage caused by the coffer dam clipping off portions of the port bow quarter and starboard stern quarter, numerous long concrete piles (0.5m x 0.5m in section) were inadvertently driven through the hull, causing considerable localised damage (Figure 2)(Nayling and Jones, 2013).

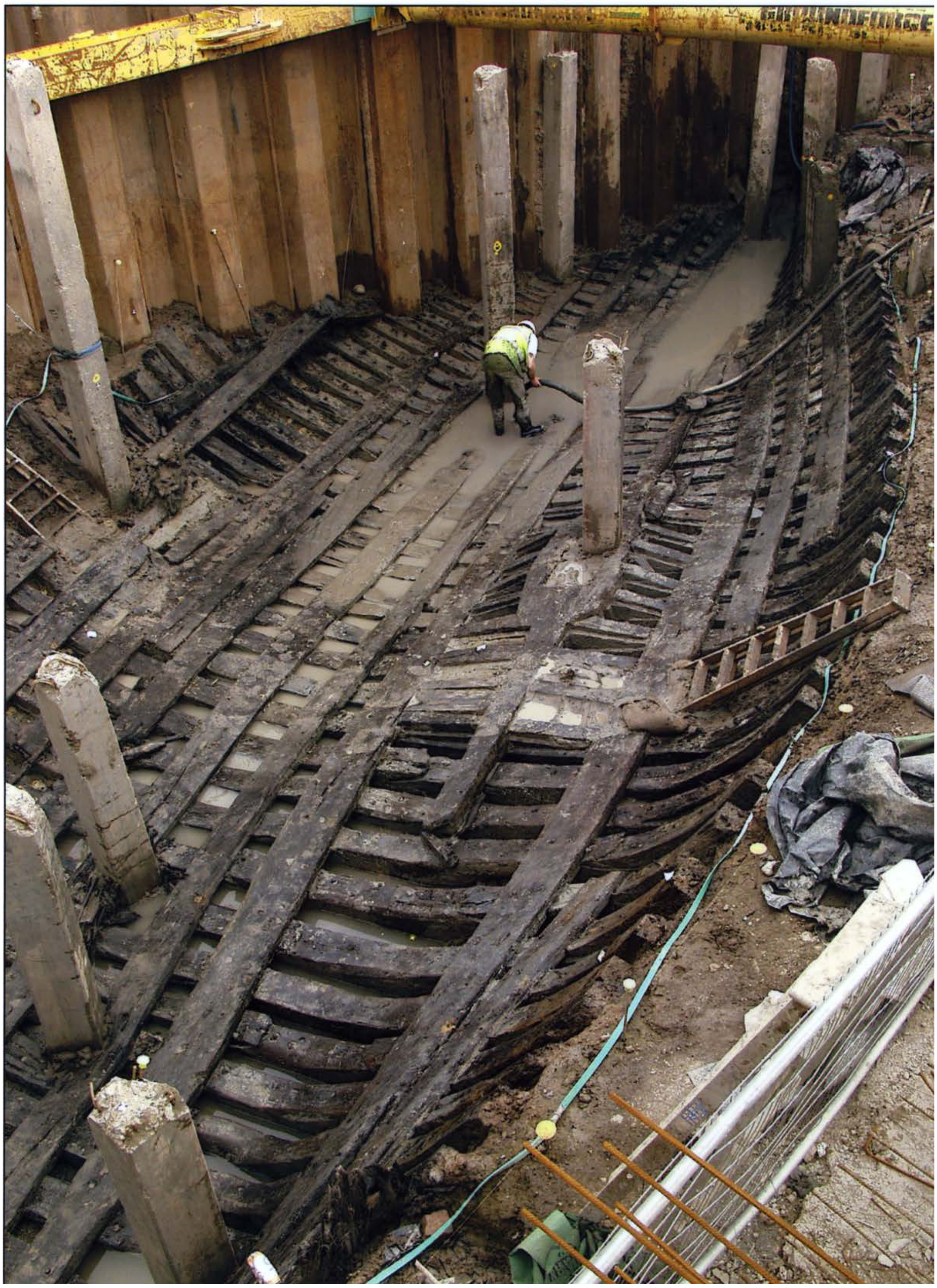


Figure 1. The *in situ* remains of the Newport Medieval Ship. The port side is to the right. Newport Museums and Heritage Service.

Figure 2. Excavated hull remains pierced by numerous concrete piles. Port side is to the left. Newport Museums and Heritage Service.

During its use-life, the Newport Ship had been brought into an inlet or pill and was positioned roughly perpendicular to the main river, with the stern facing the river and the bow pointed inland. The ship had been brought into the pill in a presumably lightship (un-ballasted) state on a high spring tide. The ship had been supported by a cradle or strut arrangement made of roughly hewn logs. The remains of the hull were found heeled over to the starboard side and resting on the collapsed strut structure. The ship could have been purposely heeled over for repair work, or it may have been upright and then rapidly heeled over during a possible collapse of the struts, with the ship quickly filling with silt and water on the next flooding tide. It appears that several holes were drilled through the planking of the vessel in an effort to drain it, however, the hull filled up with sediment and water before it could be successfully drained and righted. The weight of the overlying sediment and the eventual waterlogging of the ship timbers caused the hull to slowly distort over the strut logs and uneven ground of the inlet. At some point after the deposition of the ship, substantial portions of it, including the upper works and masts, appear to have been removed or salvaged, as evidenced by crude axe marks along the upper portions of the surviving hull. Many major components of the ship, such as stringers and beams, were missing from the articulated hull, as evidenced by partial existing timbers, open scarf joints, empty mortises, compression marks, and unexplained fastener holes. Numerous disarticulated but presumed ship timbers were also found scattered across the site, both inside and around the hull (Figure 3) (Nayling and Jones, 2013).

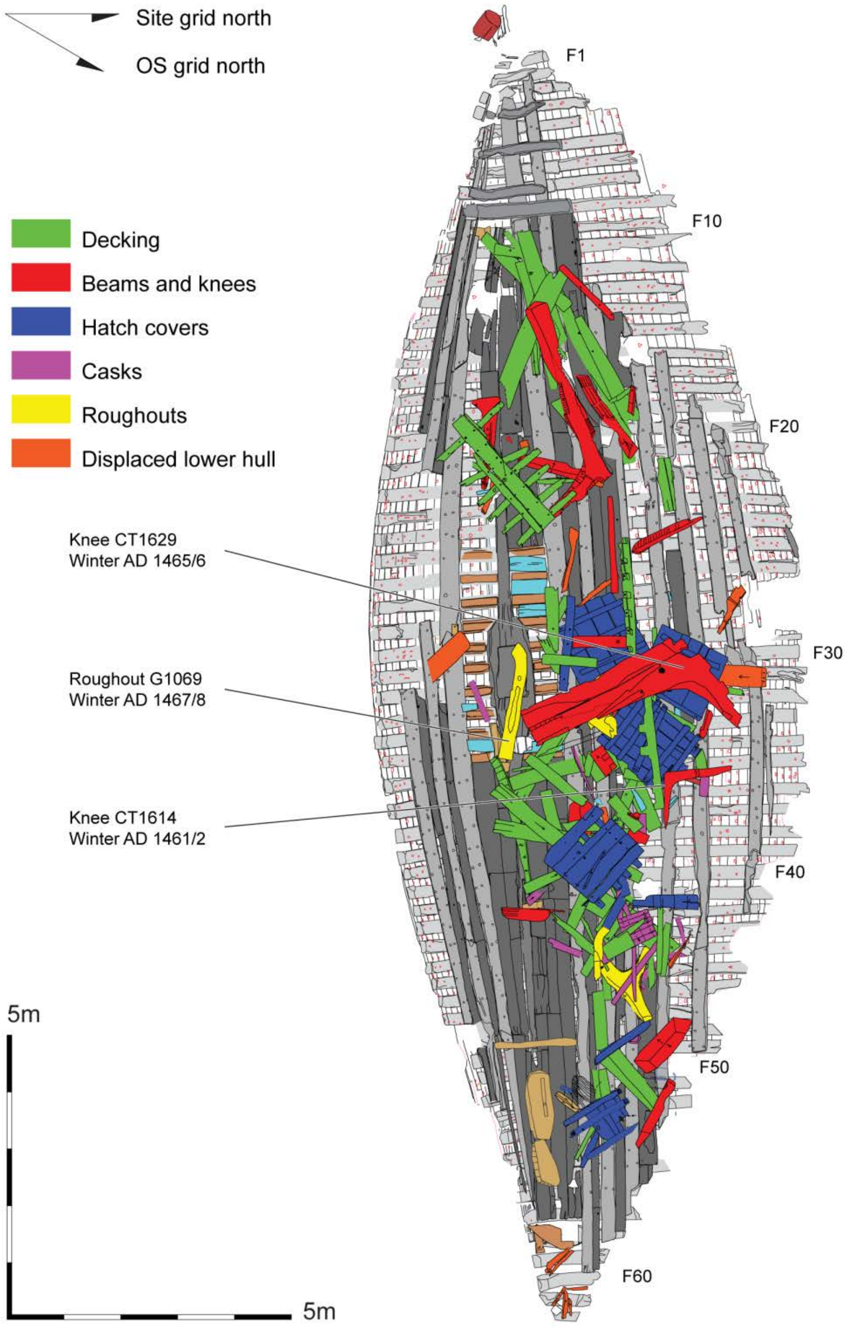


Figure 3. Plan view of site showing disarticulated material found inside of the hull. Dendrochronological dates for selected disarticulated timbers are also shown. Nigel Nayling.

Newport Medieval Ship Timber Function Codes	
Function Code	**Description**
Beam	**Beam**
BB	**Bilge board**
BRP#	**Brace (chock) to keelson port side**
BRS#	**Brace (chock) to keelson starboard side**
CP#.#	**Port ceiling plank**
CS#.#	**Starboard ceiling plank**
F#.#	**Framing timber**
F#.0	**Floor timber**
F#.[odd number]	**Framing timber port side**
F#.[even number]	**Framing timber starboard side**
Filler	**Filler Board**
Head	**Barrel/Cask Head**
Hoop	**Barrel/Cask Hoop**
Keel	**Keel**
Knee	**Knee**
P#.#	**Port side hull plank**
R#	**Rider**
S#.#	**Starboard side hull plank**
Son	**Keelson**
Stave	**Barrel/Cask Stave**
Stem	**Stem Post**
STRP#.#	**Stringer port**
STRS#.#	**Stringer starboard**
Tingle	**Tingle/patch timber**
Notes: # = number	**? = uncertain of accuracy of function code**

Table 1. Timber function codes applied during excavation and post-excavation of the Newport Medieval Ship. Toby Jones.

Ship timbers were numbered and given function codes based on their location and purpose (Table 1). The hull was disassembled by cutting through the wooden treenails that fastened many of the main structural components together. The wrought iron fasteners that were used to hold the ceiling planking in place and hold the clinker hull together had largely corroded, making the removal of these timbers relatively straightforward. Several composite timbers were fastened together with large wrought iron bolts and treenails. These timbers were lifted intact and the bolts later removed prior to conservation treatment at the ship conservation centre (Figure 4).

Figure 4. Removing an iron bolt from a large standing knee. Newport Museums and Heritage Service.

Certain oversize timbers, like the mast step, stringers and keel, were cut on site to facilitate their safe handling, lifting and removal. Most of the waterlogged timbers were kept wet on site and then moved to a temporary store at the Corus Steel Works at Llanwern on the eastern edge of Newport, before being taken to the

Newport Medieval Ship Centre (at Unit 22, Maesglas Industrial Estate, NP20 2NN) on the western edge of Newport. Several disarticulated timbers were inadvertently allowed to dry out, but were retained (Figure 5). These important structural timbers (primarily beams) were also recorded in their dry state and included in the hull form modelling efforts.

Figure 5. Dried-out composite cross-beams recovered during the excavation. Note the hooked scarf joints. Newport Museums and Heritage Service.

The individual waterlogged ship timbers were carefully cleaned by archaeologists and conservators using fresh water, dental tools, and tooth brushes, along with hammers and chisels. The latter tools were necessary to remove the concreted remains of the wrought iron fasteners (Figure 6). These concretions, made up of iron corrosion products, alluvial clay, animal fibre and wood tar, were systematically removed in order to expose the well preserved original surfaces of the hull timbers (Figure 7). In places, original construction marks, or inscribed lines, were clearly visible (Figure 8, Figure 9).

At the beginning of the cleaning process, a timber record sheet was created to help track progress and record any unusual or noteworthy features (Figure 10). This sheet accompanied the timber throughout the cleaning, documentation, and checking process. The information on these sheets was later scanned and entered into the project database.

Figure 6. Archaeologist cleaning the joggles and rebates on the outboard surface of a framing timber. Rex Moreton.

Figure 7. Concretions obscuring the outboard surface of a hull plank. The reddish stains are the remnants of the corroded wrought iron nails and roves. Newport Museums and Heritage Service.

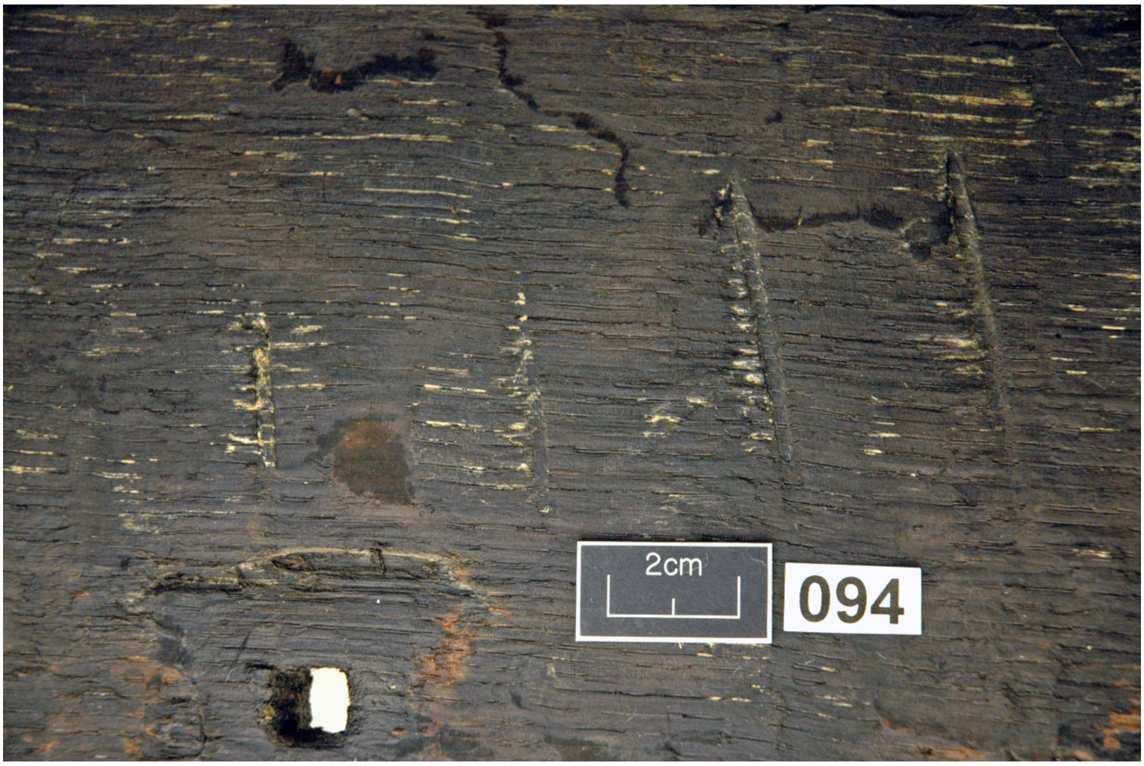
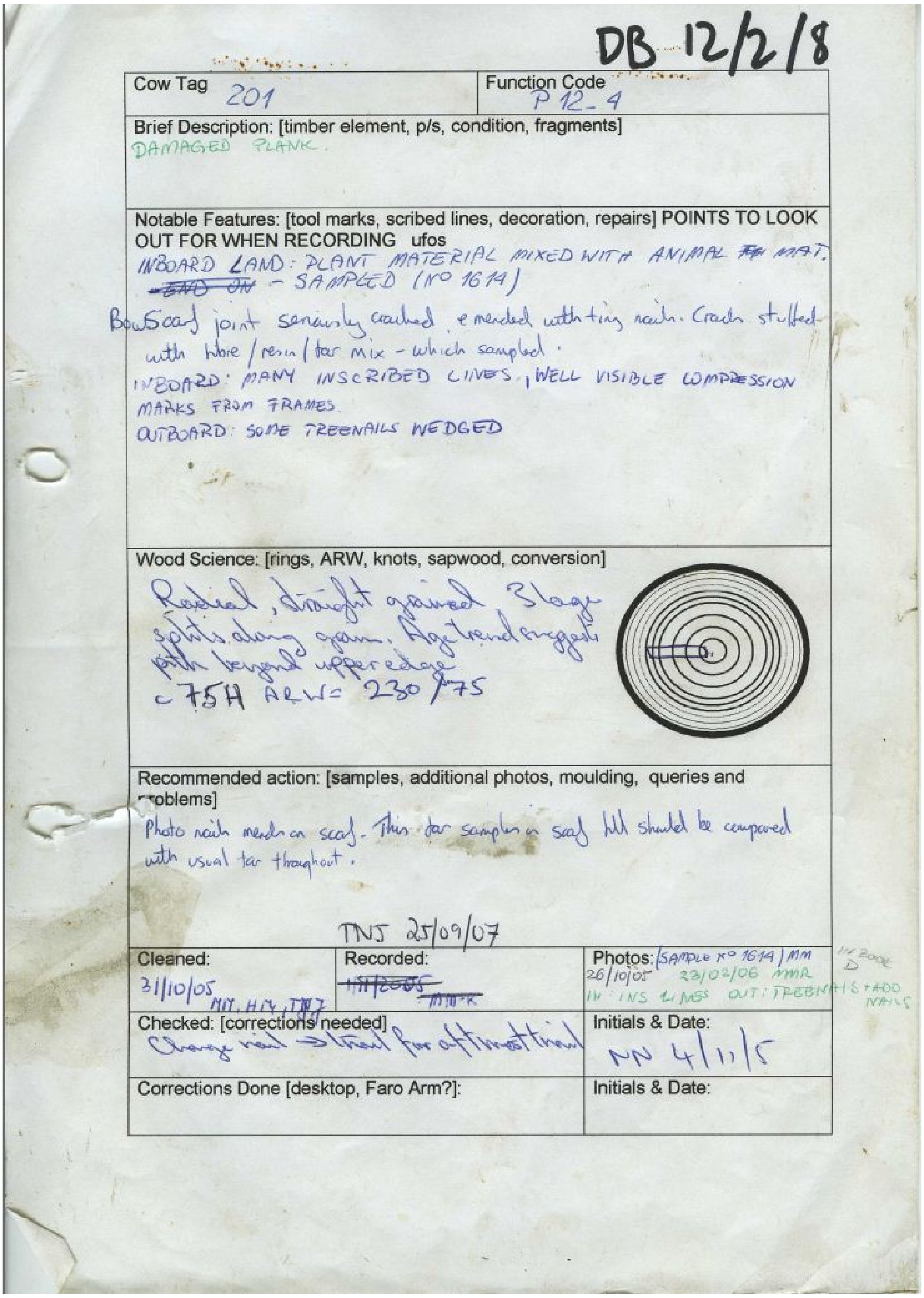


Figure 8. Parallel inscribed lines on the inboard face of a hull plank, possibly representing count marks. Newport Museums and Heritage Service.

Figure 9. Converging inscribed lines on the inboard face of a hull plank. Note the rove impression in the upper left corner. Newport Museums and Heritage Service.



DB 12/2/8

Cow Tag 201

Function Code P 12-4

Brief Description: [timber element, p/s, condition, fragments]
DAMAGED PLANK.

Notable Features: [tool marks, scribed lines, decoration, repairs] POINTS TO LOOK OUT FOR WHEN RECORDING ufos
INBOARD LAND: PLANT MATERIAL MIXED WITH ANIMAL ~~FH~~ MAT. ~~END ON~~ - SAMPLED (Nº 1614)
Bow Scarf joint seriously cracked, e mended with tiny nails. Crack stuffed with fibre/resin/tar mix - which sampled.
INBOARD: MANY INSCRIBED LINES, WELL VISIBLE COMPRESSION MARKS FROM FRAMES.
OUTBOARD: SOME TREENAILS WEDGED

Wood Science: [rings, ARW, knots, sapwood, conversion]
Radial, straight grained 3 large splits along grain. Age trend suggests pith beyond upper edge
c75H ARW= 230/75

Recommended action: [samples, additional photos, moulding, queries and problems]
Photo nails mends on scarf. This tar samples on scarf [illegible] should be compared with usual tar throughout.

TNJ 25/09/07

Cleaned: 31/10/05 MM, HM, TNJ

Recorded: ~~1/11/2005~~ ~~MMR~~

Photos: (SAMPLE Nº 1614) MM 26/10/05 23/02/06 MMR IN: INS LINES OUT: TREENAILS + ADD NAILS

IN BOOK D

Checked: [corrections needed]
Change nail ⇒ treenail for aftmost treenail

Initials & Date: NN 4/11/5

Corrections Done [desktop, Faro Arm?]:

Initials & Date:

Figure 10. Typical filled-in timber record sheet containing a description of the timber, along with wood science notes and outstanding actions. Toby Jones.

During cleaning, samples of wood tar and animal fibre (used as luting) were sampled for later analysis. Wood identification slides and features like barnacles were also collected for future analysis.

After cleaning, the timbers were documented using 3D contact digitisers and selective laser scanning and photography. The digital data was collected using a FaroArm contact digitiser and processed using Rhinoceros3D CAD software (see Chapter 3 for a detailed description of the digital recording process). The digital recording of each timber was checked by a different archaeologist before being signed off as complete. All of the digital timber records were checked by the project's archaeological consultant for accuracy, omissions and attention to detail. After final checks, the timbers were cleared to enter the conservation process. Certain timbers were documented again after undergoing conservation treatment, in order to quantify any shrinkage, distortion and loss of surface detail.

Description of the Hull

The Newport Medieval Ship was clinker-built, and can be conceived as consisting of three layers, the outer hull of lapstrake planking, the framing, and the inner hull, which consists of the mast step/keelson, stringers, ceiling and riders. The entire extant articulated structural portion of the hull was made from oak (*Quercus* spp.), with the exception of the keel, which was made from beech (*Fagus sylvatica L.*) (Figure 11). The outer layer consisted of radially split oak hull planks and tingles, while the middle layer was primarily oak framing timbers converted from compass grown timber. The inner layer of the hull consisted of sawn oak ceiling planks and stringers, as well as braces, riders and the mast step/keelson, all of which had been converted from oak.

In terms of overall size and amount of surviving timber, the Newport Medieval Ship exceeded all other archaeologically excavated ship finds in the UK, with the exception of *Mary Rose*. The large size of individual timbers and the sheer amount of surviving material presented challenges in terms of moving, storing and recording the remains. In order to get a feel for the scale of the Newport Ship project, it is necessary to first understand the general construction of the vessel and the sizes and basic features of the individual timbers.

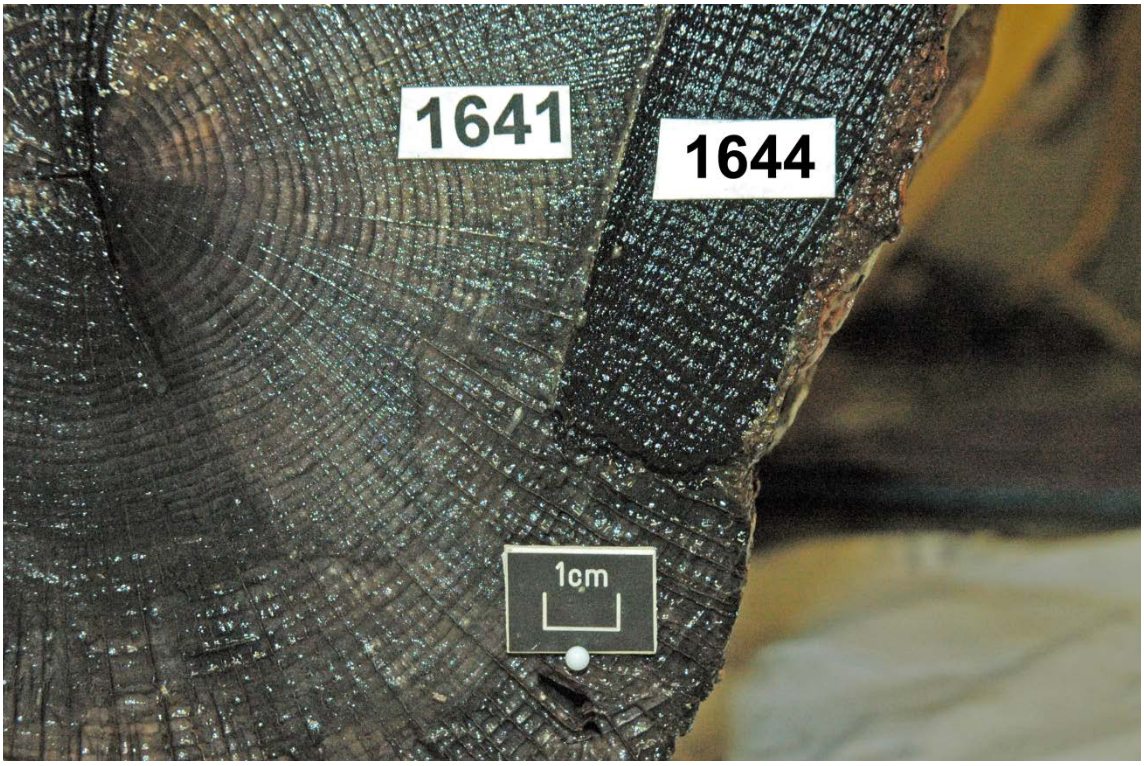


Figure 11. Section view of beech keel (CT 1641) with oak garboard strake (CT1644) still attached. Newport Museums and Heritage Service.

The basic scantlings of the remaining hull timbers are summarised below. It should be noted that the ranges and statistical averages in the following sections are derived from a detailed metrical data analysis programme which collected numerous measurements from complete and undamaged timbers (See Chapter 3). Direct measurement tools within the Rhinoceros3D modelling software were used to collect data such as centre to centre fastener spacing and linear dimensions from the wireframe drawings. This data was collected for individual timbers on a standard spread sheet template and then averages were taken by 'drilling through' the same cell on multiple work sheets.

Outer Hull

The outer hull of the Newport Ship consisted of planking and tingles, and was made entirely of radially split oak. There were 35 strakes of planking surviving on the starboard side and 17 strakes on the port side (Figure 12). There were approximately 847 planks and plank fragments. Of these, 798 fragments could be assigned to specific planks comprising 374 outer hull planks for which individual full function codes are known (i.e. which strake and the relative position within that strake). There were thirteen fragments each of both port-side and starboard-side planking which could not be assigned to a specific plank (i.e. function code was P or S) and a further 23 fragments of outer hull planking which could not be assigned to a specific side of the ship.

The intact planks ranged in length from 1280mm to 4511mm, with a mean length of 2965mm (longer and shorter length planks were a distinct possibility, as many were damaged during the initial salvage and later post-depositional site-formation phase). The plank widths, when measured at the midpoint of the length, ranged between 170mm and 256mm, with a mean width of 212mm. The planks ranged between 11mm and 33mm thick, with an average thickness of 24mm along the upper edge and 19mm along the lower edge. Planks widths tapered fairly evenly towards the ends of the vessel, with the visible width (when measured on the inboard face) ranging from an average of 176mm at F30 to an average of 147mm at F1 and F60 (Jones, Nayling & Tanner, 2013: 125).

Figure 12. View of the lapstrake hull with all inner hull timbers and framing timbers removed. Newport Museums and Heritage Service.

There were stop-splayed on-edge, face-nailed scarfs present on the forward and aft ends of each plank. The scarfs had an average length of 382mm and an average width of 210mm. There were lands on the lower inboard face and upper outboard face of each hull plank. The outboard lands averaged 49mm in width, while the inboard lands averaged 50mm.The planks were fastened with round-headed square-shanked wrought iron nails driven from the outboard through pre-drilled holes and peened over wrought iron roves. The nails were driven in along the lands of the plank strakes at an average spacing of 175mm. The clench nails had a mean shank dimension of 12mm square with the nail heads having a mean diameter of 43mm. The roves were sub-rectangular, with average dimensions of 43mm x 36mm.

Framing

There were 63 extant frame stations comprising 524 framing timbers and framing timber fragments, with many of the framing timbers fragmented from the insertion of the concrete piles. All of the framing timbers were made from compass grown oak, with some framing timbers (specifically floor timbers) reaching nearly five metres in length (Figure 13).

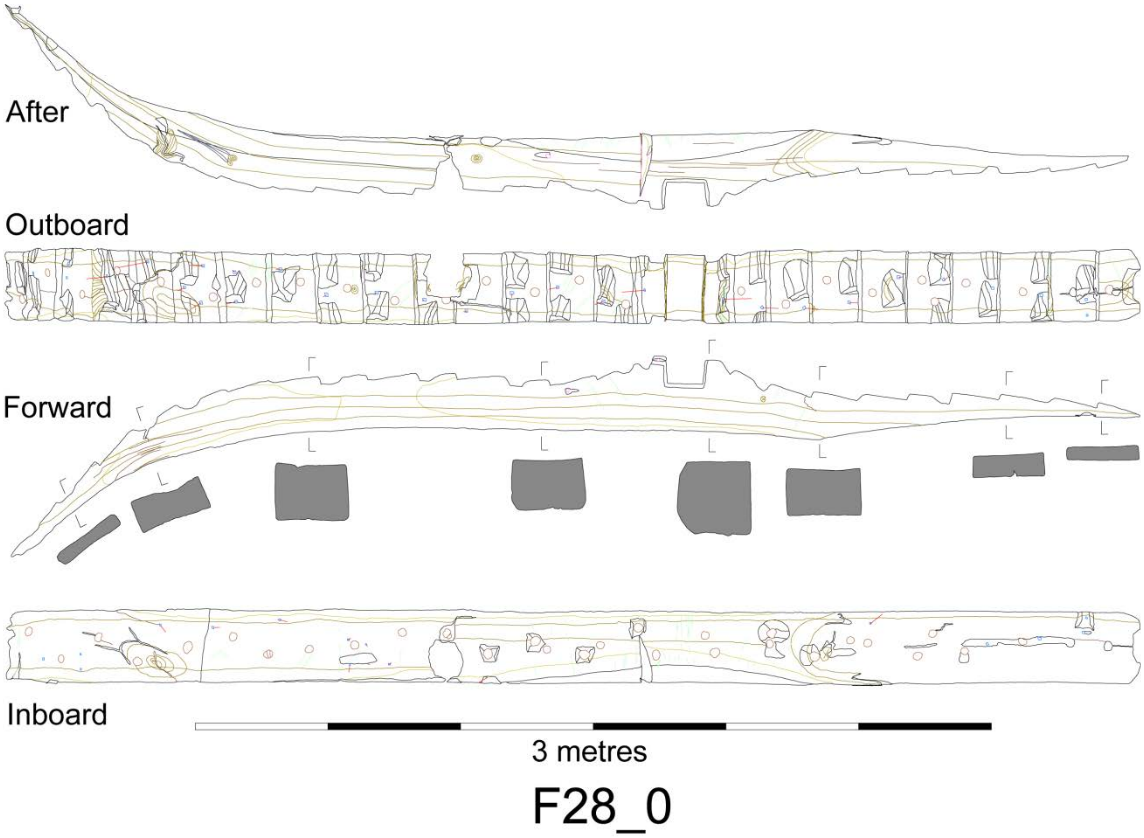


Figure 13. A typical floor timber from amidships. Note the centreline limber hole. Toby Jones.

The typical frame consisted of a floor timber and up to three surviving futtocks on the starboard side and up to two surviving futtocks on the port side of the vessel. All of the amidships floor timbers had long curved scarfs, while floor timbers near the ends of the vessels had flatter scarf joints. There was a clearly visible alternating pattern of floor timbers extending past the turn of the bilge on the port and starboard sides of the vessel (Figure 14). The sided dimension of the framing timbers were fairly regular and averaged 244mm. However, the average moulded dimension of the framing was more variable, averaging 280mm between F25 and F44, and increasing to a maximum of 528mm in the bow, and 477mm in the stern. The average centre to centre frame spacing was 361mm. The scantlings of the framing timbers at a typical frame station also decreased when moving from the centreline of the vessel towards the upper edges.

The outboard faces of the framing timbers were joggled to fit tightly against the inboard surface of the lapstrake hull planking. Rebates were cut into these joggled surfaces to accommodate the peened nails and roves standing proud on the inboard faces of the hull planking. The toolmarks in these areas were well-preserved (Figure 15). The framing timbers were attached to the hull planking with oak treenails. One (or, less commonly, two) treenails were used at each frame/plank intersection. Many of these treenails had been cut during the excavation, with fragments remaining in both the planking and framing timbers. Inscribed lines were often visible on the forward and aft faces of the framing timbers, and appeared to be marking out the position of the joggles.

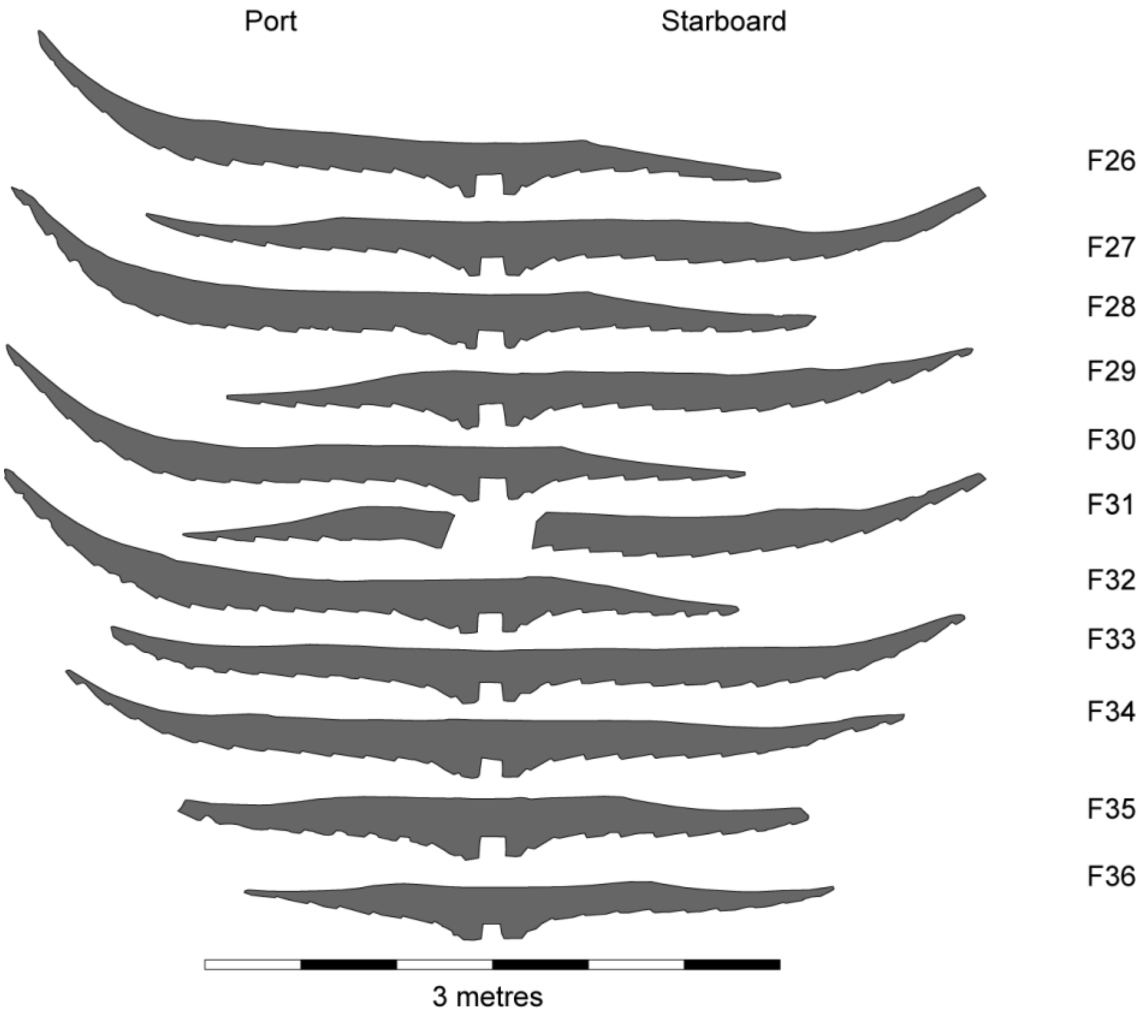


Figure 14. Alternating pattern of asymmetric floor timbers amidships. Nigel Nayling and Toby Jones.

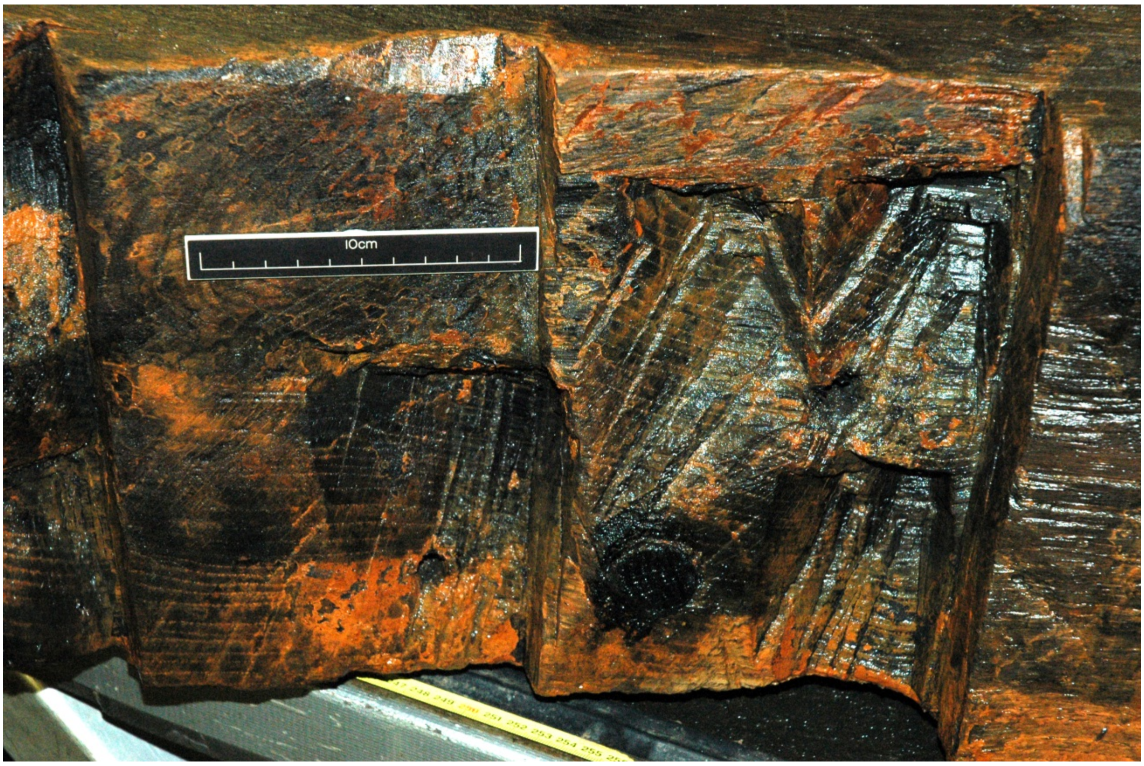


Figure 15. Joggled and rebated outboard face of a framing timber. Note the well-preserved tool stop marks. Newport Museums and Heritage Service.

Inner hull

The inner hull consisted of the stem, a number of stringers, four riders, twenty braces and the mast step/keelson, along with numerous ceiling planks and bilge boards. The mast step/keelson ran fore and aft along the centreline of the vessel, covering frames F22 through F49. It was laterally supported by pairs of braces treenailed into ten successive frames, running between F25 and F34 (Figure 16).

The stringers ran parallel to the mast step/keelson, with single stringer timbers measuring up to 12.5m in length. There were eight surviving stringers on the starboard side of the vessel and three on the port, although some of the component timbers in each stringer had been removed during the salvage of the vessel. It was possible that the central stringers on the first strake on either side of the mast step braces, STRS1_2 and STRP1_2, were from the same tree, given that they are the same length and have complimentary grain patterns. The stringers were rebated to sit down over the framing timbers, and were attached to them using treenails, which were often wedged. The mast step/keelson and associated braces were also fastened to the underlying floor timbers/framing timbers using treenails, however these treenails were square in section and driven into the round drilled holes. It was interesting to note that the treenails driven into the distal portions of the mast step/keelson were inserted in holes at each frame station that had been deliberately drilled at opposing angles, effectively locking the keelson to the underlying floors and preventing it from working free (Figure 17).

The four riders were found *in situ* in the bow of the ship, but it unclear if they were actively fastened to the hull. The stem of the ship was badly damaged by the installation of the sheet piling and concrete piles, with the large oak timber being shattered into eight primary pieces and numerous fragments. The many ceiling planks were carefully coded and removed during the excavation, and their presence indicated that the hold of the ship was meant to be dry, an observation supported by what were interpreted as five disarticulated hatch covers, found inside of the hull of the ship.

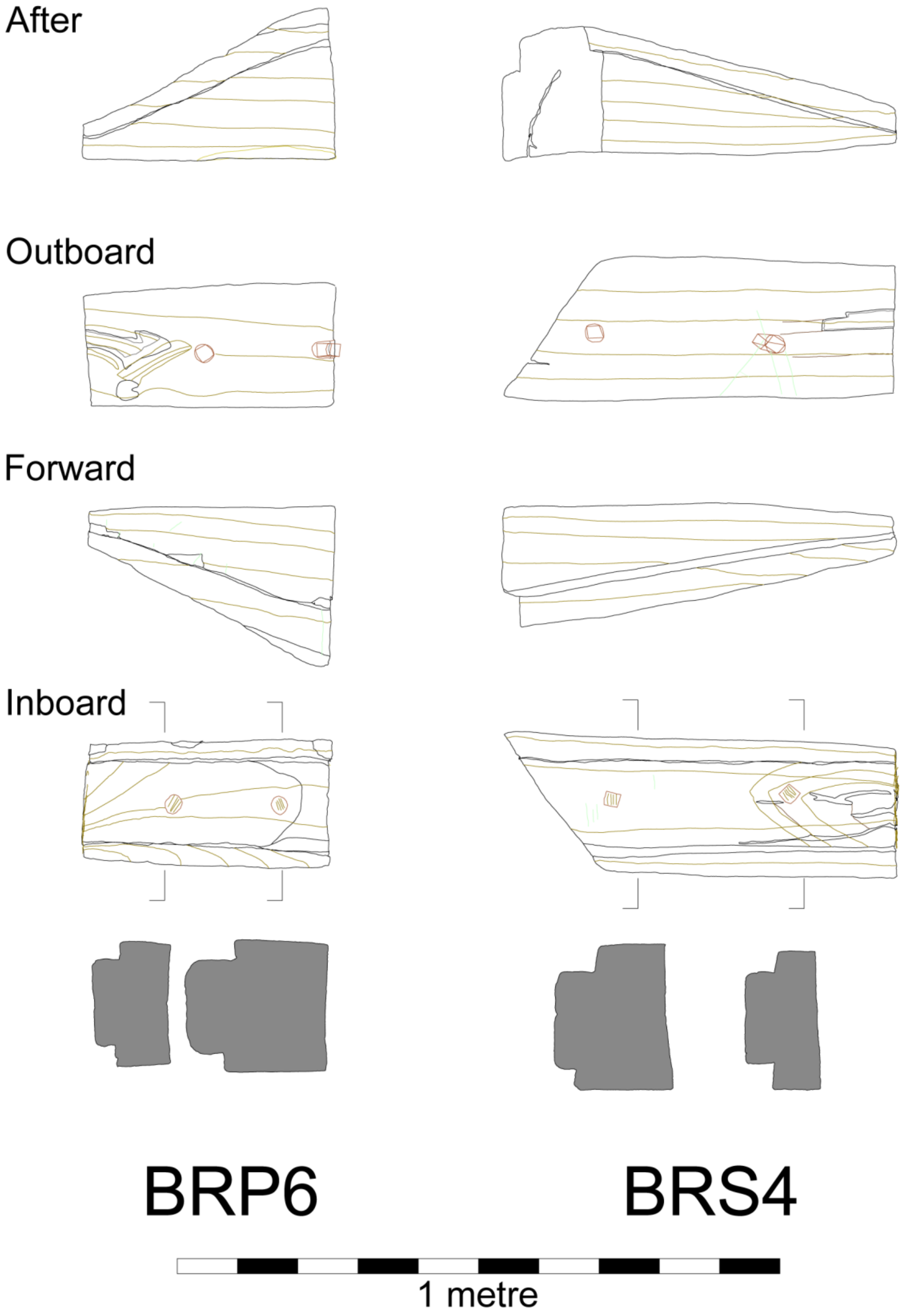


Figure 16. Typical braces found on either side of the mast step/keelson. Toby Jones.

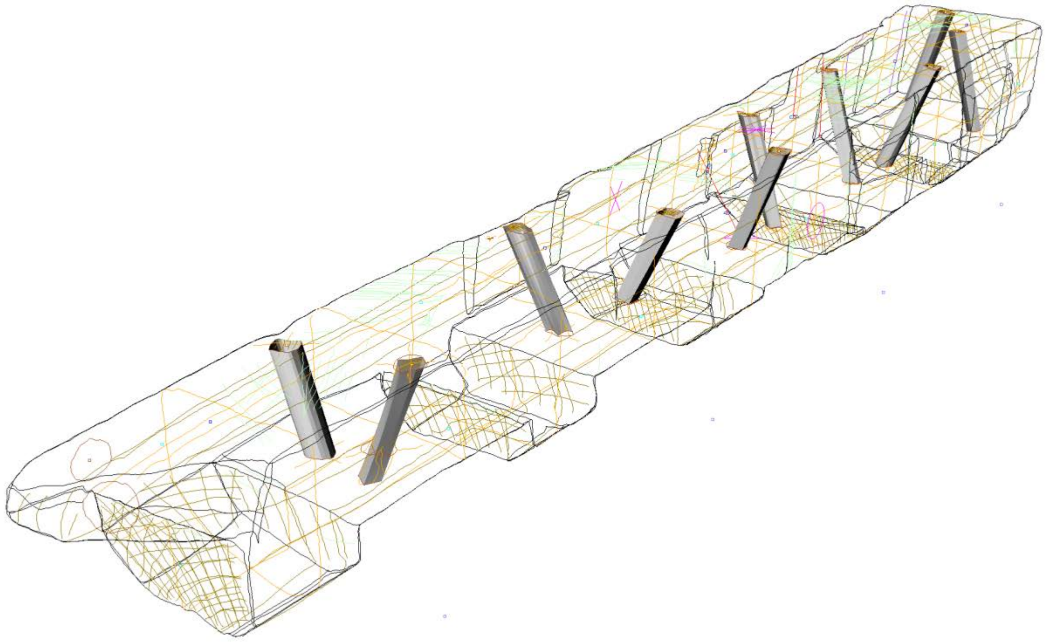


Figure 17. 3D rendered wireframe drawing of the forward-most section of keelson. Note the squared treenails inserted at opposing angles to fasten the keelson to the underlying floor timbers. Toby Jones.

Disarticulated Timbers and Artefacts

Many of the disarticulated timbers that were found during the excavation were retained, cleaned and recorded and considered as possibly belonging to the ship. A total of approximately 1750 articulated hull timbers and timber fragments were recovered during the excavation along with hundreds of disarticulated elements (Figure 18).

Figure 18. Framing timbers arranged in tank for wet storage and conservation treatment. Photograph taken between water bath changes. The tanks measured 10 metres by 5 metres with a depth of 0.5 metres. Toby Jones.

In addition to the intact hull and disarticulated timbers, hundreds of small finds, artefacts and environmental samples were recovered and cleaned, recorded and conserved. These artefacts and associated samples are beyond the scope of this thesis, but summary analyses were published in 2013 (Nayling and Jones, 2013). Further information will be included in the final Newport Ship monograph, as those non-hull areas of research have the potential to inform about wider technological, economic and social aspects of the ship’s history.

Summary

The analysis of any ship find is both a major research challenge and opportunity. The sizeable and well-preserved remains of the Newport Medieval Ship, recovered in 2002 and 2003, necessitated the development and application of an accurate and efficient system for documenting the large assemblage. The comprehensive disassembly of the vessel made it possible to clean, examine and record each part of the ship in great detail. The following chapter will look at the development of archaeological ship timber recording. A review and analysis of previous nautical archaeological documentation projects from the last 150 years will help to situate the recent methodological developments of the digital documentation techniques used on the Newport Ship Project into a broader context, which will be followed by an examination of the major documentation efforts (Chapter 3) and modelling challenges (Chapters 4 and 5) faced by the Newport Medieval Ship Project.

Chapter 2: Conceptual Approaches to Hull Form Documentation in Nautical Archaeology: The Development of *in situ* Archaeological Ship Recording and Post-Excavation Individual Ship Timber Recording

"There is no single correct way of recording an ancient vessel in situ, but it is essential that it is recorded accurately, in sufficient detail, and at a large enough scale… to be a clear statement of its form and construction."

-Peter Marsden (Marsden, 1978: 23-27)

"The tape measure is almost as symbolic of archaeology as the trowel. After the topsoil has been cleared away from the ruins of a Greek temple or the post holes of an Iron Age longhouse or the fragments of a medieval ship, a great deal of time is spent recording. The exact position and specific nature of each of the structural features and objects found must be described and measured with great care. ***These measurements, drawings, and notes are the raw material on which elaborate reconstructions of the past are based, and it is sometimes disconcerting to discover how meagre this raw material is, or how limited is our ability to recover that information."***

-Fred Hocker (Hocker, 2000: 27)

"Research and reconstruction are contributions, recording is a debt…Recording is the most important step in the whole process. The parameters of research and reconstruction are defined by the quantity and quality of the recorded information….A good shipwreck catalog can be restudied generations later, and it can perhaps be compared with later parallels to provide a more accurate or complete ship reconstruction."

-J. Richard Steffy (Steffy, 1994: 191)

Introduction

The following chapter presents a history and analysis of archaeological ship (and ship timber) recording, with emphasis placed on the investigation and documentation of hull remains *in situ* and the subsequent detailed documentation of individual hull components. The purpose of this history is to present the development of the methodology for *in situ* hull documentation and place the excavation and documentation methodology used in the Newport Medieval Ship excavation and post-excavation research into a wider context.

The case studies will serve to illustrate how changing techniques and technology were applied to the archaeological study of ancient vessels. Excavations that made significant contributions in methodology, in terms of *in situ* and post-excavation recording techniques, will be examined in detail. Methodological differences between contemporary excavations will also be examined, with an attempt made to show how and why recording knowledge/methodology was transmitted and adopted.

The case studies mentioned below (after the section on the analysis of the documentation and reconstruction debate) are presented in chronological order (by date of excavation), and have been chosen as representative of significant trends or revolutions in documentation methodology. The examples cited are not an exhaustive listing, however, an attempt has been made to select significant ship hull excavations from the last 150 years, focussing especially on those projects utilising new methodologies or technologies. In geographic terms, the examples will be primarily from North-western Europe and the Mediterranean, with several examples from North America also included.

Where possible, details about how the archaeological information was gathered and published are included. However, the focus of many project reports is on results and not the process or methodology of data selection and capture. The lack of such details in many site reports makes it difficult to understand how and, critically, why certain methods were chosen and others rejected.

The Documentation and Reconstruction Debate

In 2008, the United Kingdom Institute for Archaeologists (IfA) published *Standards and Guidance for Nautical Archaeological Recording and Reconstruction (Institute for Archaeologists, 2008).* This document, written by leading specialists with extensive and relevant experience, formally codified broadly agreed principles of and approaches to nautical archaeological research and recording in the United Kingdom. It specifically identified three levels or stages of recording in relation to ship finds, with level one encompassing the basic measuring, sketching and photography of a hull or hull remains. This minimal level of documentation should ideally contain enough information to make an educated interpretation of the vessel's form and function. Level two builds on this basic standard by incorporating widespread photography and scaled drawings of significant features, with an eye towards creating a basic reconstruction of the vessel. Level three can be summarised as the complete and thorough recording of the entire hull, covering the documentation of all timbers, fixtures and fasteners, as well as methods of propulsion, steering and detailed wood science. The goal of such a thorough level of documentation is to make a definitive reconstruction of the original hull form. The level of recording is often dictated by the site conditions or available resources, but "should be commensurate with the level of significance of the site and vessel," (Institute for Archaeologists, 2008: 7).

As a unique, highly significant, and well-preserved vessel, the Newport Medieval Ship clearly warranted the highest level of detailed examination, recording, and analysis. The creation of an authoritative reconstruction, based on detailed and comprehensive documentation, was identified as a key research outcome, with the project research design calling for detailed post-excavation recording of every timber. These records would, in turn, be used to create a 3D physical model of the vessel's remains, which was used for as the basis for a digital reconstruction of the original minimum hull form (and later a maximum or capital reconstruction). In order to comprehend why the abovementioned Newport Ship research design was formulated and implemented, it is necessary to understand the theoretical underpinnings of archaeological ship and boat reconstruction (also synonymously termed experimental boat and ship archaeology) (Coates et al., 1995: 293).

The clearly stated aims and objectives outlined in the IfA's *Standards and Guidance for Nautical Archaeological Recording and Reconstruction* are the product of over a century of methodological development in the field of boat and ship recording. In the years leading up to the IfA's statement, the debate about how to record and reconstruct ancient vessels was primarily carried out in the *International Journal of Nautical Archaeology*, a highly-regarded, peer-reviewed journal focussed on the dissemination of nautical archaeological research, methodology and theory. Between 1992 and 2007, a series of articles and critical responses helped to clarify and refine the research processes and desired outcomes relating to archaeological ship reconstruction. Using a variety of case studies (specifically the Dover Bronze Age Boat and the Ferriby and Brigg vessels) and methodological frameworks, archaeologists attempted to classify the different possible outcomes of reconstruction research. Attempts to model the hull forms of ancient vessels from varying levels of preserved remains were variously classified as minimum, maximum (or capital), scientific, and aesthetic reconstructions. Terms like as-built, as-found, torso and minimum reconstruction models were used, sometimes with partially overlapping or inconsistent definitions between authors.

Attempts to impose a single theoretical reconstruction framework or nomenclature had yet to meet with success, however McGrail helped focus the debate in 1992 by arguing that ship reconstruction needed to be more scientifically rigorous, which meant that the underlying source data (site records/timber drawings) was of a high quality, was critically assessed, and was fully published in order to be available for critical review. Of utmost importance was the suitability of the methods or techniques used for converting the source data into what he called a ‘floating hypothesis’ (McGrail, 1992: 354).

This floating hypothesis would be based on the as-found model of the remains (defined by McGrail as “a model [that] is formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat” (McGrail, 2007: 255). The as-found model would strictly adhere to the archaeological evidence, without deviation, with missing components added later in order to create a complete reconstruction of a fully working ship (also called an evidence-based reconstruction).

The ideas of approaching archaeological ship reconstruction with a more rigorous scientific approach were further refined and codified in an article by Coates et al., published in 1995 (Coates et al., 1995). In addition to advocating close collaboration between model makers and archaeologists (ideally being one and the same person) and the concept of reverse engineering, the article emphasises the need for a research design which includes well-formulated hypotheses with identifiable and measureable experimental outcomes. These experiments (or reconstructions) were also considered to be 'virtually valueless' unless published or made otherwise available for peer review or repetition (Coates et al., 1995: 301).

In a separate article in the same issue of the *International Journal of Nautical Archaeology*, Crumlin-Pedersen questioned the utility of a purely scientific approach to replica building and vessel reconstruction, and instead suggested a multidisciplinary approach to maritime archaeological research which encompasses both 'the arts and the sciences' (Crumlin-Pedersen, 1995: 303). He suggested that a broad team consisting of historians, boat builders, model makers, naval architects and wood scientists, among numerous others, be brought together in order to assist archaeologists in the thorough reconstruction, analysis and authoritative publication of ship and boat finds. Using the construction of the *Roar Ege* replica vessel (based on the remains of the Skuldelev 3 vessel) as an example, he demonstrated that archaeological evidence, when coupled with other sources, like ethnography and history, could be used to create more than just a testing platform for hydrostatics and sailing characteristics. A well-planned experimental archaeological reconstruction effort could provide insights into technological construction problems in terms of materials and techniques (Crumlin-Pedersen, 1995: 304). The blending of various evidence sources could help provide the cultural context during the construction of the original vessel. Purely scientific approaches were useful for analysing specific testable aspects of the reconstruction, such as stability and capacity, while a multidisciplinary approach attempted to bridge the gap between arts and sciences, providing a broader cultural context in which to understand the vessel (Crumlin-Pedersen, 1995: 306).

The debate arguably culminated with the publication of a seminal article by Crumlin-Pedersen and McGrail in 2006, which clearly outlined the primary principles to consider when reconstructing an ancient vessel from archaeological remains. Of crucial importance was to recognise (and avoid, where possible) the letting of pre-conceived/modern ideas influence the reconstruction efforts. The concept of a minimum reconstruction was clearly laid out, with the authors arguing that it should be completed in a way devoid of anachronistic intrusions or the introduction of foreign elements (Crumlin-Pedersen and McGrail, 2006: 53-57). Related to this was the need to avoid imposing present-day naval architecture and safety standards on potential reconstructions. Deformation and distortion of the hull, during use-life, deposition or recovery, needed to be identified and corrected. Differing configurations for elements like steering, propulsion and rig needed to be carefully considered and unfeasible ones discounted. The minimum reconstruction efforts might lead to several different but equally valid results. At this stage, the preliminary results would be presented to the group of specialists in order to get critical feedback prior to final publication.

McGrail published a slightly refined version of this methodology in 2007, which described a workflow that started with the assembly of an as-found model. This was then used for the creation of a reconstruction model or models. These models were then rigorously evaluated and the results made available in interim publications, with any impartial and informed criticism received being used to create (or identify) an agreed final reconstruction. This was followed by full publication and, where appropriate, the construction and performance testing of replicas (McGrail, 2007: 255).

This iterative process of sharing preliminary results was followed on the Newport Ship project, with the feedback being incorporated into the next version of the reconstruction. Many of the major archaeological ship reconstruction projects (Doel, Newport, Aber Wrac'h 1) in Europe employ a team of specialists to address various aspects of the research. Often this work is critically reviewed by an independent panel of experienced specialists, which provides advice and guidance. The benefits of having a transparent research framework are obvious. By presenting the process in which the data has been created or captured and interpreted/reconstructed, the researchers are allowing others to understand and challenge their assumptions, leading to a more robust and convincing end product.

Ship Find Documentation

The first quarter of the nineteenth century witnessed the first comprehensive archaeological excavation and detailed recording of ancient ship finds. The excavation and lifting of a complete vessel in Kent, England dubbed the Rother Barge, happened in 1822. In the mid-nineteenth century, the excavations of the Nydam bog, near the modern German-Danish border, revealed a variety of weapons and large boats dating to between AD 200 and AD 500. Further discoveries, in the form of the Tune ship, built around 910 AD and discovered in 1867, and the Gokstad ship, dating to 895-910 AD and uncovered in 1880, led to a growing awareness of Viking Age ritual burials within the hulls of vessels interred on land (Crumlin-Pedersen, 1997: 18-19).

The systematic excavation, recovery, documentation and publication, by amateur and professional archaeologists, of these ships signalled a shift from the antiquarian *ad hoc* approach of collecting artefacts, and instead towards the conscious gleaning of information from the contextual relationships of the objects, and treating the hull of the ship as both a technological artefact and an object relating to and reflecting the complex cultural and social realities of the time. The methods used to document the remains of these vessels changed over time, with sketches and drawings eventually being augmented with photography and improved survey techniques. Detailed and descriptive field records and illustrations became the norm, with sites like Rother, Nydam and the Viking ships from Norway contributing much to our early understanding of maritime culture in North-western Europe.

The Rother Barge

The discovery and excavation of the Rother barge in 1822 prompted much curiosity about the origin and date of the well-preserved vessel. The barge was found buried under several metres of sand in the bank of a stream running into the River Rother. The clinker-built flat-bottomed hull was made from oak and in a remarkable state of preservation. As well as recording the dimensions of various fasteners and timbers, the antiquarians investigating the remains described construction features like the mast-step, rudder, and ends of the vessel. Unique features, like the metal plates fastened to the sides of the vessel and various merchant marks, were discussed in detail. A detailed sketch of the site was created, along with at least one section drawing, showing the vessel's context within the surrounding sediment.

Fine details like the application of tar, moss, and animal hair were also noted. The positions of numerous finds around the site, including ceramics and human and animal bones, were also recorded. The accumulated information was utilised in an effort to ascertain the vessel's origin and age. The author also attempted to precisely date the deposition of the vessel by examining historical records relating to the changing riverine landscape in the area. The Rother barge excavation showed that useful historical and technological information could be obtained through careful examination and recording of the physical remains, a process which would later become a key tenet in the developing field of archaeology (Rice, 1824: 553-565).

The Nydam Bog Excavations

Several boat finds, and a diverse range of Iron Age weapons, have been recovered from Nydam Bog, located in Southern Jutland in Denmark over the last 150 years. The site, a former lake turned peat bog, was first investigated by Conrad Engelhardt between 1859 and 1863 (Engelhardt, 1865; Rieck, 1994: 49). The remains of several oak boats and a single pine vessel were discovered.

The largest recovered vessel, the oak-built Nydam Ship (or Boat), is seen as highly significant in the development of Scandinavian maritime technology, as it represents both the earliest Nordic-style clinker built vessel fastened with iron nails and the earliest example of a vessel designed to be rowed (Crumlin-Pedersen and Rieck, 1993: 39). The c. 25m long vessel was raised, conserved, and eventually put on display, first in Kiel, Germany and later in Schloss Gottorf in Schleswig (Delgado, 1997: 300-301). Illustrations of the overall find and detailed drawings of selected elements were included in the original report, with the illustrations often containing sections. Although the overall vessel illustrations are somewhat idealised, the sketches of individual components and features are detailed, with features like cracks and broken or damaged areas clearly visible.

The excavations carried out by Engelhardt, against the backdrop of territorial wars between Denmark and Prussia, were eventually halted due to the conflict. The site archive was dispersed, with parts going missing, and some site records left deliberately incomplete, in order to prevent others from disturbing the rich site (Crumlin-Pedersen and Rieck, 1993: 39-41). The bog was periodically revisited by archaeologists, with Rieck undertaking test excavations of the site, beginning in 1989, in order to find additional boat material and try and determine the exact original find spot of the various vessels. This field research was coupled with a comprehensive analysis of the archival records (Rieck, 1994: 50). The quality of the original work was such that it could be relied upon by future generations of scholars. In addition to the abovementioned work, the displayed remains of the Nydam boat were measured, with alternative hull form reconstructions being suggested. The hull remains were also sampled for dendrochronological purposes, with the trees used for the planking having been harvested between AD 310 and AD 320 (Rieck, 1994: 53, Crumlin-Pedersen, 1997: 18-19).

The Gokstad vessel

The Viking-age Gokstad vessel was one of the first boat finds that was excavated and documented in a scientific manner (although the Tune Ship was discovered earlier, in 1867, the results of that excavation were not published until 1917, together with the results from the Oseberg Ship excavations). The Gokstad vessel was uncovered by systematically digging into the side of a burial mound and removing sediment and artefacts from inside and around the vessel (Figure 19). The positions of artefacts and their relationship to the hull were noted, and stratigraphy both in and around the vessel was verbally described. The ship itself was then raised in several sections, before being towed away on a pram (Nicolaysen, 1882: 3-4).

The excavators described the boat in general detail, including scantlings, and created an excellent catalogue of drawings for the artefacts. They documented specific construction features, but they did not create a detailed recording of each timber, nor did they codify their documentation methodology (Nicolaysen, 1882: 54). The drawings of the hull are clear and detailed, but represent an idealised hull form, with most of the timbers shown as complete and unbroken. A number of section drawings are also included, but again these appear to show a completed and faired hull form as opposed to the *in situ* shape of the surviving remains (Nicolaysen, 1882: Plates 1-3).

Judging the excavation by the standards of the time shows that it was an important ‘first step’ towards modern excavation principles and documentation standards. It also serves to illustrates that archaeological methods were (and are) a continually evolving set of ideas, principles, and practices. The Gokstad excavation would have benefitted from a detailed *in situ* site plan (along with sections), showing accurately plotted fasteners and the extents of the original recovered material. However, the site records are still of a sufficiently high standard to remain archaeologically valuable today.

Figure 19. The Viking-age Gokstad vessel in Oslo, Norway. Toby Jones.

The Oseberg Ship

The Oseberg Ship was discovered in southern Norway in 1903 and excavated in 1904 (Brøgger and Shetelig, 1971:57). The highly-decorated clinker-built vessel was interred in a burial mound, along with several bodies and a rich assortment of grave goods (Christensen, 1997: 302-303). Some of the oak timbers used in the construction of the vessel have been dendrochronologically dated to AD 815-820. The 22m long vessel was carefully documented *in situ* with sketches and measurements. Much distortion and fragmentation of the timber was evident. The excavated remains were later conserved, reassembled and put on display in Oslo (Figure 20). The results of the excavation were published in 1917, along with an excavation report for the Tune Ship.

A replica of the Oseberg vessel was constructed in 1987 and dramatically capsized during sea trials. This incident led to a reassessment of the accuracy of the displayed hull form (Bischoff, 2010: 4-6). The replica had been based on drawings of the displayed hull form, raising questions about the accuracy of the hull form as reconstructed. The displayed hull form was analysed in detail, using photographic scanning, with the data being used to create scaled two-dimensional models of each component in the hull. These model elements were later reassembled in order to better understand the shape of the original hull. Researchers discovered that the hull remains had been forced together during the assembly process in order to create an aesthetically-pleasing hull form from the fragmented material. The resulting displayed hull form looked convincing, but had, in fact, been subject to substantial modifications. As it did not reflect the original shape of the vessel, the displayed hull form proved a poor starting point for the creation of a replica (Bischoff, 2010: 8-9). While the *in situ* recording of the vessel was likely adequate, deviation during the physical reconstruction process (and reliance upon the resulting hull form to build a replica) was to have profound consequences.

In the second quarter of the Twentieth century, the excavation and field documentation of the Ladby (1934-1937) and Sutton Hoo (1939) sites were notable for using novel methods to record information about the hull forms of these ancient vessels. Both sites were royal graves that originally contained interred lapstrake vessels, grave goods and human remains. At both Ladby and Sutton Hoo, the preservation of the ship timbers was adversely affected by the soil chemistry, which caused many of the organic materials, including wood, to decay or dissolve completely. However, by carefully documenting the position and angle of the extant iron concretions of the nails and roves, the archaeologists were able to tentatively reconstruct the size and shape of the respective boats (Evans, 1994: 23-29, Bischoff and Jensen, 2001: 185-191, Sørenson et al., 2001:15, 33).

Figure 20. The Viking-age Oseberg vessel in Oslo, Norway. Toby Jones.

Ladby Excavation

The Ladby Ship site, discovered in 1934, was almost completely devoid of surviving wood. However, the remains of around 2000 rivets and spike fasteners were discovered in the ground. The excavation uncovered numerous artefacts that suggested the site was a Viking-Age ship burial, and dated to the 10th century (Sørenson et al., 2001: 15). The longer spike nail concretions were interpreted as locations where the framing had been fastened to the hull, with treenails also being used in certain areas, especially along the lower strakes (Sørenson et al., 2001: 43, 217-218). These fasteners were measured, as well as being sketched and photographed. Rivets that seemed to delineate each individual strake were tied together with string, creating a visual representation of the original strakes (Figure 21).

The fastener position data was used to create a contemporary reconstruction, and was also re-evaluated using digital modelling technology in the late 1990s. This later effort resulted in the global coordinate data for each fastener being entered into a computer aided drafting system. Sections were taken from the resulting point cloud and used as a basis for the construction of an adjustable-spline scale model. The digital data was critical to the creation of the model, and served as a check or verification that the physical model was staying true to the data collected during the excavation (Sørenson et al., 2001: 204).

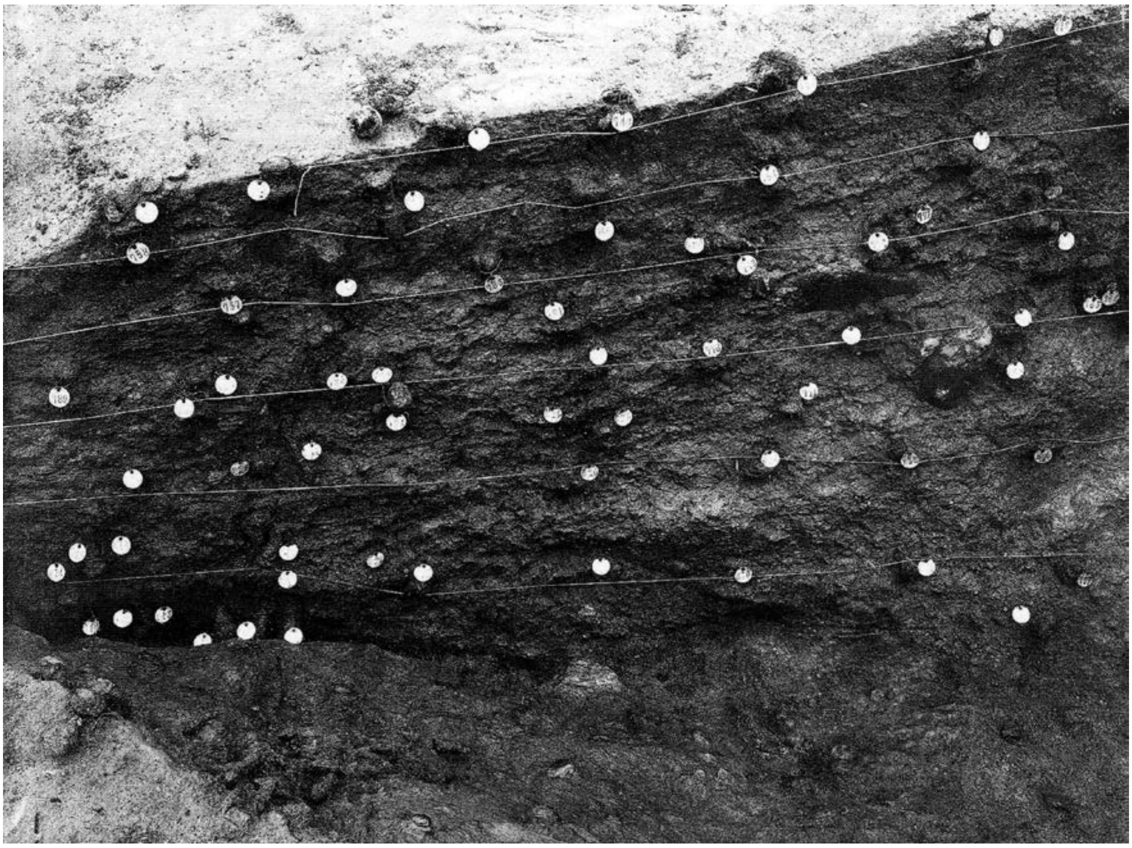


Figure 21. The excavation of the Ladby Ship. Individual fasteners were identified with metal tags and strakes delineated by string. After National Museum of Denmark, in Sørenson et al., 2001: 33.

Sutton Hoo

The Sutton Hoo ship investigations, begun in 1939, involved the exploration of a series of burial mounds on a rural property in Suffolk, England, not far from the various Snape boat finds. Using a series of stepped trenches, the archaeologists uncovered the impression of a large lapstrake-built ship within a feature called Mound 1 (Bruce-Mitford, 1974: 156-157). The ship, likely a royal burial, was filled with grave goods, which were carefully documented and removed. The wooden hull had long since decayed, leaving behind intact rows of concreted fasteners (Figure 22). It was the position of these rivets that held the key to understanding the original shape of the vessel. However, inconsistencies, errors and discrepancies in the 1939 excavation (which had been roughly backfilled) necessitated a return to the site between 1965 and 1967 to re-measure the fastener positions (Bruce-Mitford, 1974: 234-235).

Figure 22. Excavation of the Sutton Hoo ship in 1939, looking aft. Note the rows of concreted fasteners and shadows of the original strakes. Archaeologists worked from the swing visible in the aft part of the vessel, in order to avoid damaging the fragile impressions in the soil. After Uncredited, in Evans, A., 1994: 24.

The principal aim of the second excavation was to record any surviving elements (or, rather, evidence of elements) of the ship, primarily by recording the positions of over 1500 rivets (Bruce-Mitford, 1974: 245-248). The excavation proceeded by "carefully creeping along rivet by rivet," with the concreted rivets being measured onto plan using a plumb bob and planning frames. Plan view drawings showing the fastener positions were produced, along with cross-section drawings.

The rivets were labelled and removed for further laboratory analysis, accompanied by sediment samples (Bruce-Mitford, 1974: 159, 249). The concretions were examined in detail, as many had formed around the decaying wood, capturing the original pattern and orientation of the grain. After documenting the positions of the concretions, plaster casts of the hull form were created, in order to make moulds for fibreglass positives of the vessel for future research and display. These casts are the only 3D primary record of the shape in the ground, and, while acknowledged to be unusable as a reconstruction template (one of the primary intentions), they were quite important as a source of information about section data, overall size and volume (Bruce-Mitford, 1974:249, 301-302). It was also one of the first successful attempts to create a full scale physical 3D shape of an *in situ* hull form found on a terrestrial site.

In an effort to provide broader contextual information about the Sutton Hoo landscape, including additional study of selected burial mounds, a new series of investigations and excavations were carefully planned. Beginning in the mid-1980s, various geophysical remote sensing technologies, including ground penetrating radar and fluxgate radiometry, along with aerial photography and metal detecting, were used to detect and delineate any archaeological material. Field trials were conducted with various technologies being evaluated for effectiveness by first scanning a test area and then excavating it (Carver, 2005: 26).

The Sutton Hoo landscape was divided up into zones, and different remote sensing technologies applied based on a number of factors, including the expected nature and size of the finds, and physical and chemical characteristics of the soil (Carver, 2005: 14-31). Following remote sensing research, large areas of the site were opened with the resulting excavations being documented using 1:10 scale plan and section drawings and selective photography. A theodolite was used to plot in finds and features until supplanted by a total station (Carver, 2005: 41, 45). Although the excavations focussed on the wider cemetery, a useful re-analysis of the deposition of the vessel in mound 1 was provided (Carver, 2005: 198-199).

The Skuldelev Vessels

The first truly modern ship recording effort began with the discovery of the five Viking-Age Skuldelev vessels in Roskilde Fjord in Denmark. The vessels had been purposely scuttled to create a complex physical barrier, which also incorporated stones, wattles and wooden poles or stakes (Crumlin-Pedersen and Olsen, 2002: 42-46). The site was initially investigated and delineated by divers in the late 1950s. Following this survey work, a coffer dam was built around the site and the water was slowly pumped out, exposing the archaeological remains. During 1962, as the water level slowly dropped, the visible remains were documented and removed, preventing them from crushing the underlying structures. The *in situ* remains were kept wet by constant spraying. Archaeologists used a series of catwalks and elevated walkways and platforms to work above the fragile timbers. The waterlogged hull timbers and other artefacts were documented *in situ* using stereo-photogrammetry (Crumlin-Pedersen and Olsen, 2002: 38-39, Crumlin-Pedersen, 2002: 51-52) (Figure 23). These records were later used off site to create 2D *in situ* site plans of the excavated vessels. Standard photography was also used to record the position and relationship between smaller groups of timbers and individual fragmented timbers, prior to removal. The vessels were disassembled, with individual timbers and finds numbered and packaged for removal.

Figure 23. Stereo-photogrammetrical documentation of Skuldelev Wreck 3 and associated barrier material. Excavation site plans were later created from the stereo pairs. After Olsen, O. in Crumlin-Pedersen and Olsen, 2002: 31.

During the post-excavation documentation phase, the individually waterlogged ships timbers were subjected to a second, more detailed phase of recording. This second stage of recording was seen as critical to understanding the design and shape of the original hull form and probable construction sequence. With a background as a naval architect, Crumlin-Pedersen believed that it was possible to collect enough detailed data from the individual ship timbers in order to recreate the original hull form. By compiling the numerous 2D records of the hull timbers, he reasoned that it would be possible to create physical 3D scale models of the articulated hull remains. Lines drawings could be extracted from these models and published in a traditional naval architecture format.

All of the Skuldelev timbers were documented using 1:1 scale elevated plane tracing. Details such as decorations and tool marks were traced onto polyester sheets with coloured markers (Rieck, 1995: 22). This innovation, pioneered by Crumlin-Pedersen and Olsen, was the first occurrence of this type and level of recorded detail on waterlogged ship timbers. These records were supplemented by photography and written descriptions of each timber (Crumlin-Pedersen, 2002: 53-54).

The full-scale tracings were later reduced and the drawings used for reconstruction and conservation research. The high level of accuracy and recorded detail on the 1:1 tracings enabled the later authoritative analysis and reconstruction of the original vessels (Figure 24). However, there are limitations to this methodology, which records the 3D shape of the ship timbers as a series of 2D projections. Potential problems can arise due to scaling errors during the conversion of physical records to digital data files via processes like roller scanning and manual reduction.

However, the flattened nature of the surviving material meant that most of the fragments retained little of their original curvature or twist, making 2D recording an appropriate choice. Capturing and retaining the potentially complex 3D physical shapes of the original material would remain an elusive goal for some years to come.

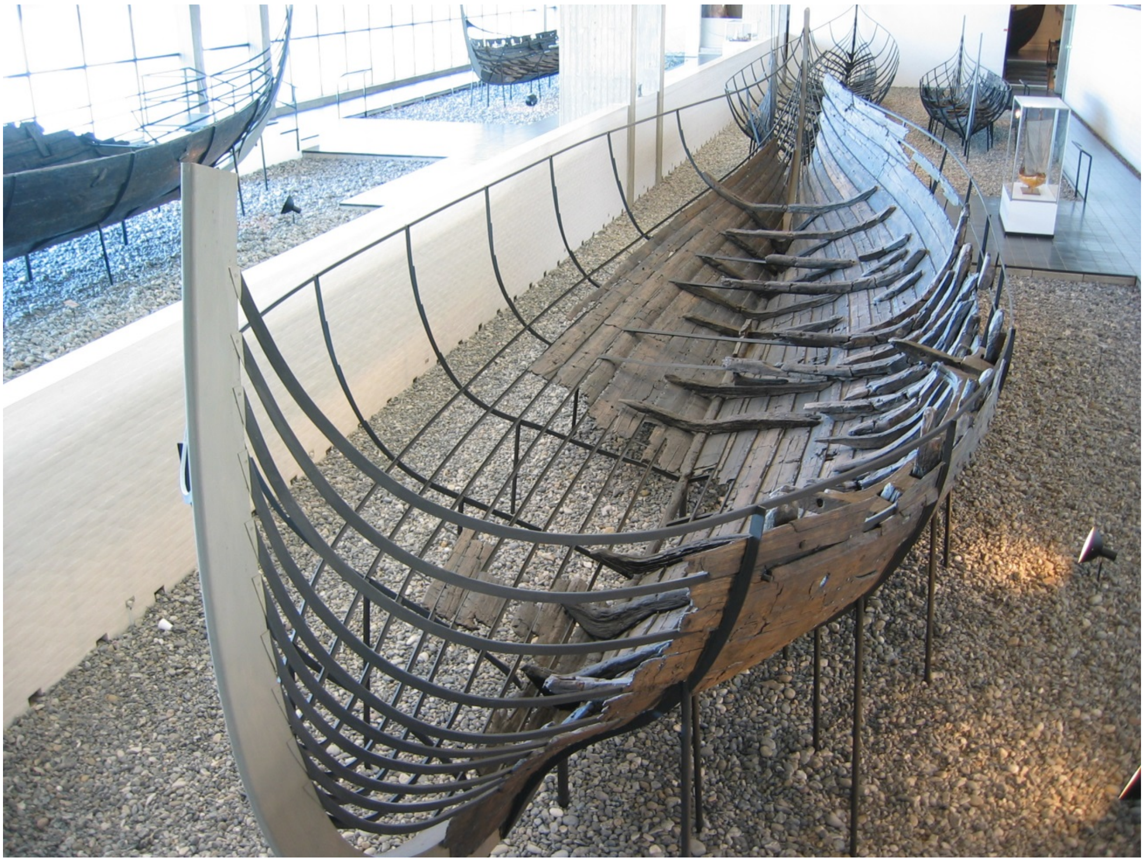


Figure 24. The Viking-age Skuldelev vessels in Roskilde, Denmark. Toby Jones.

Yassi Ada 7th Century AD Shipwreck

The documentation techniques developed during the Yassi Ada 7th century AD shipwreck excavations were revolutionary. The underwater expedition, run between 1961 and 1964, was led by George Bass from the University of Pennsylvania. The archaeological team constructed a stepped grid framework of angle iron and positioned this over the cargo and remains of the vessel (Figure 25). The resulting site grid had 2m x 2m squares that were further subdivided with line (Figure 26).

In order to speed up the recording and make the most use of the limited bottom time, the archaeologists decided that photography was probably the best way to quickly document the site (Bass, G., 1975: 96-97). A photography tower was created which held an underwater camera. Photographs were taken of each square at numerous points during the excavation. The artefacts and hull structure visible in the photographs were then traced over and then correctly scaled (correcting for scale/parallax/refraction errors). The resulting site plan was compared to direct measurements taken from the site and found to be accurate.

Later field seasons at Yassi Ada saw the introduction of stereo-photogrammetry, where photographs were taken of the site from a camera hanging from a floating bar. Pairs of photographs, showing nearly identical patches of the seabed but taken from slightly different angles, were viewed with a stereoscope and a site plan created.

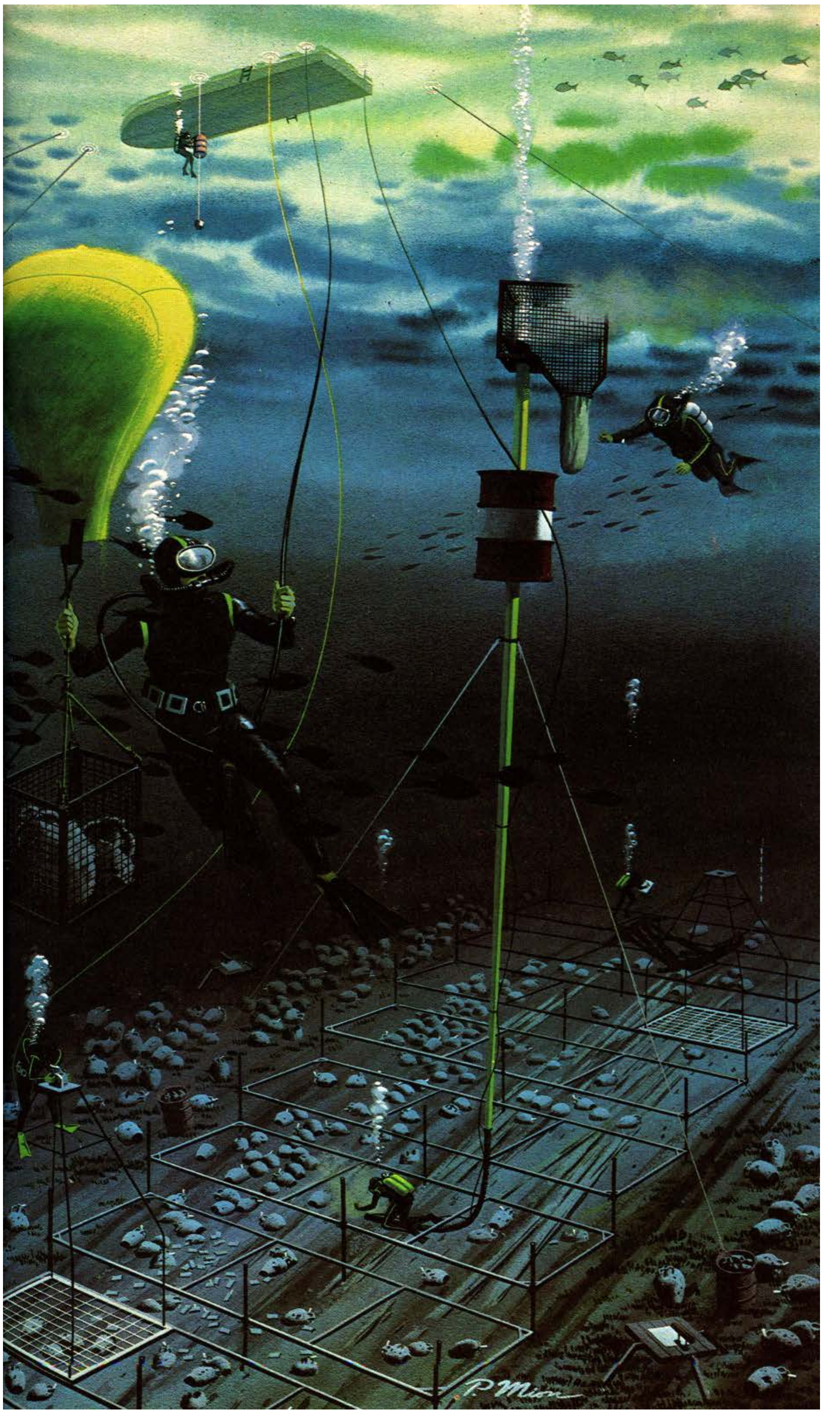


Figure 25. Artist's rendering of the Yassi Ada 7th Century Shipwreck excavation. Note the stepped framework of angle iron covering the site and the photography towers in the lower left and centre right. After Mion, P., in van Doorninck, F., 1972: 146.

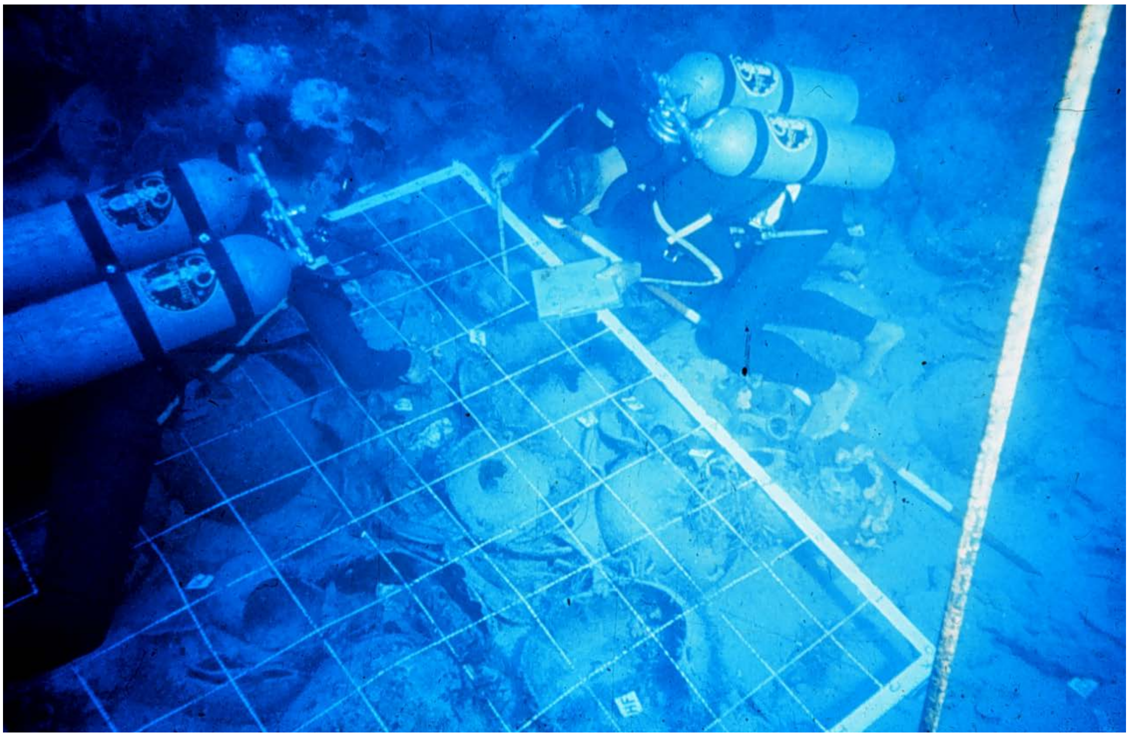


Figure 26. Archaeologists recording the position of finds on the 7th Century AD Yassi Ada shipwreck. The grid square measures 2m x 2m, and is further subdivided into one hundred 200mm x 200mm squares. Courtesy of the Institute of Nautical Archaeology (slide# YA7-212).

Three-dimensional information about the site could be extracted from the images using triangulation. By knowing the focal length of the camera and the distance between the camera positions along the bar, the elevation of artefacts could be accurately determined, without the need to take measurements using a plumb bob. Such advances greatly speeded up the acquisition of data from the seabed, creating detailed site plans which could be analysed during the post-excavation research phase of the project, as well as containing sufficient information to aid in the reconstruction research (Bass, G., 1975: 96-106). The successful application of detailed survey techniques to an underwater site was to profoundly change the way archaeologists carried out underwater survey, as well as demonstrating to previously sceptical terrestrial archaeologists that useful archaeological information could be extracted from such sites.

Blackfriars 1

A significant terrestrial excavation of a shipwreck occurred in 1962, when the remains of a Roman vessel were discovered along the edge of the River Thames in London. The rescue excavation was originally intended to quickly record the size and shape of the surviving hull remains before discarding the material. However, during this process the decision was made to partially dismantle the vessel and recover the ship in sections for further study and conservation (Marsden, P., 1994: 33-36). Basic plan and section drawings were created and augmented with photographs of key features (Figure 27).

The vessel was cut into sections be slicing through the hull planking between the frames. After the timbers were raised, scaled drawings (at 1:8) of the inboard face of each framing timber (with fragments of hull planking still attached) were created by taking offset measurements from a grid of datum lines. The aft face of each timber was also drawn in a similar manner. Cross-sections were drawn and end grain illustrated, where visible, and attempts were made to determine how the timbers had been cut from the parent log. This documentation effort was supported by photography, with the plan and section drawings of the timbers being used to create a site plan showing the *in situ* shape of the hull remains. The drawings of the timber faces were highly detailed, almost like archaeological artefact illustrations, with fasteners and wood grain clearly visible. Although only two faces of each four-sided timber were recorded, sufficient detail was captured in order to create a convincing reconstruction of the ancient vessel (Marsden, P., 1994: 36). The conscious application of a two-stage recording process, whereby timbers were documented in detail after disassembling and raising the hull, set a precedent for future nautical archaeological projects in the UK.

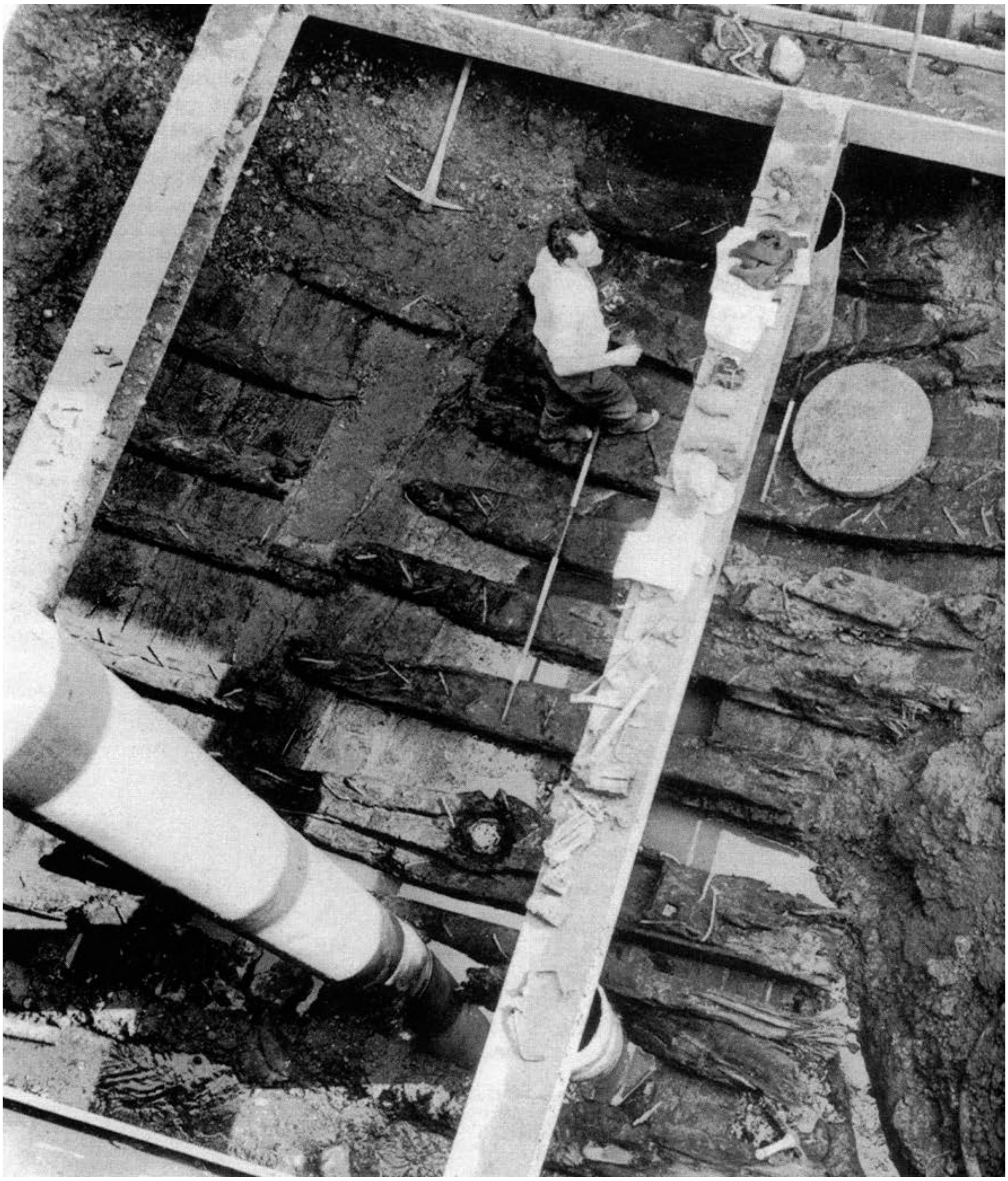


Figure 27. Excavation and documentation of the Blackfriars I vessel in 1962. The hull remains were disassembled and raised, allowing for detailed post-excavation documentation. After Uncredited, in Marsden, P., 1994: 86.

The Graveney boat

The Graveney boat, a lapstrake-built vessel discovered and excavated in Kent, England in 1970, stands as one of the most thoroughly documented boat finds up to that point. The remains of the vessel, found during drainage works, were subject to a rescue excavation lasting just over two weeks. The overall geometry of the boat was recorded *in situ* using direct measurements, sketches and photography (Evans and Fenwick, 1978: 9). The waterlogged timbers were then dismantled and placed in tanks and polythene bags, like the remains of the Skuldelev vessels excavated in the previous decade, with an eye towards cleaning and documenting each timber in detail at a later date offsite (Crumlin-Pedersen and Olsen, 2002: 41).

There were several options available at the time for *in situ* documentation of the hull remains, including photogrammetry and survey measurement. The advantages of photogrammetry included rapid and accurate data acquisition, but the lack of specialist equipment, finance and time pressure forced the team to opt for the more traditional methods. Another important factor to consider was that the photogrammetric data could not be processed or checked on site, and any necessary re-shooting of the photographs would have caused unacceptable delays (Marsden, 1978: 23). Longitudinal and transverse horizontal datums were established and used as a framework from which to measure features on the hull, like strake edges, frame positions and sections (Figure 28). Over 700 measurements were taken during two days of onsite recording. These measurements were accompanied by comprehensive black and white photography and copious field notes. Scaled site drawings of the extant hull remains were then created after the excavation by plotting out the tables of direct measurements (Marsden, 1978: 23-28).

Figure 28. Documenting the *in situ* hull remains of the Graveney boat in Kent, England in 1970. Image courtesy of Faversham Town Council (GB16_150).

The initial *in situ* recording of the Graveney boat was followed by detailed post-excavation recording included photography and direct measurements of individual timbers placed on a large grid table (McKee, 1978: 37-42; Tremain, 1978: 29-31). The recording efforts were preceded by careful removal of the extant mud and concretions. The general geometry of each timber was documented using direct measurements which were recorded in tables and on annotated sketches. Contact tracings of each timber face were then used to record features like fasteners location and orientation, concretions and wood grain (Figure 29). These transparent tracings of opposite plank faces were overlaid and compared, with the archaeologists noting any discrepancies, like missed through fasteners, and making the necessary corrections. These tracings, coupled with the tables of direct measurements, photographs, and annotated sketches, were then utilised to manually create 1:10 scale drawings of each structural timber (McKee, 1978: 37-43). The quality, accuracy and thoroughness of the recorded data enabled the archaeologists to provide a detailed analysis of the vessel’s construction and create a convincing reconstruction of the original hull form, hydrostatics, and sailing characteristics. The comprehensive, accurate, and detailed records from the Graveney boat excavation set a benchmark in the UK for the documentation of a nautical archaeological find. The results were thoroughly published and have remained valid and useful decades after the find was first published.

Figure 29. Archaeologist using direct contact tracing to document a plank from the Graveney boat. Image courtesy of Faversham Town Council (GB19_153).

Mary Rose

The hull structure of *Mary Rose* was documented using a variety of techniques, including planning frames, sketching, photography, and direct tracing. Triangulation was used to plot the horizontal position of artefacts relative to fixed datums, with a plumb bob or straight edge used to determine the elevation. However, difficultly was encountered as trenches became deeper and poor visibility prevented the archaeologists from simultaneously seeing the end of the plumb bob and the intersection of the three tapes. Nick Rule, a project staff member, developed a method for taking direct measurements from a fixed datum to a point on an object. The use of four tapes running from fixed datums allows the measurements to be averaged and quantified the level of error in the measurement. Further refinements to the so-called Direct Survey Method (DSM) included a computer programme to make the calculations and more sophisticated algorithms. The DSM method remains in use today, and is a straight forward and effective system for capturing complex geometry underwater using simple tools (Marsden, P., 2003: 47-49).

The Hedeby Harbour Wrecks

The town of Hedeby, on the German-Danish border, was an important Viking Age settlement, and subject to extensive terrestrial and marine excavations throughout the Twentieth century. In 1953, divers discovered the remains of several shipwrecks, along with numerous other artefacts, in the local harbour. In 1979 and 1980, the remains of these vessels were recorded *in situ* within a coffer dam and subsequently recovered. The Hedeby harbour excavations were similar, in methodological terms, to those excavations carried out by Crumlin-Pedersen and Olsen at Skuldelev in the early 1960s. Work within the coffer dam was facilitated by the installation of elevated walkways and a measuring grid system, which divided the excavation area into squares (Crumlin-Pedersen, 1997: 63-68, 81-85). The area inside the coffer dam was drained, and the uncovered material kept wet by a series of sprinklers.

After the excavations were completed, the individual timbers from the largest vessel recovered, a Viking-Age long ship (referred to as Wreck 1), were documented using 1:1 scale elevated plane tracings and selective photography (Figure 30). A 1:5 scale wooden model was constructed, and, from this, a composite reconstruction plan was produced. Scaled tracings of the actual timbers of the vessel were later superimposed on the hull lines drawing, in order to gauge agreement (Crumlin-Pedersen, 1997: 74). The other vessel remains, small finds, and disarticulated ship timbers were documented in a similar fashion.

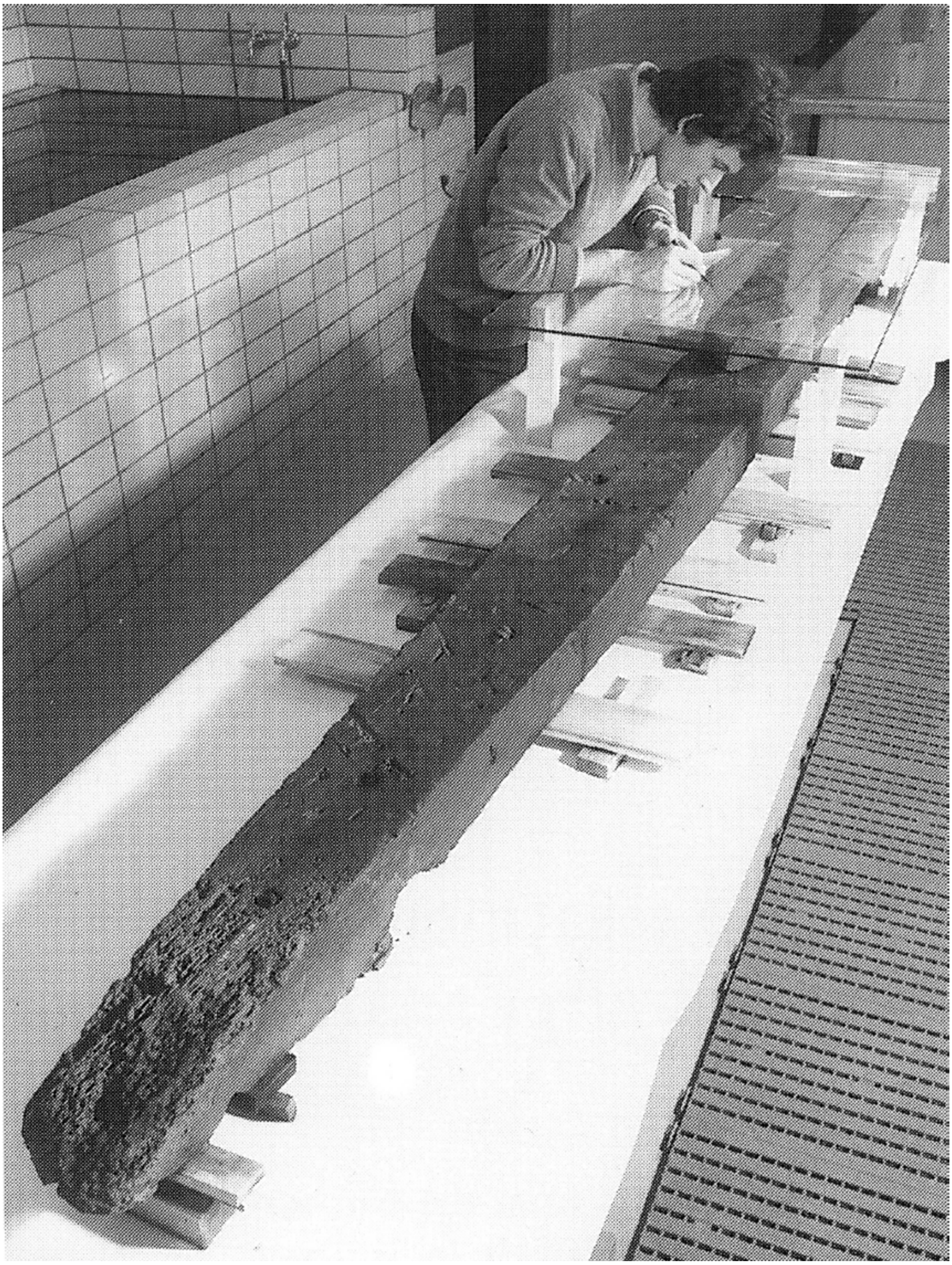


Figure 30. Full scale elevated plane tracing of timbers from the Hedeby I ship. After Archäologishes Landesmuseum, Schleswig, in Crumlin-Pedersen, 1997: 74.

Red Bay Shipwrecks

The nautical archaeology conducted at Red Bay, Labrador, Canada occurred between 1978 and 1985 (Grenier, Stevens & Bernier, 2007). Several shipwrecks were excavated, including the 24M wreck, thought to be the *San Juan*, a 16th C Basque whaling vessel lost in a storm in 1565. The 24M wreck was excavated and recorded *in situ*, using traditional underwater documentation methods, which included the use of a site grid, planning frames and 1:10 scaled drawings. The drawings from each grid were plotted onto a master site plan or mosaic that was filled in over the subsequent excavation seasons.

Additional *in situ* documentation of selected hull components of the 24M wreck was carried out underwater using direct contact tracing onto drafting film, which was stapled directly to the timber being recorded. Coloured grease pencils were used to record features, and the resulting tracings were then brought to the surface where they were retraced with permanent markers. These tracings were later reduced to a manageable scale (1:10 or 1:25) using a photocopier. Some areas of the *in situ* hull, covering up to 40 square metres, were recorded using contact tracings (Figure 31). It was deemed an efficient and accurate method for documenting complex areas of hull structure, although problems with recording areas with substantial three dimensional relief were encountered (Grenier, Stevens & Bernier, 2007: 123).

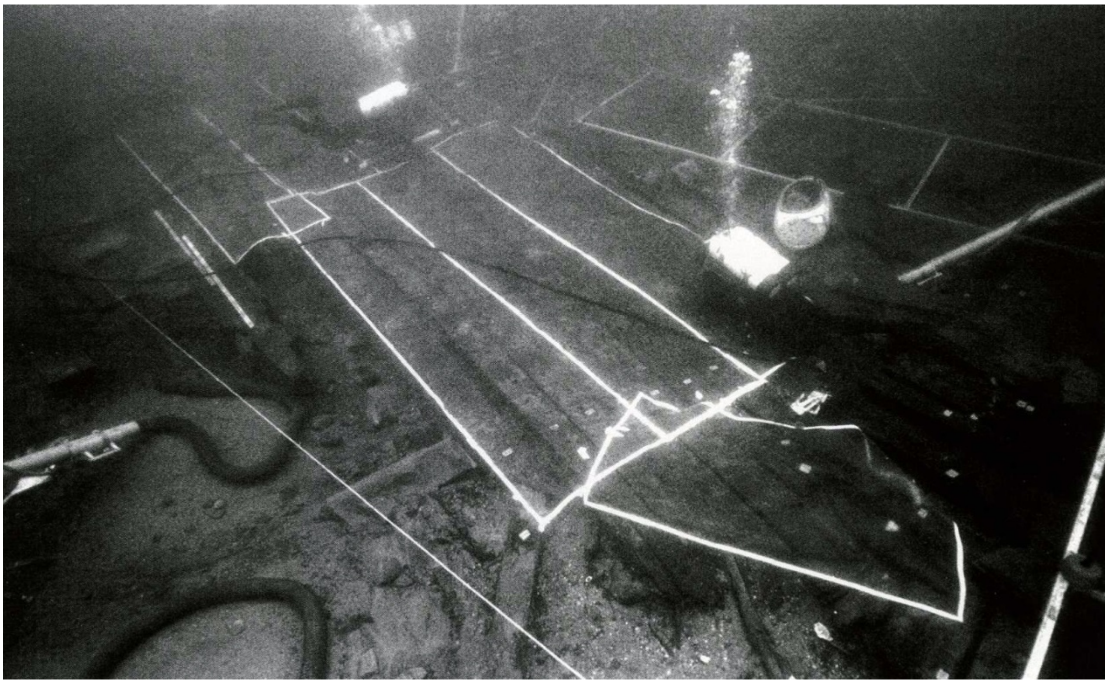


Figure 31. During underwater excavations of the 24M vessel in Red Bay, Labrador, full scale contact tracings of the *in situ* hull were created. After Waddell, P., in Grenier, Stevens & Bernier, 2007: 125.

After mapping the entire site, the archaeologists set about tagging individual timbers and artefacts using cow ear tags and copper nails. Loose or disarticulated timbers were labelled and removed, exposing the articulated hull structure. The basic dimensions of each timber were recorded, and a brief description written, accompanied by field photographs and any other notes. This data was collated into a timber catalogue which ran to some fifty volumes (Grenier, Stevens & Bernier, 2007: 129). These detailed records were instrumental in creating the scaled reconstruction of the 24M wreck.

Two other documentation techniques were used to record the 24M hull *in situ*: stereo photogrammetry and video. The stereo photogrammetry produced similar results when compared to hand drawn records in the same area. It was tested as a method of saving valuable working time underwater, but ended up taking about the same amount of time as hand drawing. A further limitation included the inability to perform other work in the vicinity while the photogrammetry was in progress. Resolution and definition of detail was also an issue, with small features, such as treenail wedges and other fine details, becoming indistinct or even invisible. Around 42 hours of video and film were shot, providing a useful archive that supplemented the 53,000+ still photographic images (Grenier, Stevens & Bernier, 2007: 127-134).

As the 24M shipwreck was disassembled, individual timbers were temporarily raised to the surface and recorded using photography and tracing or scaled drawings. Scaled drawings were made on polyester drawing film, often with only the inboard face of the planking being drawn (along with sections). The outboard face was covered with tar and often degraded, and was usually only documented using photography. When documenting the planks, the scaled drawings of the inboard face were developed or flattened, removing any twist or curvature from the record. This curvature or twisting was not considered essential or even useful in the reconstruction of the vessel (Grenier, Stevens & Bernier, 2007: 143-145).

Tracing began to be used in the 1981 field season, and involved the use of acetate film and permanent markers. The tracings were developed, and sections were drawn on at selected intervals. The completed tracings presented some practical handling and storage problems, with frequent tearing and expensive transportation and reduction costs. An internal analysis of the tracing methodology suggests that it be used only on planking and similar material. The scaled drawings and tracings of all the structural elements were then used to create scaled physical reconstructions of each individual piece, with any noted twist or bevel being added by hand (Grenier, Stevens & Bernier, 2007: 143-148). It should be noted that the timbers from the Red Bay excavation were reburied after documentation, limiting access to the material for future reassessment.

Barland's Farm Boat

The following two examples, Barland's Farm Boat and the Magor Pill vessel, are included, not for any revolutionary contribution to the field of ship recording, but rather the association of certain staff (and museums) with the Newport Ship Project. Nigel Nayling was involved in both excavations and was to use the experiences gained on both to help plan the excavation and recording of the Newport Ship. The Newport Museum was also the receiving museum for the Barland's Farm boat.

In 1993, the remains of a Romano-Celtic boat were found on the edge of the Caldicot levels approximately 2kms west of Magor, Wales. The hull remains, preserved in an in-filled paleo-channel, were found during excavations in advance of building works. The *in situ* vessel remains were documented using traditional scaled plan, profile and section drawings and augmented with photogrammetry, as well as the use of an electronic distance measuring (EDM) machine and traditional photography (Nayling and McGrail, 2004: 5). The hull was disassembled, raised and transported to an offsite waterlogged timber store. There, the timbers were cleaned and sampled prior to detailed recording by Richard Brunning, who drew the timbers using traditional methods at a scale of 1:5 (Nayling and McGrail, 2004: 111-116). Following the initial recording, 1:10 scale drawings were made from each 1:5 scale primary record, with these 1:10 scales drawings being used to build a wooden research model to explore the original hull form of the ancient vessel.

Magor Pill Vessel

The following year, the remains of another ancient vessel were located nearby, this time at Magor Pill along the northern coast of the Severn Estuary. Dating from the 13th century, the vessel was clinker built and well-preserved. Like the Barland's Farm boat excavation, the *in situ* site documentation methodology consisted of scaled (1:5) drawings, along with photographs and photogrammetry (Brunning, Nayling & Yates, 1998: 45-46). After raising the vessel, the articulated remains were cleaned, recorded and then disassembled. Individual timbers were then documented at a 1:5 scale on paper and also documented by 1:1 direct tracing onto polythene in a conservation studio. These 1:1 scale direct tracings were later transferred onto acetate to facilitate the creation of a full-sized model of the hull (Redknap, 1998: 131). The scaled drawings from site and the direct tracings were compared to one another as a sort of accuracy check prior to completing the final timber drawings for publication. An illustrated timber catalogue was published at a consistent 1:15 scale in the final publication (Brunning, Nayling & Yates, 1998: 45-103).

It is interesting to note that, in 1998, Mark Redknap suggested that one of the most accurate way to predict, model and test the probable original hull form would be to use 3D modelling, while acknowledging that the then currently available software was unsuited for detailed and meaningful manipulation of individual ship timbers and hull form. Instead he suggests that a full size replica be constructed from the 1:1 tracings in order to determine the original hull form (Nayling, 1998, Redknap, 1998: 142). A partial 1:1 scale model of the vessel was eventually constructed and analysed in the mid-1990s (Figure 32).

Figure 32. A partial 1:1 scale model of the Magor Pill vessel. Toby Jones.

La Belle

In 1686, *La Belle*, a French light frigate sailing ship, wrecked in Matagorda Bay, Texas, USA. The remains were discovered in 1995 and excavated between 1996-1997 (Bruseth and Turner, 2005: 47-63). The excavation of *La Belle* shares many similarities with the Newport Medieval Ship excavation. Both ships were excavated inside of 'dry' coffer dams, both were documented *in situ* using a variety of techniques and both were disassembled and raised for further study and detailed recording. Archaeologists working on *La Belle* used one square metre planning frames to record the structure of the hull and position of the numerous artefacts. They also employed comprehensive photography and stereo photogrammetry on selected parts of the hull. In addition, a total station was used to plot the artefacts prior to removal and also to record frame and plank intersections (Figure 33). Hull cross-sections were recorded in this manner, as well as being taken using the more traditional method involving tapes and plumb bobs. A digital wireframe drawing, created using the total station data, was available on site. The effective use of multiple *in situ* recording methods, including photogrammetry, photography, total station survey, and traditional approaches helped to ensure a thorough and detailed (and redundant) composite site record that could also allow for the analytical comparison of different approaches (C. Meide 2013, pers. comm 1 Apr.).

Figure 33. During the excavation of *La Belle*, archaeologists used a Sokkia SET5E total station to plot the 3D position of all hull timbers and artefacts, prior to recovery. After Uncredited, in Bruseth and Turner, 2005: 56.

Following the *in situ* documentation, the individual timbers were labelled using cow ear tags and then removed by severing the extant fasteners. Timbers were then brought to the interim project headquarters where the concretions were removed and 1:1 scale elevated plane tracings were made of every face of each timber before they were transported to a conservation facility (Bruseth and Turner, 2005: 47-63). The documentation work performed during and after the excavation of *La Belle* was of a high standard and has served as an example of best practice for subsequent excavations.

Renaissance ships from Copenhagen

In 1996-1997, during redevelopment work in Copenhagen, Denmark, the well-preserved remains of eight ships were found. They were all found in an ancient harbour that had been filled in. The assemblage of carvel-built wrecks dated to between 1580 and 1738. Like the Graveney boat excavation, there was pressure to document the remains as quickly as possible in order to allow construction to continue. The decision was made not to conserve the timbers which meant that there was only one opportunity to gather as much construction information as possible about each vessel. The recording system used on the B&W wrecks was a synthesis of advanced digital surveying technology and traditional archaeological recording techniques, including direct survey measurements and photography (Lemée, 2006: 315-320).

The primary survey tool used to record the *in situ* remains at the B&W site was a total station, which is an optical/electronic device that can provide highly accurate line-of-sight three dimensional coordinate measurements. Early total stations took some time to record and process a set of coordinates, which led the project team to configure the total station to take only *x* and *y* datum points while ignoring the *z* axis measurement. This was a conscious decision, taken in order to create a digital 2D site plan as quickly as possible.

The edges of the exposed timbers were plotted with the total station and then these measurements (single points of data) would be connected with lines using Computer-Aided Design (CAD) software (Figure 34). This digital drawing, containing each outlined ship timber element, was then transferred to transparent drafting film and carried on site, where it was used as a template on which to record direct measurements, fasteners and any relevant wood science. The drawings were then checked a final time against the hull remains. As each layer of the hull (ceiling, framing, planking, etc.) was surveyed, it would be removed and the process of documentation repeated. The resulting drawings from each layer were then corrected and overlaid, before a final composite drawing was inked, resulting in a detailed two-dimensional scaled site plan (Lemée, 2006: 77-95).

Figure 34. The use of a total station to measure in points on the hull of one of the Renaissance Ships in Copenhagen. After Gyldenkaerne, B., in Lemée, 2006: 83.

As mentioned above, the '*z*' measurement was not taken during the total station survey. This decision was based on the need to take total station measurements as quickly as possible (averaging 2-3 seconds per *x* and *y* measurement), with the acquisition of the *z* coordinate adding 7-8 seconds to each measurement. Instead, elevations and cross-section data was recorded using traditional horizontal and longitudinal reference lines, the positions of which were recorded using the total station, which allowed these cross-sections to be integrated with the 2D site plan. The total station recording system was primarily used on weekends when the heavy equipment (and associated vibrations) was not present. Up to 1200 *x and y* measurements could be taken on a typical weekend day (Lemée, 2006: 82-84).

After *in situ* documentation, selected timbers and hull cross-sections were removed from the B&W wrecks using a chainsaw. The remainder of the hulls were discarded, but the retained hull sections were later documented off-site using traditional manual hand drawing at a 1:10 scale. Most of these timbers were also discarded after documentation, removing any chance of re-analysing the actual ship timbers in the future (Lemée, 2006: 90-95).

The advantages and disadvantages of using the total station versus traditional survey methods were clearly laid out by Lemée (2006: 89). The decision to omit the z coordinate was based on the limited time available to study the remains *in situ*. The current technology (c.2014) used in total stations allows for much quicker acquisition of data points, and it would be unusual today not to include the elevation when taking survey data. Total stations have since become common place on modern excavations, and are widely used when documenting *in situ* remains of ships found on terrestrial sites, including the Newport Medieval Ship bow excavation and the Barcode Wrecks.

The Roskilde vessels

During expansion of the Viking Ship Museum in Roskilde, Denmark, a substantial number of shipwrecks were discovered. Between 1996 and 1997, a total of nine vessels, dating from the late Viking Age and Medieval period, were excavated. Some had been damaged by machine excavation, while others were severed into two parts by the installation of a sheet pile coffer dam (Myrhoj and Gøthche, 1997: 3-7). The *in situ* shape and arrangement of the exposed parts of the vessels were documented using traditional techniques, including the use of tape measures, scaled drawings, and photography.

One of the vessels, called Roskilde 1, was found in a shallow area of the harbour, and was excavated and raised in 1997. The traditional hand tape measurements taken on site were entered into a 3D data plotting software programme called WEB, which had been developed by Nick Rule for use on the *Mary Rose* excavation (Rule, 1989: 157-162, Gøthche, 2006: 255). The WEB software programme was useful for plotting out measurements taken using the Direct Survey Method, where desired positions were recorded in relation to fixed datums (Figure 35). The software displayed the resulting network of measurements (and residual errors), and this data could be utilised within a CAD software programme (or by hand) when creating a site plan.

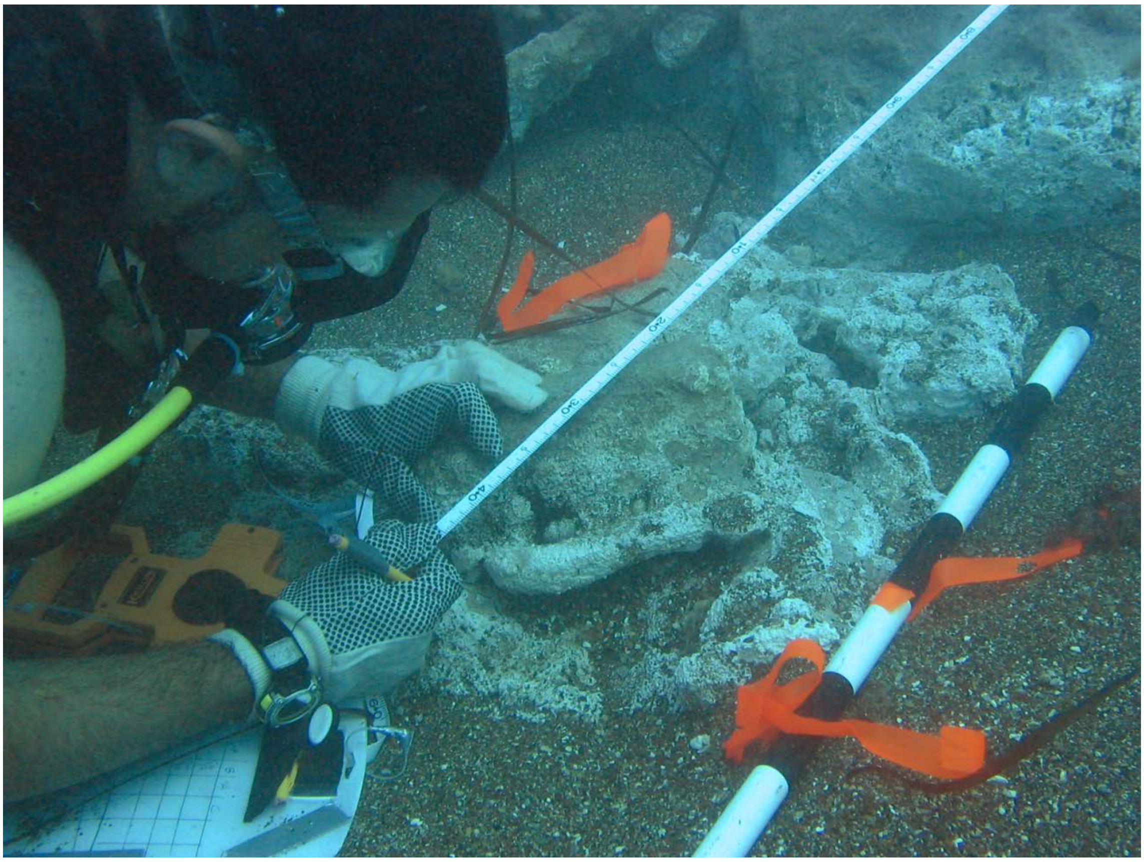


Figure 35. Archaeologist using the Direct Survey Method technique on a submerged site in Cyprus. Multiple measurements are taken between fixed datums and several points on an object, allowing for the creation of a 3D network of points describing the spatial relationship between objects. Toby Jones.

Timbers from the recovered vessels were subsequently cleaned and documented at a 1:1 scale using traditional tracing methods and also by using a FaroArm contact digitiser and Rhinoceros3D software, coupled with comprehensive digital photography (Figure 36) (Gøthche, 2002: 16-17, Gøthche, 2006: 258).

Figure 36. Documenting a ship's timber using a contact digitiser at the Viking Ship Museum in Roskilde, Denmark in 2004. Toby Jones.

The Doel Cog I

The Doel Cog I was discovered in 2000 during excavations for a shipping container terminal/port near Antwerp, Belgium. Archaeologists and conservators were given eight weeks to record, disassemble and remove the vessel, which was found upside down in a silted-up channel. Given the nature of the rescue excavation, careful comparisons of the advantages, disadvantages and costs of various recording systems had to be considered. The initial primary record consisted of a sketch of the site annotated with timber function codes and unique identifying numbers. No 1:1 scale drawings were produced, however a conscious decision was made to document the individual timbers in detail at a later date offsite.

It was decided that there was insufficient time to use a total station to record the position of timbers *in situ*. However, concessions were made to document the overall *in situ* hull form using a terrestrial laser scanner. Other considerations in favour of laser scanning included the potential of using the resulting 3D point cloud data for taking direct measurements (including scantlings and fastener spacing) and the ability to make a site plan after the excavation. The digital format was also seen as a prerequisite for enabling future animation possibilities (Van Hove, 2005: 52-54).

The remains were uncovered and scanned in several phases, with the first phase capturing the outboard surface of the hull planking, and the second phase capturing the outboard face of the floor timbers and framing timbers (Van Hove, 2005: 52-54). It took a total of 31 hours on site for the two phases of laser scanning, with an additional 90 hours of post processing (Terve, 2002: 10, 14). The estimated cost of the laser scanning was €75,000. A physical scale model of the *in situ* hull remains was later constructed. In 2007, it was noted that the 3D scan data was in a proprietary format that could not be accessed, exported or migrated to a useable format (Fix, 2007: 19).

The Newport Medieval Ship

The Newport Medieval Ship hull excavations were led by Nigel Nayling, who had previously excavated the Barland's Farm vessel and the Magor Pill boat, both found just to the east of Newport on the Gwent Levels. The methodology used by Nayling was strongly influenced by the archaeological work done at the Viking Ship Museum in Roskilde. There had been collaborations between Nayling and Crumlin-Pedersen concerning the post-excavation research programme on the earlier projects, with the latter keen to share the knowledge accrued during the excavation and post-excavation research of the Skuldelev vessels. This willingness to share/export methodologies was to have a strong influence on the excavation design and post-excavation research of the Newport Ship. Roskilde was seen as an international centre for excellence in terms of nautical archaeological research and recording, and both Newport and Roskilde benefitted from the international association (This relationship lasted long beyond the initial exaction, with the project team being trained in contact digitising at Rosklide in 2004).

The articulated hull was documented *in situ* using a variety of traditional two-dimensional recording techniques, including scale plan (using planning frames) and section drawings, offset measurements, colour and black and white photography and colour videography. Stereo photogrammetry was used at two epochs or stages to document the *in situ* hull. The first epoch recorded the shape of the entire internal hull with the ceiling planking removed, while the second epoch recorded the geometry of the inboard face of the hull planking after the stringers and framing had been removed. Certain areas were obscured by standing water or obstructed by the concrete piles, however a relatively comprehensive photogrammetric record was achieved. The site photogrammetry was processed and delivered to the ship project as a series of 3D vector graphics files and traditional 2D scaled plan view drawings. Disarticulated material was drawn on plan, and removed prior to the photogrammetric surveys. A total station was used to record the location of control points attached to the bow timbers, which were excavated in April 2003 (Nayling and Jones, 2013).

Sørenga 7 Shipwreck

The documentation of the Sørenga 7 wreck was carried out by the Norwegian Institute for Cultural Heritage Research (NIKU), which excavated the vessel in 2006. This wreck was documented using a total station, in additional to laser scanning and photography (T. Falck 2013, pers. comm., 27 Feb.). However, the laser scan point cloud data was not fully utilised. This 3D data set was instead flattened and traced over with a pencil in order to produce a site plan. Archaeologists working on the project questioned the high cost and expert knowledge necessary for creating the laser scans, and have suggested that it may be unsustainable to have a large-scale laser scanner available on a stand by basis for documenting the multiple layers of most shipwrecks. Instead, they argue that a judicious use of a total station, coupled with extensive digital photography and supplemented with hand drawings, is a more practical way to document *in situ* remains of vessels like the Barcode wrecks mentioned below.

However, it is likely that large-envelope laser scanning will play an increasing role in the future of documenting *in situ* hull remains, given the decreasing costs, increasing availability, and ability of computers and software to rapidly process and display large point clouds. The acquisition of accurate 3D point cloud data should be seen as a complimentary data set that can be used to efficiently document the post-depositional shape state of the *in situ* remains. However, the lack of archaeological interpretation or control when using a laser scanner relegates the methodology to second place when compared to interpretative methods where the archaeologist can intelligently pick out features that are worthy of detailed recording. Nevertheless, laser scanning might usefully be seen as a ‘belts and braces approach’ allowing the archaeologist to revisit the point cloud data at a future point with new questions, whose answers might have otherwise been lost during the disassembly phase.

The Barcode Wrecks

The Norwegian Maritime Museum developed new recording methodologies while excavating the 'Barcode' ships in Oslo, Norway in 2008 (Gundersen, 2012: 80). The project was a good example of the application and integration of modern digital survey technology coupled with the use of traditional recording methods. The remains of thirteen 16th-17th century lapstrake vessels were discovered during redevelopment work in a filled-in ancient harbour.

In common with similar projects where large numbers of ships are found simultaneously, there was intense pressure to document the finds as quickly as possible, so as not to delay the construction work any longer than necessary. The Norwegian Maritime Museum developed a method of taking aerial site photos of each excavated shipwreck which included geo-referenced pegs (plotted using a total station) visible in each image. A plan view photograph of the site could be produced in 30 minutes and was then laminated and made available to the excavators. The photographs were annotated with the timber identification codes as they were applied to each timber.

The ship timbers were then removed, piece by piece, and layer by layer, with additional photographs taken as necessary. These photographs were also used for making digitised site plans during the field documentation and disassembly stage. Initially direct measurements and offsets were also taken and recorded on forms, but increasing time pressures forced the archaeological team to forgo this step and abandon all direct measurements of the *in situ* remains (Vangstad, 2012: 307-308).

The rushed recording on site was followed by a programme of methodical off-site contact digitisation, with the resulting detailed digital drawings being plotted back onto the site plans and photographs.

Summary of *in situ* ship find documentation techniques

The abovementioned case-studies help illustrate the development of documentation methods, with new techniques and technologies being applied as they become available. Innovative processes, like using photogrammetry and a total station, were quickly adopted by various excavators and adapted for diverse conditions. There was a clear trend towards gathering more data with increasing accuracy and rapidity, as evidenced by the migration towards digital approaches. As can be seen, there was steady progress towards capturing progressively more detail about the *in situ* hull form, except when time pressures forced excavators to take shortcuts.

A parallel trend was the need for a greater level of documentation detail than could be obtained from *in situ* recording alone. The ability to create a comprehensive, meaningful and convincing reconstruction depended on the accurate documentation of small, seemingly inconsequential features, like additional nails or plugged holes. These features were difficult to detect and decipher in the field, and could really only be properly documented during a secondary stage of more detailed cleaning and recording of individual timbers. This secondary stage of recording has now become standard practice and will be discussed in detail below.

It is worth thinking about why methods for recording have changed over time. What drives innovation in archaeological recording? Many methods have been used to archaeologically document ships and ship’s timbers, with various institutions or regions adopting or adapting methods to suit specific conditions or traditions.

Despite differences in approach, the core requirements of accuracy and utility have always remained of paramount importance. Technology, in the form of computers and electronic measuring devices, has arguably been the primary driver or enabler of innovation. The utilisation of such equipment has allowed for the collection, organisation and storage of increasingly accurate data relating to the geometry and constructional features of ships and ship timbers, both *in situ* and during the post excavation research phase. Most, if not all, of these technological tools used by archaeologists were developed for uses other than archaeology. They were adapted or modified by archaeological practitioners in the field or lab, with their use spreading wider as knowledge or methodology was disseminated and staff moved between excavations.

There are often pressures on archaeologists to document a ship find as quickly as possible, especially if it is holding up construction work or funds are limited. The pressure to do more, in less time, for less money, is a common situation facing the ship archaeologist. The ability to capture accurate data quickly is therefore an obvious advantage. Technological innovation in the field of archaeological recording has been led by the application or adoption of tools or methods that are ever more accurate and efficient at gathering data. Development in this field is hardly static, with technologies like side-scan sonar, photogrammetry and film photography being augmented, and indeed, superseded by laser scanning and digital photography/photogrammetry. Further refinements to the abovementioned tools include the development of full colour laser scanning, underwater laser scanning and multi-beam and sector-scanning sonar. Each of these technologies is constantly being refined or improved in terms of speed, accuracy and resolution. On some level, this innovation is driven by profit, with commercial competitors striving to offer the fastest/most accurate/most ‘clever’ machine to capture useful data. This quest to increase market share has the added bonus of driving down the sometimes eye-watering prices of the latest equipment to more affordable levels.

The utility of the data captured also needs to be carefully considered. What are the advantages and limitations of having the data in analogue (paper) or digital formats? In what ways can the data be disseminated or shared? Can it be effectively archived? Is the data in a format that can be readily accessed and compared to data captured and published in a different way? This last question highlights the fact that although archaeologists work on specific sites, the knowledge that they generate becomes part of the collective pool, where it is subject to analysis and review. Having detailed data that is accurate, trustworthy, and in a commonly understood and accessible format is clearly advantageous.

At the end of the day, it is the quality and utility of the data that is ultimately of interest to the archaeologist. The considered adoption and adaptation of available technology to the documentation of sites and ship timbers is of critical importance. While there are limits to the accuracy and utility of older methods, newer technologies, like laser scanning, are not without shortcomings, including the inherent lack of interpretation, necessity of line-of-sight view of the material to be recorded and substantial post-processing requirements. A system that purports to quickly document an entire site might in the end prove to be a false economy, with post-processing time, on expensive software and hardware, exceeding that spent in the field by a considerable margin. Such limitations, along with the overall significance of the find, need to be considered when choosing the most appropriate methodology and available technology to document a site.

Traditional Post-Excavation Ship Timber Documentation Techniques

During the post-excavation research phase, timbers from ship finds have traditionally been recorded via 1:1 scale direct (or elevated plane) tracing onto clear film, as was the case with the Magor Pill vessel and with the Skuldelev vessel excavations (Brunning, Nayling & Yates, 1998: 46, Redknap, 1998: 131, Crumlin-Pedersen, 2002: 49-56). These methods were well established and provided the framework for producing fairly accurate two dimensional records. To enable physical modelling, these two dimensional drawings can be projected onto paper and printed out. The cut out ‘paper’ planks can be backed with card and fastened together with pins to create a tentative hull form (lapstrake vessels are built shell first with the framing inserted after the shell has been erected – in conceptual terms, the hull form is determined by the planking, as opposed to more modern carvel built ships, in which the frames are erected first and then covered with a planking skin). However, the method is subject to some error, as a two dimensional record can ignore considerable detail or curvature in the undocumented third dimension or along edges and end grain.

Producing 1:1 scale drawings or tracings of ship timbers has been the traditional method utilised to record individual timbers (often in a laboratory setting during the post excavation research phase of the project – a peculiarity of ship timber excavation projects, due to the complications of working underwater or in other adverse environmental conditions). Timbers were documented in this fashion because it captured important curvature and fine detail that would be lost if the initial drawings of the timbers were made at a 1:10 (or similar) scale. The potential for the introduction of error, when making a 2D paper reconstruction or 3D physical reconstruction model from scaled records, was inherently higher than it would be for 1:1 scale tracings. The effects of cumulative error over multiple strakes and frame stations might create a set of hull lines that were not accurate or true to the archaeological material (Note: photography and stereo photogrammetry are also useful and important tools for recording material from archaeological sites such as shipwrecks, but they are beyond the scope of this thesis, which is focused on digital contact recording and modelling).

Traditional tracing can be accomplished in two ways, direct contact tracing and elevated plane tracing. The first method, direct contact tracing, involves laying a sheet of clear Melinex directly on the surface of the timber and recording the surface detail and edges using permanent markers in a variety of colours and predefined symbols, which represent different features like nails or wood grain. The second method, elevated tracing, involves suspending a clear, hard and flat surface (often perspex) above the timber on which the Melinex or clear drafting film is placed. Again, using permanent markers, the archaeologists would document the edges, fasteners, and wood grain on each face. Laser pointers and pens could be coupled together in a block in order to reduce parallax error when using the elevated plane method.

The end product in both cases is a 1:1 scale 2D tracing of each face of the timber, resulting in four drawings in total for a frame, and two drawings for each plank or stringer. Notes, sections and offset measurements can be added directly to the drawing to provide additional detail about unusual fasteners or features. Neither method is perfect, however, with contact tracing introducing distortion along the length of a curved timber, while the elevated method can have distortion created by parallax error (Steffy, 1994: 202-203). The resultant 1:1 scale tracings are typically scaled down to a more manageable scale, usually 1:5 or 1:10 and then corrected for distortion (provided an accurate scale is included on the drawing and that the drawing has been scanned without slipping or stretching). They can then be vectorised to create a 2D digital plan (CAD file or scaled vector graphics file) of each face of the timber. This 2D end product is suitable for most traditional publication requirements, where each face of a timber is displayed, often at a reduced scale.

A History of Contact Digitising In Nautical Archaeology

The following section examines the development and application of contact digitising in the field of marine and nautical archaeology, and presents the foundation from which the Newport Ship documentation methodology developed. A series of brief case studies will show how the idea of using contact digitisers started and grew, as well as helping to place the Newport Ship Project recording methodology into a broader context.

Contact Digitising in Practice

To mitigate or reduce the error inherent in attempting to convert the geometry of a physical artefact into a 2D record and then into an accurate 3D model of the original object, it is desirable, when possible, to document the 3D geometry during the recording process. This can be achieved by a variety of methods, including contact digitising, laser scanning and structured-light scanning. All of these 3D recording methods require expensive hardware and software, with the costs possibly mitigated by the potential increase in throughput when compared to traditional documentation methods. However, the greatest benefit would undoubtedly be in the quality of the record, with 3D geometry recorded with sub-millimetre accuracy in a digital format.

Contact digitisers are sophisticated coordinate measuring machines that typically consist of several rigid tubes that are connected by joints that both rotate and extend (although some modern contact digitisers, like the Creaform HandyProbe C-Track, utilise a portable wireless handheld probe (Ranchin-Dundas, 2012). The multiple axes of rotation allow the probe tip on the end of the arm to reach anywhere within in sphere shaped envelope. They work by constantly tracking the position of a probe tip or stylus in three dimensional space (Figure 37).

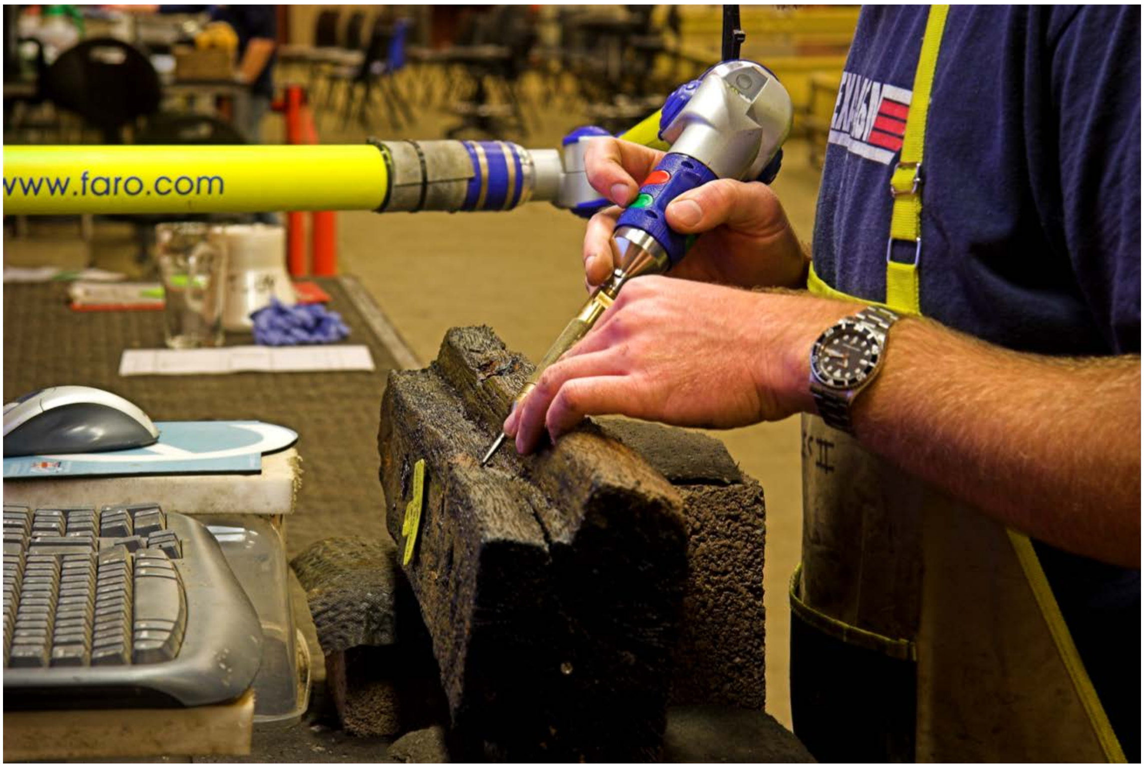


Figure 37. Archaeologist using a FaroArm contact digitiser to document a brace from the Newport Ship. Rex Moreton.

The tracking system inside the digitiser constantly detects the degrees of rotation/angles in each joint and, using the known fixed distances between joints, applies trigonometric equations to determine the x,y,z coordinates of the probe tip relative to a fixed base. Provided that neither the timber (or other object) being recorded, nor the fixed base, move relative to one another, the fine detail and geometric data captured by the probe is accurately plotted and displayed in the chosen software. They have traditionally been used in quality analysis, quality control and reverse engineering applications, and are exceptionally accurate and precise tools. Their application and utility in marine archaeology, although relatively recent, has been widely adopted. In fact, the ability to simultaneously accurately record and interpret an artefact using digital technology and in three dimensions is proving revolutionary in marine archaeology.

Using Contact Digitisers to record ship's timbers

When recording a timber, the user selects a capture tool (usually single point, polyline, or digital sketch (DigSketch) and the probe measures x,y,z data points that are recorded in a Computer Aided Design (CAD) software programme like Faro CAM2 Measure, AutoCAD, or Rhinoceros3D. Rhinoceros3D software uses N.U.R.B.S. (non-uniform rational basis-spline) mathematics to define curves, surfaces and solids. A detailed discussion of the software structure, capabilities, and mathematics is beyond the scope of this thesis, but further information can be found on the extensive Rhinoceros3D software website (McNeel, 2008). The Newport Ship Project used Rhinoceros3D software to capture all of the data produced by the contact digitiser. The project used Rhinoceros3D Version 3 to capture the data, and Version 4 to model the timbers. Rhinoceros3D Version 5 was used to create the master composite files, which lined up all of the recorded timbers in their right relative positions.

Nearly all of the digital data captured by the contact digitiser was created using the single point, polyline, and DigSketch tools. The single point tool was used to record locations of samples, control points, and fastener centres. Polyline (which connects individually chosen single points with a line) was used to trace around fasteners and roves. The DigSketch tool was similar to polyline, except that points could be automatically taken at predetermined intervals, allowing the recorder to draw long edges or wood grain accurately and quickly. Points and lines are displayed in real time, as they are captured. Settings in the software allow the recorder to view the lines or the lines with their constituent points, which are normally hidden.

When using the DigSketch tool, accuracy can be affected by inadvertently changing a particularly important setting in the Rhino software. When drawing with the DigSketch tool, there is an option to change the degree of the curve. Degree 1 curves are those in which the curve or polyline is drawn through each recorded point. Degree 2 and 3 (and higher) curves are smoothed or faired by the software, with the displayed curves merely passing near the actual points. Any degree setting other than Degree 1 causes areas where there is a sharp bend or corner to appear more rounded than they actually are in reality (For further information see section on Rhinoceros3D modelling software below).

When taking multiple points, with the polyline of DigSketch tool, wireframes were automatically constructed from the point data collected by the digitiser. The resulting digital record of each timber is an accurate three-dimensional wireframe drawing, which was saved as a read-only file in the proprietary Rhino .3DM file format and archived (also for editing and digital solid modelling). The resulting wireframe drawing could also be saved in a variety of other proprietary and open source formats, including .DXF, and .DWG. Rhinoceros3D software was utilised throughout the project because it was inexpensive, intuitive, and versatile. It has since become the standard software used by maritime archaeology digital recording projects around the world. Data produced by the contact digitiser was captured, stored and manipulated on a standard modern laptop or desktop computer. Although the data was captured and edited in the proprietary .3DM format, the final files were later converted into the .DWG format for archiving and widespread dissemination.

Informed interpretation was critical when recording the ship timbers. Surface details of the artefacts, including edges, fasteners, tool marks and wood grain were interpreted by the archaeologist, who then chose the appropriate software layer and data capture tool to record the information. The use of a 'common visual language' for the layering system, which consistently assigned specific colours to specific layers, allowed archaeologists to understand and compare ship timber drawings from other shipwrecks even if they couldn't understand the language of the layering system. Using such a layering system correctly and consistently allowed many important details of how shipwrights converted the raw tree into a finished ship timber to be documented. It also provided a singular opportunity to explore a tangible link to the actions and thoughts of ancient craftsmen. Significant emphasis was placed on the accurate recording of the ship timbers because future research and reconstruction would depend how well the original material was recorded (Steffy, 1994: 191).

The Early Days: from the 1990s to 2005

Mystic Seaport, Connecticut, USA

One of the first known uses of a contact digitiser to record maritime cultural heritage was the documentation of ship's half models by Mark Starr at Mystic Seaport Museum in Connecticut in the United States (Starr, 1996: 69-72) (M. Starr 2013, pers. comm., 5 Jun.). Mystic Seaport first used a total station to document the hull forms of larger ships and boats in the mid-1990s, and soon thereafter acquired a FaroArm to record ship's models (Note: While a detailed discussion of non-contact digitisers, such as large envelop laser scanners and total stations, is beyond the scope of this paper, it is clear that their utilisation for documenting full-size hulls and sites is comparable to the use of contact digitising on smaller hulls and models, with a sort of parallel technological and methodological evolution taking place). The point cloud data captured by the FaroArm was processed using a marine engineering surface modelling programme called MultiSurf, which was created by the naval architecture design company Aerohydro. The exterior hull surface of wooden ship models was carefully digitised and the resulting point cloud was then surfaced. This surface was then sliced in order to extract sections, waterlines and buttock lines, which were then arranged for publication in a traditional two-dimensional printed format. Accuracy and efficiency were the primary reasons for choosing this digital documentation methodology, with the process being codified into a manual and shared with other museums participating in the research project (M. Starr 2013, pers. comm., 5 Jun.).

National Museum of Denmark

A similar research project got underway a few years later in Denmark. The need to collect higher quality (i.e. more accurate/useable/efficiently gathered) site data, and develop digital methods for modelling, analysing, sharing and archiving this data, led to the creation of a technological development programme at the Centre for Maritime Archaeology at the National Museum of Denmark. One aspect of the project, set up in 1998, was to examine ways in which new and existing technology and ever increasing computing power could be applied to make the acquisition of primary site date more effective.

Under this programme, researcher Jørgen Holm (and later, Fred Hocker), began experimenting with using an early coordinate measuring machine, called a Cimcore Immersion Microscribe, to digitally record small objects three dimensionally. These trials were followed by attempts to record larger objects, such as intact hulls, individual ship timbers, and even some non-nautical objects, including a painting on a church wall. Attempts were made to combine the data generated by the contact digitiser with other digital data sets, including laser scans and total station data. The archaeologists also experimented with the resulting wireframe drawings by applying surfaces and correcting areas of damage (Hocker, 2001: 16-22, Hocker, 2000: 27-30).

One of the first major applications of contact digitising in maritime archaeology was the documentation of the hull form of the Hjortspring boat replica, *Tilia Alsie*, using a FaroArm and a Cimcore Microscribe XLS between 1999 and 2000 (Crumlin-

Pedersen and Trakadas, 2003: 84-89, Hocker, 2000: 27-30). The research design for the documentation of the *Tilia Alsie* identified four primary types of documentation, including traditional direct measurements, total station survey, contact digitising, and photography/videography. The direct measurements were intended to be used as a baseline against which the digitally recorded data could be compared. The digital data captured by the total station and contact digitisers were integrated, using control points common to both files. These control points allowed the smaller, more localised areas recorded by the contact digitisers to be accurately positioned or referenced within the overall, or global, point cloud created by the total station (Crumlin-Pedersen and Trakadas, 2003: 85). This method was found to gather coordinate data that was at least as accurate as direct measurement, while being quicker, and crucially, produced a digital three-dimensional data set.

After considerable research and testing and the *Tilia Alsie* trials, the Cimcore Immersion Microscribe was found to be less than ideal, however, with the inability to change or modify the probe tip a major drawback. It was at this point, in August 2000, that the National Museum of Denmark's Centre for Maritime Archaeology (Techniques and Auxiliary Sciences section), decided to purchase a FaroArm Sterling model 10-foot contact digitiser, after trialling it on the documentation of a stone sculpture. The *Tilia Alsie* project, along with the other test projects, had proven the viability of using contact digitisers to digitally document cultural heritage.

Kolding Cog

The Kolding Cog was to serve as a test bed for a number of new documentation methodologies in nautical archaeology. The vessel, dating to the late 12th century, and discovered in 1943, was built of oak and approximately 18m in length. It was partially excavated, and the material documented by a naval architect, with selected timbers and artefacts being recovered and sketched. The site was revisited by Ole Crumlin-Pedersen in 1967 during a sub-bottom profile survey (F. Hocker 2013, pers. comm., 26 Apr.).

The site was relocated using an AUV in 2000 and fully excavated in 2001 by the National Museum of Denmark. In March 2001, archaeologists, working in 0° C water, used direct survey measurement to create an underwater site plan (F. Hocker 2013, pers. comm., 26 Apr.). For datums, they screwed in at least three stainless steel screws into each timber, with the plan to keep these points in the timbers at least through the detailed recording of each timber. The concept was to create a three dimensional reconstruction of the *in situ* hull form using the recorded geometry of each individual timber and fitting this shape within the framework provided by the datums. After inserting the datums and mapping the site the vessel was dismantled piece by piece and raised. The timbers were then cleaned and packaged.

These timbers were contact digitised by Fred Hocker and Steffan Wessman in two phases, from 1 May – 5 June and 1 September – 15 November 2001, with the operational methodology continuously evolving. The digitiser was setup in an archaeological timber storage facility in Herringløse, Denmark. The excavated material consisted of 56 individual timbers, which varied in weight between 150 and 600kg. The point data captured by the contact digitiser was initially processed using Faro's own recording software, CAMtoMeasure, but, once software drivers became available, the archaeologists switched to using Rhinoceros3D Version 2 modelling software. Rhinoceros3D software was chosen because the NURBS modelling that the software was based on produced geometry that was ideal for documenting the complex compound curves present on ship's hulls (F. Hocker 2013, pers. comm., 26 Apr.).

Roskilde Wrecks

The next maritime application of contact digitising was the Roskilde I wreck, one of several vessels discovered and raised during the enlargement of the Viking Ship Museum in Roskilde. Beginning in the autumn of 2002, the digital documentation of this vessel's individual timbers marked the commencement of 'production' use of contact digitisers in maritime archaeology (Hocker, 2003: 1). The recording workshop, previously arranged to enable the efficient traditional recording of archaeological ship's timbers was slightly modified for the inclusion of a contact digitiser. The workshop already had an overhead system of digital cameras and specialised lighting, allowing the timber recorder to simultaneously document multiple aspects of the timber while minimising handling (Figure 38).

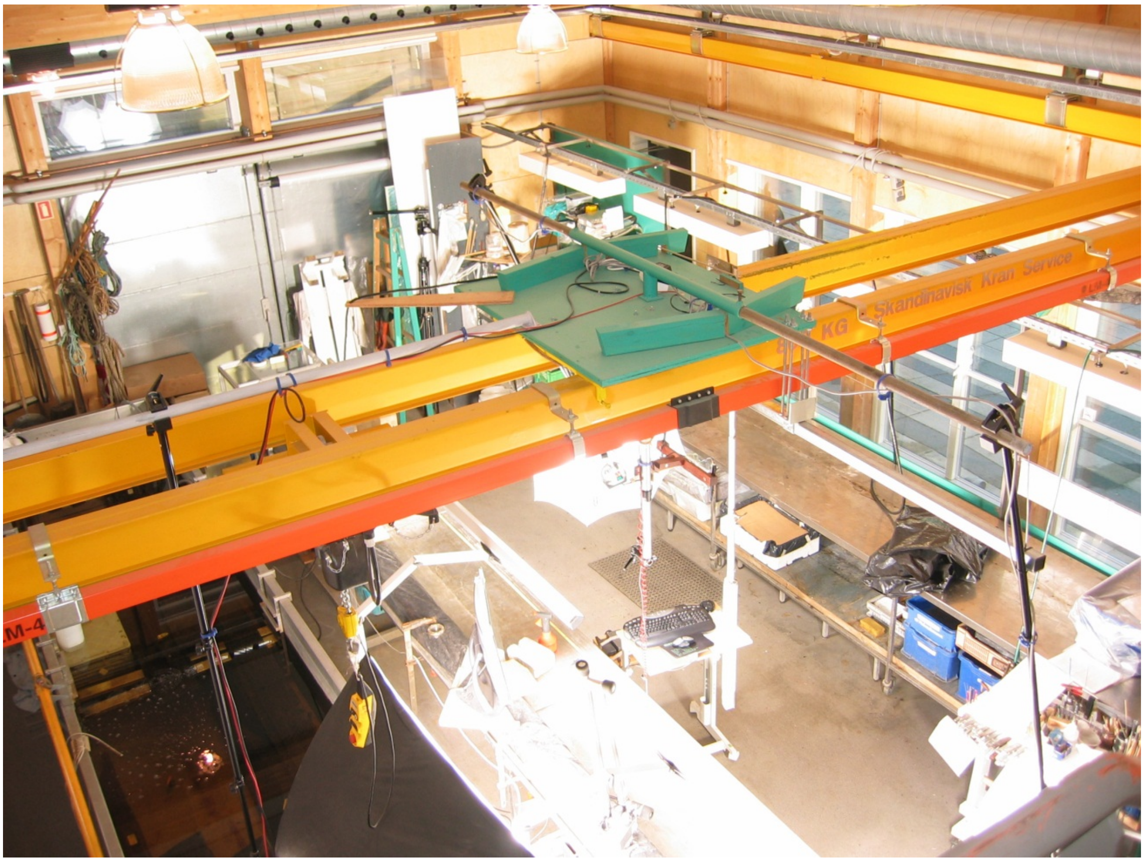


Figure 38. The recording workshop at the Viking Ship Museum in Roskilde, Denmark, was set up in an efficient way that allowed the timber recorder ready access to a variety of tools besides the digitiser, including digital cameras and specialised lighting, allowing them to simultaneously document multiple aspects of the timber while minimising handling. Toby Jones.

Gota Wreck

Shortly after the full scale introduction of digital documentation at the National Museum of Denmark, a similar digitising project was carried out in Sweden. The Götavraket or Gota Wreck, a seventeenth century clinker-built boat discovered during tunnel excavations in Gotebord, Sweden, was disassembled and raised in 2001. In the autumn of 2002 the individual ship timbers were digitised using a FaroArm (a Silver-model arm loaned from Volvo) contact digitiser by staff from the Riksantikvarieämbetet, or Swedish National Heritage Board. The digital files of each ship timber were then used in an attempt to reconstruct and analyse the vessel completely within the digital realm, using CAD software. Nestorson states that the distorted models of the planks were straightened and flattened, but there is no indication of how this was achieved or controlled. The idealised digital hull form was used for further tests regarding seaworthiness and sail handling characteristics (Nestorson, 2004: 8).

U.S.S. Monitor

In April 2003, at the Mariner's Museum in Newport News Virginia, USA, Fred Hocker used a contact digitiser to record the engine from the U.S.S. Monitor. The steam engine, weighing 30 tons, was covered in concretion, and needed to be documented prior to disassembly and conservation (Broadwater, 2012: 162-165). This project was also a test of the digitiser's ability to accurately document larger objects, as well as developing methods for creating 3D virtual models, (Civil War News, 2003, F. Hocker 2013, pers. comm., 26 Apr.).

Vasa

Elsewhere in Scandinavia, the *Vasa* Museum, in Stockholm, Sweden acquired a used FaroArm Sterling model in 2003, and began a programme of documenting *Vasa's* reconstructed longboat, which measured some 12m in length (Cederlund, 2006: 472). The numerous gun carriages were also digitised and digitally reconstructed and modelled during this period. Special templates were used to organise the data, with the gun carriages being digitally reassembled.

Netherlands Institute for Ship and Underwater Archaeology

In 2003, Frank Dallmeijer, a model builder and archaeologist from the Netherlands Institute for Ship and Underwater Archaeology (NISA) based in Lelystad, began using a Cimcore Immersion Microscribe to document the De Meeren ship, a Zwammerdam-type vessel (Figure 39). The project team initially consulted with the National Museum of Denmark Centre for Maritime Archaeology about using contact and non-contact digitising in field, after noting the success in using a total station for the documentation of the B&W wrecks in Copenhagen, Denmark.

In 2003, NISA opted to use a total station to document the *in situ* hull remains and a contact digitiser to record sections across the hull. A laser scan of the *in situ* hull was also created for comparison purposes, but the resolution was found to be inadequate in terms of accuracy (F. Dallmeijer, 2013, pers. comm., 26 Apr.).

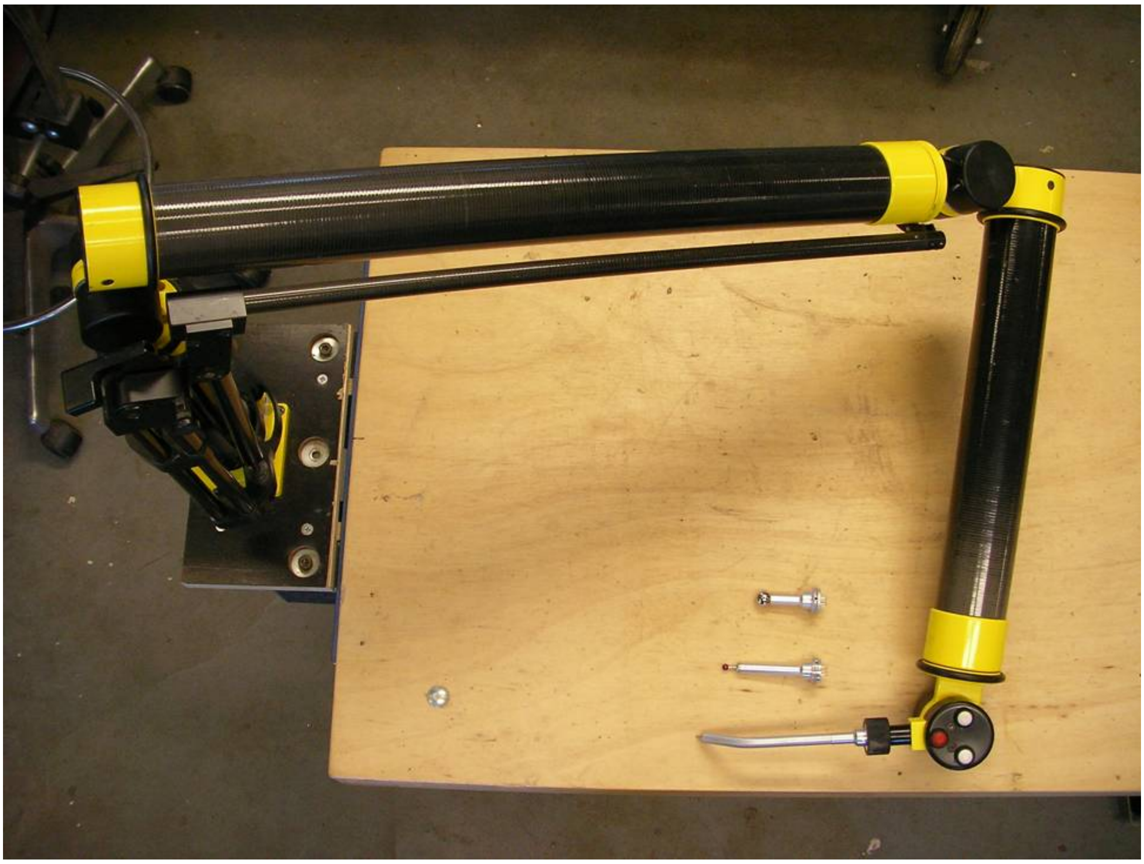


Figure 39. A Cimcore Immersion Microscribe Stinger II contact digitiser belonging to the Netherlands Institute for Ship and Underwater Archaeology in Lelystad. Rijksdienst voor het Cultureel Erfgoed.

The use of the contact digitiser in the field (normally a laboratory or workshop-based machine) required considerable logistical planning, with the need for a durable portable computer, electricity, and some way of anchoring and stabilising the contact digitiser so that it did not move relative to the hull remains. NISA developed a system where the contact digitising arm was anchored using a strong magnetic base stuck to a heavy steel sheet (Figure 40).

Figure 40. Archaeologist using a Cimcore Immersion Microscribe Stinger II contact digitiser to document the in situ remains of the De Meeren ship. Rijksdienst voor het Cultureel Erfgoed.

Such a system allowed the arm to be positioned near an object on a variety of less than ideal surfaces. After the excavation, the digitiser was used indoors to record smaller artefacts and selected disarticulated timbers that had been recovered. The use of the same digitiser, both in the field and in the lab, continued in this fashion until 2010, when NISA purchased a FaroArm to replace the Cimcore Microscribe (Figure 41) (F. Dallmeijer, 2013, pers. comm., 26 Apr.).

Figure 41. A FaroArm contact digitiser magnetically clamped to a portable heavy steel base. Toby Jones.

Mary Rose

The *Mary Rose* Trust purchased a used FaroArm Gold model in 2004-2005. The Trust performed recording work on the *HMS Victory* (specifically the capstan, recorded *in situ*) in Portsmouth, England for the UK Ministry of Defense during this period. Members of the trust staff, including Doug McElvogue, Emily Parish, and Charles Barker, were trained in digital documentation techniques at the National Museum of Denmark Centre for Maritime Archaeology at Roskilde in Denmark. Subsequent recording work involved the documentation of the rudder from the *Mary Rose* and the digitising of the Gela wreck, a 21m long sewn boat recovered off the coast of Sicily in 2008 (Valsecchi, 2010, C. Barker 2013, pers. comm., 19 Apr.).

Summary of the early uses of contact digitising in nautical archaeology

The use of digital documentation in archaeological fields became a possibility with the confluence of increased computing power, available metrology technology, and desire for greater accuracy and efficiency in documentation. The tools and hardware, as well as the software, were not developed specifically for archaeological purposes, however the innovative application of contact digitising technology to marine archaeology would have positive effects on the discipline, with widespread adoption of the techniques, technology and methodology over a span of just 15 years.

It is hoped that the reader will have gained a better understanding of the benefits and drawbacks of both traditional and innovative approaches to ship and ship timber documentation. As has been seen, there are multiple ways to accurately and effectively document ship finds. There are numerous valid documentation methodologies, which provide the framework and tools necessary to complete the job.

The careful and considered application of new technologies or methodologies can create or capture increasingly detailed and accurate data sets. However, the archaeological interpretation of the object or find is of more importance than the method used to document it. The latest technology or newest methodologies will still produce poor results in the absence of a well-trained archaeologist following a clearly defined and consistent research strategy. The documentation methodologies applied to the recording of the Newport Ship assemblage were carefully designed and tested prior to full implementation. The development of these methodologies is detailed in the following chapter.

Chapter 3: The Documentation of the Newport Medieval Ship

The following chapter provides a comprehensive and detailed overview of the post-excavation documentation tools and methods developed and utilised by the Newport Ship Project. Aspects covered include the initial recording trials and the formulation of a work plan. A description of the hardware and software used, as well as sections on checking and archiving the digital data are also included. Several examples demonstrating the value and comparability of the digitally-derived data sets are provided, including a metrical data capture exercise, a comparison between Newport Ship timbers and those from the medieval shipwreck Aber Wrac'h 1, and comparison of selected Newport Ship timbers before and after conservation treatment. The chapter concludes with a section on the growth of contact digitising in nautical archaeology in the wake of the Newport Ship Project.

Introduction

In common with many rescue excavations, there was intense pressure to remove the Newport Medieval Ship timbers and artefacts as quickly as possible. In line with standard procedures for recording the remains of vessels found underwater (where difficult and expensive working conditions and limited bottom time make detailed cleaning and recording impractical), the general shape and arrangement of the component ship timbers were documented *in situ*, and then raised to the surface for further detailed recording during the post-excavation stage of research. This second stage of recording is necessary in order to deduce the fastening pattern, construction sequence and ultimately the original hull form of the vessel, which has typically distorted and collapsed during or after deposition. Important features like fastener holes, wood grain, and inscribed lines or tool marks can often only become visible after carefully removing the mud, sand and concretions.

It was critical to accurately record these details in order to understand the design concepts of the shipbuilders who crafted the vessel. As no plans or blueprints of how these ships were built exist from the late medieval period, the archaeological remains of an actual vessel are unique and invaluable. By methodically and analytically ‘reverse-engineering’ the hull, the construction sequence can be determined and insights gained into the way medieval craftsmen designed and created complex objects like boats and ships (Crumlin-Pedersen, 2004: 37-63, Jones and Nayling, 2011: 54-60). The methods chosen (and the reasons why) are explored in the following sections.

Initial Recording Trials

In 2004, recording tests were set up to determine the most accurate and efficient method for documenting the geometry and surface details of the several thousand geometrically complex Newport Ship timbers and associated artefacts. Contact digitising, along with traditional 1:1 scale elevated plane tracing (detailed above) and laser scanning, were tested by staff at the Newport Ship Project. A representative floor and stringer were recorded using the abovementioned methods and the results were compared in terms of time, accuracy, ease of use and utility of final record (Figure 42, Figure 43, Figure 44).

For the contact digitising portion of the trial, archaeologists utilised a FaroArm 8-foot Platinum digitiser. The following excerpt from the recording trials clearly identifies the benefits of utilising contact digitising:

> *Whilst it is recognised that recording the Newport ship timbers using this technology will entail a steep learning curve for those involved and significant capital outlay, a number of advantages over traditional recording methods are evident from the trial. Final 3-dimensional models, once corrected for use of ball tip probes during measurement, can be used for direct measurement of attributes needing detailed description…These models can be compared with timbers after conservation, and during display to test shrinkage/dimensional stability. The models can also be utilised in interim displays prior to release of the conserved timbers, to assist in the*

> *development computer-based and physical models elucidating original hull form, and hence facilitate the reassembly of the timbers for eventual display.*

Newport Medieval Ship Recording Trials: Comments on FaroARM and Tracing Methods, (Nayling, 2004: 1-9)

Figure 42. Newport Ship Recording Trials. Using a laser scanner to document a stringer. Newport Museums and Heritage Service.

Figure 43. Newport Ship Recording Trials. Documenting a ship's timber using elevated plane tracing. Newport Museums and Heritage Service.

The recording trials showed that contact digitising was faster in terms of time and had a higher level of accuracy when compared to traditional tracings, and, significantly, the three dimensional geometric data was captured, stored and manipulated digitally. It was not necessary to create a traditional table of offsets, as any desired measurement, such as fastener spacing or tool mark width, could be taken from within the digital file at any future date. Using contact digitisers, the trial archaeologists were able to analyse and record the ship timbers in real time, concentrating on interpreting and drawing the features while letting the digitiser plot the point and line data.

It was envisioned that the end products of the digital documentation phase would include 3D CAD vector graphics files which could be read by a variety of software packages, with the files being readily sharable between researchers. These wireframe files could then be used to create 3D digital and physical models, with these 'building blocks' being used as a foundation for a reconstruction of the original hull form, much like the more traditional 2D tracings or scale drawings.

Figure 44. Newport Ship Recording Trials. Using a contact digitiser to document a floor timber. Newport Museums and Heritage Service.

The potential sub-millimetre accuracy of the digital record was considered to be of paramount importance to the archaeologists, as even a few millimetres of error in the recorded width of each plank could result in a cumulative error of many centimetres over the entire hull, causing fasteners or other features to not line up during the reconstruction effort.

There was a conscious and well-thought-out decision to choose contact digitising to document the remains of the Newport Ship. The Newport Ship Project chose to trial several methods, and carefully considered the results before choosing the method that gave the most accurate and efficient results. Many factors converged to make it possible to select contact digitising to record the vessel. The decision to test various methods of recording, including innovative ones, represented a paradigm shift in terms of thinking about the possible and potential outputs before embarking on the recording of the vessel. There was a conscious intent from the start of the project to collect enough accurate data to create a convincing reconstruction based on the remains of the ancient vessel.

Other factors, including political and academic ones, influenced the course of the project. There was popular public support for the saving of the ship and its subsequent documentation and conservation. This public support was reinforced by a political will, which took the form of various grants. There was funding available to do the trial and rent the laser scanner and contact digitiser, and later to purchase the recording equipment. Finally, there was favourable feedback from peers about the trial methodology and results. These factors combined to create an environment that made the development and application of contact digitising to a major nautical archaeological find a reality. It is difficult to see how this development might have occurred if these various factors had not been in alignment.

Recording the Newport Medieval Ship Timbers

Given the success of contact digitising during the recording trial in 2004, the project purchased a FaroArm Advantage 12 foot model contact digitiser. A team of archaeologists and conservators were appointed for one year to develop the most efficient work flow for cleaning and recording the large assemblage of ship timbers. Several staff members, including the author, went to the Viking Ship Museum in Roskilde, Denmark for training in the use of the FaroArm in November 2004. During the week-long training course, the instructor, Ivan Hansen, demonstrated the use of their contact digitiser and related software, as well as what details to look for when examining the ship timbers prior to recording. Back in Newport, the ship team worked to organise the facility for the efficient cleaning and recording of the substantial assemblage.

The waterlogged ship timbers had been sorted into component types and stored in numerous 5m x 10m tanks filled with fresh water arranged in a large warehouse. Recording equipment and wash tables were situated around the site, leaving broad aisles to enable the safe movement of the larger timbers using lifting gear (Figure 45).

Figure 45. The Newport Medieval Ship Centre. Timbers were organised by function (planks, framing timbers, stringers, etc. and placed in tanks for storage. Note the mobile overhead gantry, used to handle larger timbers, in the top left. Toby Jones.

After the successful conclusion of the one year pilot study, three additional FaroArm Advantage 12 foot model contact digitisers were purchased with the help of the Heritage Lottery Fund. The entire assemblage of over 3000 timbers and fragments was cleaned and recorded in two years between 2006 and 2008 (Figure 46).

Figure 46. Four identical contact digitiser work stations were created to efficiently record the large assemblage. Newport Museums and Heritage Service.

Before recording could commence, the ship timbers had to be cleaned. The surface detail was often obscured by layers of clay, tar, and iron concretion. Dental tools, toothbrushes, and large amounts of water were used to remove the softer concretions, while hammers and chisels were employed to remove the harder concretions that formed around the clench nail holes. The surface detail was well preserved, with clearly visible tool stop marks and intentionally inscribed carpenter's marks. During the cleaning process, tar, iron and animal fibre samples were taken for future analysis. Sample locations were temporarily marked with Tyvek tags and pins, which were documented and removed during the recording process (Figure 47).

Figure 47. Sampling tar and animal hair for analysis. Multiple samples were taken along the lands and scarfs of the planking, with the sample positions marked with map pins. These pins (and temporary labels) were removed after documenting their position with the contact digitiser. Newport Museums and Heritage Service.

In order to provide training for future staff members and ensure consistency in documentation standards, a timber recording manual was developed specifically for the Newport Medieval Ship Project (Figure 48) (Jones, 2013). A complete digital version of the manual (In PDF format) can be downloaded from the ADS archive at the following address: http://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-1563-1/dissemination/pdf/Newport_Medieval_Ship_Project_Timber_Recording_Manual.pdf.

The manual explains the setup of the recording equipment, and associated computer hardware and software, as well as including information about calibration, plug-ins and drivers. There are sections covering the layering system used in Rhinoceros3D, explanations of templates, and pages of tips and hints for improving efficiency. The manual has been made freely available to all interested parties, and has been frequently updated.

The timber recording manual served as a teaching document for training the numerous staff members employed at the peak of the recording project, and has also been used as a reference on several other similar ship recording projects around Europe, including the Drogheda Project, the Doel Kogge Project and by the Norwegian Maritime Museum and University of Southern Denmark. Using the timber recording manual as a guide, and with one week of supervised training, the archaeologists quickly developed proficiency in using the new digitisers. They were soon able to record the individual hull components of the Newport Ship with minimal supervision. The typical newly trained recorder might take around one work day to record an average hull plank, but, after a period of one or two months of daily contact digitising, could comfortably draw two planks in one day. The author recorded over 300 of the main structural timbers, and directly supervised the rest of the team in the recording of the remaining ship timbers. In order to achieve this, an organised and efficient workspace and detailed work plan/work flow was formulated and followed.

The Newport Medieval Ship

Timber Recording Manual

Digital recording of Ship Timbers
using a
FaroArm 3D Contact Digitiser,
FaroArm Laser Line Probe
and
Rhinoceros 3D software.

With additional sections
on
Digital Modelling and Metrical Data Capture

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Newport Medieval Ship Project
Newport, Wales, United Kingdom
Updated: 23 September 2013

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Figure 48. The cover of the Timber Recording Manual, which was used to train staff in the documentation methodology used at the Newport Ship Project. Toby Jones.

Arranging the Workspace and Setting-Up the Contact Digitiser

It was important to carefully setup the digitiser and workspace before recording a timber. This process involved assembling and configuring the recording table, setting up and calibrating the contact digitiser and ensuring that all the relevant computer software, hardware, cables and drivers are functioning and properly configured. The heavy duty stainless steel decked tables used by the Newport Ship Project were designed to fit and safely support the largest timbers from the ship site. The tables were five metres in length and one metre in width, with the heavily cross-braced deck 1m tall (Figure 49).

The stainless steel deck was covered with a single layer of capillary matting that helped protect the surface of the timbers. The marine grade stainless steel deck was chosen because it would be constantly exposed to wet organic material, which would quickly rust normal steel. Each table had six 4-inch (100mm) 360 degree swivel caster wheels with brakes that were locked during the active recording stage. The centre upright along the forward edge of the table was recessed in order to allow the recorder to walk back and forth along the edge of the table without inadvertently kicking the leg and potentially shifting the timber. Special anti-fatigue matting was placed along the edge of the table on the concrete floor and served to protect the operators during long shifts in the cold warehouse.

Figure 49. Archaeologist using a contact digitiser to record one of the large struts found under the Newport Ship. The use of tripods and moveable support tables and computer monitors allowed for flexible approaches to setting up the workspace. Newport Museums and Heritage Service.

The tables were wired for mains electricity with armoured cable running into waterproof sockets. Immediately beneath the stainless steel decking were reinforced steel plates that were drilled and tapped for the fasteners that held the stainless steel screw mounting rings for the contact digitiser base. The male threaded mounting rings provided a solid attachment for the female treaded oversize locking ring on the base of the FaroArm contact digitiser. Three mounting rings were attached to the top back edge of each table. From these three positions, it was possible to record a timber more than five metres in length without moving the timber. Identical male screw rings were attached to a variety of other bases, including portable and heavy tripods and flat metal or wood plates that could be clamped to any appropriate surface. Inorganic surfaces were found to be more suitable, as the dimensions of organic materials, like wood, can fluctuate with changes in humidity and temperature. Other optional screw ring bases included a magnetic mount and a suction cup base, although these were not used on the Newport Ship project. A custom made extension tube that added approximately 300mm between the base ring and contact digitiser was often used to extend the operating range of the digitiser (Figure 50).

A framework of 50mm angle iron was attached to the back of the recording table using g-clamps. Four two metre long uprights were clamped to the table and a long crosspiece clamped across the upper ends of these columns. This structure was gusseted in the corners and reinforced at key points. The framework supported an adjustable lighting system, an LCD monitor and an overhead spring counterbalance system (Figure 51). The entire framework was designed to be easily erected and removed or modified to meet the requirements imposed by certain timbers. As well as being inexpensive, the entire framework was modular and could be made from material readily available locally.

Figure 50. FaroArm Base extension tube. This 300mm long threaded tube increased the range of the contact digitiser considerably. Toby Jones.

Figure 51. Contact digitiser supported by a counterbalance system suspended from a carriage and cable. Toby Jones.

The spring counter balance system consisted of a wheeled carriage that ran along a cable stretched taut between two beams projecting forward from the rear of the table. A turnbuckle on either end was used to keep the cable taut. The counterbalance served to take up most of the weight of the digitiser and allowed it to run smoothly along the table. It also reduced operator fatigue and allowed them to record larger timbers without tiring. The counterbalance tension was adjustable, allowing individual recorders the ability to create an ideal workspace, which produced greater efficiency and ergonometric comfort. For some timbers, it was necessary to temporarily remove the spring counterbalance cable on the recording table before lowering the timber with the gantry.

The lighting system consisted of four individually adjustable conservation grade dual fluorescent tube lights. These could be angled and positioned to provide raking light in order to reveal faint tool marks or inscribed lines. A high resolution 40-inch (1016mm) LCD monitor was suspended from chains along the back rail in the centre or the table or from the corner of the table, depending on recorder preference (Figure 52).

Figure 52. The use of large LCD monitors enabled archaeologists to work at considerable distance from the screen and still see details. Rex Moreton.

The large size of the monitor was ideal, as it allowed the recorder to draw an object up to five metres distance from the screen and still see the data being collected. This monitor was attached to a laptop or desktop computer situated underneath the screen. Receivers for a wireless mouse and keyboard were also connected to the computer, which allowed the recorder to work at some distance from the monitor and return to a fixed keyboard or mouse to issue commands. Other cables included a long USB cable connecting the contact digitiser to the computer and power cables for the computer, monitor and digitiser, as well as the lights and computer speakers. Small handheld lights were also useful when examining details on the ship timbers. A minimum of ten plug points were installed on each table to ensure ready access to power.

The tables, when fully configured, were self-contained recording stations, requiring only electricity to be fully functional (Jones and Nayling, 2011: 54-60). An identical set of dental tools, different length probe tip holders, pins, magnifying glasses, cotton tape and various hand tools were kept at each recording station, allowing any of the timber recorders to use any of the tables. All of the computers were connected to a common server via a wireless local area network, where templates could be downloaded and newly drawn records uploaded. As fully contained units, the recording tables could be easily rolled around the warehouse and positioned as needed. Several two by one metre rectangular tables with stainless steel decks were designed to be used in conjunction with the long recording tables. These smaller tables were the same height as the larger ones and could be positioned to accommodate timbers that did not readily fit on the long tables. For example, the short edge of a small table could be butted against the centre of a long table, creating an L-shaped working surface to accommodate the knees or V-shaped floors.

When placing a timber on the deck, it was important to place Plastazote® foam squares down to pad the heavier timbers. Leaving a gap between the timber and the table was also necessary in order to remove the slings used to lift and transport the timbers (Figure 53). Planking could generally be set directly on the capillary matting surface, but sometimes twists in the planking needed to be supported with foam wedges. Smaller fragments were more prone to movement, and these pieces were often placed on a bed of foam and braced by backwards facing wedges, similar to the way machinists clamp metal to a milling machine bed. This method allowed unimpeded access to the upper surface and sides of a timber.

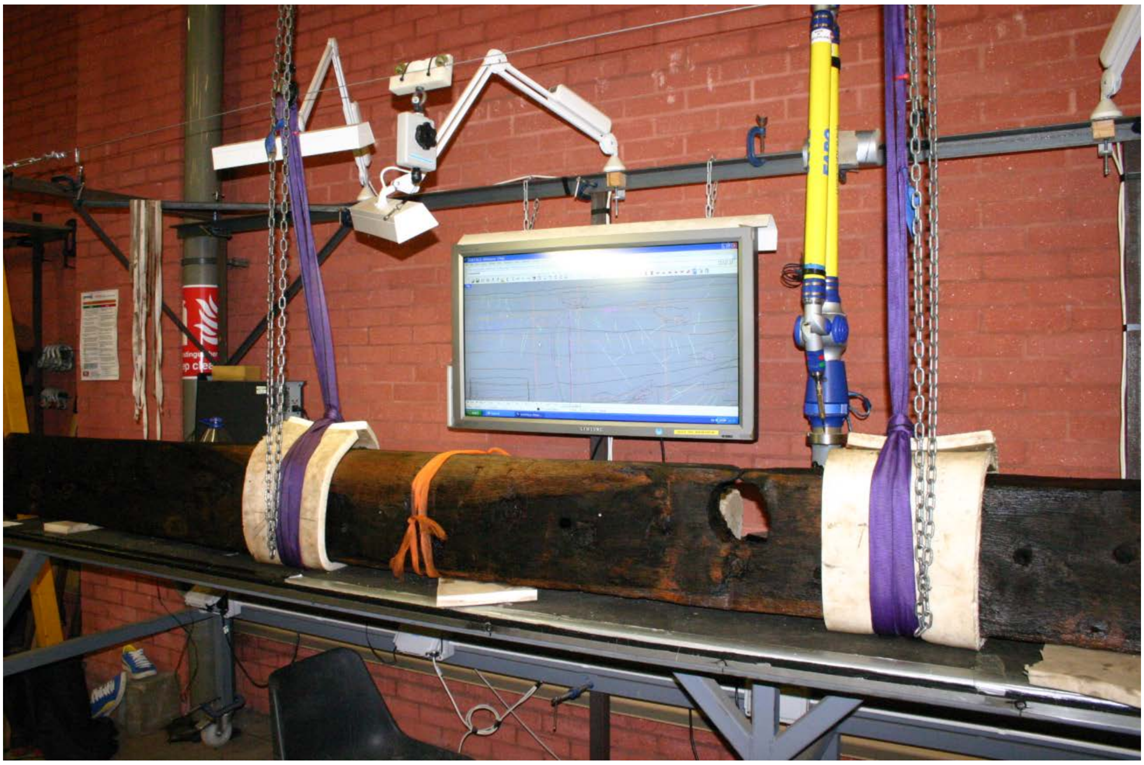


Figure 53. The use of padded slings and thick foam was essential in order to prevent damage when moving the large timbers. Toby Jones.

The centre of the timber (i.e. at a point equal distance from both ends) was generally placed in front of base of the digitiser, near the front edge of the recording table. It was possible to measure a 3.5m long plank or frame in this manner. Small or light timbers, including hull planking, could be handled and placed on the table by two staff members. Larger timbers were handled and shifted by slinging and lifting using padded straps, foam, and an overhead gantry or forklift truck (Figure 54).

Figure 54. A mobile overhead gantry was used to lift and move the larger ship timbers. Newport Museums and Heritage Service.

Four-sided timbers were usually recorded two faces at a time (typically the forward/outboard faces followed by the after/inboard faces). The timber was then moved so as to reach the remainder of the first two faces, or rotated 180 degrees along the lengthwise axis to record the remaining faces. It was often easier to return the timber to a storage tank and rotate it in the water and lift it back on to the table in the required orientation, than to handle it in the air. It was most efficient to draw timbers without moving the arm or the timber more than necessary. It was necessary to position longer timbers with the centre offset to one side, in order to record the timber in two moves. In rare cases it was necessary to move the timber or contact digitiser three times in order to capture all of the details before turning the timber over and repeating. This was the case on timbers that were close to five metres in length or those with exceptional scantlings like the mast partner.

The timbers were oriented on the surface of the table in a consistent fashion. Two-sided timbers, like planks, were always placed on the table with the inboard surface facing up, and the lower edge towards the front edge of the table. Planks from the starboard side of the vessel were oriented so that their forward scarf pointed to the right, while port side planks had their forward edge pointed to the left. Four-sided timbers, like framing timbers, were always placed with the forward face facing up (i.e. timber resting on its aft face) with the outboard face facing towards the front edge of the table (As a general rule, nearly all of the framing timbers were labelled on the forward face during the excavation. The cow tag was also typically attached to the forward face). In this manner, all the timbers were consistently oriented and recorded (and thus consistently displayed in the CAD software in the same orientation), which facilitated the construction of master composites built up of adjacent timbers from areas of the hull.

Using the Contact Digitiser

The Newport Medieval Ship Project used four FaroArm Advantage model 12 foot contact digitisers to record the entire waterlogged ship timber assemblage. The Advantage FaroArm consisted of a series of rotating joints connected by hollow carbon fibre tubes. The contact digitiser had six axes of rotation, allowing the probe tip on the end of the arm to be moved almost anywhere within a sphere with a diameter of 12 feet (3.7m). Each joint contained a rotation bearing and a digital encoder that detected the changing degree of rotation in each joint. By continuously monitoring the degrees of rotation from each encoder and by using the known fixed distances between each encoder, the contact digitiser was able to mathematically determine the relative position of a probe tip in three dimensional space relative to a fixed origin (the base of the digitiser/origin of the sphere). As varying temperatures would cause certain construction materials in the digitiser to expand or contract, it was constantly monitored and any dimensional changes taken into account when determining the location of the probe tip. Such attention to detail, precision and rapid processing allowed the contact digitiser to supply accurate real time positions of the probe to the software quickly and easily.

The contact digitiser itself was threaded onto the desired mounting ring on the recording table and then the locking ring was tightened just past hand tight. After removing the dust cover and making sure the cables were properly connected, the digitiser could be powered up. At this point it could be connected to the Rhinoceros3D software by clicking the relevant icon. A series of prompts then had to be followed in order to orient the digitiser to the three dimensional digital work space within the software. The first step was to carefully spin each joint on the digitising arm through its full rotation. This action activated the reference encoders in each part of the device. A live on-screen representation of the digitiser showed which joints still needed to be rotated.

When this task was finished, the first prompt on the command line read ‘Enter Origin with digitiser’. This origin was created on the work plane of the recording table. It was created by choosing points in an L-shaped pattern on the surface of the table (Figure 55). The first point was the corner of the L, with the second point at the right end of the lower leg, and the third point at the top of the ‘L’. The software then prompted the user to enter the world origin (coordinates 0, 0, 0). After this process was completed, the work plane in the software and the surface of the recording table were in three dimensional alignment, meaning that what the recorder could see in plan view on the recording table was shown in plan (or Top) view in the Rhinoceros3D CAD software.

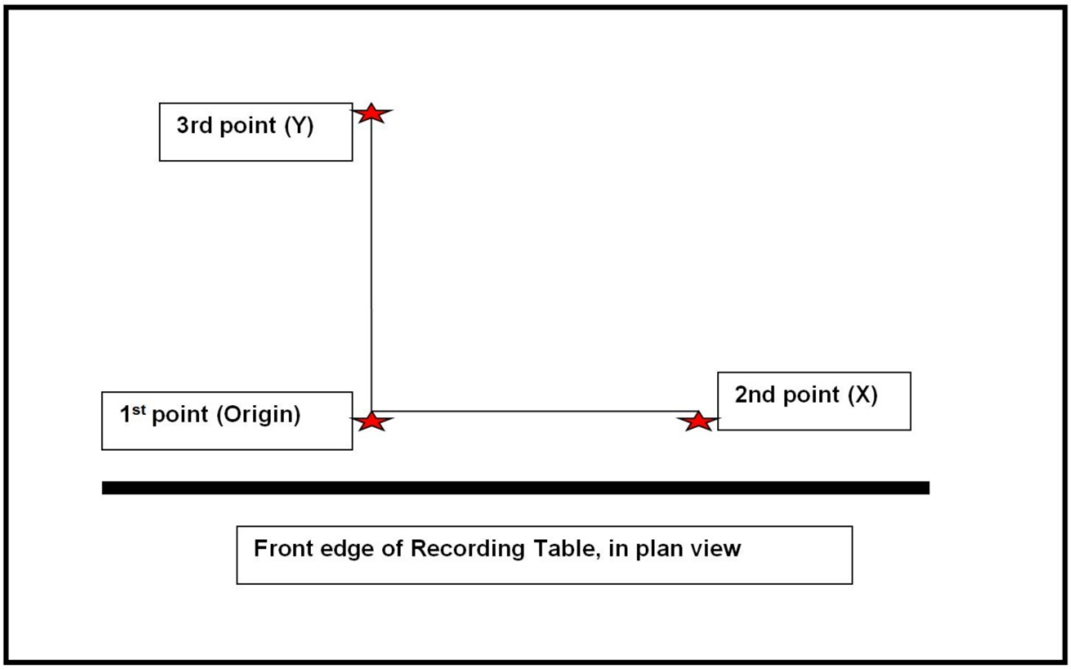


Figure 55. The position of the x,y, and z orientation points when setting up the work space. Toby Jones.

A quick check was performed using the contact digitiser to mark out a pattern of points and lines in three dimensional space, which could then be confirmed by panning and rotating the data set within the software. At this point, the computer, the Rhinoceros3D software and the contact digitiser were properly configured, connected, and with aligned workspaces.

The contact digitiser itself was fairly easy to use, with the operator grasping the end of the arm (or pistol-grip handle, if equipped) and lightly touching the probe tip against the surface of the ship timber while pressing the green data acquisition button (Figure 56). A second, red, button was used to cancel the last point (or points) taken or to reset to the last tool used.

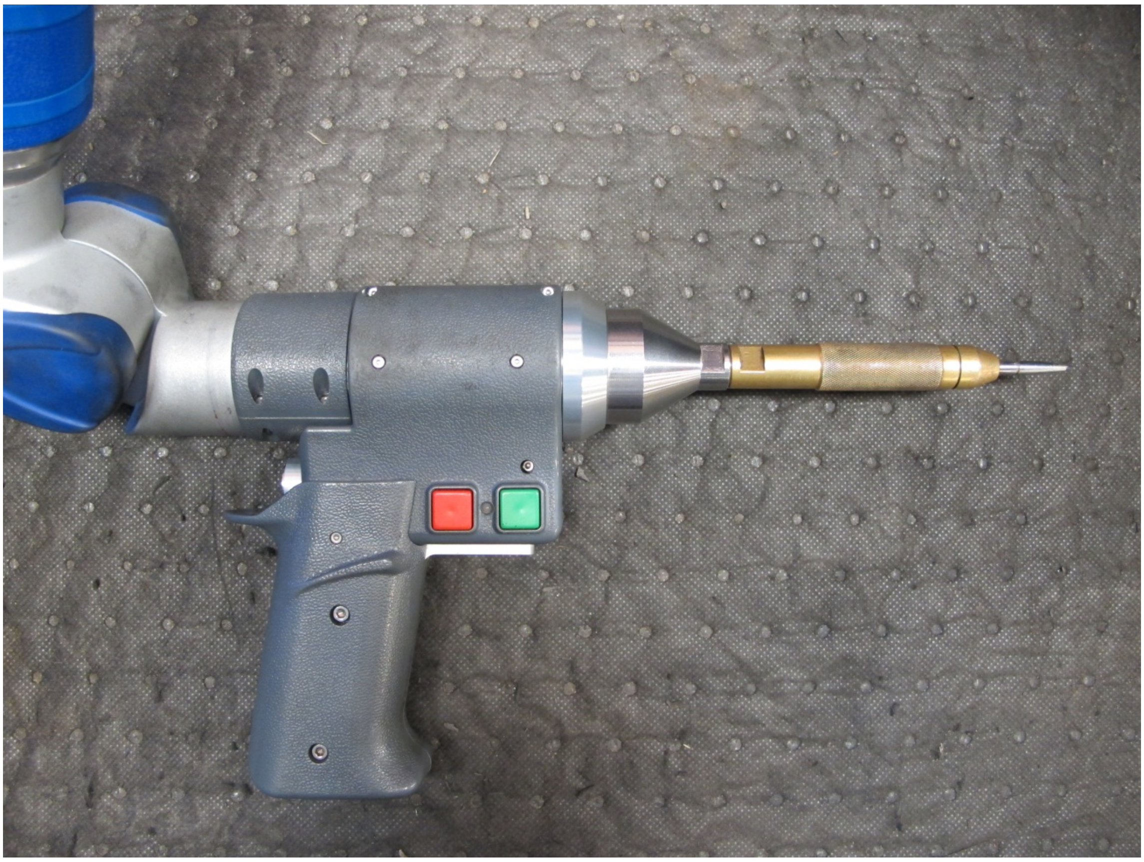


Figure 56. The pistol-grip handle and custom made probe tip holder of the FaroArm contact digitiser. Toby Jones.

Most recorders worked left to right, methodically reading the surface of the timber like a book. The action of drawing the probe tip along the surface of the timber caused the probe tip to wear down, and necessitated the regular replacement of the tip. It was essential to identify a replaceable probe tip that would not damage the surface of the timber, while also being economical and durable. The carbide tip supplied by Faro was too sharp and scored the timber, while the plastic (Delrin®) tip was too expensive for frequent replacement. An ideal solution was found in the form of replacement styli for PDA (personal digital assistant) devices. A probe tip holder was designed that threaded onto the FaroArm and firmly held the replaceable probe tip (Figure 57).

Figure 57. Machined FaroArm contact digitiser probe tip holder with a non-marking PDA stylus used as a probe tip. Toby Jones.

The holder was machined out of brass and one end was threaded to attach to the digitiser, with the other end drilled out to accept the replacement stylus. The stylus was held in place by a grub screw, and the length could be adjusted to suit the user. Several different lengths of probe tip holder were manufactured, with the longer ones used on specific occasions to document extra deep blind treenail holes (Figure 58). Brass was chosen as it was durable and easy to machine, with fine knurling being added to the probe tip holder to ensure a positive grip even with wet hands.

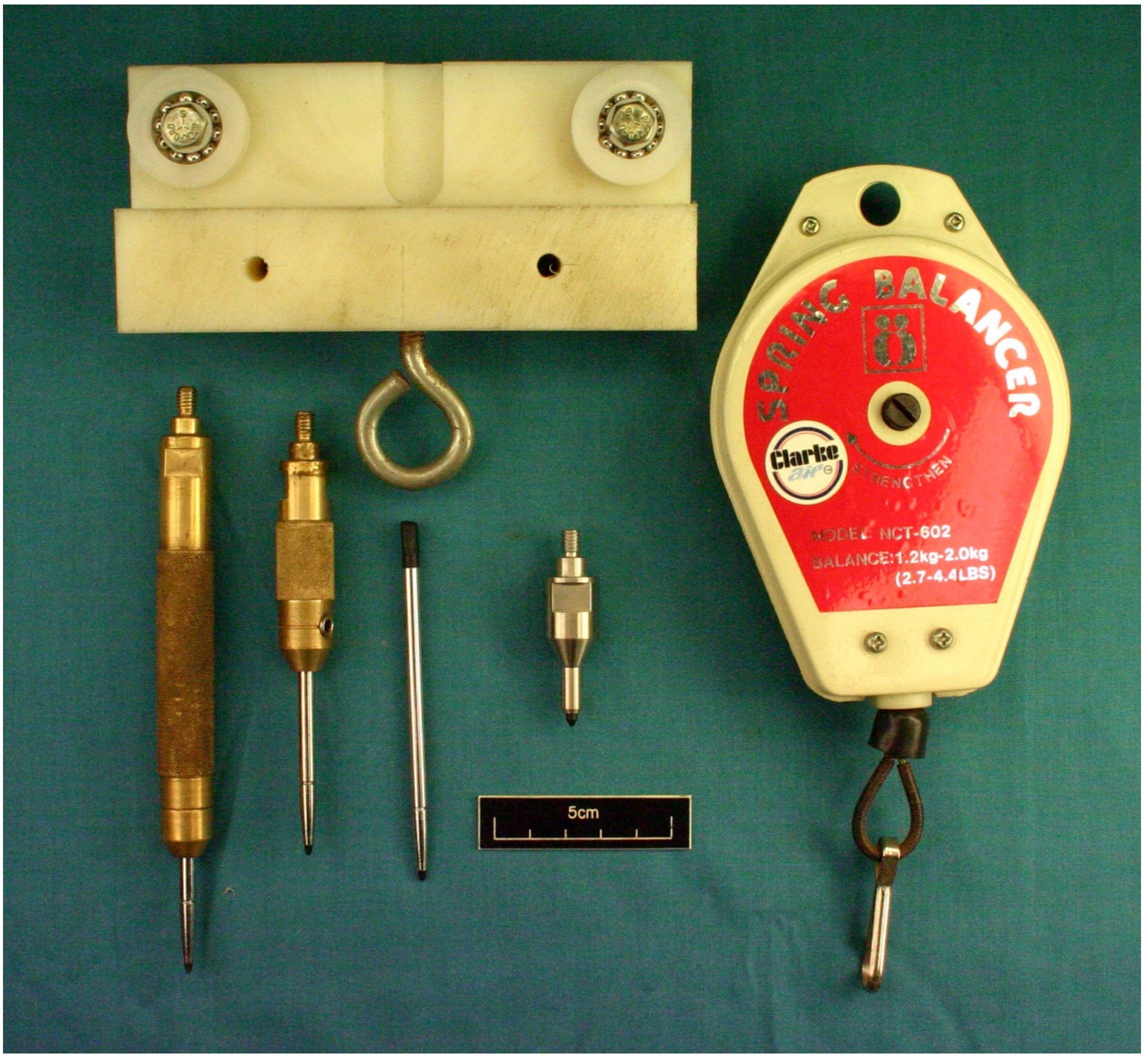


Figure 58. Counterbalance, carriage and custom probe tip holders used in conjunction with the FaroArm contact digitiser. Toby Jones.

It took some experimentation to find a comfortable grip that best suited handling the contact digitiser. It helped to hold one hand near the probe tip, using this hand and fingers to control the motion and location of the probe tip while using the other hand to push the buttons. The fingers could be used as 'outriggers' for helping to accurately trace edges and surface detail like grain and cross-sections. It often helped to warm up by spending a minute or two tracing along the edge of the recording table or other object with the probe tip. Care was taken to tread lightly and keep the probe tip from damaging the surface of the timber. As most people are right hand dominant, the work stations were typically set up to accommodate them, as they tend to work from left to right when recording the timber. However, the contact digitisers and recording table could be configured to work just as well in the opposite direction. Regardless of which direction of travel was chosen, the probe tip was typically held at an acute or low angle to ensure that the tip travelled lightly over the surface as opposed to digging in.

It was possible to use the contact digitiser in a variety of situations, including fastened to a work bench, tripod, or suction pad. Magnetic bases and other mounting plates could be attached to an assortment of surfaces, and readily moved as necessary. The contact digitiser could also be used outdoors in dry conditions. It was even possible to use the FaroArm contact digitiser in a water filled tank, with an extended probe tip being utilised to take measurements on a submerged timber, prior to cutting the timber into sections for further detailed recording (Figure 59).

Figure 59. Using the contact digitiser to record the position of control points prior to sawing the large mast step/keelson into smaller pieces. Newport Museums and Heritage Service.

Control Points

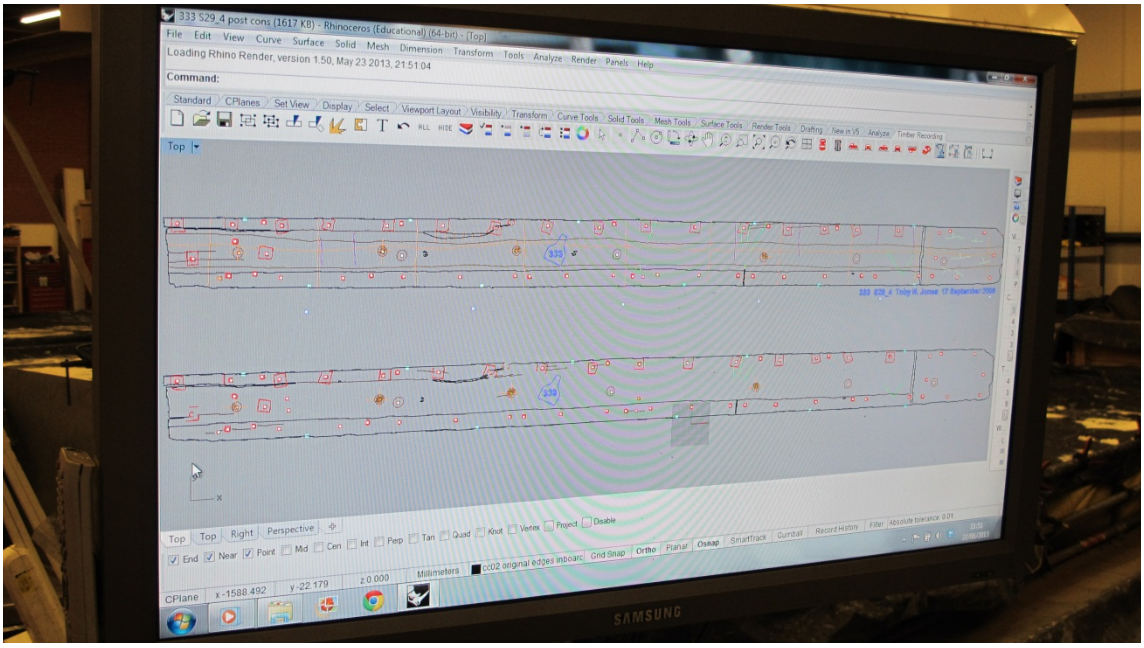
The next step in preparing the timber for recording was to drive small marine grade stainless steel wood screws (3.5mm diameter x 20mm length), known as control points, into the edges of planks and along the inboard and outboard faces of framing timbers. The cross (Phillips) head of the wood screws serve as fixed reference points that allowed the digitiser to realign the digital drawing to the physical object. This procedure was necessary when moving or rotating a timber. The control points will remain in the timbers through the conservation process, and will provide a useful baseline against which distortion or shrinkage in the timber can be checked.

Three control points were necessary to accurately orient the contact digitiser probe tip to the timber. The control points were inserted using an electric drill approximately every 100mm to 250mm along each plank edge or on each joggled outboard face of a framing timber, with a similar number and spacing of screws inserted on the inboard face. Control points were placed in areas that were thicker than 10mm, and far enough from edges to prevent cracking. Control point locations were carefully chosen to avoid running the screw into the void created by a fastener hole. In order to ensure even spacing, the wood screws would be laid out on the surface of the timber along both edges before inserting them.

Smaller disarticulated elements still attached to larger timbers could be screwed back into position or temporarily held in place until the recording was completed. The insertion of control points in areas of sapwood were generally avoided, but longer stainless steel woodscrews (5mm in diameter x 50mm in length) could be used in these areas if required. As a general rule, the more flexible the timber, the more closely spaced the control points were. Control points were inexpensive and easy to install and could be immensely valuable later on when trying to recalibrate a timber. Screws were run into until just below the surface of the timber. Any screw heads left standing proud of the original surface were at risk of being bumped and moved, or tearing holes in the PVC skin of the storage tanks.

Rhinoceros3D modelling software

The primary computer-aided design software used by the Newport Medieval Ship project was called Rhinoceros3D. The project utilised Rhinoceros3D version 3.0 to capture the point data produced by the contact digitiser. Rhinoceros3D version 4.0 was used to make digital solid models of each timber, and Rhinoceros3D version 5.0 was used to create master composites of sections of the hull. The software was user-friendly and intuitive, with many commands available as icons that could be clicked with the mouse cursor. The software interface consisted of a viewing window displaying a 2D view (or views) of the 3D workspace (Figure 60).



Loading Rhino Render, version 1.50, May 23 2013, 21:51:04

Command:

Figure 60. Graphical user interface of the Rhinoceros3D modelling software. The archaeologist can see the curves captured by the contact digitiser appear in the drawing in real time. Toby Jones.

Features like a command line, toolbars, and a layer menu were situated around the edges of the work space, along with object snap selection settings. Customisable hot-keys allowed text commands to be activated with the single stroke of a

Function key. These keys were configured to automatically save the file when, for instance, F5 was pressed or enable the digital sketching tool when F3 was pressed. The software would run well on standard desktop or laptop computers. Drivers and plugins were required to make the contact digitiser and computer communicate with each other. Once configured, the digitisers and the Rhinoceros3D software would automatically default to the settings in the template files.

Templates

With the timber prepared for recording, the next step was to choose the appropriate Rhinoceros3D recording template, which contained a set of layers with discrete names and colours. A read-only template file was chosen, based on timber type, and then opened and labelled according to the unique identifier number (cow tag) and timber function code. The standard plank template contained around 30 layers for each face, including edges, clench nails and additional nails, treenails, wood grain, tool marks, and compression marks. The template was designed to include all of the features commonly encountered on a typical plank. It was easy to add additional layers or sub-layers when a new feature was encountered. The set of layers acted like a checklist, and could be worked through in a sequential order, ensuring that a layer was not accidentally omitted. Standard templates were created for each functional timber type, including planks, framing timbers, and stringers, with more generic two and four sided templates being created for unique or disarticulated timbers.

Toolbars and Tools

Rhinoceros3D has thousands of commands, tools and associated icons. The vast majority of them were of little or no use to archaeologists using contact digitisers to record ship timbers. A custom toolbar was created that contained the 44 most commonly used tools and commands related to recording timber with a digitiser (Figure 61). This freed up the maximum amount of display screen workspace and saved time by eliminating the need to search for commands via drop down menus or text based commands. Time savings of even a few seconds were important as the same sets of commands would be needed for each face of the thousands of different ship timbers. The digitisation commenced by working through the layering system and recording all examples of each feature, such as rove impressions or treenail holes.

Figure 61. Timber Recording Toolbar used by the Newport Ship Project. Toby Jones.

The three most commonly used tools for 3D coordinate capture were the single point tool, the polyline tool, and the Digital Sketching tool. These tools were clustered together on the timber recording toolbar and could also be activated using the hot-keys. The single point tool was used to record the position of any discrete points, including control points, sample locations and fastener centres. The polyline tool took a 3D coordinate whenever the acquisition (green) button was pressed. In this manner a series of points along an edge or feature were automatically connected by a line in real time as each point was added to the existing line. The polyline tool was used for recording fastener holes and areas where fine control was required to accurately capture the shape. A handy option when creating a polyline was the ability to close it, which caused the last point taken on the line to be connected by a line segment back to the first point taken. This feature was especially useful when recording around a fastener hole. By closing this line (and creating a closed polyline), it allowed the Rhinoceros3D software to automatically place a mathematically determined centre point within the ring. The accurate placement of this centre point was of critical importance during later modelling efforts (See section of digital solid modelling below).

The digital sketching tool (often referred to as DigSketch within the Rhinoceros3D software programme) was arguably the most useful tool to capture 3D point data. This tool would basically capture 3D point data quickly and automatically as long as the data acquisition button was held down. The points could be collected as discrete single points or connected together with polylines. Other settings allowed the spacing between captured points to be set at desired intervals. The tool proved to be a highly customisable program with a variety of settings that could be tailored to capture just the right amount of detail. For example, on the Newport Ship Project, much testing resulted in the creation of a series of settings that accurately and efficiently recorded the right amount of 3D coordinate data from the ship timbers. These settings were visible on the command line when the DigSketch tool was selected as ‘Points=No, Curve=No, Polyline=Yes, Planar=No, Point Spacing=1’. The last entry, for point spacing, allowed the user to select any desired spacing between the points, from fractions of a millimetre to many tens of millimetres. It was decided to use one mm spacing between points, as this allowed all the fine details to be recorded without creating overly large numbers of points and consequently larger digital files.

Another setting that was carefully monitored involved the nature or degree of the curve being drawn. Curves were automatically drawn through or near points taken by the contact digitiser. Degree 1 curves, known as polylines, were those which passed through each and every point on a line or arc. Curves with higher degrees, including degrees 2 and 3, did not pass directly through each and every point. Instead, the modelling software generated smooth or fair arcs to best fit the points, which resulted in corners or fine changes in detail becoming softened or rounded (Figure 62). The higher the degree curve, the more the line could deviate from the control points. The Newport Ship project exclusively used degree 1 curves during the documentation and individual digital solid modelling phases of the project (Higher degree curves were consciously avoided early in the project, but were acknowledged as being potentially useful during the later total hull form modelling phases).

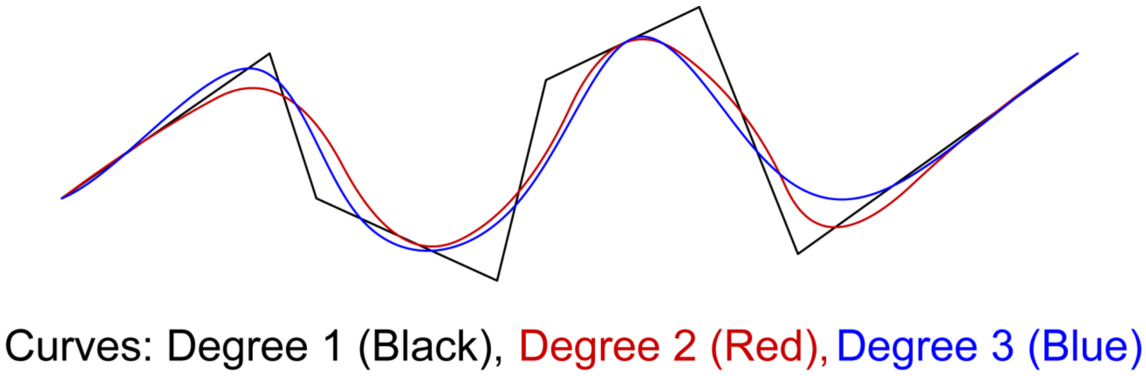


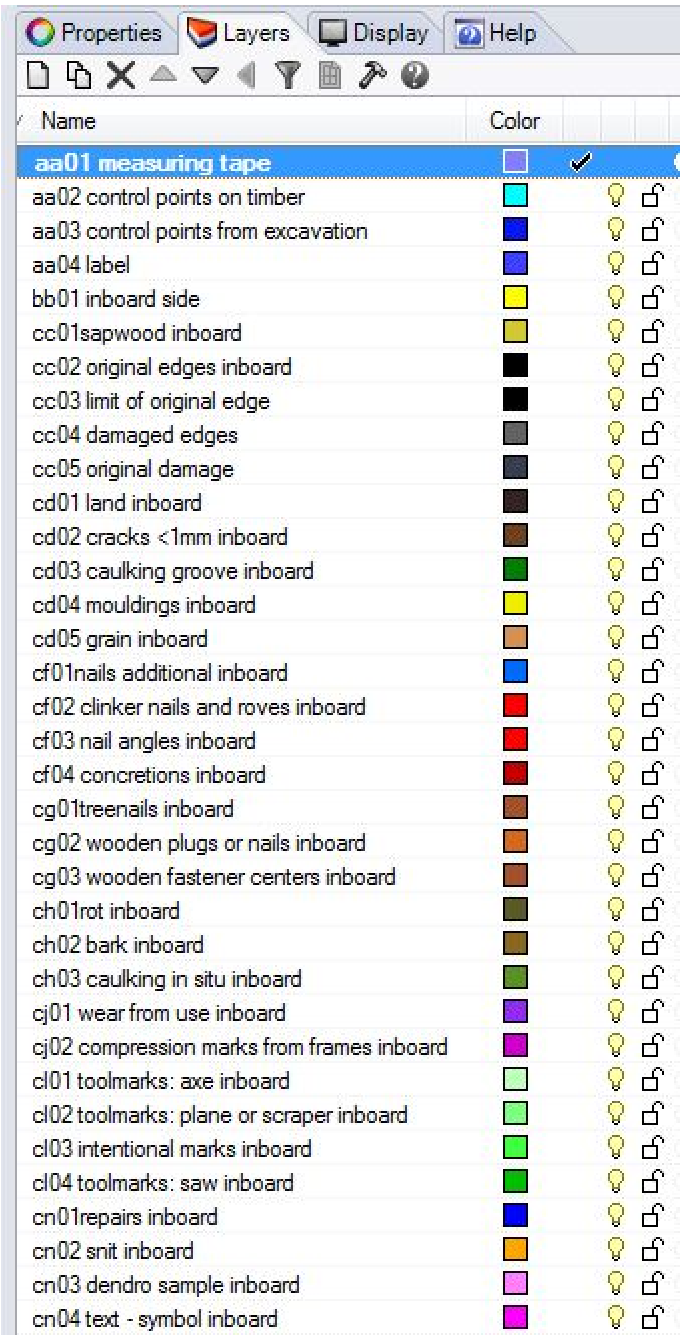
Figure 62. Curve Degrees. Degree 1 curves pass through all control points, while higher degree curves can deviate from the control points. Toby Jones.

It was important that lines drawn with the Digital Sketching tool be carefully checked for accuracy and completeness. Failure to fully and firmly depress the data acquisition button on the digitiser would cause the digitiser to capture points in short segments, leaving small gaps along what should have been a continuous line. These inadvertent line breaks, especially on edge layers, could cause problems in the future when the line data was used for digital solid modelling purposes. As a general rule, all lines were edited (either with short filler segments or by moving the underlying control points) so that they intersected into other lines. In the Rhinoceros3D modelling software, the edges were used to define and create surfaces, and any gaps along the edges could create invalid surfaces that required extensive post-processing.

The Layering System

When recording a ship timber with the contact digitiser, the selected details and geometry are systematically assigned to specific layers within the Rhinceros3D modelling software. These layers have a unique name, unique alphanumeric prefix, and a unique RGB colour recipe. The use of different colours allows for the visual differentiation of contrasting features, while the use of discreet layer names allows the layer list to serve as a readable checklist to ensure that all features are recorded.

The use of alphanumeric prefixes allows these layers to be placed in a convenient and logical order (Figure 63). Rhinoceros3D automatically orders the layer menu alphabetically. This system is used as opposed to straight sequential numbering, which would maintain a strict sequence and would not allow for modification or expansion without upsetting the original order of the layers. In order to allow the addition or deletion of layers, without upsetting the 'timber face' order, it is necessary to use alphanumerical prefixes that allow for the controlled expansion of the system.



aa01 measuring tape
aa02 control points on timber
aa03 control points from excavation
aa04 label
bb01 inboard side
cc01sapwood inboard
cc02 original edges inboard
cc03 limit of original edge
cc04 damaged edges
cc05 original damage
cd01 land inboard
cd02 cracks <1mm inboard
cd03 caulking groove inboard
cd04 mouldings inboard
cd05 grain inboard
cf01nails additional inboard
cf02 clinker nails and roves inboard
cf03 nail angles inboard
cf04 concretions inboard
cg01treenails inboard
cg02 wooden plugs or nails inboard
cg03 wooden fastener centers inboard
ch01rot inboard
ch02 bark inboard
ch03 caulking in situ inboard
cj01 wear from use inboard
cj02 compression marks from frames inboard
cl01 toolmarks: axe inboard
cl02 toolmarks: plane or scraper inboard
cl03 intentional marks inboard
cl04 toolmarks: saw inboard
cn01repairs inboard
cn02 snit inboard
cn03 dendro sample inboard
cn04 text - symbol inboard

Figure 63. The layering system used by the Newport Ship Project. Note the alphanumeric codes preceding each layer name. Toby Jones.

The layering system relevant to each timber type is saved in a read-only template file which also contains the requisite toolbars and settings (see toolbars and templates for more information). It is important to insure that the details of each face have been completely recorded on the proper layer before moving on to the next layer on the list or a new face, otherwise, it will be necessary to reorient the contact digitiser to the timber, which can be a time-consuming exercise.

General layers (those that are not face specific) are prefixed with an ‘aa’. On two sided timbers, inboard layers are prefixed with a ‘c’, and outboard layers with a ‘g.’ Generic layer names like bb01 inboard side or face and eb01 outboard face were included in the templates, but were not actively used. They may or may not appear on the individual drawings (depending on whether or not the timber recorder used the Purge command to remove any unused layers). On four sided timbers, forward layers are prefixed with a ‘c’, inboard layer with an ‘e’, aft faces with a ‘g’, and outboard faces with an ‘i’.

Layers were ordered in the same standard sequence for each face, beginning with general information that was not face-specific, including control points, measuring tape and labels. This was followed by sapwood, edges, land, cracks and grain. The various fastener layers, including clench nails, treenails, additional nails, wooden spikes and fastener angles and centres followed. Wear, tool marks and inscribed lines layers were purposely placed towards the end of the layering list. They were put here so that the recorder, who had had the opportunity to examine or ‘read’ the wood in-depth by this point, would notice even the smallest or faintest features. Cross-sections and labels were the last to be drawn on the timber before it was rotated to reach the unrecorded faces.

The use of layers and sub-layers in Rhinoceros3D software versions 4 and 5 allowed for greater flexibility and organisation. For instance, several individual layers could be grouped under a single Inboard or Outboard layer, allowing the user to turn off one complete face of the timber with a single mouse click, instead of having to select all of the desired layers and turning them off. The use of sub-layers also allowed the option of creating a hierarchy of layers to hold meshes and polysurfaces, which were used during the production of the digital solid models. The creation and use of a predetermined and well thought out layer hierarchy template would later pay dividends in terms of organisation when compiling large numbers of individual timber drawings into a master composite file.

Annotated wireframe drawings of typical timbers were produced as illustrated guides for the timber recorders to follow (Figure 64, Figure 65). Time was spent ensuring that each timber recorder could consistently and correctly interpret features and boundaries when archaeologically recording the waterlogged material.

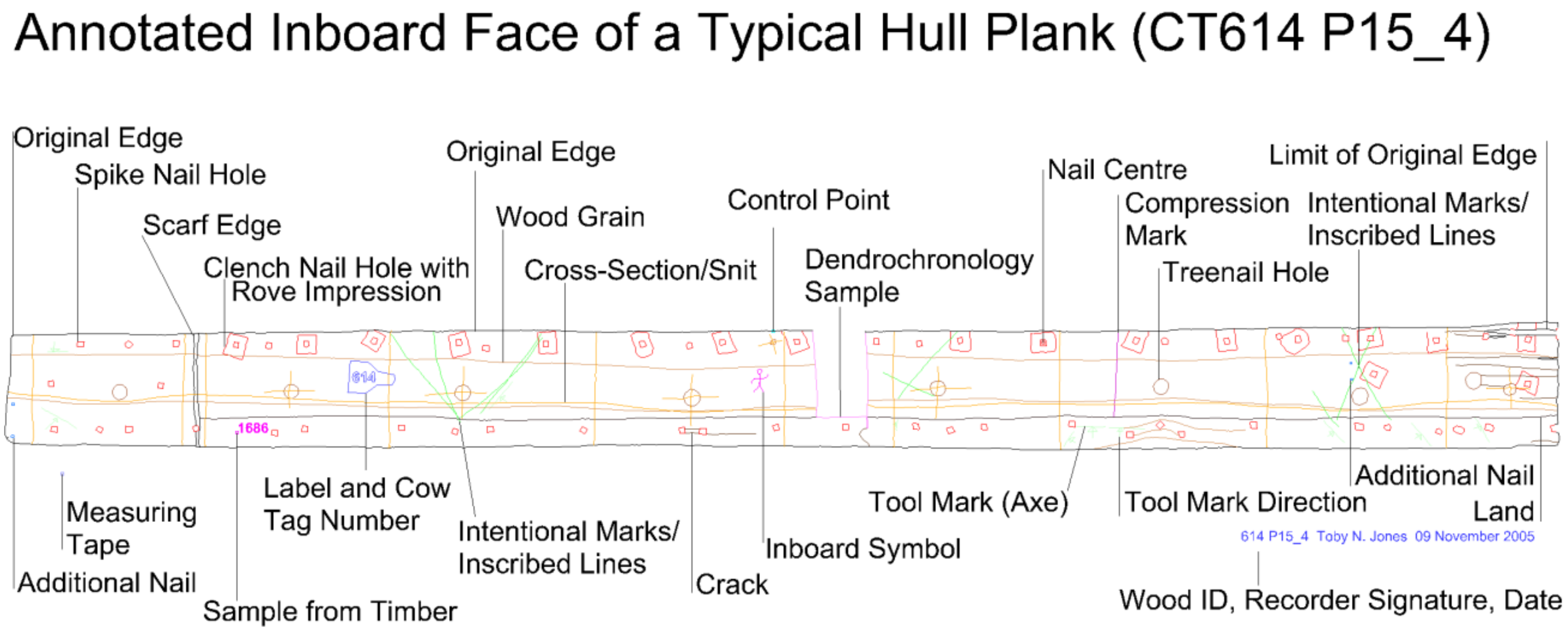


Figure 64. Annotated digital drawing of the inboard face of a typical hull plank from the Newport Ship. Toby Jones.

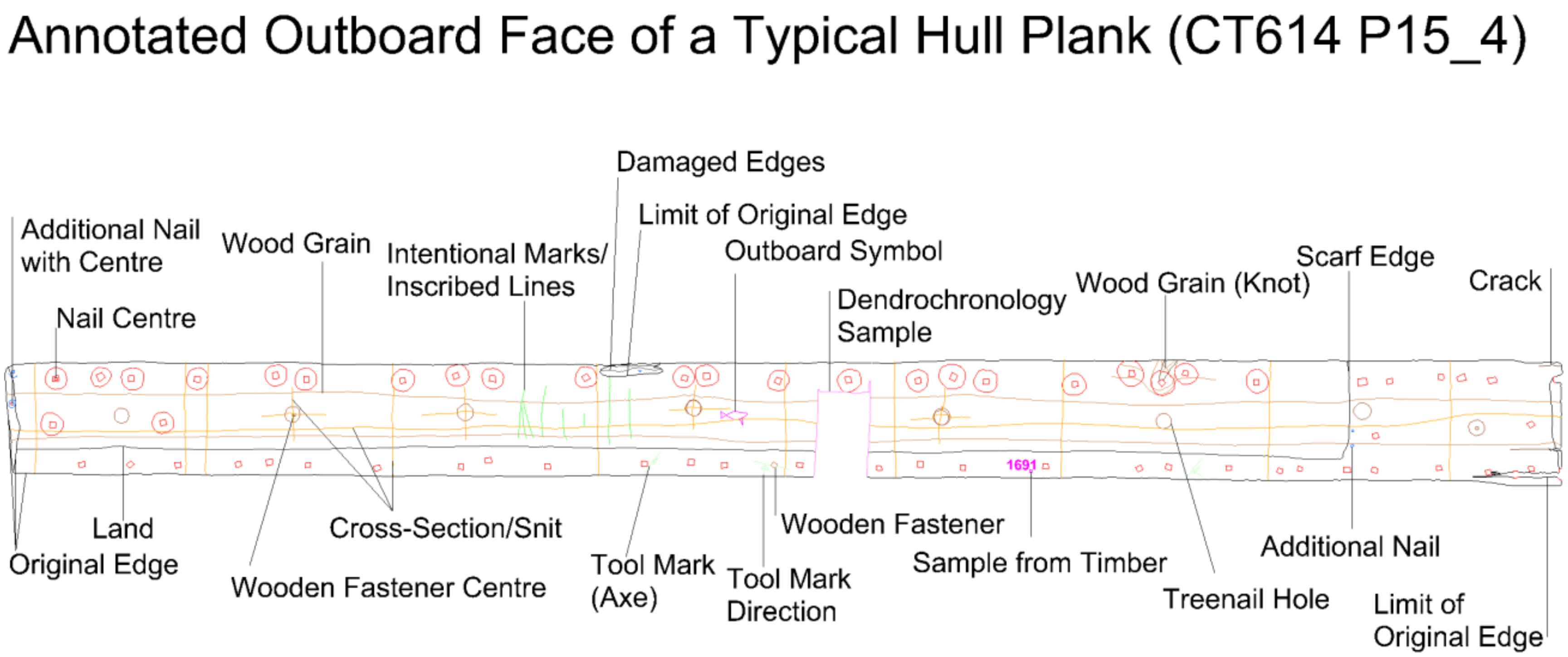


Figure 65. Annotated digital drawing of the outboard face of a typical hull plank from the Newport Ship. Toby Jones.

Layer Names and Descriptions

The following layer names and descriptions are listed in the order found on the most commonly used two and four sided timber templates.

Measuring Tape

The measuring tape layer is used to record a series of points spaced 500mm apart along the front edge of the recording table. These points serve as a reference scale and provide a quick visual clue as to the size of the timber. These points provide an internal scale that might prove useful if the inbuilt scaling became unstable in the Rhino software program. Points spaced 500mm apart along a line were punched onto the stainless steel forward edge of the timber recording tables, creating a quick and convenient pattern for the timber recorder to capture using the contact digitiser.

RGB Colour Code: 127, 127, 255

Base alphanumeric code: a01

Control Points on Timber

Control points are the cross-head (Phillips) stainless steel wood screws inserted into the timbers during the post excavation recording process. They served as permanent reference points against which the contact digitiser and the Rhinoceros3D CAD software can be re-oriented to the timber. It was important to apply only enough pressure to seat the probe tip against the screw when recording the point, as excessive pressure could cause the timber to shift, and make calibration difficult or impossible.

RGB Colour Code: 0, 255, 255

Base alphanumeric code: a02

Control Points from Excavation

Control points are cross-head (Phillips) stainless steel wood screws inserted into the timbers during the on-site recording process. They serve as permanent reference points against which total station data can be integrated with contact digitiser data within the CAD software.

RGB Colour Code: 10, 22, 241

Base alphanumeric code: a03

Label

The label layer contains text relevant to the timber drawing, including unique identifying number (CT/cowtag), function code, recorder, and date.

(Example: 563 P2_5 Toby N. Jones 27 August 2005)

This layer may also be used to provide textual information/annotations about interesting features on a timber, such as the beginning or end of a frame on the inboard surface of a plank.

RGB Colour Code: 63, 63, 255

Base alphanumeric code: a04

Sapwood

Line used to define the heartwood/sapwood boundary and the extent of sapwood present. As sapwood was often present on two different faces of the timber, the lines on one face would stop where the lines on the other face began, with the result being an ‘island’ of sapwood when the timber drawing was viewed in three dimensions in the modelling software.

RGB Colour Code: 210, 199, 52

Base alphanumeric code: c01

Original Edges

Line used to define where an original surface meets another original surface. This layer is often the first one drawn, and helps define the overall shape and outline of the timber. Care was taken to capture the position of the edges by using the Digital Sketching tool with point spacing at 1mm intervals. Joggles and rebates on the outboard face of the framing timbers were also recorded with this layer, with each the extent of each rebate being outlined and several additional lines added to show the depth. This was seen as a sufficient level of detail for recording what were hastily carved features.

RGB Colour Code: 0, 0, 0

Base alphanumeric code: c02

Limits of Original Edges

This layer was used to define where an original surface meets a damaged or otherwise non-original surface, including teredo boring, erosion, or piling/coring damage and cracks or splits over 1 mm in width. Areas of excessive damage, as from pilings, were drawn in a cursory fashion, as there was negligible information contained in the numerous wood fibres. A single line would be drawn to delineate the edge of the original surface, while a second line (damaged edges layer) would be used to define the extent of the damage, with several other damaged edge lines to provide and necessary contour information.

RGB Colour Code: 0, 0, 0

Base alphanumeric code: c03

Damaged Edges

This layer was used to record the geometry where two non-original surfaces met. This layer was commonly used to record the overall extent of highly damaged areas that had limited information potential.

RGB Colour Code: 99, 97, 97

Base alphanumeric code: c04

Original Damage

This layer was used to define damage caused during the construction or use-life of vessel, i.e. hammer dents and nail gouges. Such damage can also include the marks created by an axe peeling or pulling the wood along the grain around a knot.

RGB Colour Code: 54, 62, 79

Base alphanumeric code: c05

Land

On planks, this layer was used to draw a line defining the boundary between the areas overlapped by the next higher and lower strakes and the body of the plank.

RGB Colour Code: 53, 34, 34

Base alphanumeric code: d01

Cracks

This layer was used to draw lines to show the cracks in the timber that were less than 1mm in width. Cracks often emanated from the edges of planks or from fastener holes. It was possible to detect the smallest cracks by lightly pressing on the waterlogged wood in these areas, which caused water to upwell from within the cracks up onto the surface, revealing the crack's location and length. Larger cracks were drawn using the Limits of Original Edges layer.

RGB Colour Code: 107, 65, 35

Base alphanumeric code: d02

Grain

The Grain layer was used to record information showing representative wood grain extending the length of the timber, with additional lines used to record any knots or unusual rays, end grain and rings, if possible. Grain was also recorded on treenails and wooden nails if visible. The careful recording of end grain in multiple locations on timbers like framing timbers and stringers allowed for the reconstruction of the parent tree and the determination of the conversion process.

RGB Colour Code: 139, 90, 0

Base alphanumeric code: d05

Additional Nails

This layer was used to record the position and size of any iron spike (non-clenched) nail holes and corresponding fastener heads. These were often small nails that were used for repairs along the edges of planks (to close cracks) and to tack down the feathered edge of plank scarfs on the outboard face. Closed polylines were used to denote fastener holes that were complete and undamaged.

On framing timbers, this layer was used to record the large spike nail holes found on most of the joggles on the outboard face of the timbers. These spike nail holes correspond with the spike nail (non-clenched) holes seen on the planking (although these were recorded on the Clinker Nails and Roves layer, as the relationship between the two fastener holes only being realised at a later date).

RGB Colour Code: 0, 106, 255

Base alphanumeric code: f01

Clinker Nails and Roves

This layer was used to record the impressions of the nail heads and roves visible on the hull planking. This layer was also used to record the nail holes produced by spike nails driven through the planking and into the outboard face of the framing timbers (see Additional Nail layer description above). Deeper rove impressions were recorded by drawing an additional line along the upper and lower edges of the impression. The clench nail and spike nail holes were generally square in section, with fairly regular spacing along the edges of the planking.

RGB Colour Code: 255, 0, 0

Base alphanumeric code: f02

Nail Angles

This layer was used to record information about metallic fastener holes, including fastener centres, nail angles and depths of blind fasteners. Single points were used to record fastener centres, while polylines were used to define the depths of blind fastener holes/axes of fasteners. The overall length of the standard nail angle rod was 150mm. One end of the rod was inserted into the blind fastener hole, and where the rod emerged a polyline was started and then finished on the top of the metal rod. By subtracting this length from 150mm, it was possible to determine the depth (and angle) of the fastener. If the fastener/corrosion product completely filled the hole, the rod was placed on the surface and a 150mm line created. A 150mm long line indicated that the hole was plugged (alternatively this could have been illustrated using the snit/cross-section layer). There would be a note on the relevant timber recording sheet if the nail angles and/or depths were in doubt, or if a different length rod was used (i.e. for a hole deeper than 150mm).

This layer could also be used to draw a polyline between the fastener centres on a single fastener that appeared on two faces of a timber. In this way, an axis for the fastener would be produced, which would prove useful in the future during the solid modelling phase of the project. This might also have been usefully done on a separate layer or by dividing the nail angles/axes, nail centres, and nail depths onto separate layers.

RGB Colour Code: 255, 0, 0

Base alphanumeric code: f03

Concretions

This layer was used to record the extent of ferrous concretions around iron fasteners. These concretions were typically removed during the cleaning process, but significant ones were retained and only removed after recording and prior to conservation treatment.

RGB Colour Code: 191, 0, 0

Base alphanumeric code: f04

Treenails

This layer was used to record treenails and treenail holes, as well as treenail wedges, along with dimples (depressions from where the treenail was turned) and domed or faceted heads. Treenails and treenail holes were generally recorded with closed lines using the polyline tool. Treenails were typically recorded using 12-24 points spaced evenly around the base of the treenail head or edge of the hole. Taking fewer than 12 points caused the round-in-section treenail to appear to have faceted surfaces. When recording an empty blind treenail hole, an extra-long probe tip was used to capture the depth and shape of the hole. Square treenails inserted into round drilled holes were occasionally seen in areas where the keelson and braces were attached to the underlying inboard face of the floor timbers. These features were all recorded on the normal treenail layer. Other features, including wedges and facets on the treenail head were drawn on with polyline segments. Knurling was sometimes seen immediately under the domed head of removed treenails, but this detail was better captured using photography or laser scanning.

RGB Colour Code: 160, 82, 45

Base alphanumeric code: g01

Wooden Spikes and Plugged Holes

This layer was used to record wooden fasteners (generally square- in-section wooden spike nails for repairs) and plugged holes. Some fastener holes contained wooden spikes, but they had been created for and occupied by iron fasteners (as evidenced by residual staining or nail head impressions). These features were recorded on both the iron fastener layers and wooden spike layers. Wooden spikes were often well preserved, and left *in situ* for future conservation treatment. Their shape, projecting through and away from the plank, was documented using polylines to define the edges and tip of the tapered spikes.

Plugged holes were typically (but not universally) round in section and were round drilled holes that had probably been drilled in error and then plugged with a round wooden plug, as an iron spike would have squared the hole, left residual staining, or penetrated into an adjacent timber.

RGB Colour Code: 210, 105, 30

Base alphanumeric code: g02

Wooden Fastener Centres

Single points are used to record the fastener centre on all wooden spikes, plugs and treenails. If enough of a partial treenail hole remains, a single point can be manually placed in the centre by the timber recorder.

RGB Colour Code: 160, 81, 45

Base alphanumeric code: g03

Wear From Use

This layer was used to document wear caused by running ropes or foot traffic. Areas of damage could be recorded with an outline and supplemental digital photography used to provide detail.

RGB Colour Code: 145, 44, 238

Base alphanumeric code: j01

Compression Marks

This layer was used to record compression marks from timbers riding on or rubbing against other timbers (i.e. bottoms of floors pressing into keel or against inboard face of planking).

RGB Colour Code: 205, 0, 205

Base alphanumeric code: j02

Axe Marks

This layer was used to record stop marks, beard and blade striations caused by axe usage. A polyline with an arrowhead marked the tool travel direction, while two parallel lines perpendicular to the stop mark indicated tool blade width. The best representative examples of axe marks (as well as other tool marks) were generally chosen for recording.

RGB Colour Code: 191, 255, 191

Base alphanumeric code: l01

Scraper/Planer Marks

This layer was used to record stop marks, beard and blade striations of scraper and plane usage. A polyline with an arrowhead marked the tool travel direction, while two parallel lines perpendicular to the stop mark indicated tool blade width.

RGB Colour Code: 127, 255, 127

Base alphanumeric code: l02

Intentional Marks

This layer was used to record inscribed lines and intentional boat builder’s marks, often seen along the forward (‘x’) and after (‘o’) faces of framing timbers (presumably marking joggle locations) and on the inboard and outboard faces of planks (a variety of purposes). As many different tool marks were eventually discovered, it would be advisable to create a system of layers and sub-layers to accommodate and organise the various intentional marks.

RGB Colour Code: 63, 255, 63

Base alphanumeric code: l03

Saw Marks

This layer was used to record both ancient and modern saw marks. Modern saw marks are often seen around treenails on the outboard face of framing timbers and the inboard face of planks, and were created during efforts to dismantle the vessel. Ancient saw marks were often seen on stringers and ceiling planks.

RGB Colour Code: 0, 191, 0

Base alphanumeric code: l04

Cross-section (Snit)

This layer was used to record cross-sections and contour information in areas of rapid surface change or voids in the timber. When drawn over a fastener hole, it meant that the fastener was still present. The Cross-section layer was also used to record the depth of shallow blind treenail holes and rebates cut for tingles on the hull planking.

Cross-sections were drawn at 150mm-300mm intervals around most timbers. Cross-section locations were chosen to avoid areas containing treenails and rebates, and were ideally laid out perpendicular (at right angles) to the edges of the timber. Properly recorded cross-sections could be used to quickly determine the overall form of a timber and be used to create a basic model of a timber. Cotton tape was used to mark out the contour lines and also served as a surface on which to draw with the probe tip. This helped prevent damage to the wood caused by moving the probe tip against or across the grain.

RGB Colour Code: 255, 165, 0

Base alphanumeric code: n02

Dendro Sample

This layer was used to mark the cuts or slices made during the removal of timber samples for dendrochronological analysis. This information was routinely added to the digital file during a second phase of recording, as the timbers were generally contact digitised and photographed intact before being selected for dendrochronological analysis.

RGB Colour Code: 255, 127, 255

Base alphanumeric code: n03

Text and Symbol

This layer was used to record the position and number of samples, including luting, tar, molluscs, seeds, nuts and iron, taken from the timbers. It was also used to record the orientation of the timber, which was achieved by drawing a specific symbol on each face of the timber. The symbol layer was also used to denote the inboard/outboard face of the plank or the four sides of a frame. On the inboard face of a plank, the symbol was a man, oriented so that his head was facing the upper edge of the plank, and his forward (bow facing) arm was raised. Out the outboard face of a plank, the symbol was a fish that was ‘swimming’ in the same direction as the ship (towards the bow). The fin of the fish was pointing towards the upper edge of the plank.

There are four symbols that denoted the four sides of a frame. These were drawn approximately 50mm in diameter, near the centre of the timber face, but not near any other features. The symbol for the inboard face was a star, while the aft face was a circle and the forward face an X. The symbol for the outboard face was a triangle.

Other symbols were utilised on specialised timbers like the stringers, which were marked with an empty box to denote the upper edge and a box with an x in it to denote the lower edge. The inboard and outboard faces of stringers were marked with the star and triangle respectively. On timbers with no known orientation, the symbols were assigned arbitrarily with a note to that effect being made on the timber recording sheet.

RGB Colour Code: 255, 0, 255

Base alphanumeric code: n04

Reorientation and Calibration

It was necessary to reorient the contact digitiser to the timber after moving either the timber or recording equipment. This reorientation process typically occurred after turning a timber over to record the remaining faces or shifting the timber or contact digitiser in order to reach previously inaccessible areas. To achieve an accurate reorientation, the recorder chose the Calibrate Digitiser icon in Rhinoceros3D, and, at the Enter Origin with digitiser prompt, selected three control points (ideally widely spaced apart along opposing faces of a timber. After shooting in these points, the recorder used the mouse (set to Object Snap) to click on the three control points in the same order as they were shot in with the contact digitiser. Control point tolerances on all axes needed to be less than 0.4 mm. It was generally easier to move the timber than the contact digitiser, although both were feasible solutions to recording an oversize timber.

The accurate reorientation of the timber to the contact digitiser was critical in order to produce an accurate and precise 3D composite record of the complete timber (Hocker, 2003). Any movement between the timber and the contact digitiser, no matter how slight, needed to be recognised and the reorientation process initiated and successfully completed before continuing with the recording work.

It was necessary to routinely calibrate the contact digitiser. This process involved measuring a precision ground steel sphere attached to a calibration block and checking to see if the measured values fell within permissible ranges (Figure 66). The calibration process was usually performed once a week, and also took place whenever a probe tip (or probe tip holder) was replaced, adjusted, or the contact digitiser itself was moved (Jones, 2013).

Figure 66. Calibrating the FaroArm contact digitiser. This important check was performed at least once a week, and ensured that the device was in peak operating condition. Toby Jones.

Checking the Digital Record

Each completed digital drawing was checked by another archaeologist while the timber was still on the recording table. If mistakes or omissions were noted during the checking process, it was a straightforward process to reference the digitiser back to the original timber and record the missing features or modify areas that were incorrectly recorded. After final checks, the digital drawings were saved as read-only files and archived for future analysis and modelling. The resulting .3DM wireframe files averaged 1- 5 MB each in size (Jones and Nayling, 2011: 56).

The vast majority of timbers were subsequently examined by the author (as timber recording coordinator), checking for consistency and completeness in the digital record. The digital records were then converted into 2D paper printouts and analysed by the archaeological consultant for wood science purposes (Figure 67. Print-out of a four-sided digitally recorded timber. The archaeological consultant would compare the details in the drawing to the features on the timber and note any deficiencies.). The archaeological consultant would compare the details in the drawing to the features on the timber and note any deficiencies. The archaeological consultant also used this opportunity to make photographic recommendations.

Any discrepancies between the drawing and the features on the timber were noted and passed back to the recording archaeologist for correction (Figure 68). These multiple levels of checking and rechecking helped to ensure that all relevant features were accurately and consistently recorded, resulting in an extremely detailed and useful digital data set. This quality control process was documented and monitored by a series of date and initial fields in the project database.

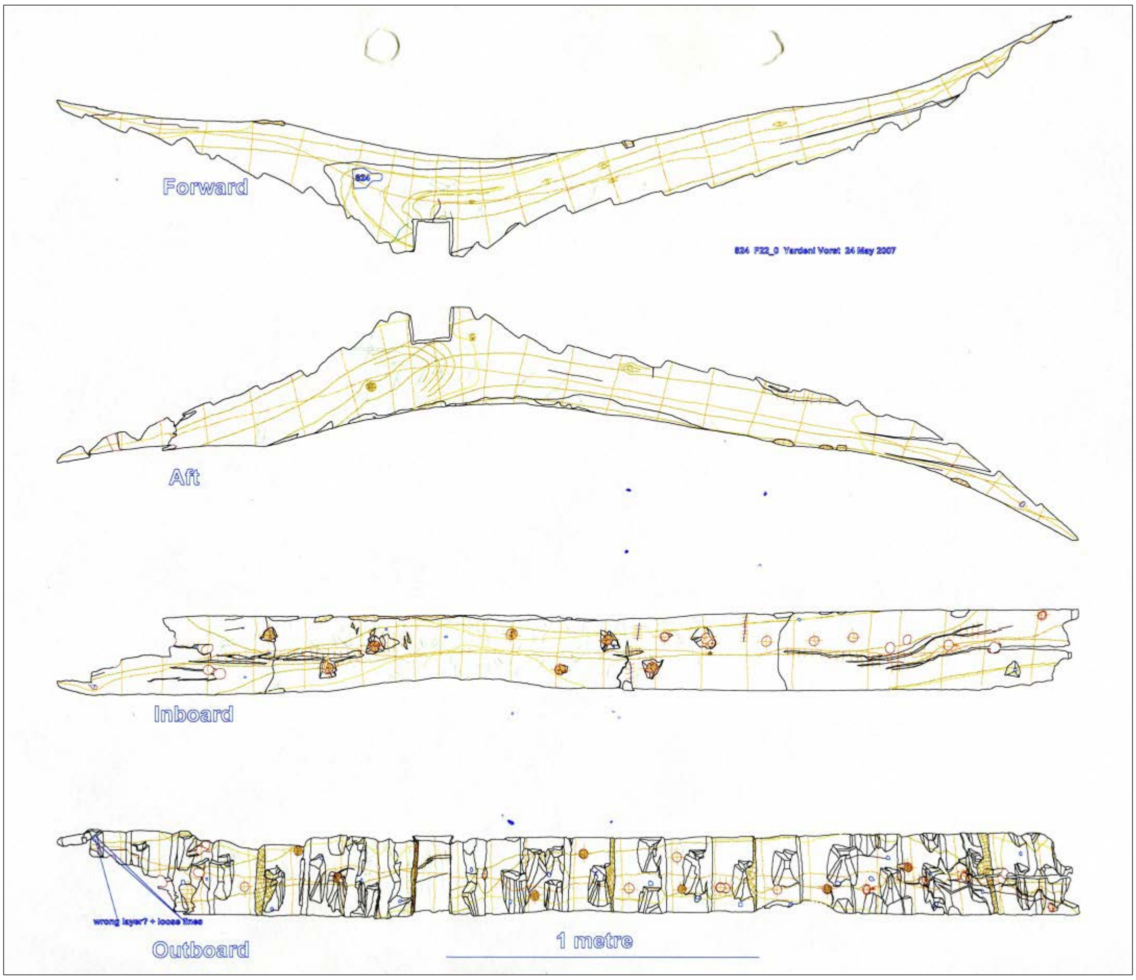


Figure 67. Print-out of a four-sided digitally recorded timber. The archaeological consultant would compare the details in the drawing to the features on the timber and note any deficiencies. Toby Jones.

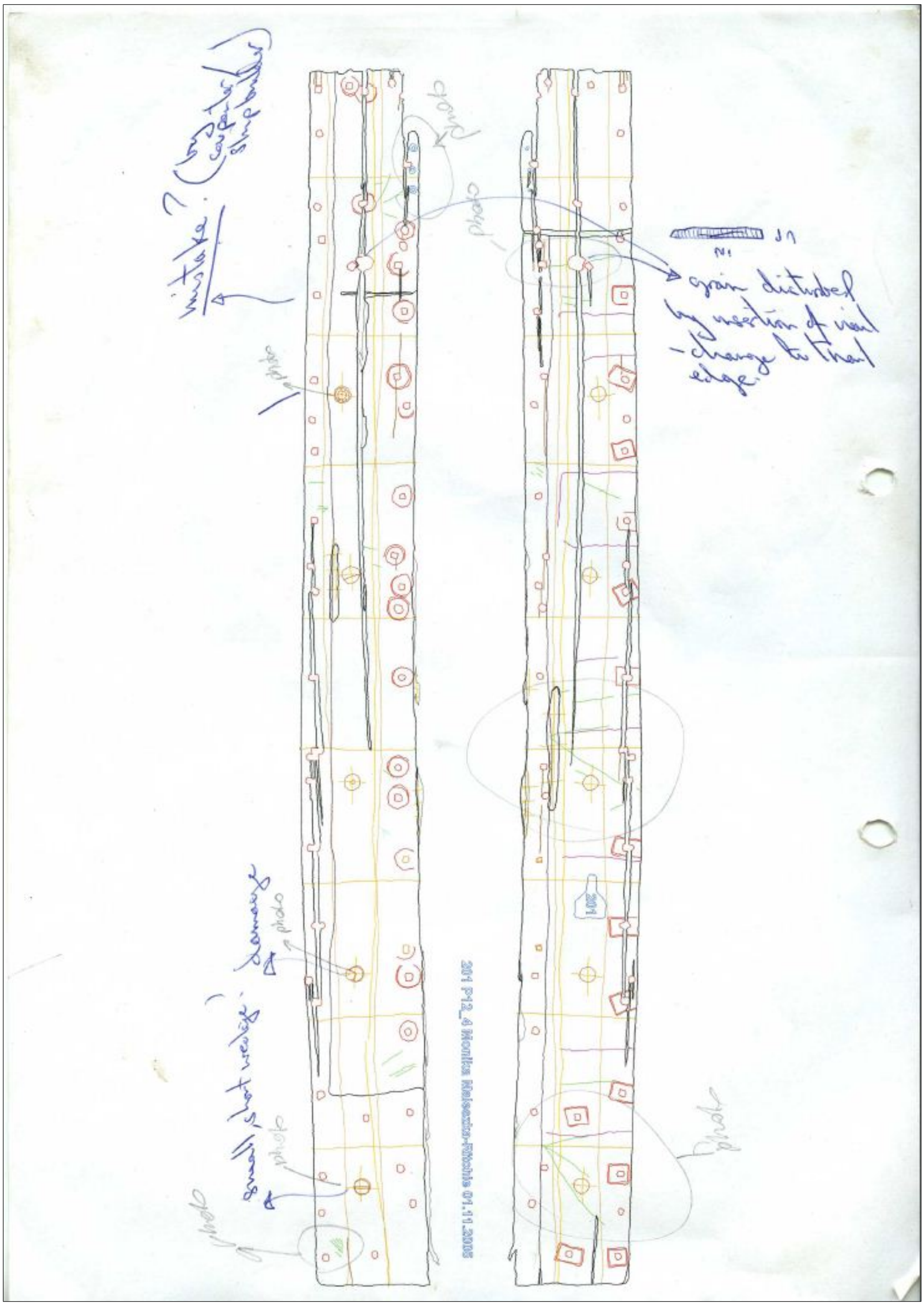


Figure 68. Annotated print-out of a two-sided timber. Any notes are incorporated in the database, while any necessary corrections are made to the original digital drawing. Toby Jones.

The digital documentation methods were complemented by selective digital photography and laser scanning or casting of special features. The selective photographs were requested at this stage by notations on the printouts and on the timber record sheets. Requests for changes and corrections to the Rhinoceros3D files became increasingly rare as the recording team acquired a high level of competence and consistency in the recording process.

Details about each timber, including function code, description and its progress through the documentation process were tracked on physical clipboards and in a Microsoft Access database file. Timbers were moved from storage tank to storage tank as they progressed through the documentation process, helping to maintain a level of physical organisation, which was matched by the timber's record sheet being moved from one clipboard to another. Timbers could be held in a pre-cleaning area, a post-cleaning area, a post-recording area, and a pre-photography area, before being placed in a final storage location prior to conservation. Physical timber locations were also tracked by the abovementioned database.

After completing the initial recording process, certain timbers were selected for further analysis including coring for sulphur-reducing bacteria or sawn to provide dendrochronological samples. After these samples were taken, the ship timber might be in several pieces. Using contact digitisers, the archaeologists referenced existing control points on the fragments and opened the original wireframe drawing file containing the complete timber. They then recorded the dendrochronological saw marks or sulphur cores on specific layers. It was then possible to view the complete timber while simultaneously seeing where the cuts or cores had been taken. Newly assigned cow tag numbers were also inserted into these digital drawings. The files were saved again as read-only and backed up both on and offsite. These files, showing the modern cut marks and bores holes, will be of value to the conservators, especially for mitigating the damage when preparing the material for display after the PEG pre-treatment and freeze-drying.

Archiving

The Newport Medieval Ship project reached an agreement with the Archaeological Data Service (ADS) regarding the deposition of and access to the copious amount of digital records associated with over ten years of archaeological research. The ADS guaranteed free and open access to the archive in perpetuity. The Newport Medieval Ship Digital Archive contains over 12,500 files including Timber Record Sheets, Hull Schematics, Specialist Reports, Artefact Catalogues, 3D Timber Drawings, Site Photogrammetry, Site Drawings, Digital Solid Models of each structural timber, Excavation, Timber and Artefact photographs, and a Project Database (http://archaeologydataservice.ac.uk/archives/view/newportship_2013/) (Nayling and Jones, 2014a). These files are in a variety of formats, including common standards like .PDF and .TIF along with other, less common formats, like .DWG, .STL and .3DM, covering the CAD vector graphics data. The Newport Ship digital archive will eventually be linked to an Internet Archaeology Journal article explaining the structure and function of the archived resources.

In the Newport Medieval Ship Project Digital Archive, the vector graphics files of the ship's timbers were available in the following three distinct formats, .3DM, .DWG, and .STL. Each of these formats contained data derived from the digital documentation and modelling of individual ship timbers. The individual.3DM files could contain wireframe data, mesh data or a combination of the two. Single .DWG files contained wireframe data, while .STL files contained only mesh data. Both .3DM and .STL files could contain data on a single timber or on a group of related timbers. However, .DWG files would only contain wireframe data for an individual timber. Multiple timber drawings could not be saved together in a single .DWG file, as that format did not support the Group command used in Rhinoceros3D to create discrete collections of layers.

All of the data was organised using the layering systems present in the Rhinoceros3D modelling software, as this was the programme used to first capture or create, and then edit, the data. Although the native file format for Rhinoceros3D was the proprietary .3DM format, it was widely used by other practitioners (those creating and using similar data sets of wireframe ship timber drawings) and deemed the ideal way to archive, access and share the data. The layering system consists of alphanumeric base codes coupled with text descriptions of each layer and sub-layer along with an RGB colour recipe for each layer or sub-layer. These layers and sub-layers were used to provide organisation and clarity to the vast quantity of complex detail contained in each file.

All wireframe drawings of articulated ship timbers, in .3DM format, were assembled into three master composite digital files known as Outer_Hull, Inner_Hull, and Frames (for further information, see section below on master composites). These files have a layer and sub-layer system that consisted of three levels. The top level contained two layers, Wireframe and Mesh. These layers contained a second tier layer name consisting of the function or type of the timber, such as Plank or Frame. The third or lowest level contained the alphanumeric base code and the specific layer. Ship timbers drawings were saved out of these master composites into groups of timbers from each frame station, strake or similar combination, in order to create smaller, more manageable, file sizes. Disarticulated timbers, such as bilge boards, beams and knees, were digitally drawn and saved as .3DM files and later converted to .DWG files, with both of these file formats displaying a straight layering system without parent layers/sub-layers hierarchy.

Given the structural differences between the Rhinoceros3D .3DM files and the .DWG preservation/migration format, some alterations in the organisation and display of the layers and groups in the data were present. The .3DM files contained the wireframe data and resulting meshes in a hierarchical structure of layers and sub-layers. The .DWG format recognised the different layers and sub-layers, but displayed them serially as a single layer, albeit with breaks (with the breaks taking the form of a dollar sign, $) between each layer/sub-layer. A typical layer structure in .3DM format would look like (expression::expression::expression). An example file name with parent layers/sub-layers might be called the following: [WIREFRAMES::BracesWireframe::aa01 measuring tape], with the double semi-colons representing the step between a parent layer and a sub-layer. The same layer structure in .DWG format would look like: (expression$expression$expression), with the parent layer/sub-layer expression consisting of the following: [WIREFRAMES$BracesWireframe$aa01 measuring tape]. Files that were saved out in .STL format contained a single layer containing one or meshes of the digital solid models in that section of the vessel.

The final vector graphics data files were saved out of the master composites in .3DM formats for dissemination, and into .DWG and .STL formats for archive preservation/migration purposes. Files were saved out of the master composites along with information about that timber's relative position to a set origin. In practice this meant that two individual files opened in the same CAD work space would be in their right relative positions to one another.

The Utility and Comparability of Data Sets Produced Using Contact Digitisers

The use of contact digitisers and consistent templates, coupled with common software and training, to record ship timbers is creating a data set that is easily understood, shared and compared. The digital nature of the data allows for timber drawings from different projects to be imported into the same workspace and compared side by side, or for the researcher to take selected measurements from within the drawings for comparison. This concept has been utilised in several ways, including capturing and comparing measurements from individual Newport Ship timbers, comparing selected timbers from the Newport Ship to the similar Aber Wrac'h 1 shipwreck, and for capturing and analysing the dimensional changes in a Newport Ship hull timber before and after conservation treatment. These examples are explored more fully in the following sections.

Capturing and Comparing Measurements from Individual Newport Ship Timbers

During the course of the ship timber digital recording project, it was decided to create tables of measurements taken from the wireframe files. Normally in two dimensional paper recording, this data would have been captured by direct measurement and recorded in tables. Given that all of the hull planking from the Newport Ship was digitally recorded, a subset of intact and undamaged planking was selected and analysed in greater detail using the measuring commands available in the Rhinoceros3D modelling software. In contrast to the more traditional recording methods, these measurements were extracted after the recording phase, and often by someone other than the original recorder. The results of this project, referred to as metrical data capture, were used to create tables of measurements covering timber dimensions and fastener spacing and size. These tables of measurements were grouped and analysed in order to detect patterns and trends in the hull planking scantlings.

The outer hull of the Newport Ship consisted of planking and tingles, and was made entirely of radially split oak. There were 35 strakes of planking surviving on the starboard side and 17 strakes on the port side. A total of 165 complete and undamaged planks were recovered, along with many more fragmented planks (Figure 69).

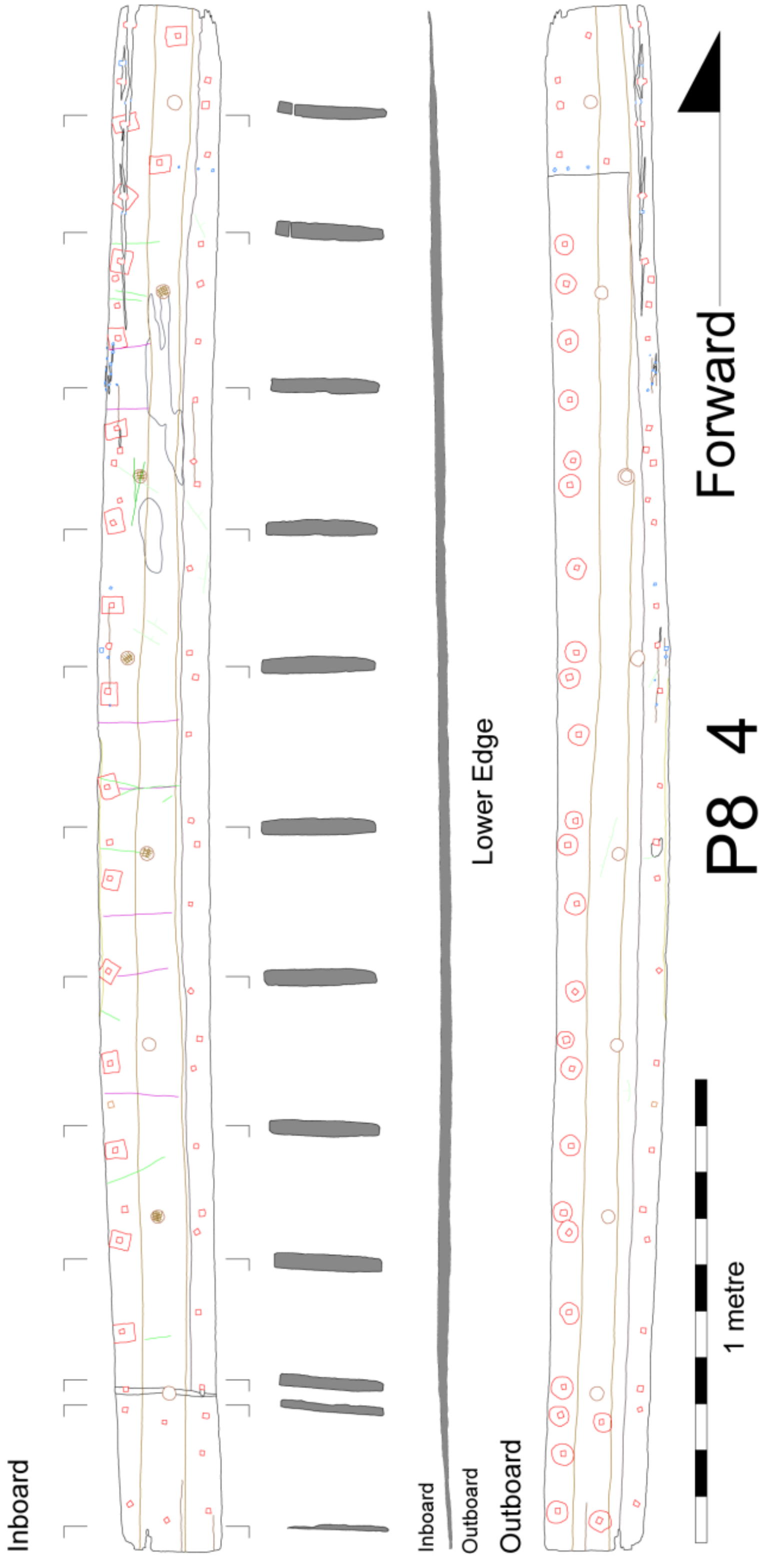


Figure 69. A typical hull plank from the Newport Ship. This 2D drawing has been created from the original 3D wireframe drawing. Toby Jones.

The relatively consistent nature of the planking allowed for meaningful comparative measurements to be taken. Various features, including edges, fasteners, and wood grain, were recorded onto distinct layers, enabling sophisticated analysis and comparison along a single plank and across multiple timbers. The accurate digital recording of these timbers and the subsequent analysis and extraction of metrical data from the drawings created a useful statistical data set, from which averages could be calculated and anomalies identified. The metrical data capture was largely confined to the outer hull planking, although efforts were made to expand the metrical data capture exercise to some of the framing timbers, however the wide variations in scantlings of the framing made the creation of averages problematic.

Newport Ship Hull Plank Metrical Data Capture Exercise: Process and Results

In order to test the accuracy and efficacy of the metrical data capture exercise, several test planks were chosen. Features on these planks were digitally measured by the different project archaeologists and compared. As expected, the results, which included centre to centre fastener spacing, were found to be identical between all the archaeologists. When the odd discrepancy appeared, it could be traced to the archaeologist mistakenly choosing the wrong point when measuring between two features (such as selecting the inboard instead of outboard fastener centre). The accuracy and consistency of the measurements was not surprising, given the digital nature of the data set. With minimal training and oversight, various project archaeologists set about measuring features on hundreds of ship timbers and entering the data onto spreadsheets. Some of the more interesting results are presented below. The measuring process revealed many interesting features and patterns, as well as showing a high degree of consistency of certain features across many ship timbers, from scantlings to fastener spacing.

The following description of the hull planking was created using data gleaned from the metrical data exercise. There were lands on the lower inboard face and upper outboard face of each hull plank. The outboard lands averaged 49mm in width, while the inboard lands averaged 50mm. A pronounced bevel on the land was visible on the second and third strakes, with little or no bevel apparent on the other strakes. The surfaces of the lands were well-preserved, having been protected by a layer of animal fibre and wood tar, along with the overlapping planking.

Occasionally an inscribed line or carpenter’s mark was visible marking out the area to be trimmed for the land.

There were stop-splayed on-edge, face nailed scarfs present on the forward and aft ends of each plank. The scarfs had an average length of 382mm and an average width of 210mm. The forward scarfs were thicker than the aft scarfs, which tended to taper to a near feather-edge. Two extra nails and roves are used to fasten the scarf, in addition to the standard nails and roves along the lands. On a typical scarf, these nails were placed along the centreline of the plank, with one near the end of the plank and one set back from the lip of the scarf.

The scarf joints were generally staggered across the hull, although there appeared to be some general patterns (with some notable exceptions). On the port side of the ship, there were areas where each successive strake tended to have a scarf slightly further forward than the one on the strake below. There was a clearly visible pattern between P2 and P10 and between F30 and F45 (Figure 70). As the planks in each strake vary considerably in length, it seems unlikely that the pattern is a random coincidence, but equally, the majority of scarfs have no discernible distribution.

The planks were fastened with round-headed square-shanked wrought iron nails driven from the outboard through pre-drilled holes and peened over wrought iron roves. The nails were driven in along the planking strakes at an average spacing of 175mm. The nails had a mean shank dimension of 12mm square with the nail heads having a mean diameter of 43mm. The roves were sub-rectangular, with average dimensions of 43mm x 36mm. It was interesting to note that the average maximum width of the rove and the average nail head diameter were identical. The roves are generally oriented with the longer edge vertical or near-vertical on the inboard face of the hull plank, with some rove impressions extending off of the upper edge of the inboard surface of the timber. It was not possible to determine the thickness of the nail heads or roves as they had substantially corroded, however, the other dimensions could be readily measured from the clear impressions left in the surface of the planking. Several nail head impressions contained clear star-shaped indentations, which was interpreted as evidence of a maker’s mark standing proud on the underside of the nail head (Figure 71).

The standard pattern of inserting the nails from the outboard was reversed in the extant bow area of the vessel. Here the nail head impressions were visible on the inboard face, with corresponding rove impressions visible on the outboard face. This practice, while not universal in the bow, was certainly addressing a practical problem of having enough clearance for the hammer to peen over the nail onto the rove.

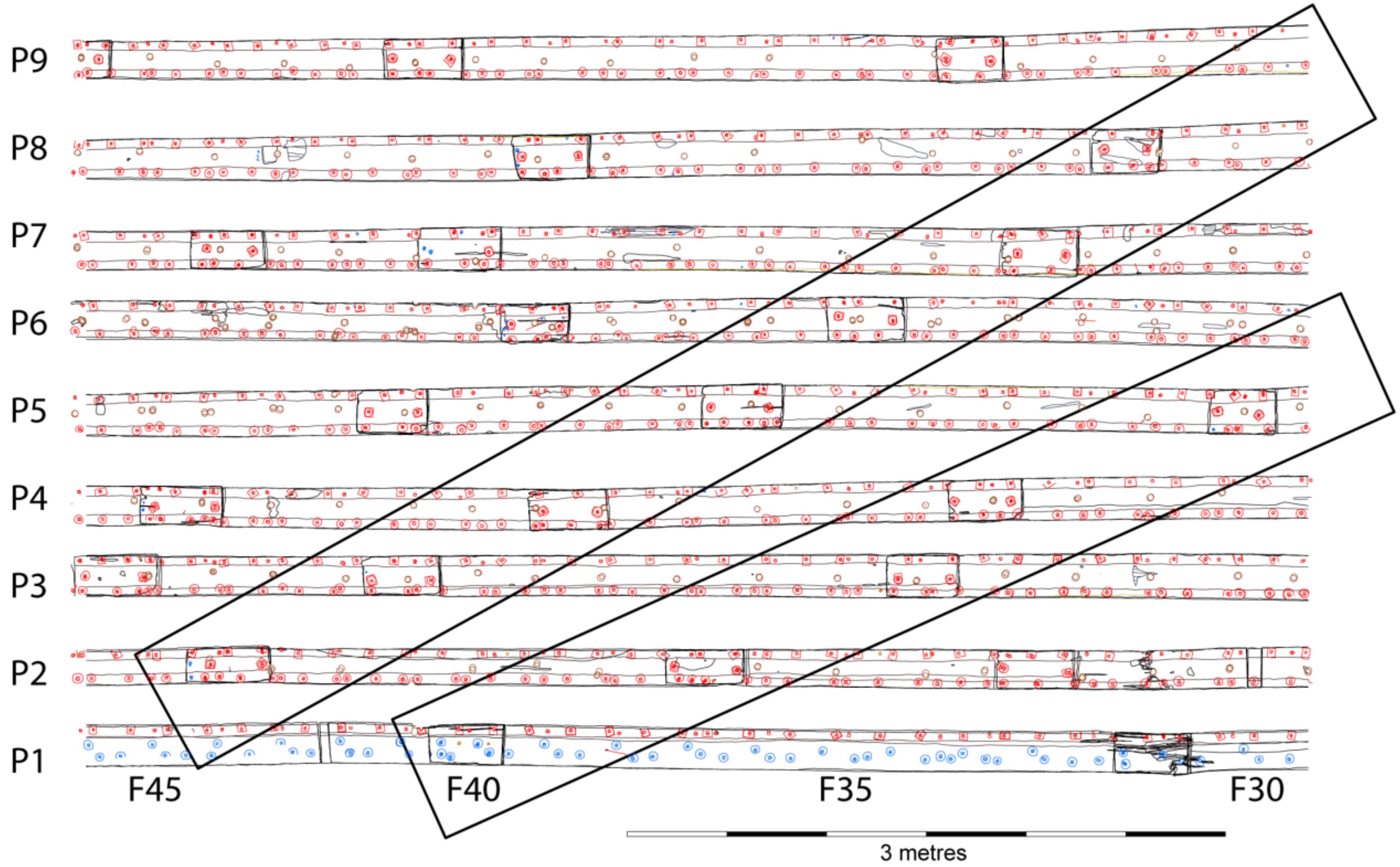


Figure 70. On the port side of the ship, there were areas where each successive strake tended to have a scarf slightly further forward than the one on the strake below. There was a clearly visible pattern between P2 and P10 and between F30 and F45.

Toby Jones.

Numerous additional nail holes were recorded on the hull planking. Several small nail holes were often seen on the after scarf ends, serving to tack down the feather end of the outboard scarf to the underlying outboard face of the forward scarf. It is not known if these nails were inserted during the original construction of the vessel or represent a repair phase. Other small additional nails were used to close up cracks that might appear along a land. These nails were often driven in from the lower outboard edge of the planking upwards toward the underlying plank. The small additional nails had an average head diameter of 16mm and an average shank of 5mm square, with a considerable amount of variation.

A peculiar feature seen on the hull of the Newport Ship was the insertion of iron spike nails through the hull planking and into the framing. These nails are similar in size to the clench nails, with an average shank measurement of 13mm square and an average head diameter of 50mm. It could be that these spike nails, with their slightly larger heads and shanks, represent a distinct event, perhaps tightening up the hull of the ship at some point during the use-life of the vessel. Alternatively, they could have been used to tack the framing in place while it was being drilled to accept the treenails. With few exceptions, these iron spike nails were driven into every plank/frame intersection (literally thousands), often in close vertical proximity to the treenail. Numerous small blind (and through) additional spike nail holes were seen on the inboard face of the planking in the bow area. Their function has not been discerned, but could relate to the construction process, as they lie near the centreline of the vessel. On one occasion, sintels or staples were used to keep a crack from spreading on S17_4 CT269 (Figure 72).

Figure 71. Nail head impression and hole on the outboard face of a hull plank. Note the star-shaped impression left by a maker's mark on the underside of the nail head. Newport Museums and Heritage Service.

Figure 72. Four sintels or staples were used to close a crack on this hull plank. Newport Museums and Heritage Service.

Other repairs to the hull planks included the insertion of wooden (oak) spike nails driven into holes previously occupied by wrought iron nails (as evidenced by the presence of an iron nail head impression. Other wooden spikes appear to be driven into purpose-drilled holes (i.e. no iron nail head impressions present). These minor repairs could be interpreted as the regular maintenance and inspection of the hull.

Tingles or repair planks covering over areas of cracking or damage were primarily found attached to the outboard faces of the hull planking (Figure 73). Tingles were recorded in the lower bow area as well as the amidships area. The tingles were classified based on the presence or absence of rebates on the inboard face. Tingles with such rebates were designed to accommodate the proud-standing extant fastener heads, while tingles without rebates were applied to those areas of the hull where the original fastener heads had been purposely removed (or rotted/corroded away).

The treenails, used to fasten the framing to the planking shell, were present at nearly every frame/plank intersection, with occasional areas having two treenails. The treenails, made from split and turned oak, had a mean diameter of 30mm and an average spacing of 371mm along the strakes. It was difficult to judge the length of many of the treenails, as they could not be removed from the framing. Small dimples were sometimes visible on the heads of the treenails, along with striations around the shoulder (which were visible on removed treenails), indicating that at least some, if not all, of the treenails were produced using a lathe (Figure 74). Some treenails had pronounced heads, while others were driven in flush with the outer surface of the planking, although none of the hull planks appear to have been rebated on the outboard face. Certain treenails had a distinct faceted head with three or more cut faces (Figure 67). Rectangular oak wedges were visible in certain treenails heads (Figure 76).

Figure 73. Outboard tingle fastened to a hull plank. The surface between the plank and tingle was filled with tar and animal hair and typically used to patch areas of cracking in the original lapstrake hull planking. Newport Museums and Heritage Service.

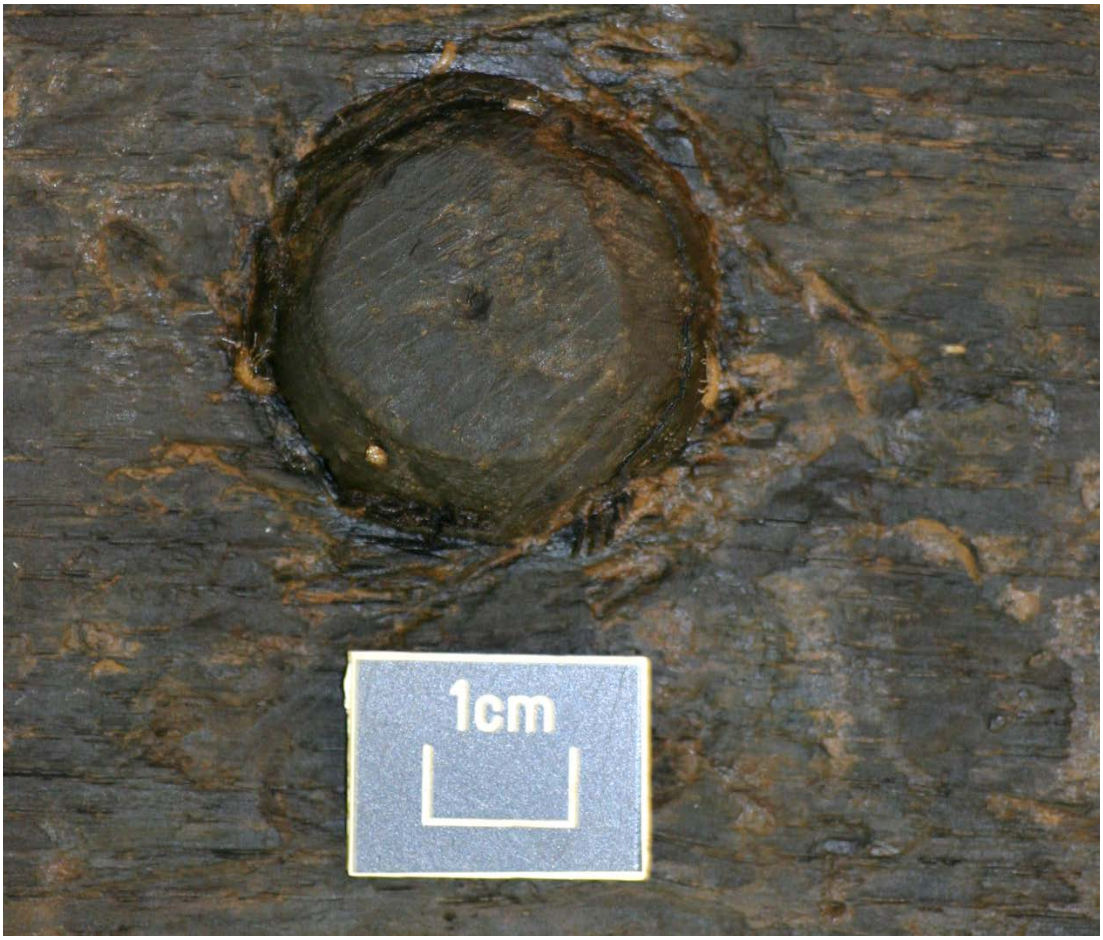


Figure 74. Treenail head on the outboard face of a hull plank. The dimple was created by a lathe during the manufacturing process. Newport Museums and Heritage Service.

The measurements and ranges mentioned above represent but a fraction of the geometrical data contained in the digital wireframe drawings of the Newport Ship timbers. This information is easily accessible and readily captured using the various measuring commands within the Rhinoceros3D software. Such detailed information can be used to compare features across the hull or to scantlings from other vessels. The ability to revisit (and extract measurements from) a 3D wireframe drawing of a ship timber long after it was originally recorded will prove to be of immense value to future archaeologists, who will undoubtedly have new questions to ask of the material.

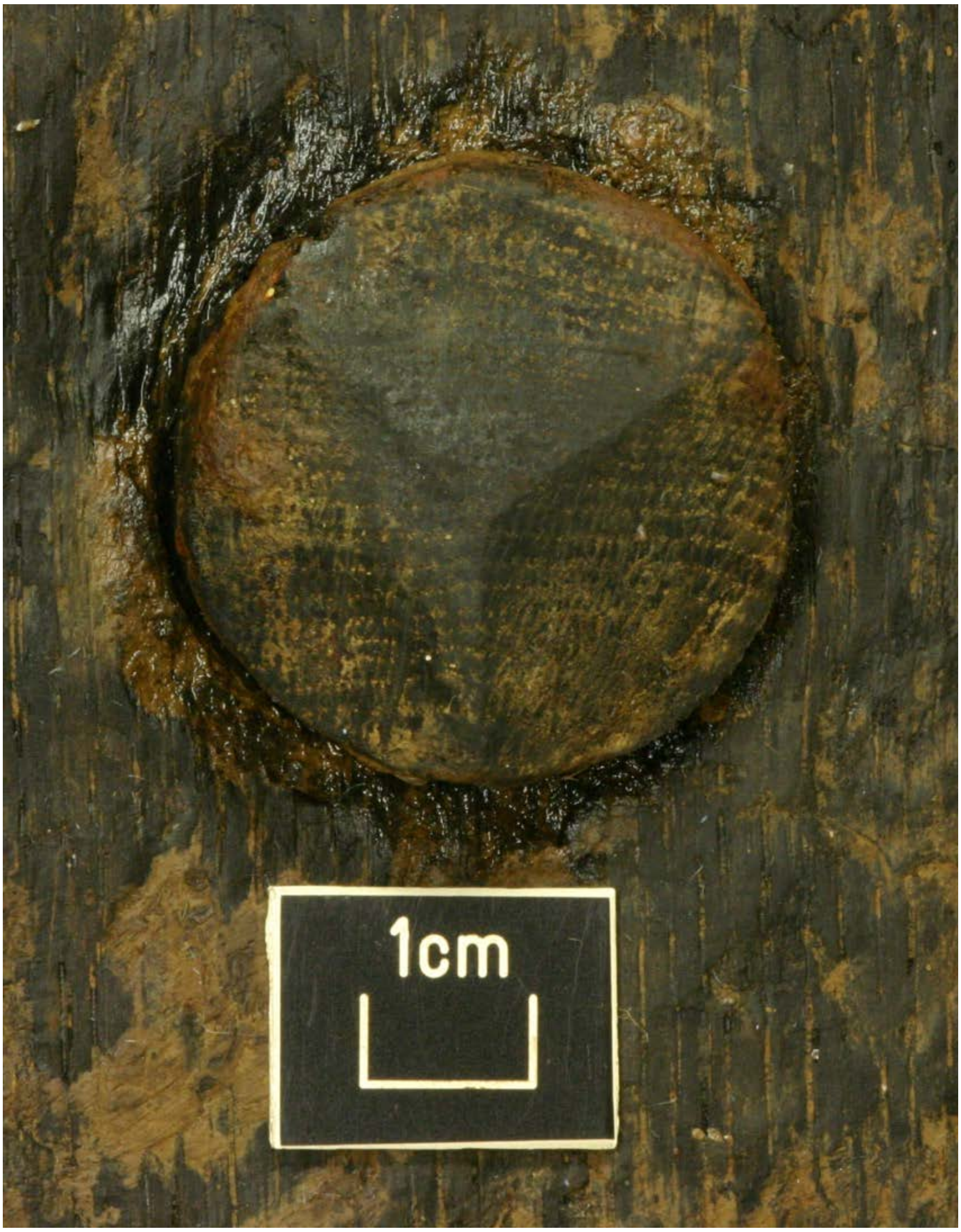


Figure 75. Faceted head of a treenail seen on the outboard face of a hull plank. Newport Museums and Heritage Service.

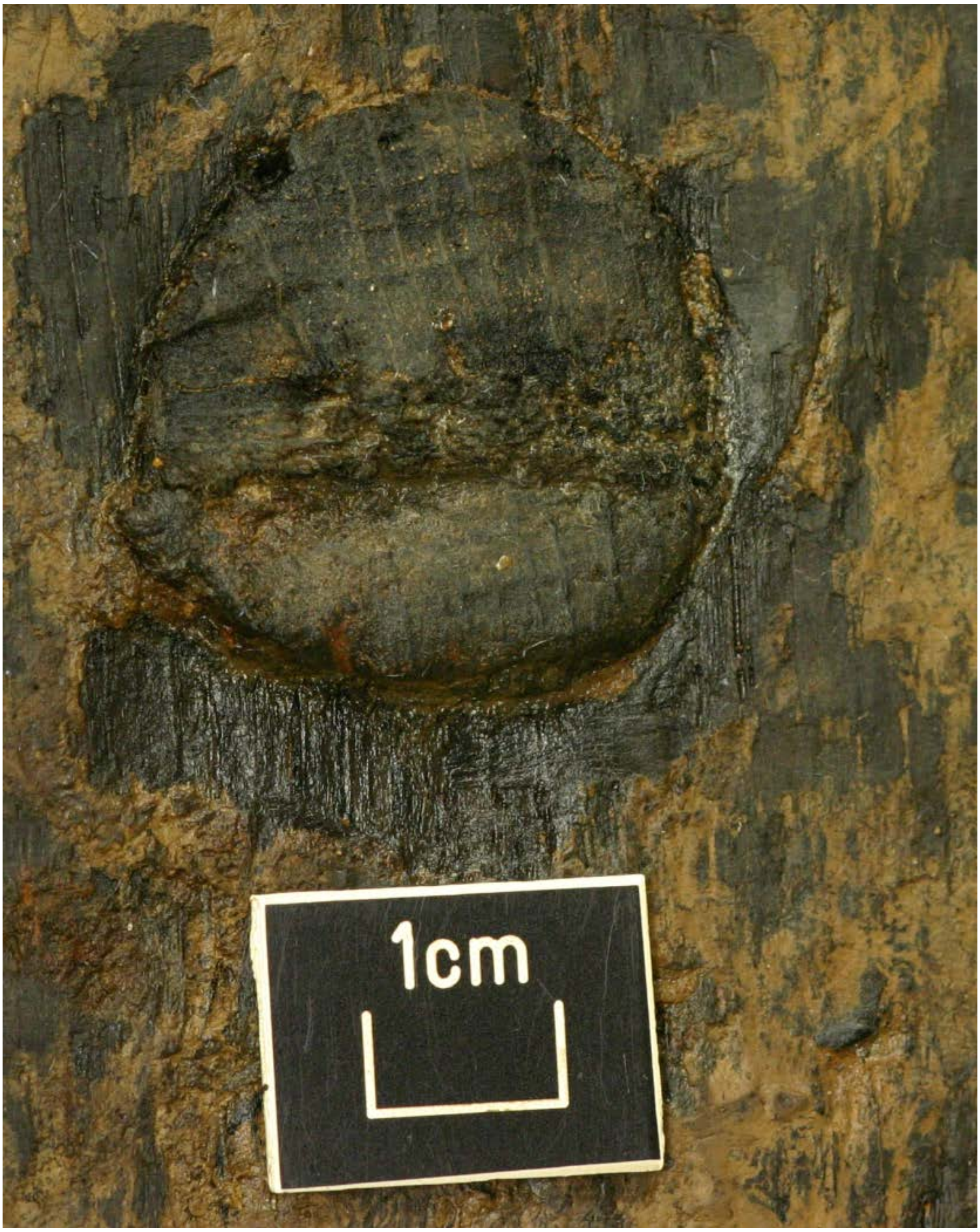


Figure 76. Wedged Treenail head seen on the outboard face of a hull plank. Newport Museums and Heritage Service.

Aber Wrac’h 1 and Newport Medieval Ship Hull Plank Comparison

Case Study

In July 2013, the author was invited to digitally record selected timbers raised during the re-excavation of the Aber Wrac'h 1 site in Brittany, France. The Aber Wrac'h 1, a lapstrake vessel dating to the 15th century, represented the closest parallel to the Newport Medieval Ship in terms of construction, size, and date, and as such, was deemed to be unique opportunity to gather detailed information from the hull timbers (L'Hour and Veyrat, 1994: 165-180, L'Hour and Veyrat, 1989: 285-298, Grille, 2013). During the re-excavation in 2013, a variety of timbers, including a fragment of keel, framing timbers, stringers, and hull planking (both garboards and normal planks), were raised and cleaned prior to documentation using a contact digitiser. A new-model FaroArm Edge (with a spherical working volume of 2.7m) was configured with a 3mm ball probe and connected to a workstation computer (Figure 77).

Figure 77. Using a FaroArm contact digitiser and associated laser scanner to document a stringer from the Aber Wrac'h 1 vessel. The emitted laser from the scanner can be seen as a red stripe in the foreground. Anais Pajot.

Rhinoceros3D 4.0 software was used to capture point data, while a Faro-built ScanArm laser scanning attachment was used in conjunction with Geomagic software. Laser scan data of toolmarks, rebates and fastener heads was integrated into the wireframe drawings using Rhinoceros3D Version 5.0, which allowed both data sets to be positioned and viewed simultaneously (Figure 78).

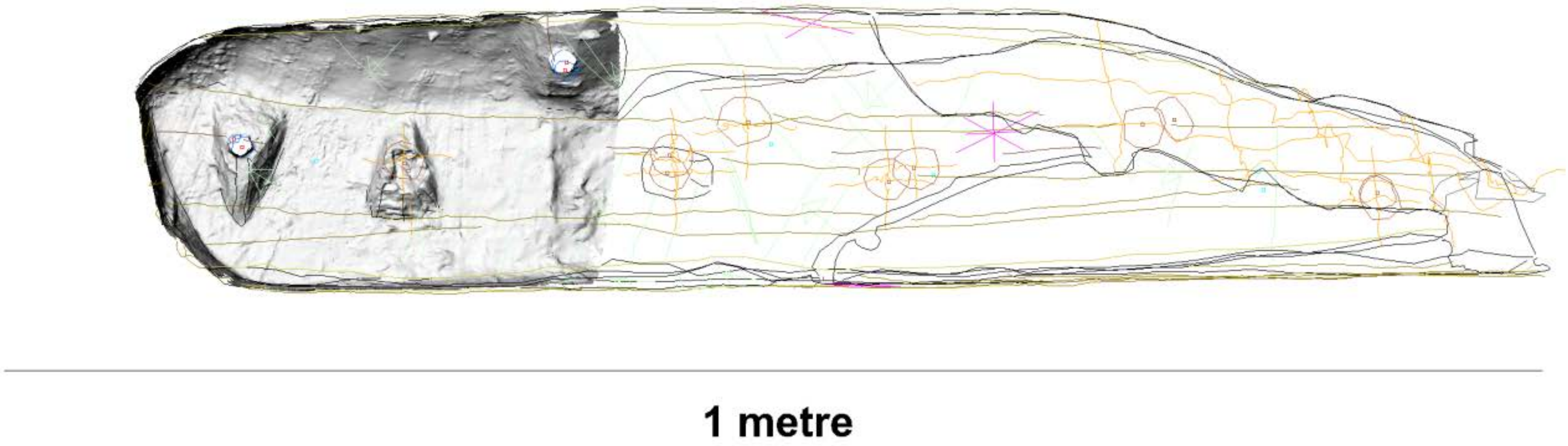


Figure 78. Laser scan data of toolmarks, rebates and fastener heads was integrated into the wireframe drawings using Rhinoceros3D Version 5.0, which allowed both data sets to be positioned and viewed simultaneously. Toby Jones.

Individual Aber Wrac’h 1 timbers were documented using the templates and toolbars developed for the Newport Medieval Ship Project, with the author consciously attempting to select ‘typical’ or average timbers, with an eye to comparing the digital drawings with comparable material recorded from the Newport Ship assemblage (Figure 79). The opportunity to record similar ship timbers from different sites using the same methodology, technology and personnel has allowed for the direct three-dimensional digital comparisons of the respective timbers, enabling sophisticated analysis.

The areas of analysis included general timber shape and scantlings, fastener dimensions, spacing, and scarf form. Equally valuable was the fact that the identical layering system allowed for the timbers to be placed side by side or even overlaid within a single Rhinoceros3D file. The ability to place timber records in this fashion made it straightforward to detect similarities or common features, but also highlighted differences (Figure 80). For example the ubiquitous spike nails present in the hull of the Newport Ship (a single iron spike nail attaching planking and framing at each plank/frame intersection) were noticeably absent on the recorded Aber Wrac’h planking.

Figure 79. Using a FaroArm contact digitiser to document the outboard face of a stringer recovered from the Aber Wrac'h 1 vessel. Anais Pajot.

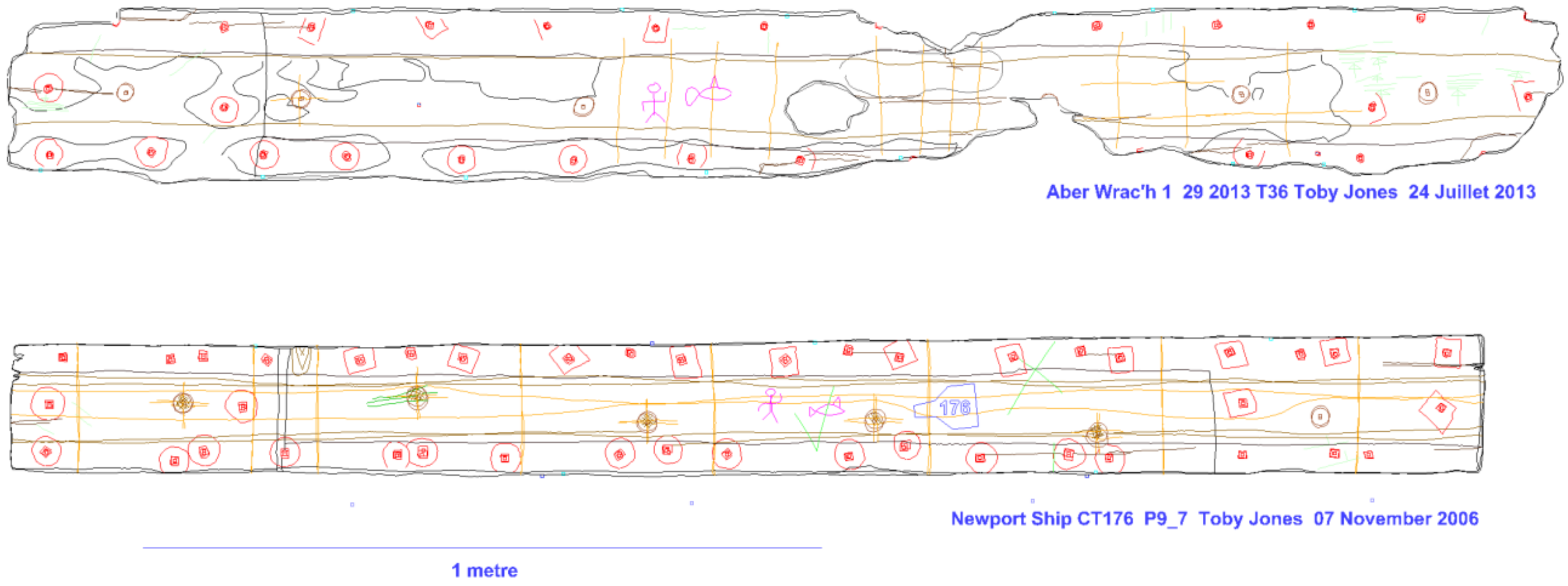


Figure 80. Comparison of the digital records of two medieval lapstrake port side hull planks. The top plank is from the Aber Wrac'h 1 vessel, and the bottom plank is from the Newport Ship. Both timbers are at the same scale. Toby Jones.

A rapid comparison of two nearly identical port side hull planks from the Newport Ship and the Aber Wrac’h 1 vessel show a broadly similar pattern of fastener dimensions and spacing, with the Newport Ship having an average spacing between clench nails of 175mm, while Aber Wrac’h has an average spacing of 164mm. The average spacing of treenails on the Newport Ship was 371mm, while the Aber Wrac’h had an average spacing of 320mm. Treenail head diameters averaged 27mm in diameter on Aber Wrac’h and 30mm in diameter on the Newport Ship. The average dimensions of the sub-rectangular roves were also similar, with Newport averaging 43mm x 36mm and Aber Wrac’h 1 averaging 42mm x 31mm. Clench nail heads and shank sizes were also similar, with Newport nails having an average head diameter of 43mm and a shank of 12mm. Nail holes on the Aber Wrac’h hull plank had an average head diameter of 41mm and a shank of 10mm. When considered together, the fastener sizes and spacing are, on average, 10% smaller on the Aber Wrac’h vessel than the Newport Ship, which is interesting, as the Aber Wrac’h vessel was somewhat smaller than the Newport Ship (c. 25m long compared to 28.6m). It should be noted that this study covered a small sample, and may not be representative of the entire extant hull. However, the study does demonstrate that valuable comparative information can be obtained using this methodology, and that it is potentially a powerful tool for comparing fine details and scantlings between similar shipwrecks.

Comparison of Digitally Recorded Newport Medieval Ship Timbers Before and After Conservation Treatment

In the summer of 2013, Newport Medieval Ship hull timbers began to become available for study following PEG (polyethylene glycol) pre-treatment and vacuum freeze-drying. Several timbers, including a hull plank (CT333 S29_4) and a floor timber (CT636 F50_0), were selected for detailed digital recording after completing conservation treatment (Figure 81, Figure 82). It was important to document the timbers in their post-conservation state, as the drying of waterlogged timbers typically caused them to shrink in all dimensions (Cronyn and Robinson, 1990: 254). The exercise was designed to quantify the changes in size and shape between the waterlogged and conserved dried timbers. The detailed re-recording of the timbers during the post-conservation documentation stage would potentially reveal any shrinkage, distortion or loss of sapwood or surface detail (Ravn, 2012: 313).

The Newport Ship starboard hull plank CT333 S29_2, was originally recorded by the author on 17 September 2006 in a waterlogged state. The same plank was recorded again on 22 June 2013 after completing conservation treatment (Figure 83). There was a noticeable loss of surface detail, especially when comparing the extent of inscribed lines still extant on the surface of the timber. On both drawings of the same plank, measurements were taken between the same selected features.

The calculations for determining the percentage of shrinkage were based on measurement of the distance between selected fasteners, as well as the overall length of the plank and the thickness in selected areas. The numbers from the pre-conservation recording and post-conservation recording were compared, and differences determined. Percentages of shrinkage were then calculated for each set of measurements and then an overall mean determined. On CT333 S29_2, there was an average radial shrinkage of 4.1%, a longitudinal shrinkage of 1.5%, and a tangential shrinkage of 8.3%.

The floor timber CT636 F50_0 was originally recorded by the author on 2 March 2007 in a waterlogged state. The same floor timber was recorded again on 25 January 2014 after completing conservation treatment (Figure 84). There was some loss of surface detail and the presence of several large gaping cracks, where previously none had been recorded. The most noticeable difference between the two digital wireframe records was the visible contraction of the two distal ends of the V-shaped floor. The ends were 2131mm apart before conservation and 2085mm apart after freeze-drying. The difference of 46mm equates to a shrinkage rate of 2.2% in that particular dimension.

By highlighting the treenail fastener centres on the inboard and outboard faces of the respective models, and connecting these points with polylines, it was possible to visualise and compare the treenail axes (angles and lengths) before and after conservation (Figure 85). The screen capture shows the location and degree of

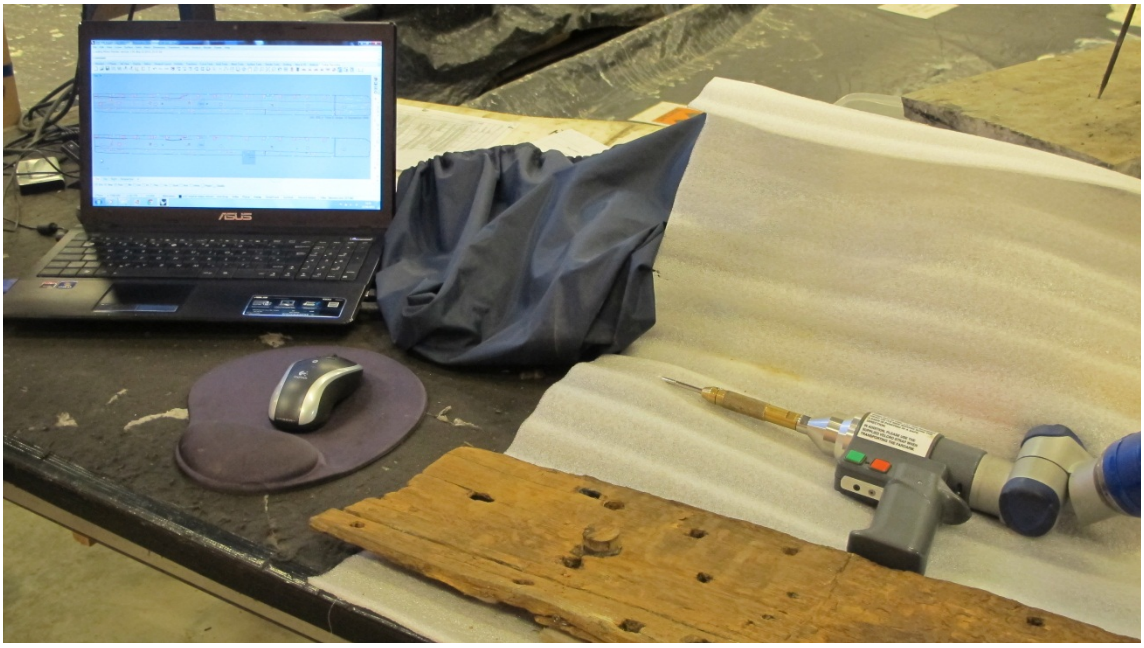


Figure 81. Recording a conserved (freeze-dried) plank from the Newport Ship. Toby Jones.

distortion with the waterlogged timber treenail axes in black and the conserved timber treenail axes in red. The corresponding treenail centres were an average of 5.85% closer together after conservation treatment, with an average distance between centres being decreased by 5.25mm. Minimal distortion was noted in the thicker central portions of the timber, with the three closest treenails on either side of the central limber hole having an average shrinkage rate 4.2%. The distances between the treenail centres in this area of the floor timber were consistently 6mm to 7mm shorter following conservation treatment. The distal ends of the conserved timber exhibited more variability in terms of treenail axe length and angle, with some examples displaying shrinkage rates in excess of 15%.

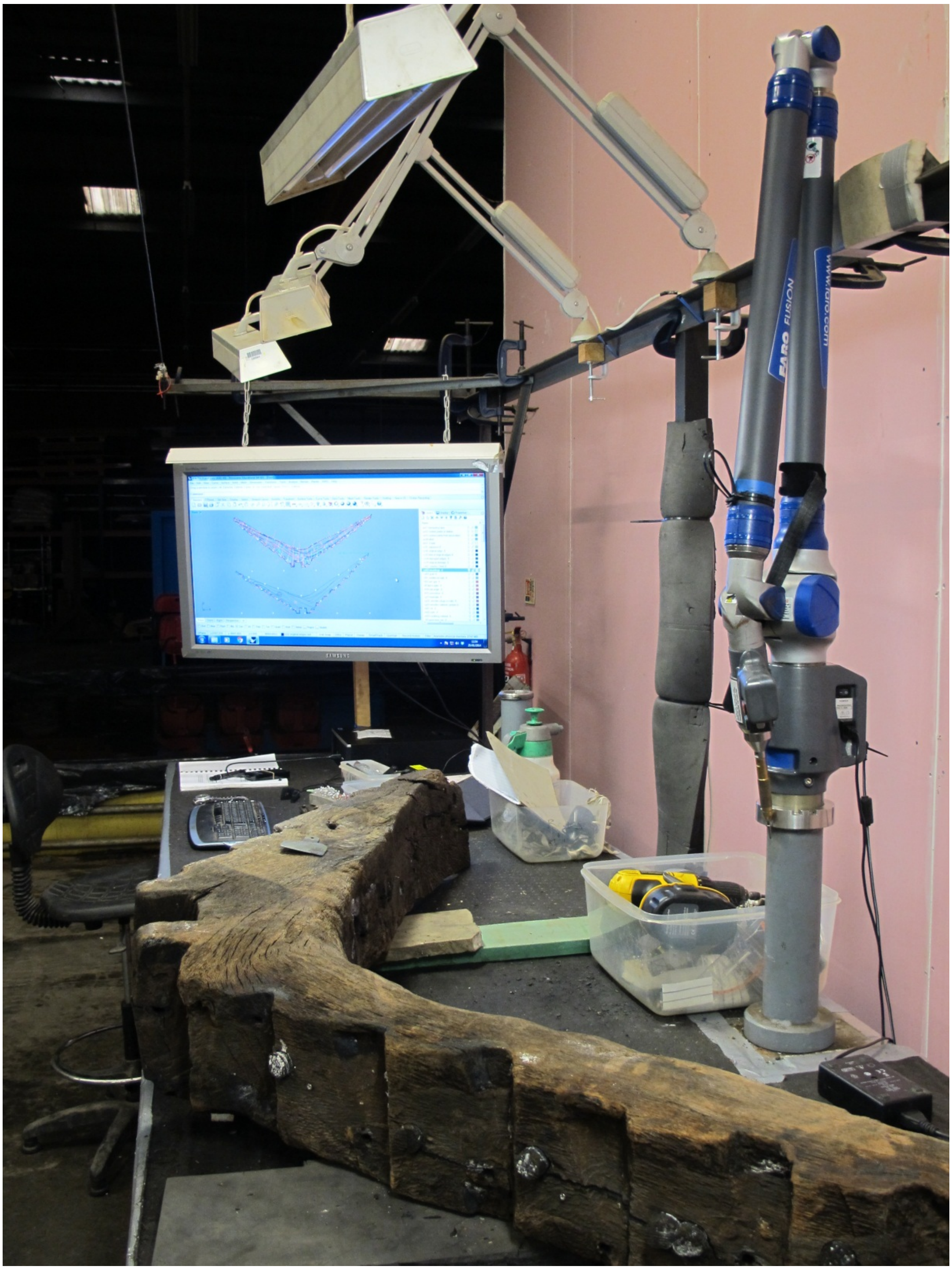


Figure 82. Digital recording of floor timber F50_0 after PEG pre-treatment and vacuum freeze-drying. Toby Jones

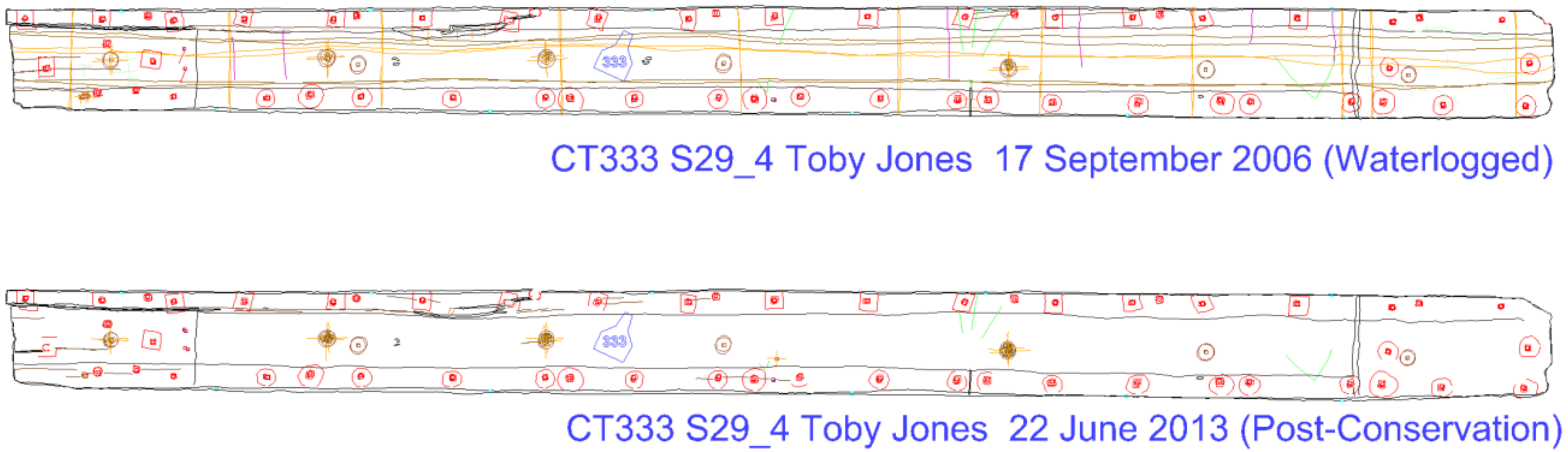


Figure 83. The waterlogged and post-conservation digital records of CT333 S29_4. There was a noticeable loss of surface detail evident, especially when comparing the extent of inscribed lines still extant on the surface of the timber. Toby Jones.

Figure 84. Digitally recording tool stop marks on a conserved floor timber. Toby Jones.

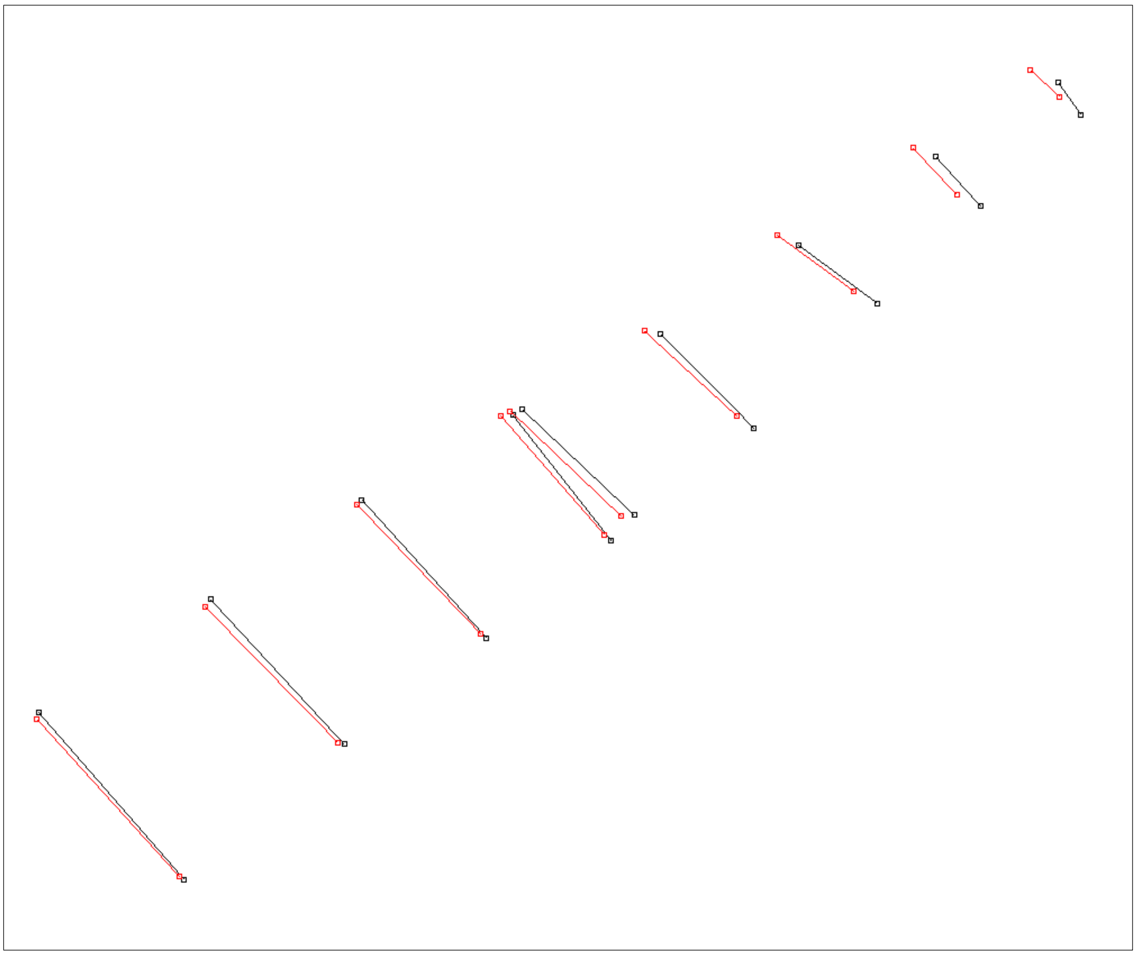


Figure 85. Screen capture showing the location and degree of distortion of selected treenail axes on part of floor timber F50_0, with the waterlogged timber treenail axes in black and the conserved timber treenail axes in red. The corresponding treenail centres were an average of 5.85% closer together after conservation treatment, with an average distance between corresponding centres being decreased by 5.25mm. Toby Jones.

Other features were noticed on the conserved timbers that had escaped detection during the initial waterlogged timber recording process. Wedges were clearly visible on the inboard faces of the treenails, features which had mostly been missed during the waterlogged recording phase. The contrasting grain structure visible in the dried treenails and wedges was visually quite clear (as opposed to the treenails in their waterlogged state), and this information was recorded in the post-conservation digital record.

The fact that certain information, like inscribed lines, may only be recorded in the waterlogged wireframe drawing, while the treenail wedges existing only in the post-conservation drawing, make it necessary to consult both drawings, where available, in order to gain a more complete picture of the total information available. As it is possible to place both 3D records in the same Rhinoceros3D file, it may become standard practice to bundle the two records together, albeit on different layers. In this manner, it is possible to overlay them and quickly detect and quantify changes in timber size and shape. To date, only a few timbers have been recorded after conservation treatment. It is likely that valuable conclusions regarding shrinkage and distortion can be formulated following a more comprehensive programme of post-conservation recording and analysis. Digital documentation can readily facilitate the comparison of timbers from different shipwrecks or the same timber at different points during conservation. It might also be possible to record the shape of the timber again after hull assembly, in an effort to quantify the changed shaped of a timber within a more rigid hull structure. The preservation of the stainless steel control points in the timber (from excavation or documentation all the way through reassembly) should allow for a useful set of fixed reference points.

The Growth of Contact Digitising in Nautical Archaeology 2006-2014

Since 2006, numerous other nautical archaeological projects or institutions have started to use contact digitisers to record individual ship timbers. These include the Drogheda boat project and the Traditional Boats of Ireland Project in Ireland, the Norwegian Maritime Museum in Oslo, the German National Maritime Museum in Bremerhaven, the Maritime Archaeology Programme at the University of Southern Denmark at Esbjerg, the Center for Maritime Archaeology and Conservation at Texas A&M University, the Doel Kogge Project in Antwerp, Belgium, and the Swash Channel Wreck documentation project, run by Bournemouth University. All of these projects have employed staff members who have been directly trained (or provided with the timber recording manual/templates) by the author in the documentation methodology developed at the Newport Medieval Ship Project. Brief summaries of some of these projects are provided below.

In addition to the abovementioned projects, detailed advice has been provided to the University of Connecticut and the Portuguese Centro de História de Além-Mar (C.H.A.M.) about the specification and setup of contact digitisers for use in nautical archaeological applications.

In addition to projects with direct ties to the Newport Ship Project, there are several other groups or institutions that have developed 3D digital recording methodologies with guidance from other early practitioners, including Fred Hocker. The use of digitising technology by these groups, including the Viking Ship Museum in Roskilde, Denmark, the Yenikapi project in Istanbul, Turkey, and the Arles-Rhone

3 project in Marseille, France, are also briefly discussed below. Finally the section on the recent growth of digital recording concludes with a description of the Faro-Rhino Archaeology Users Group (F.R.A.U.G.) and its influence on promoting cooperation and knowledge sharing between the various groups.

The Drogheda Boat and the Traditional Boats of Ireland Project

The remains of a well-preserved clinker built boat were found during dredging operations on the River Boyne in Ireland in 2006. The vessel was recorded *in situ*, disassembled, and then raised for further study and conservation. The post-excavation project research design closely followed that of the Newport Ship Project, with the individual timbers being cleaned, photographed and then documented with a contact digitiser (Figure 86).

Figure 86. Archaeologists recording the Drogheda boat timbers using a contact digitiser. Toby Jones.

The resulting digital files were edited in order to create digital solids, which were subsequently manufactured using selective laser sintering. These pieces were assembled into a 1:10 scale 3D physical model, which was, in turn, digitally documented using a laser scanner. The laser scanner was found to be an ideal tool for digitally documenting the 3D printed scale model of the reconstructed Drogheda boat hull. Even with the lightest of touches, the pressure of a contact digitiser probe tip caused deflection in the model. The non-contact laser line probe proved ideal for accurately recording the model without deforming or damaging it. The resulting 3D data was used as a basis for making a digital reconstruction model of the original hull form.

The Drogheda boat post-recording hull form research methodology was created after close consultation with the Newport Medieval Ship Project and was undertaken by the Traditional Boats of Ireland Project. They acquired a FaroArm Platinum Arm (12-foot model) in October 2007 for the express purpose of documenting half models and small traditional working boats up to 4.5m in length. At the same time they also purchased a Faro Laser Line Probe Version 2. This laser scan head attached to the end of the FaroArm and was used to scan half and full models of boats and ships.

In 2010, the Traditional Boats of Ireland project started using a large envelope laser scanner to document working boats ranging from four to twenty metres in length. Rhinoceros3D was used to capture and process the point and wireframe data created by the contact digitiser. Geomagic Studio software was used to capture and process the laser scan point cloud data, which was then imported into Rhinoceros3D, where the hull forms were rebuilt and faired before being analysed in the Rhinocerso3D plugin Orca Marine (Schweitzer, 2012: 225-231, Tanner, 2013:

137-149). As will be shown, the success of the methodologies developed for use on Drogheda project directly influenced the course of development at the Newport Ship Project.

Norwegian Maritime Museum

The Norwegian Maritime Museum, in Oslo, Norway, began utilising contact digitisers in 2007 to document individual ship timbers from the Tunnel Project and Barcode wrecks. The team acquired more staff and more digitisers as the number of wrecks needing documentation increased substantially. The timbers are recorded using standardised templates, with emphasis being placed on the accurate documentation of fasteners and fastener holes. For research and archiving purposes, the project has chosen to separate the individual faces of each digitally recorded timber and print these out in two dimensions on paper and card. However, selected digital files of framing timbers, posts and the keel are being manufactured using additive manufacturing technology. Composite scaled models, made from the manufactured physical solid model pieces and the card planks, are assembled and the final hull form documented using a contact digitiser (Falck, 2013) (T. Falck 2014, pers. comm., 5 May).

Deutsches Schiffahrts Museum (German National Maritime Museum)

The Deutsches Schiffahrts Museum has been using a contact digitiser since 2009 to record small boats, ship related finds, and selected non-maritime artefacts. They have also documented several logboats. The data created by the contact digitiser is collected and displayed in Rhinoceros3D software and organised on templates based on those created by the Newport Ship project. The research aims of the institute are focused on the documentation of an object's overall geometry, and archiving of this record, along with the creation of basic surfaced 3D models (M. Belasus 2013, pers. comm., 5 Oct.).

The University of Southern Denmark

The Maritime Archaeology Programme at the University of Southern Denmark at Esbjerg has, in conjunction with the German National Maritime Museum in Bremerhaven (Deutches Schiffarhrt Museum), the German state authority of Mecklenburg-Vorpommern, and Gazprom (who are funding the work), been using a FaroArm contact digitiser to record timbers from the Moenchgut 92 wreck, a Baltic clinker-built vessel dating to 1449 (Auer and Maarleveld, 2013: 37, H. Schweitzer 2013, pers. comm., 15 Nov.). The university has also used the contact digitiser to record ship timbers found in Lundeborg, Denmark during an archaeological field school, and actively incorporates training in contact digitising into the maritime archaeology course curriculum (Figure 87).

The Center for Maritime Archaeology and Conservation at Texas A&M University

In 2009, the Center for Maritime Archaeology and Conservation at Texas A&M University purchased a FaroArm contact digitiser and associated laser scanner. The equipment, based at the Conservation Research Laboratory, was initially used to record a variety of artefacts relating to the propulsion system recovered from *Heroine*, a western river steamboat that sank in the Red River in 1838. Traditional

2D drawings were created directly from the 3D wireframe drawings produced by the contact digitiser or from the resulting point clouds produced by the laser scanner. Rhinoceros3D and Geomagic 11 software were used to capture and process the data (Krueger, 2010: 36-38).

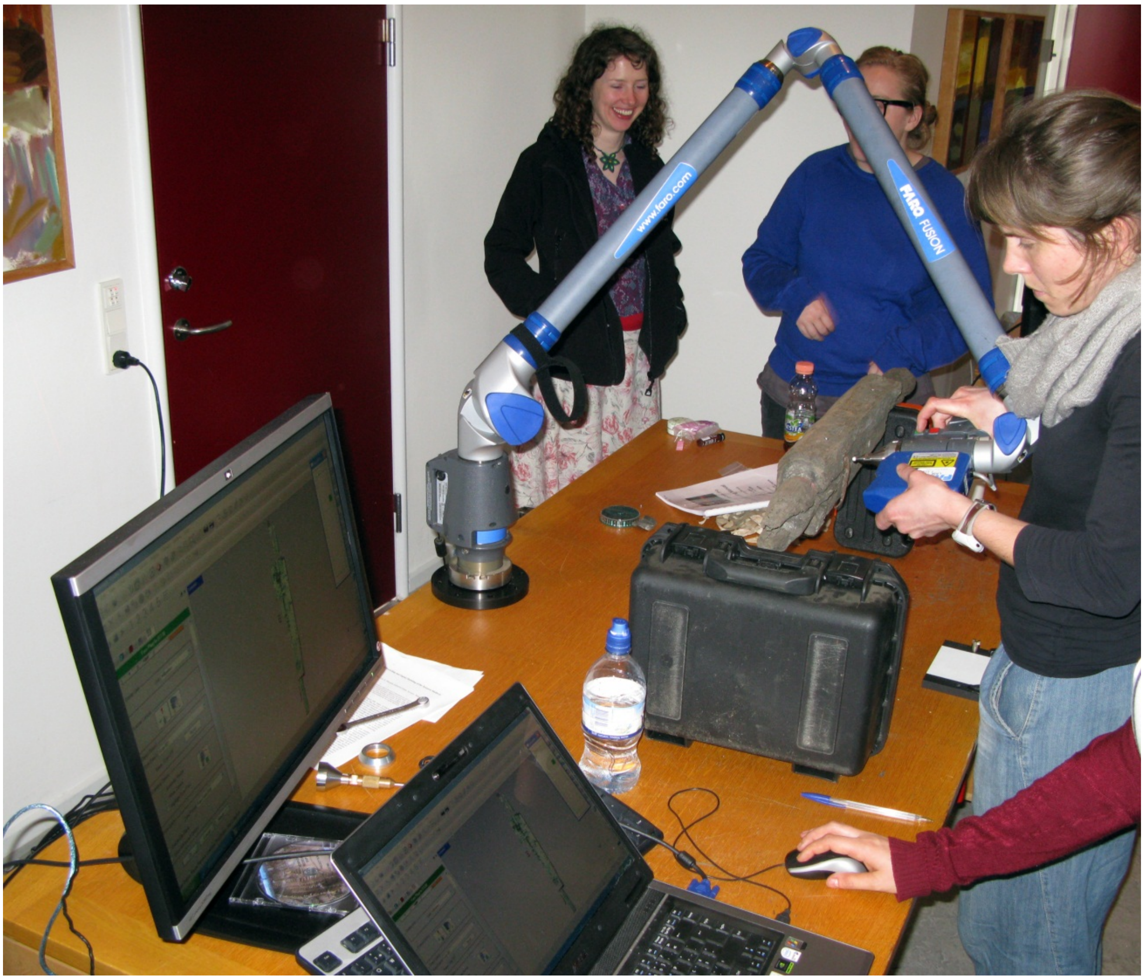


Figure 87. Students at the University of Southern Denmark learning how to use the contact digitiser, associated laser scanner and relevant software. Toby Jones.

Doel Kogge Project in Antwerp, Belgium

In 2010, The Doel Kogge project in Antwerp, Belgium began using a FaroArm Fusion 12 foot contact digitiser to document the individual hull timbers (Figure 88, Figure 89). They used Rhinoceros3D software version 4.0 to capture the coordinate data.

Drawings were made on modified templates, which included layers specific to cog-type vessels. A ship archaeologist from the Doel Kogge project staff had previously been a member of the Newport Ship Project team, ensuring that a wide variety of skills and practices were transferred from one project to the next (Lenaerts et al., 2011: 15-16).

Figure 88. The recording tables and contact digitiser arrangement used at the Doel Kogge Project in Antwerp, Belgium. Note the moveable clamp with mounting ring in the lower right. Toby Jones.

Figure 89. Archaeologist at the Doel Kogge Project using a FaroArm contact digitiser to document a ship's timber. Note the overhead framework and associated photographic equipment and light sources. Toby Jones.

The Swash Channel Wreck and Bournemouth University

Archaeologists at the Swash Channel Wreck documentation project, run by Bournemouth University, began the digital documentation of hull timbers from the wreck in April 2013. The remains of the vessel, discovered in 1990, were later partially excavated with selected timbers and artefacts lifted for further study and conservation (Parham, 2011: 103-106). The vessel, thought to be a Dutch, dendrochronologically dates to around 1628. From a ship construction perspective, the assemblage is especially important as it contains numerous bow castle timbers, which typically do not survive the wrecking/site-formation process (Figure 90). Selected individual hull timbers, along with decorative elements, were brought to the Newport Medieval Ship centre for cleaning and contact digitising, with project staff using similar Rhinoceros3D software templates as those used to record the Newport Ship. At the time of writing, the project archaeologists were concluding the documentation phase for the bow castle timbers and moving on to the digital solid modelling phase.

Figure 90. Archaeologists handling bow castle timbers from the Swash Channel Wreck. Newport Museums and Heritage Service

Viking Ship Museum, Roskilde, Denmark

The Viking Ship Museum at Roskilde in Denmark continues to utilise a FaroArm contact digitiser to document archaeological ship timbers. Their primary focus in recent years has been the documentation of the numerous 'Roskilde' vessels discovered and excavated during the expansion of the museum in the late 1990s. After digitising the timbers, the 3D wireframe data is then projected onto a 2D plane and printed onto paper or card, which is then cut out and fastened together in order to make a reconstruction model (Ravn et al., 2011: 233-237). The contact digitiser has also been used to document the resulting hull forms of these scale model hull reconstructions, with the resulting point and line data being edited in Rhinoceros3D modelling software (Ravn, 2012: 314-316).

The Yenikapı Shipwreck Project

During extensive excavations for a new underground Metro station in Istanbul, Turkey, the remains of at least 36 vessels dating from the 5th through 10th Centuries AD were discovered (Kocabas U., 2012a: 309-323). Rescue excavations took place in 2006 and 2007, and a variety of *in situ* documentation techniques were utilised (Figure 91). Two research groups, the Istanbul University Department of Conservation of Marine Archaeological Objects and the Institute of Nautical Archaeology at Texas A&M University, were involved in the excavation and documentation of the vessels. As new wrecks were found, each research group was given the opportunity to bid on recording the remains, with the most cost-effective and time efficient bid typically winning (M. Jones 2015, pers. comm., 3 March). Both teams utilised similar documentation approaches in the field, using scaled drawings, tracings and photographs to record the *in situ* remains. Photogrammetry and high-resolution photomosaics were also used to document the extensive cargo remains and selected construction features present within some of the hulls.

Figure 91. The *in situ* remains of one of the Yenikapı vessels found in Istanbul, Turkey. The ships were disassembled and later documented using a contact digitiser. Toby Jones.

Midway through the excavations, the use of total stations was trialled for recording framing timbers details, and the results were compared with the traditionally obtained records. The project directors were satisfied with the accuracy and impressed with the efficiency, and the framing positions from the subsequently excavated vessels were recorded using the total station, with collected data sent to AutoCAD modelling software (Kocabas, U., 2008: 39-64).

After removing the artefactual material and framing, the planking shells of the vessels were drawn *in situ* at 1:1 scale using both direct tracing and elevated plane tracing techniques.

The two teams differed fundamentally in their approach to the post-excavation phase of archaeological ship timber documentation. The INA team made 1:1 tracings of the individual timbers on clear plastic film, while the IU team made use of a FaroArm contact digitiser (Figure 92) (Kocabas, I., 2012: 115). The Yenikapı 12 wreck was the subject of a trial study into the suitability of using contact digitising to record the individual ship timbers. Based on the impressive results, the IU team acquired an additional FaroArm contact digitiser, with plans to digitally document the remaining shipwrecks prior to active conservation treatment (Kocabas, U., 2012b: 112).

It is interesting to examine the reasons for the differences in post-excavation methodology used by the two groups. The Institute of Nautical Archaeology considered using a contact digitiser shortly after the wrecks were found, but, owing to the high initial costs, customs charges and expensive warranties, opted to use more traditional methods to document the individual timbers. However, cost wasn’t the only reason (INA eventually had access to a FaroArm in the Conservation Research Lab at Texas A&M University). The project directors explicitly followed the documentation methodology developed during the excavation of the Yassi Ada and Serçe Limanı shipwrecks in the 1960s and 1970s, respectively (Pulak, C., et al., 2015: 42, 44). These techniques, while undoubtedly effective, were several decades old, and failed to take into account the efficiency, accuracy and utility of contact digitising.

Even though INA archaeologists captured the ship timber data using traditional methods, the resultant 1:1 scale physical drawings/tracings were ultimately digitally scanned to enable the archaeologists to use Rhinoceros3D software to create digital plan and section drawings, The digitisation of the ship timber data was integrated with site data captured by the total station, with the total station data being used as a check against any errors introduced during the scanning process (M. Jones 2015, pers. comm., 3 March). This mix of using old and new technology (and related methodologies) is not exclusive to archaeologists at INA, but it is interesting that they selectively adopted certain digital tools and methods without fully committing to the use of digital documentation approaches from the start of the project. They obviously recognised the power and utility of using CAD software to analyse and display hull form data, but seemed reluctant to use such tools during the post-excavation recording phase.

In contrast to INA, archaeologists from Istanbul University were willing to apply innovative methods to solve the documentation problem of the ever-growing assemblage of ship’s timbers. A variety of factors influenced Istanbul University’s decision to utilise a contact digitiser. They received a large grant from chemical company BASF and had strong institutional support in the form of a local campus. The University built a Shipwreck Research Centre at Yenikapı, creating the right physical (and academic) environment, with wet and dry lab areas for documenting and conserving the recovered timbers and artefacts. They were given advice and training by Fred Hocker relating to the use of contact digitisers and Rhinoceros3D modelling software for recording timbers and the creation of layering templates. For such a significant assemblage of waterlogged timbers, a contact digitiser made economic sense, as well as producing a superior and versatile digital record. With academic and financial support of Istanbul University and corporate sponsors, coupled with international guidance/advice, the Yenikapı shipwreck team at Istanbul University became the first group in Turkey to use a contact digitiser for archaeological documentation purposes (Kocabas, U., 2015: 9). In the future it will be useful to analyse how both Istanbul University and INA finally present and publish the results of the Yenikapı ship excavations. It will be a good case study of comparative documentation methodologies, with similar ships excavated at the same time but documented using fundamentally different approaches.

Figure 92. The FaroArm contact digitiser used by the Istanbul University recording team at the Yenikapı excavations. The digitiser was mounted to a rail that ran the entire c.10m length of the recording table. Toby Jones.

Arles-Rhône 3 Documentation Project

A recent archaeological project worth mentioning took place in 2011 in Marseille, France. The remains of a Roman stone-carrying barge, dubbed Arles-Rhône 3, were excavated and raised in sections cut transversely through the hull (Ranchin-Dundas, 2012: 48). Detailed recording of each of these intact sections was undertaken using a type of wireless contact digitiser called a *Créaform 3D* HandyPROBE. This device consisted of a handheld probe tip that was tracked in three dimensions using two infrared cameras, along with a system of survey reference targets placed around the recording area. The documentation system was used to capture 3D point data, which was exported to Rhinoceros3D modelling software (Ranchin-Dundas, 2012: 51-55). Each section of the barge was recorded intact, as there was not time available to disassemble and record the individual pieces. Archaeologists were able to effectively document the shape and location of the hull timbers and fasteners using the HandyPROBE, however challenging environmental conditions, including high humidity, temperature and dust caused the machine to occasionally malfunction. Further investigations into the suitability of this digital documentation tool for archaeological applications are needed, as the potential advantages of a wireless/armless system are clear.

Faro-Rhino Archaeological Users Group (FRAUG)

Nearly all of the ship timber recording projects using contact digitisers and Rhinoceros3D modelling software throughout Europe and North America belong to the Faro-Rhino Archaeological Users Group (FRAUG). The group is an informal network of archaeological researchers that are linked through the sharing of methods, recording templates and layering systems. There have been seven meetings of the group, which began with the inaugural meeting at Roskilde, Denmark in 2006. In 2008 and 2009, the FRAUG meetings were held at the *Vasa* museum in Stockholm. In 2010, the FRAUG meeting was held in conjunction with a week-long digital timber recording training workshop at Southern Denmark University in Esbjerg. In 2011, the meeting was hosted by the Norwegian Maritime Museum in Oslo.

In 2012, the meeting was again held in conjunction with a weeklong course covering digital timber recording, laser scanning, and digital solid modelling. The meeting was held at the Newport Medieval Ship Project in Newport, Wales (Figure 93). Here participants were also exposed to Rhinoceros3D plug-in Orca Marine. In April 2013, the meeting was hosted by the Doel Kogge project in Antwerp, Belgium. The Traditional Boats of Ireland Project hosted the 2014 meeting in Baltimore, Ireland. In 2015, the annual meeting was held by the Netherlands Institute for Ship and Underwater Archaeology (N.I.S.A. - part of the Rijksdienst voor het Cultureel Erfgoed) in Lelystad. The 2016 meeting of the group will be held at the Deutsches Schiffahrtsmuseum (German National Maritime Museum) in Bremerhaven.

Goals of the group include further development and adoption of a common visual language for the 3D documentation of ship timbers, exploring publication methods for the 3D data, and effective archiving systems, the results of which will be made be publicly available on a website and via social media. The use of social media to create an online forum for debate has increased the accessibility of the group.

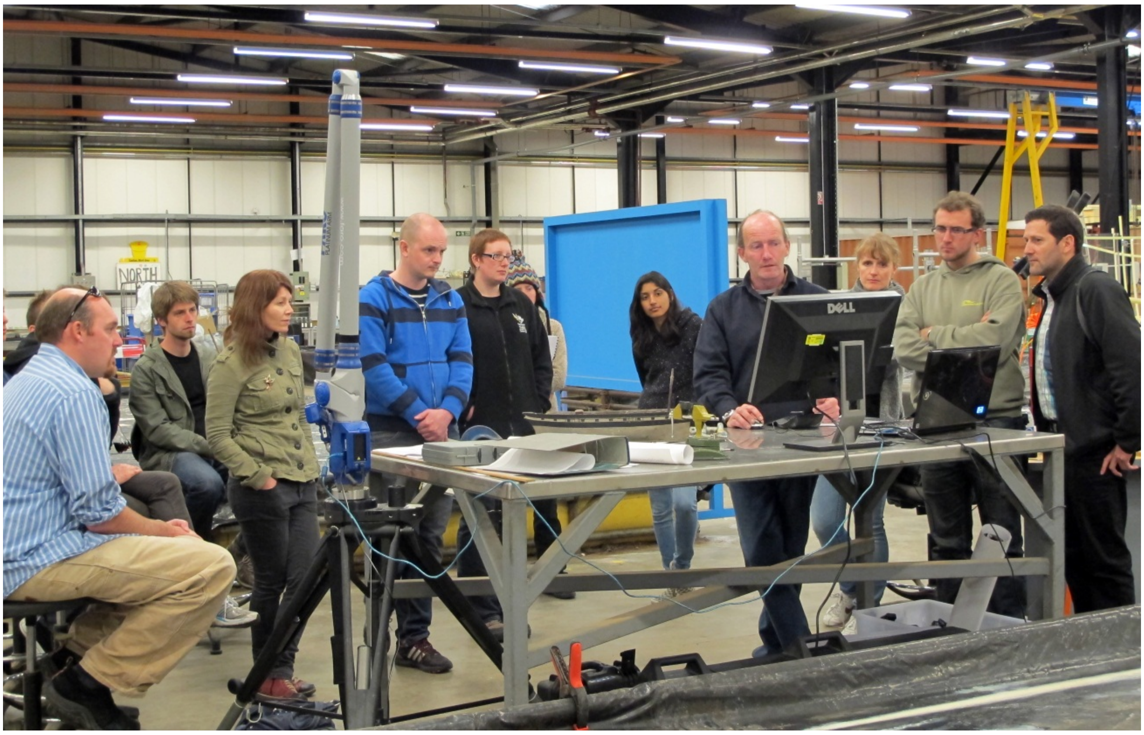


Figure 93. Members of the Faro-Rhino Archaeological Users Group research network learn about the Orca Marine plugin for Rhinceros3D at the Newport Ship Centre in May 2012. Newport Museums and Heritage Service.

Chapter 4: Digital Modelling Methodologies

Introduction

The Newport Medieval Ship Project developed a concise, efficient and effective methodology for turning the 3D digital timber records (wireframes) into digital solid models. The techniques were developed, evaluated and refined through a series of small scale pilot studies. Developing a standardised method for the production of the digital solid models was necessary in order to achieve a consistent and accurate end product, given that a number of individual archaeologists were involved in the modelling effort, and planned manufacturing of scaled physical model pieces would leave scant room for error. The results of the pilot studies were codified into a detailed step-by-step manual that was used to train staff and provide commentary and metadata for subsequent data archiving (Jones, 2013).

Digital Modelling Process Overview

The final digital modelling process for all timbers was divided into four distinct phases: wireframe simplification, surfacing, fastener modelling, and quality control. To create a digital solid model, it was first necessary to reduce the detail and complexity of each vector graphic drawing. Separate modelling guidelines for the two largest groups (by numbers) of timbers, planking and framing, were drawn up. Slight modifications to these primary guides were then employed when converting wireframe drawings of stringers, braces, riders and other, less common, timbers into digital solid models. However, the vast majority of steps and settings were similar, and a conceptual nature of the process is described below.

The modelling process began by selecting the archived wireframe drawing (.3DM file) and opening/importing it into a specially created modelling template. Cutting and pasting the visible wireframe data into the modelling template became common practice, as this process left behind any empty layers. Alternatively the Purge command could have also been used to remove any unused layers, creating a smaller file. Rhinoceros3D Version 4.0 was the latest software iteration available during the period (primarily 2008-2010) when the digital solid modelling was taking place, and all of the Newport Ship solid models were created using this version. A custom toolbar was created that contained the commonly used tools for creating and analysing digital solid models (Figure 94).

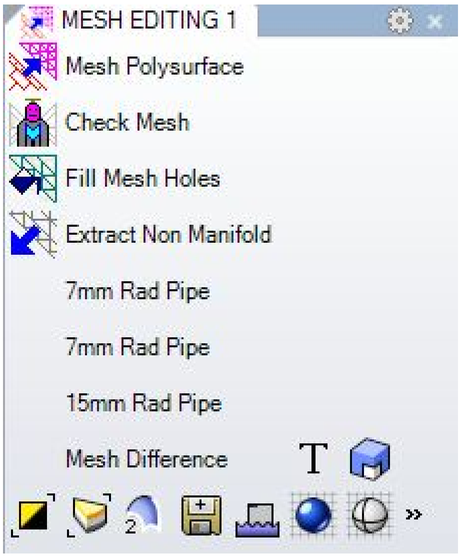


Figure 94. Solid modelling toolbar used in Rhinoceros3D to create digital solid models from the wireframe drawings. Toby Jones.

Modelling complete intact timbers was more straightforward than those that were composed of multiple fragments. Small fragments were not generally digitally modelled, however larger timbers composed of two or more fragments would be digitally reassembled. For planking this meant aligning the fragments against adjacent strakes (using the strake diagrams), specifically by lining up the overlapping common fastener holes along the lands. In this manner it was possible to accurately align the fragments to each other in two dimensions, with the third dimension (elevation) being done by eye until a best fit was achieved. This was usually straightforward as the majority of the planking was flat to begin with and recorded in that position on a consistently rigid table. In all cases, the tentative alignment was checked against any available constraints to ensure accuracy. At this stage, no attempt was made to artificially flatten planks with obvious twist or deformation. Orienting fragments of framing together was achieved by moving the fragments together and repeatedly viewing the wireframes from different set views, until agreement was achieved. Faired curves on the inboard face and scarfs of framing timbers, along with joggles on the outboard face of the framing, helped serve as guides when lining up wireframe fragments.

After the wireframe fragments (or complete timbers) were open in the template, the file was immediately saved out as a working file. Incremental saving was an important part of the modelling process. Each time a significant stage in the modelling sequence was completed the incremental save icon was pressed. The software then automatically saved out the file and added a three digit number after the file name (i.e. CT259 P11_5 001, followed by CT259 P11_5 002, CT259 P11_5 003, etc.).

A vector graphics drawing of a typical lapstrake hull plank recorded with a contact digitiser consisted of long lines for the edges and scarfs, shorter lines for the ends, outlines of fastener holes, and various surface details, like construction marks, cracks and wood grain, as well as cross-sections (Figure 95). These polylines were based on hundreds or thousands of points captured by the digitiser. The point spacing, while appropriate for the archived primary record, was excessive for digital modelling. For example, the upper edge of a typical three meter long plank might have been drawn with approximately 3000 points using the one millimetre point spacing setting. It was necessary to sample or decimate the number of points in a way that decreased the

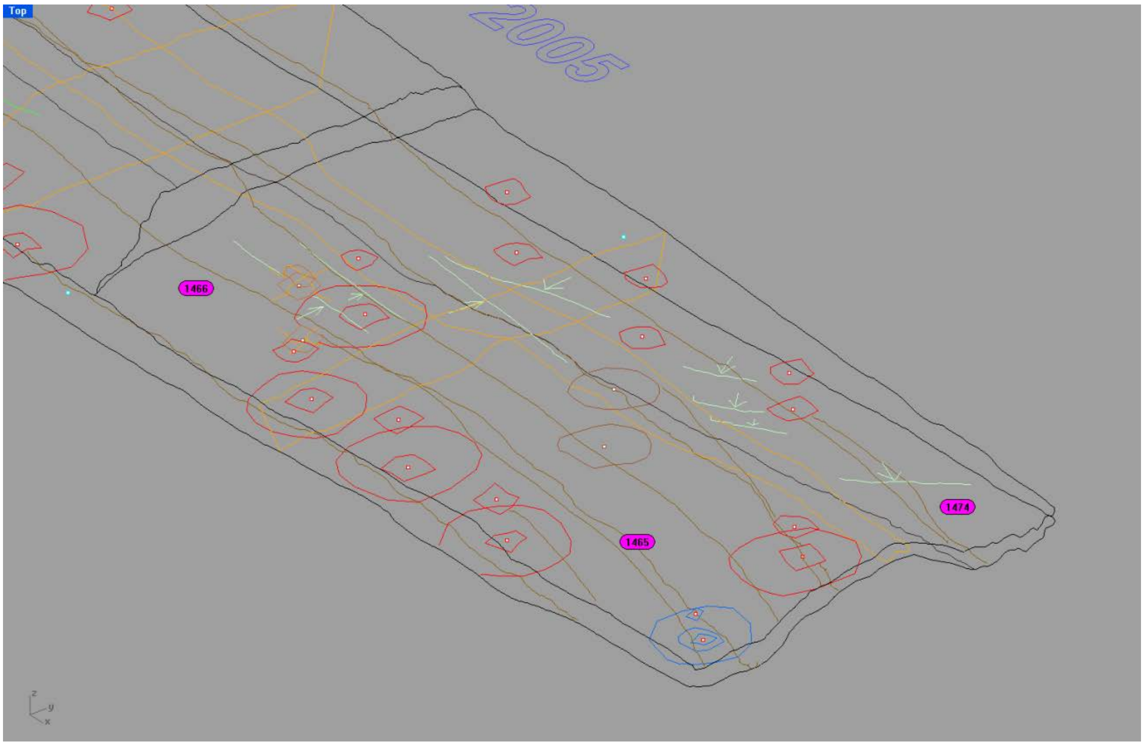


Figure 95. Vector graphics wire-frame drawing of a typical hull plank scarf. The drawing was created using a contact digitiser and Rhinoceros3D software. Toby Jones.

overall number without compromising the accuracy of the line. This task was rapidly achieved using either the rebuild curve command in Rhinoceros3D or by manually drawing simple polylines along an existing edge line (Figure 96).

The automatic simplification process involved rebuilding the edges using the Rhinoceros3D command Edit>Rebuild and selecting between 1-10% of the original number of points. The software would then redraw the line through the points remaining after the sampling. The ideal end result would be a line with just enough points to accurately represent the edge geometry, and not the minute surface variations, of the timber. It was important to remember that if the digital solid model was to be scaled down and physically manufactured, then much surface

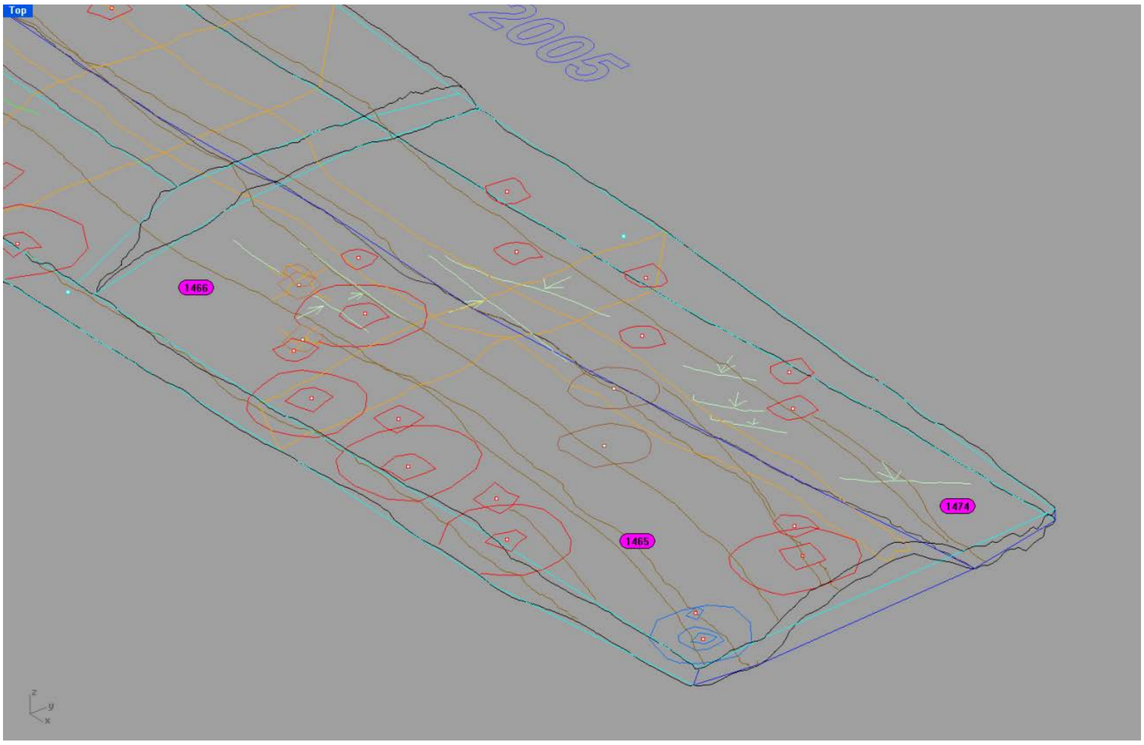


Figure 96. Vector graphics wire-frame drawing of a typical hull plank scarf with simplified or rebuilt edges visible in blue. Toby Jones.

detail would be lost. For example, a two centimetre wide crack on a plank would show up as a 2 mm crack on a 1:10 scale digital or physical model. It was probable that whatever physical manufacturing technique was used, it would not be able to recreate the finer details at the reduced scale. The purpose of the modelling needed to be considered when accounting for the level of required/necessary detail. If the ultimate goal was a scaled hull form reconstruction model, or a floating hypothesis, then small features, like the above mentioned crack, would be of little consequence. Additionally, given that some shared edge lines were purposely duplicated on different layers during the recording process, it was only necessary to simplify one example of each line. Typically, there were seven lines or edges (Upper edge, Lower edge, Forward end, Aft end, Land, Scarf upper step, Scarf lower step) that needed to be simplified on the inboard face of a hull plank, and six lines (Upper edge, Lower edge, Forward end, Aft end, Land, and Scarf edge) on the outboard face. Rebuilt lines were placed on new layers, with one layer being used to hold all of the information for the inboard face of a plank, and another layer to hold with outboard face information. Other layers were used for the cross-sections and the fasteners. Shorter lines, like the forward and aft edges and the scarf steps/edges could be accurately rebuilt with as few as five points. It might require between 30 and 100 points to accurately rebuild the long edges of a plank. Suggested ranges, as opposed to hard and fast numbers, were provided, given the variability in the individual timbers. Small areas of localised damage, such as a missing fragment along the edge of a plank, were modelled through, meaning that the edge lines before and after the damaged area were connected, effectively bypassing the smaller areas of damage and distortion.

In certain areas, especially at the distal ends of the plank scarfs, the actual timbers could be shaped to a near-feather edge. The wireframes for the inboard face and the outboard face would occasionally intersect or even run through each other, the latter a geometric impossibility in the physical world, but a real situation in the digital realm. In these areas, usually a corner, the offending edge lines would have to be pried apart to make a geometrically possible shape. In these situations, the corners were sometimes artificially set 10mm apart, which would end up creating a 1mm thick feather edge when at 1:10 scale. This distance was chosen because it would create the thinnest surface that could be physically produced in an accurate and consistent manner using the additive manufacturing process (laser sintering) discussed below.

The second major step in creating a digital solid was surfacing the simplified vector graphic drawings. The most straightforward way of surfacing the simplified wireframe drawing was a process called sweeping (similar to lofting). Using the Sweep Two Rails command in Rhinoceros3D, the archaeologist selected two simplified long edges (for example, the upper and lower edges of the inboard face of a plank) and then selected a number of cross-section curves that intersected both of these long edges. These cross-section curves would often be created from the cross-sections layer (also known as snit, after the Danish word for cut), which were drawn at regular intervals during the primary digital recording. After executing the command, the software created a surface that was constrained by all of the edges and cross-section curves. The process was repeated on each face or ‘facet’ of the timber (Figure 97).

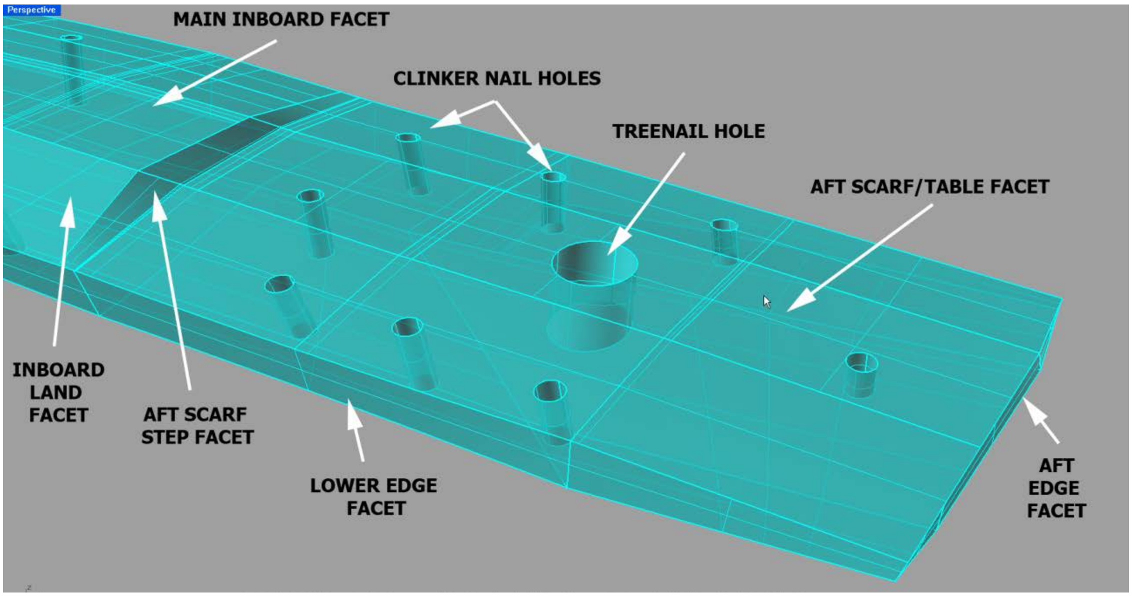


Figure 97. Digital solid model of a typical hull plank with various facets and features labelled. The digital solid model was produced from the 3D wireframe drawing. Toby Jones.

Complex areas, such as scarfs or damaged edges, were subdivided into smaller facets, which were individually simplified and surfaced, always with common edges that were shared with adjacent facets. After surfaces have been applied to the entire simplified wireframe drawing, they are selected and joined together using the Join command. The Join Command created a solid polysurface model, which was then converted into a polygon mesh. The resulting mesh file was checked for holes and naked edges, which are errors in the modelling process that would have made the final solid model invalid. Once a valid polygon mesh had been created and checked, attention was turned to modelling the fasteners.

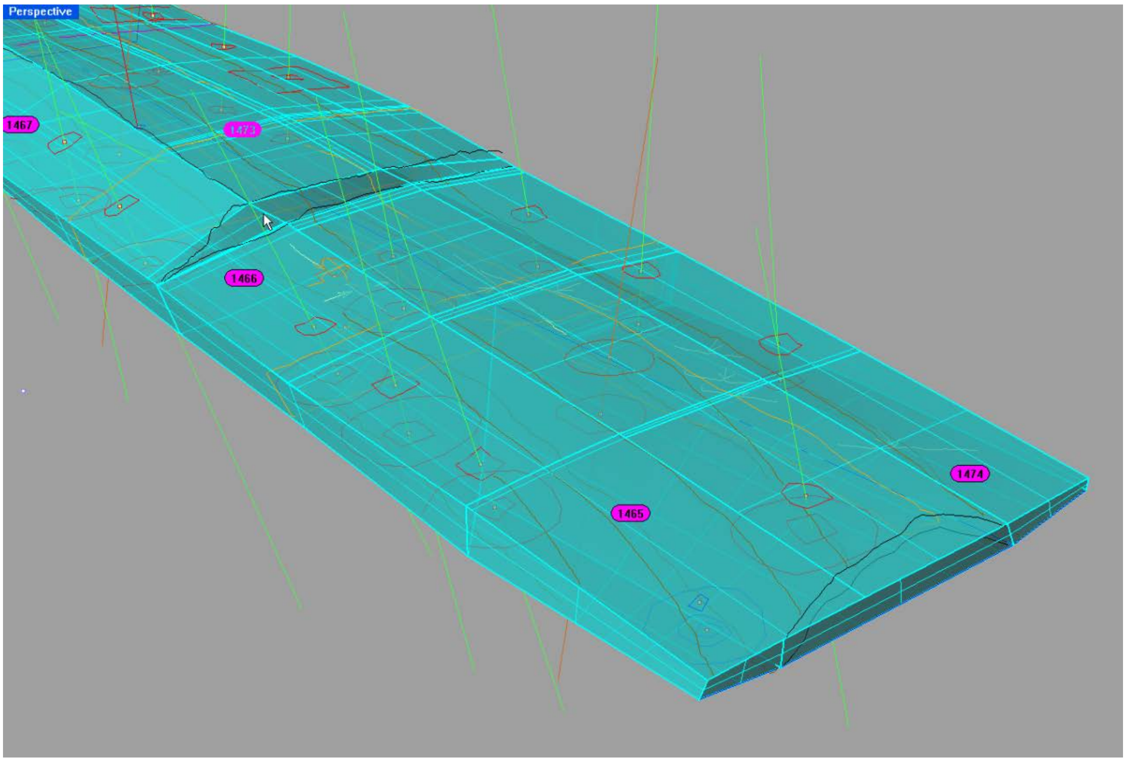


Figure 98. Modelling the fastener centres. The axes for the fasteners were created by projecting or extending a curve between the inboard and outboard centres of each fastener. Toby Jones.

The fastener modelling methodology consisted of creating correctly sized, angled and positioned digital models of the fastening holes and subtracting them from the polygon mesh solid, which created idealised but correctly positioned fastener holes. There were two main types of fastener holes that were recorded in the Newport Ship timbers. One type of hole was created by the auguring of a round hole through two lapstrake planks. A square-shafted wrought iron nail measuring approximately 10mm wide in cross-section was inserted into this hole. This nail was clenched over a sub-rectangular rove or metal plate placed on the inboard face of the planking, essentially creating a rivet to hold the planks together. There were thousands of these clench nails and roves fastening the hull planking of the ship together. Both the nail head and rove left visible impressions in the surface of the planking.

However, these features were not modelled. The key piece of recorded information was the centre of the fastener hole. In Rhinoceros3D, a polyline was used to connect the inboard and outboard fastener centre points, with the resulting axis forming the basis for building a model fastener (Figure 98).

Using the Pipe command, a 14mm diameter digital solid pipe was created for each clench nail hole. This process was repeated for all of the structural fasteners, from nails to treenails. Pipes were used to model all of the fastener holes, even those created by the square-shanked clench nails (Figure 99). This decision was made because of the desire to fasten the physical model together with standard cylindrical fasteners (This minor variation in original and modelled fastener shape was not thought to affect the reconstruction of the scaled physical model hull form in any significant way).

The digital fastener solids were then automatically subtracted, using the Boolean difference equation command, from the solid model of the plank. The result was a digital solid model of a plank with correctly sized and placed fastener holes (Figure 99). The modelling process outlined above was employed on other structural elements, like framing timbers and stringers, with minimal modifications. The timber’s cow tag number was also modelled and Boolean subtracted from the surface of the digital solid model,

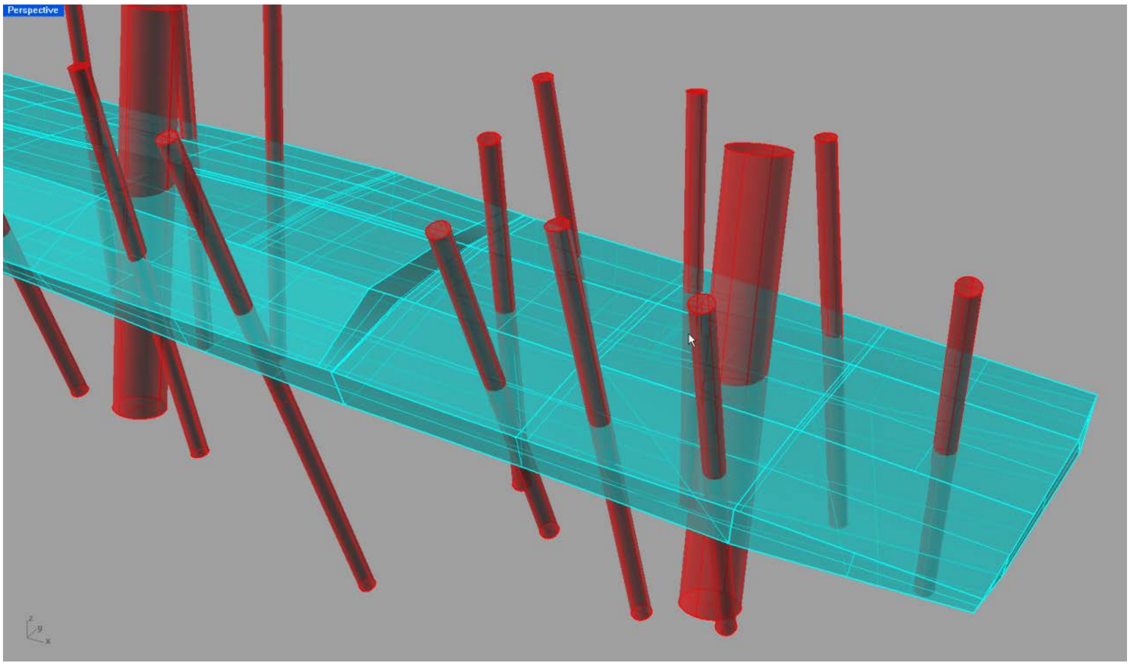


Figure 99. Pipes are created around each of the fastener axes. Toby Jones.

effectively labelling it (Figure 100). The numbers were typically placed on the forward face of framing timbers and on the outboard face of the planking, just aft of the forward scarf. This placement was a conscious decision so that the numbers were always visible and not hidden by overlying timbers. Sometimes function codes were used instead, especially if the space to place a visible label was limited.

After individual hands-on training, and with a detailed step-by step guide, the responsibility for creating a reasonable digital solid model was left to the archaeologist, with the digital solid model end product being analysed and compared to the original wireframe data for accuracy and agreement. The digital solid models were modelled at the same scale and with the same relative origin as the individual wireframe drawings, which meant that the two sets of data occupied the same relative space, albeit on different layers.

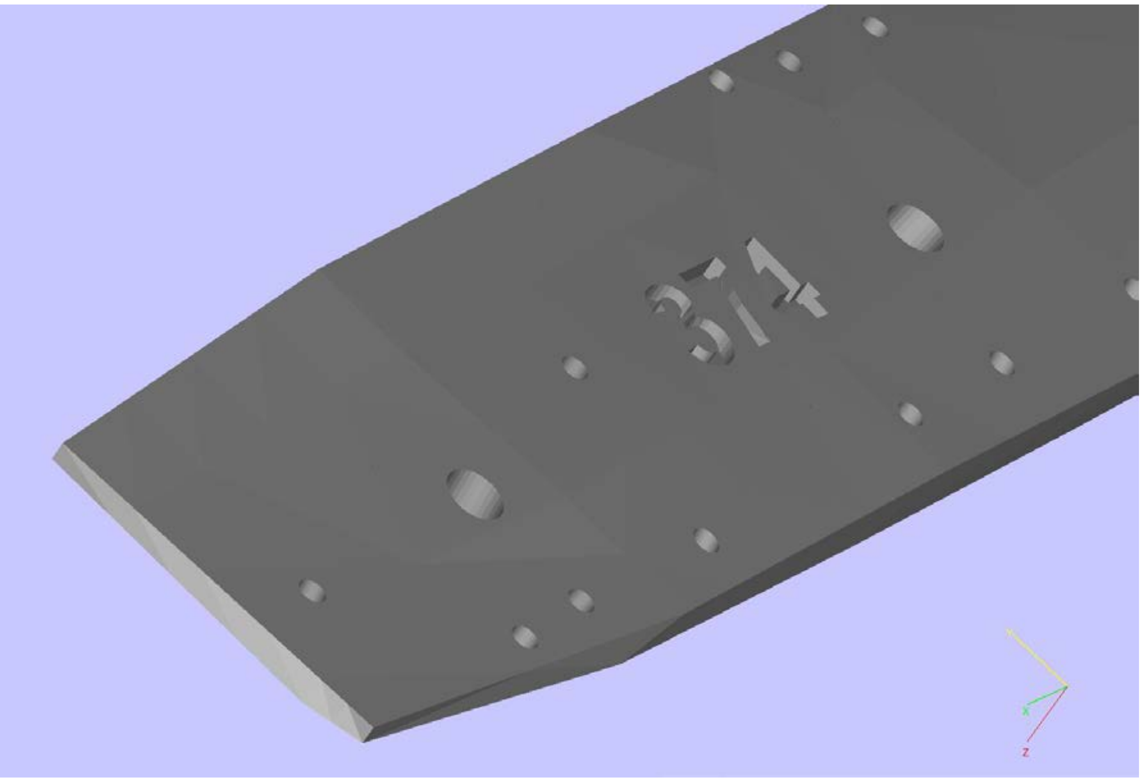


Figure 100. Rendered view of a completed digital solid model of a plank with the cow tag number (CT 374) visible. Toby Jones

Programs like Rhinoceros3D and Materialise MiniMagics were used to check the integrity of the mesh and assess the model's suitability for 3D manufacture. It was necessary that the digital solid models be 'watertight,' meaning that there were no holes of any size in the mesh. Any holes that were found were patched or filled in order to create a flawless and watertight surface. A final pre-production check would be performed by archaeologists, using the free version of Materialise MiniMagics software (Jones and Nayling, 2011: 54-60). After passing the final checks, the digital model was then scaled to the desired level (typically 1:10) and saved as both a 3D .PDF file and as an ASCII .STL file. The 3D .PDF version was suitable for visualisation purposes and was easy to share via email with colleagues, who could examine the 3D model using free viewing software (Abobe Acrobat Reader). The ASCII .STL (stereo-lithography) file format was commonly used by rapid prototyping machines, and was the preferred format for the physical solid modelling procedure detailed below. The ASCII format .STL file was also the preferred preservation file format for archiving digital mesh data, as specified by the Archaeological Data Service (Archaeology Data Service, 2012a). All files were saved in a read-only format to ensure retention of the primary records.

Keys to successful digital solid modelling included using standardised templates, low tolerances, and following established work flows (note: before commencing the modelling process, the Absolute, Relative, and Angle tolerance settings in Rhinoceros3D were all set at 0.000001, which greatly reduced the incidences of naked edges). The digital modelling methodology developed for the Newport Ship project created accurate and consistent individual digital solid models of each structural part of the hull. This accuracy and consistency was demonstrated during the later assembly of the physical model pieces, where the fastener holes lined up extremely well across the hull.

In terms of time, an archaeologist (once proficient in the modelling techniques), could model most structural timbers from start to finish in one to three hours using a standard laptop or desktop computer and Rhinoceros3D modelling software. The modelling process for individual timbers was not memory or processor intensive, and could therefore be carried out on non-workstation computers. However, the later massing of multiple wireframes and digital solid models to create the master composites created file sizes of hundreds of megabytes that required the use of powerful graphics cards, increased RAM and fast processors.

Recognition of Distortion in the individual Hull timbers

During the digital modelling process, no attempt was made to flatten distorted timbers, although some areas of planking damaged by the concrete piles were ghosted in, with fastener locations being based on information gleaned from intact adjacent strakes. There was a conscious decision to model the timbers in their recorded 3D state, and not in any idealised or flattened way. When sections taken from the model were compared to sections taken from the excavation photogrammetry, the burial environment distortion was evident. However, this distortion had largely, though not completely, disappeared during the assembly of the model. The model provided much insight into the probable original hull form, with only minimal fairing required to create a preliminary set of lines, and provide a starting point for extrapolating those existing hull lines into a complete hull form.

The recovered timbers represented a completely unique shape state, which was neither the as-built nor as-found shape. The timbers comprising the Newport Ship had undergone several events or stages of damage and distortion relative to their original shape when attached to the newly built hull in the mid-15th century. The timbers likely changed shape during the use life of the vessel, as fasteners worked loose and areas of the vessel began to hog or sag. The ship also may have been refastened as some point as evidenced by the insertion of a spike nail into each plank-frame intersection, although this may have also occurred during the initial construction of the vessel. The comprehensive nature of this additional plank-to-frame spike fastening would have resulted in a slightly tighter hull, and would have affected the shape of the individual timbers.

When the ship was brought up the River Usk into Newport in the late 1460s, the vessel was towed into a large wooden cradle built into the river bank. The parts of the hull came to rest hard against the structure as the tide receded (Figure 101). This point loading may have caused localised distortion, however more substantial damage was probably caused when the cradle structure collapsed and the hull heeled over on the starboard side. The starboard side of the vessel was now lying directly on top of a criss-crossing pattern of large logs that had comprised the cradle. As the heeled over vessel flooded with water on the incoming tide, the suspended sediment began to settle out and collect in the bottom of the hold, gradually filling the vessel.

Figure 101. Artist's impression of medieval Newport. Perspective view of town, with the castle, wall, bridge and town pill (inlet) clearly visible. The Newport Ship can be seen in the centre of the image. Anne Leaver.

Unsuccessful attempts were made to drain the vessel, as evidenced by the row of holes carefully drilled through the hull planking between the framing timbers along S19_6 and S19_7. The weight of the incoming sediment and water caused the hull to distort downward into the voids between the cradle timbers. The distortion may have been gradual, as the timbers were not broken or shattered, but rather 'reformed' around the hard cradle timbers and natural ground. Along with the visible distortion of the planking hull, there was clear distortion of the framing timbers along the scarf joints, with some of the distal ends deflecting downward more than 100mm from a fair curve (Figure 102).

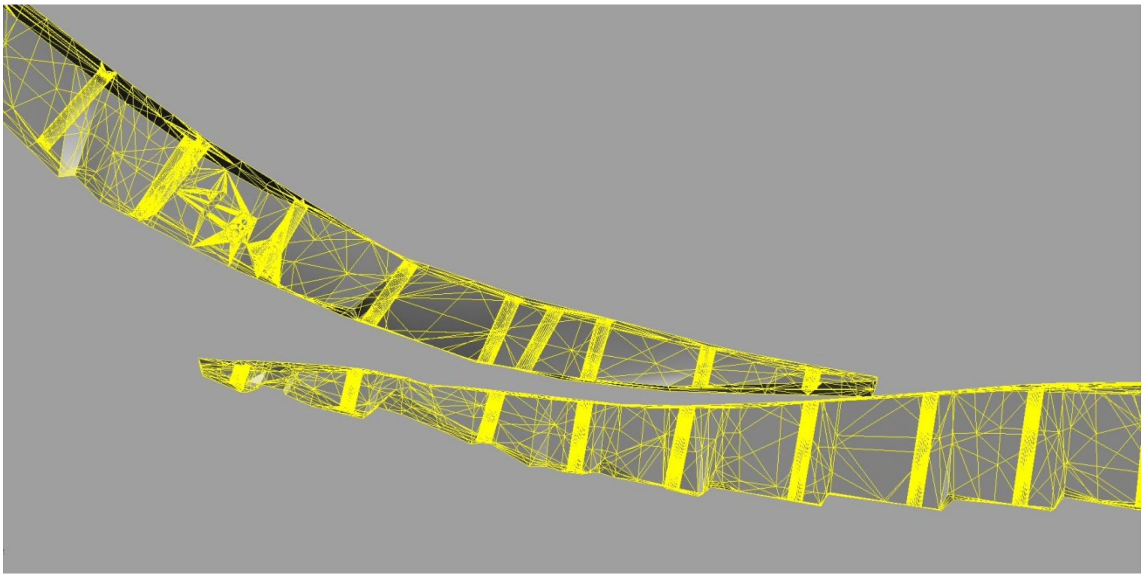


Figure 102. There was distortion present in selected framing timbers at the scarf joints, with some of the distal ends deflecting downward more than 100mm from a fair curve. It is thought that this distortion was caused by the substantial amount of sediment lying on top of the vessel. Toby Jones.

The hull remained locked in the mud for around 530 years until uncovered in 2002 and 2003. By this time, there were many metres of sediment over-laying the hull.

This thick layer of immense weight probably caused the nearly horizontal starboard side of the vessel to flatten out even further. Prior to the ship's discovery contractors drove around 92 concrete piles through the entire site. At least seventeen of these 0.5m^2 square-section piles pierced the hull remains. These piles caused substantial localised damage and distortion. Further damage was caused by the installation of a sheet pile coffer dam around the site, which severed portions of the port bow quarter and starboard stern quarter from the main part of the hull. The timbers in the port bow area, including stem fragments, hull planking and framing, were recovered by digging an additional trench outside of the coffer dam. The timbers outside of the cofferdam in the starboard stern area were not recovered.

The excavation and disassembly of the vessel introduced another phase of damage and distortion, affecting the original shape of the timbers. The vessel was fastened with wrought iron clench nails and oak treenails. These fasteners were cut or broken as the timbers were pried apart and lifted. Without the shape constraints and tension provided by adjacent timbers, many individual hull components relaxed as they were removed. Many timbers were also cut on site for dendrochronological analysis or for safety and ease of handling. These cuts released tension in the timbers and caused them to change shape. After being removed from the vessel, the timbers were removed from site and stored in water filled tanks, with planking placed on edge and framing stored on the aft moulded face. When the timbers were eventually removed from the water for detailed recording, which took place on a flat metal bench, certain planks were seen to visibly flatten when placed on the hard recording surface.

Despite the abovementioned phases of damage and distortion, the individual timbers still held valuable and discernible information about the original shape state of the medieval hull. Three dimensional scaled physical modelling (planned after completing the digital modelling phase) was seen as necessary and desirable, as it provided an evidenced-based foundation for further hull form research. The future physical model would also provide a reality check against which the purely digital modelling efforts could be compared.

The digital modelling phase encompassed all of the articulated structural ship timbers found during the excavation. No attempt was made to create models for missing timbers. However, several hundred disarticulated timbers were found during the excavation, many of which resembled ship timbers. Many of these were modelled and some, like a large crossbeam with an attached knee, were tentatively fitted to the digital and later physical models. Given more time and resources, it would have been visually informative to physically manufacture the ceiling planks, bilge boards, and other non-structural timbers (these parts were digitally solid modelled but not physically manufactured, due to cost).

Master Composites

At this stage, each mesh model and its associated original wireframe data could be imported into a master composite file and then oriented and aligned in two or three dimensions in order to create a digital reassembly of adjacent hull timbers (Figure 103). Rhinoceros3D version 5.0 was used to create the master composites. A template file containing the site photogrammetry was used as a foundation to ensure the accurate relative positioning of the digital models in each schematic. The keel and mast step/keelson models were included in each master composite file and had the same position relative to the origin. The template file also contained a layer hierarchy system that grouped material under mesh or wireframe data parent-layers, and further divided it up by function onto sub-layers. Such a system, containing parent layers and sub-layers, allowed for sophisticated visualisation by readily hiding and displaying selected parts of the hull.

The building of these master composites allowed for the visual analysis of fastening patterns and tool marks and revealed clues about the construction sequence and repair patterns. Three master composites were created, with the hull timbers being divided up into three groups, the Inner Hull, Framing, and Outer Hull. The master composites files, containing mesh and wireframe data, were saved as .3DM files. The placement of the timbers in their right relative positions aided in the future construction of true 3D digital re-assemblies (Figure 103).

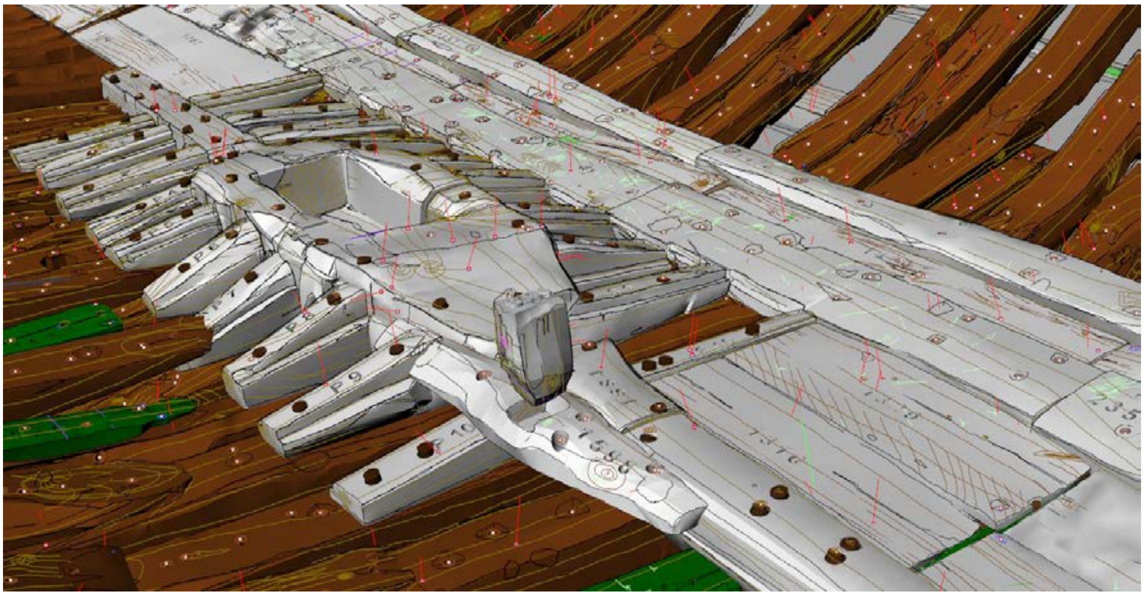


Figure 103. Rendered perspective view of digitally modelled timbers in the amidships area. The mast step/keelson can be seen in the centre, flanked by braces, stringers and ceiling planks. The brown transverse elements are framing timbers. Pat Tanner.

The three master composite files varied in size between 412MB and 828MB, and required a powerful workstation computer to open and use. Smaller sections of the master composites, like strakes of planking or frame stations could be saved out and opened on normal computers. File were typically viewed using the Render setting in Rhinoceros3D version 5, which typically allowed the wireframe data to be visible on the surface of a solid looking mesh. All three files could be theoretically combined into a single file, allowing the user to view all three data sets simultaneously and in their right relative (schematic) positions, however, a powerful computer and graphics card would be required to explore this data set. It seems likely that future advances in computing power and improvements in graphics capabilities will enable the three master composites to be viewed together.

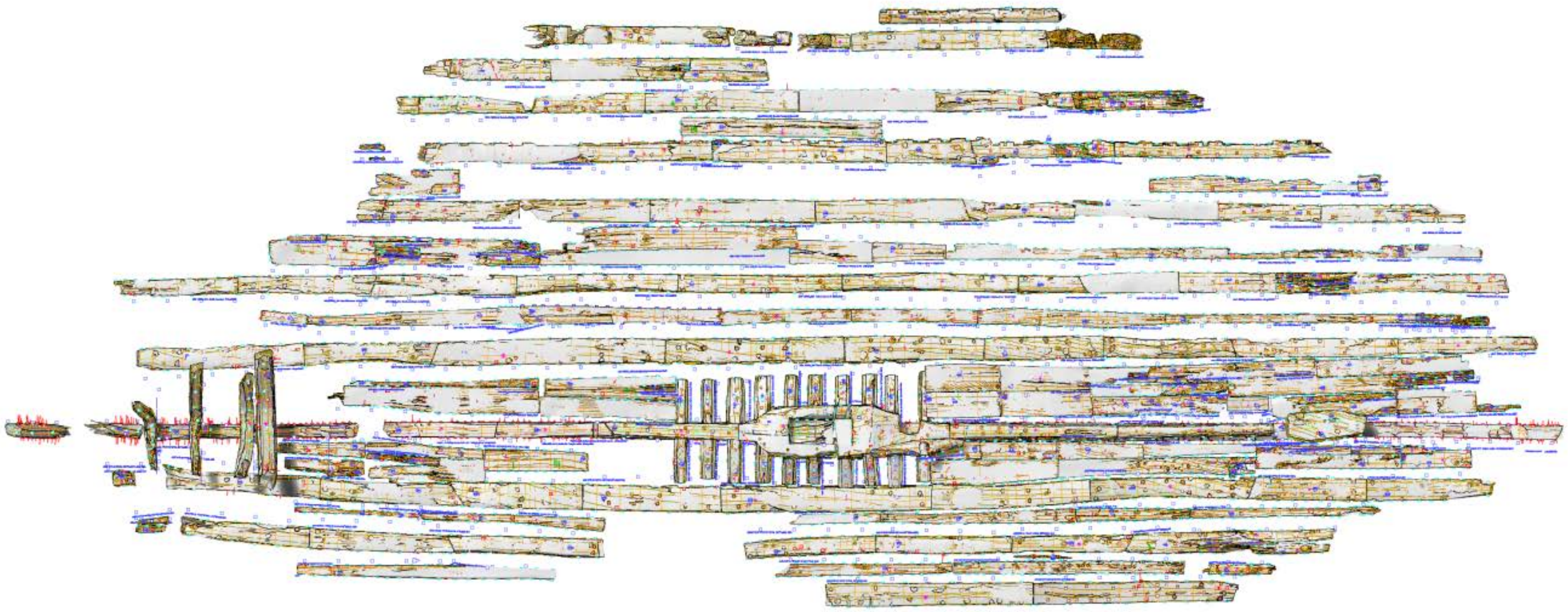


Figure 104. Screen capture of the Inner Hull master composite, consisting of wireframe drawings and mesh models of the mast step/keelson, braces, stringers, ceiling and riders, along with several miscellaneous timbers. The bow is to the left. Toby Jones.

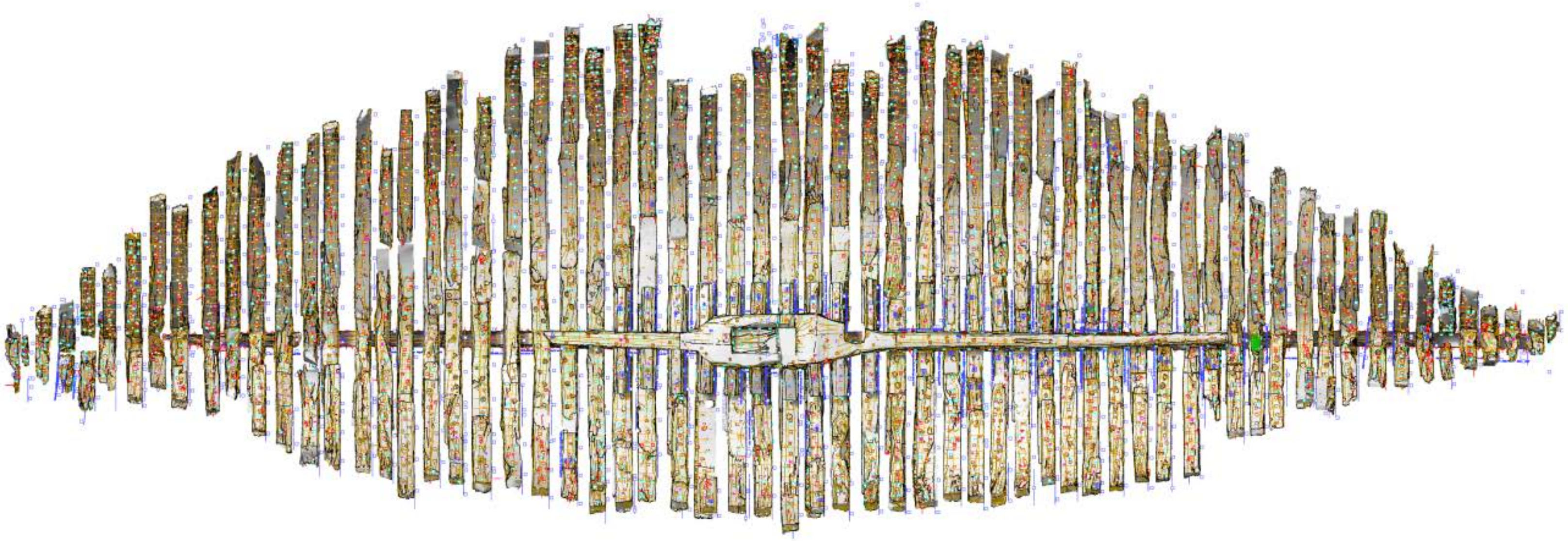


Figure 105. Screen capture of the Framing master composite file. This plan view depicts the vessel with the bow to the left. Toby Jones.

The Inner Hull master composite file consisted of the mast step/keelson, braces, stringers, ceiling and riders, along with several miscellaneous timbers (Figure 104). The Framing master composite file consisted of floor timbers, futtocks, and fillers (Figure 105). The Outer Hull master composite file contained the outer hull planking and tingles, as well as the keel (Figure 106). All the master composites contain the same relative origin, near the centre of the mast step, with the bow of the vessel oriented to the left in plan view. The photogrammetric data was used to help align the framing in plan view, while the planking and inner hull timbers were laid out in a more schematic fashion (slightly exploded) with the garboards being aligned to the keel (and then rotated to a horizontal plane), and each subsequent strake aligned to the fastener holes on the previous one. The mesh and wireframe data for each timber were grouped, and then whole strakes or frame stations grouped again.

In the outer hull master composite file planks were laid out in strakes that were evenly spaced with adjacent strakes (Figure 107). Plank scarfs were overlapped so that common through fastener holes lined up. Planks along a strake were grouped together, which allowed the user to grab, move and hover one strake over an adjacent strake. By lining up the fastener holes on adjacent strakes, they could be accurately positioned, allowing for the visual analysis of the fastener holes that passed through adjacent timbers (Figure 108). Blind fastener holes were immediately evident and small repairs that were difficult to understand when looking at a single timber began to make sense when the relevant wireframes and solid models were correctly positioned. Inboard and outboard tingles were placed in their correct positions, and then moved approximately one metre above or below the planking (in plan view).

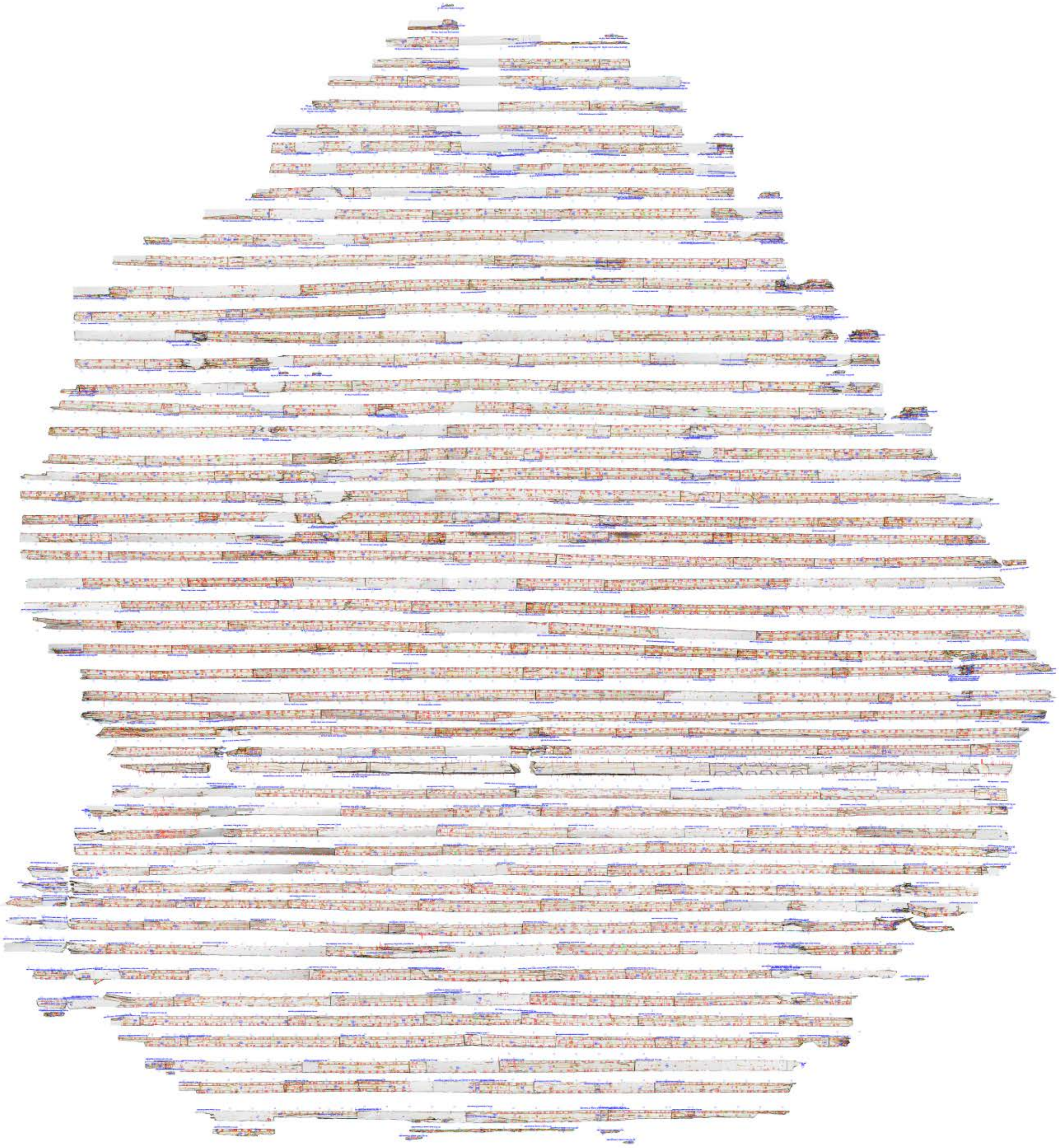


Figure 106. Planking master composite. Bow is to the left. Toby Jones.

Figure 107. Detail of Planking master composite. Bow is to the left. Toby Jones.

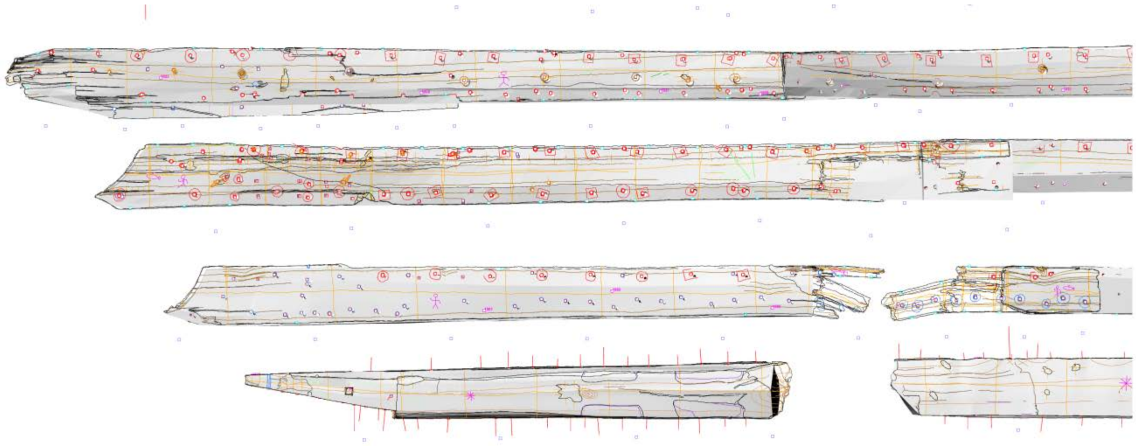


Figure 108. Detail of the Planking master composite showing the forward-most section of the keel and first three strakes of planking on the starboard side. Note the hood ends. Toby Jones.

The Framing master composite file contained all the floor timbers, futtocks, and fillers aligned to the site photogrammetry (Figure 109). At each frame station, an individual framing timber mesh model is grouped with its corresponding wireframe data set. Each of these timber groups in a frame station were then grouped together. This hierarchy of grouping allowed the user to move or manipulate an entire intact frame station or select a single timber from this group and move it without disrupting the position of the other timbers. In section view, the data in each frame station was aligned in as fair a curve as possible. No attempt was made to modify the shapes of the timber models, even where the tips of the scarfs had visibly distorted, especially along the starboard side in the amidships area.

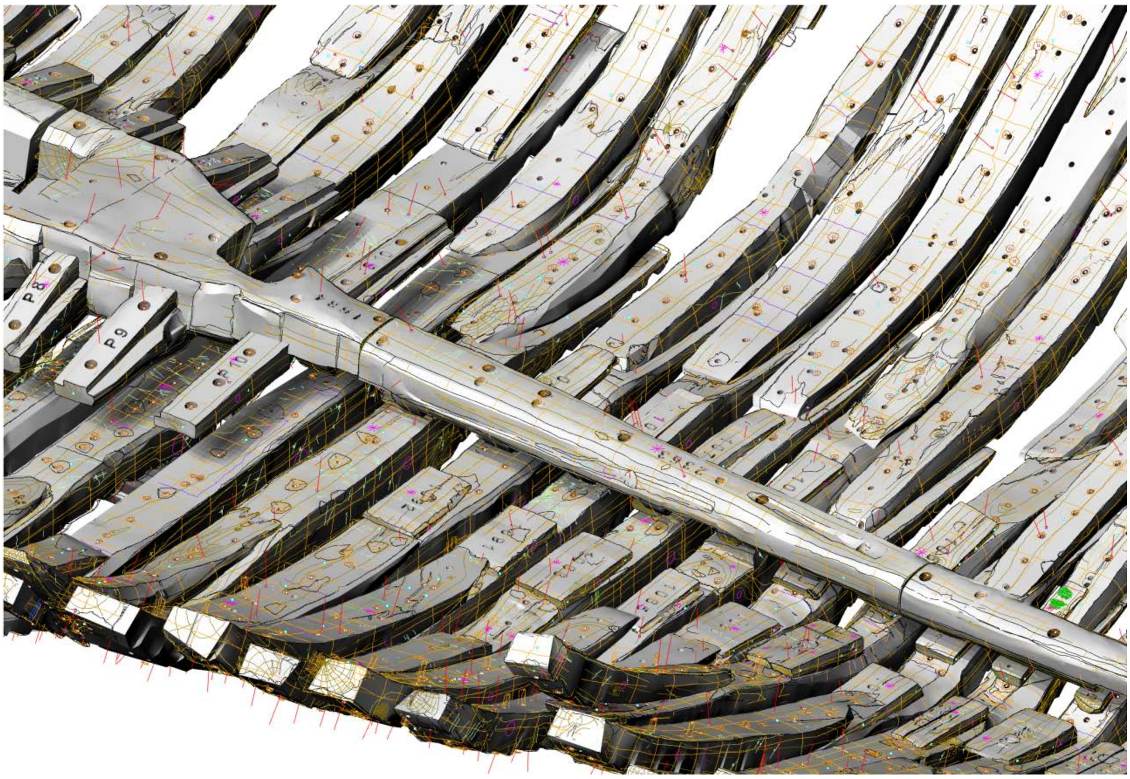


Figure 109. Perspective view screen capture of the Framing master composite, showing the mast step/keelson, braces and framing. Note the filler pieces used to bring up the level of selected floor timbers. Toby Jones.

The Inner Hull master composite file was laid out flat (and schematically) in plan view, using the mast step/keelson position on the photogrammetry as a starting point. Braces were correctly positioned, followed by the stringers and ceiling planks (Figure 110). The timber model data was laid out in rows, with scarfs overlapping forward and aft. Gaps were left between the alternating strakes of ceiling planks and stringers. The exploded schematic view showed all of the inner hull timbers in their right relative positions, with the riders in the bow of the vessel slightly elevated in profile view, while the so-called mini mast step (a timber with a sub-rectangular mortise containing a stanchion) was placed in its correct position near the aft port section of the mast step.

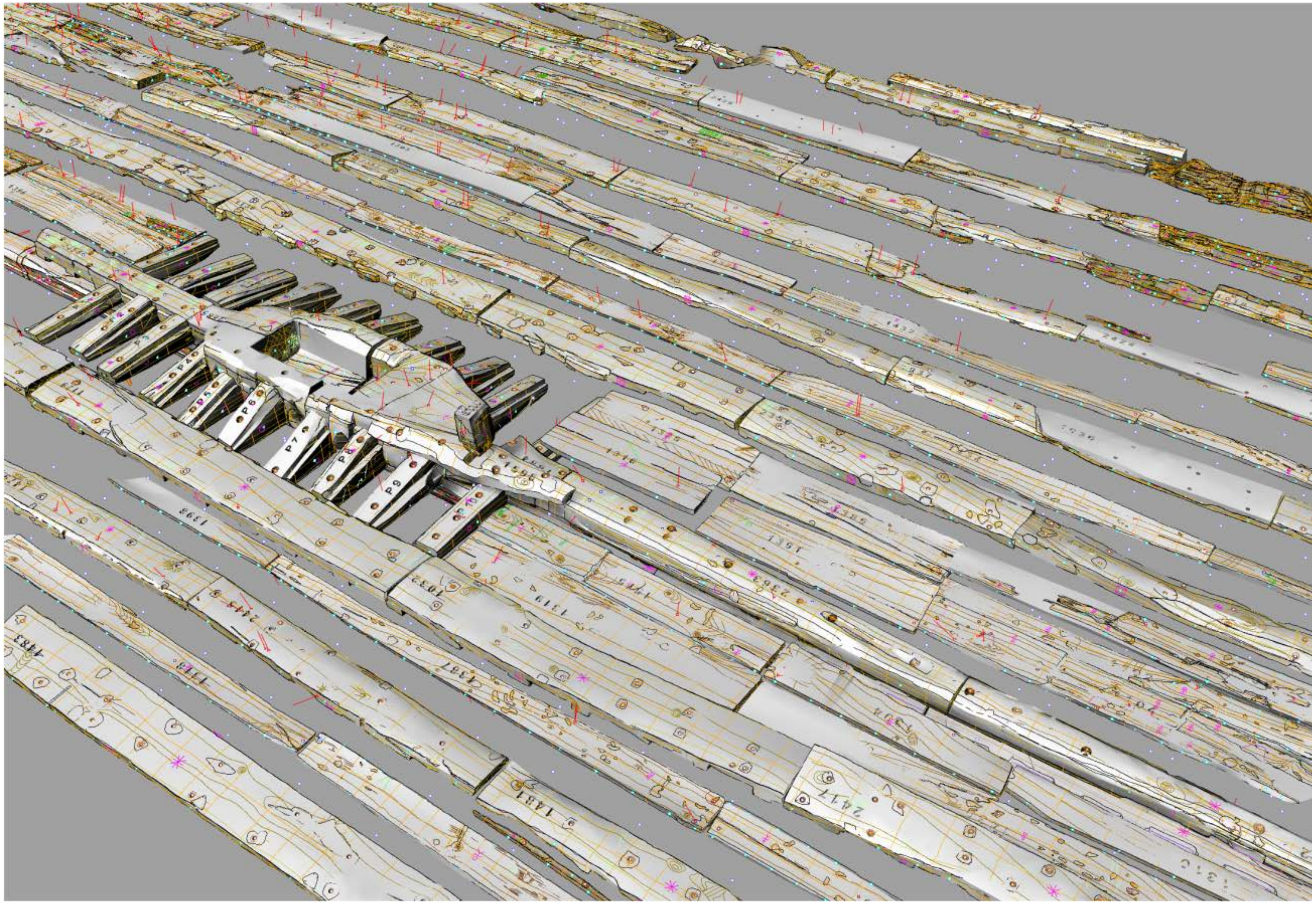


Figure 110. Detail of the Inner Hull master composite showing the mast step/keelson, braces, stringers and ceiling planks. Bow is to the left.

Toby Jones.

Special care was taken in building the 3D master composite of the inner hull, especially around the complex keelson/mast step area (Figure 111). Braces were correctly aligned based on the position of the fasteners in the underlying framing, as well as rebates in the sides of the mast step and stringers (Figure 112). Digital modelling allowed the visualisation of the underside of the mast step area (Figure 113).

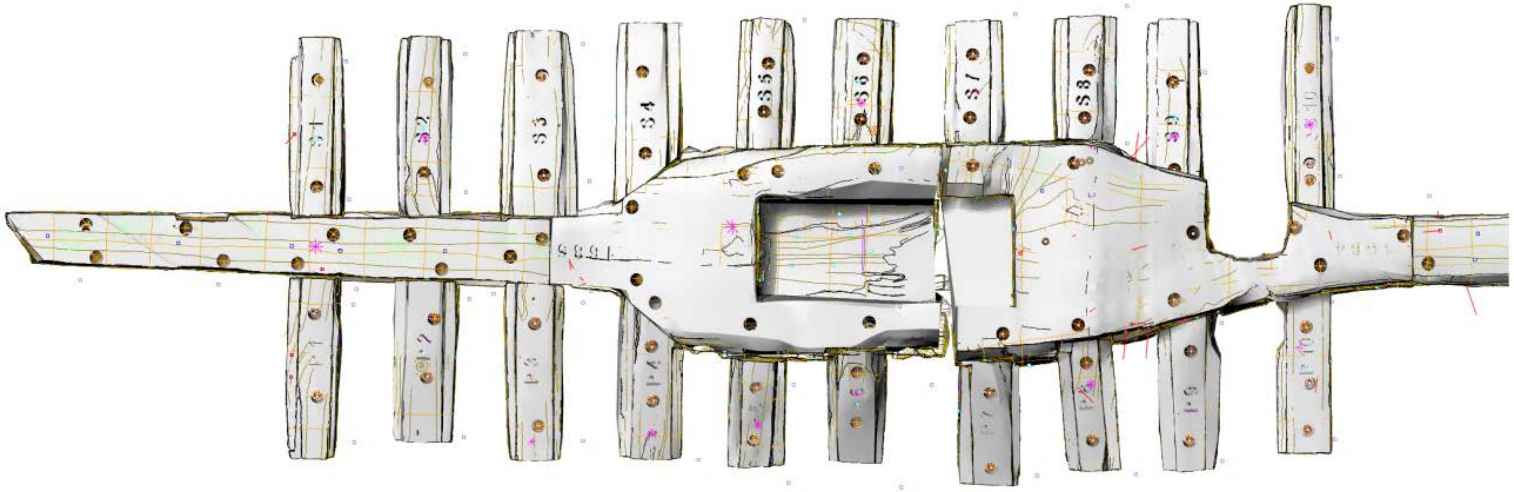


Figure 111. Plan view of the mast step/keelson and braces. Note the pump hole. Bow is to the left. Toby Jones.

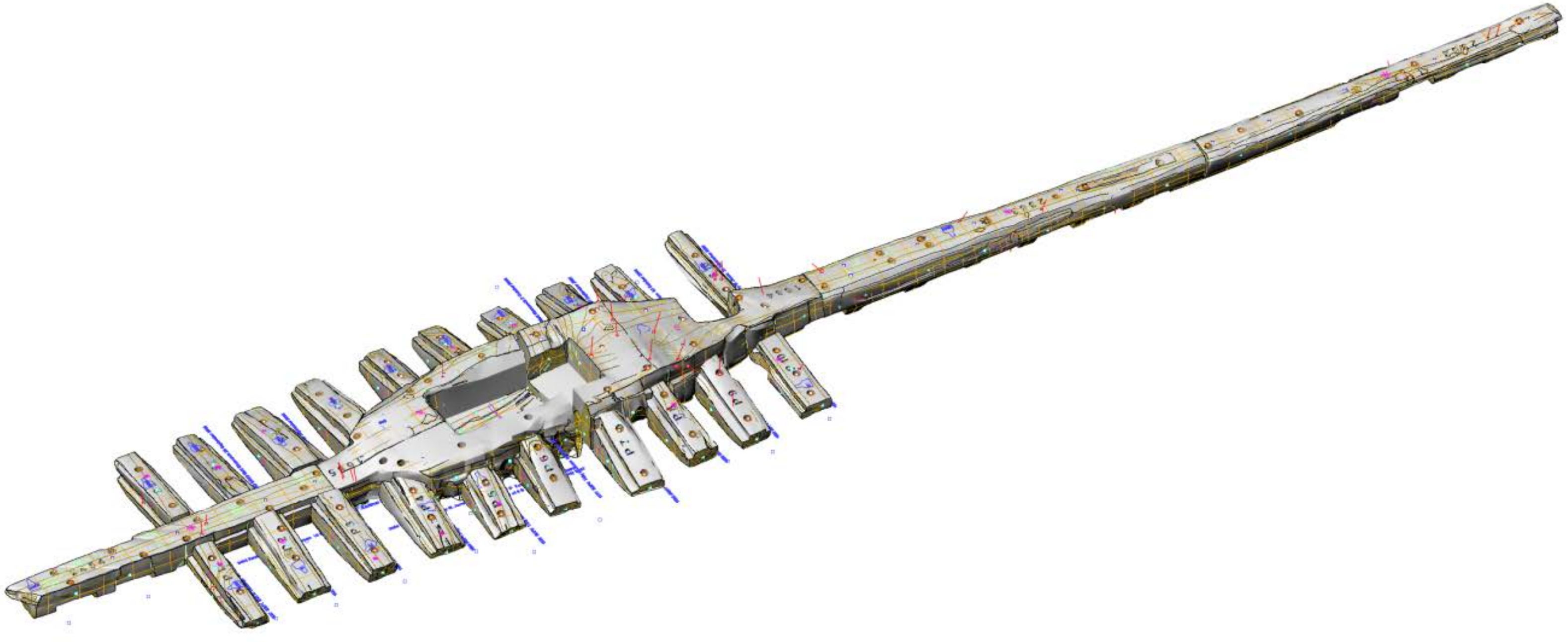


Figure 112. Perspective view of the mast step/keelson and braces. Bow is to the left. Toby Jones.

Figure 113. Perspective view of the inverted mast step/keelson and braces. Note the rebates on the underside of the mast step/keelson where it fits over the floor timbers. Toby Jones.

The clear presentation of the primary data in the master composites allows for analytical work and pattern recognition. There was an enigmatic collection of numerous fastener holes on the inboard face of the hull planking in the bow area. Their function was uncertain, but given their proximity to the centreline of the vessel, they may have had something to do with the initial design or construction of the hull. However, there was no known comprehensive design system in place for building large clinker built vessels in the late medieval period. Referring to the medieval *Grace Dieu* vessel , McGrail argued that the shipbuilders must have had physical controls or design aids in order to help define the shape of the vessel while under construction (McGrail, 2003: 124-126). These design aids could have taken the form of temporary moulds, or plank breadths and bevel angles at specific stations, which could be detected by analysing, in detail, the digital data sets. Small fasteners on individual timbers might be dismissed as inconsequential whereas a visible pattern might emerge when multiple digital timber records are placed in the right relative positions and patterns become evident. McGrail also highlighted the need to look for repeated ratios and any patterns in linear dimensions as clues to design intent and construction origin. The clear presentation of the primary data in the master composites allows for this type of analytical work and pattern recognition.

The completed master composite files were powerful tools for analysing and deciphering many aspects of the ship’s construction. Fastening patterns, repairs and inscribed lines could be viewed simultaneously, with relationships between these features detected for the first time. Construction sequence could be determined by looking at the overlapping joints between certain timbers and reconstructing the logical sequence of events relating to assembly and thus gaining insights into the original working patterns of the shipwrights. The Rhinoceros3D version 5 modelling software allowed the user to select certain features by layer, colour or object property, even when grouped. These items could be hidden or highlighted, facilitating detailed pattern analysis work.

The creation of digital solid models from the wireframe data resulted in the ability to determine the volume of ship timbers. This volume measurement could be used to estimate the approximate weight of the timber by multiplying the volume by a selected coefficient. Various coefficients, for green, seasoned, waterlogged, or conserved oak could be used to estimate the mass or density of a timber at various stages. These coefficients could be further refined by taking volume measurements and weights of selected ship timbers before conservation pre-treatment, after PEG treatment, and after freeze-drying. This process is potentially useful for determining the weight of the hull remains after conservation treatment, in order to inform engineers designing a cradle structure for display.

Chapter 5: Physical Modelling Methodologies

Introduction

The digital solid modelling phase of the Newport Medieval Ship Project created over 800 digital solid models of the main Newport Ship hull timbers. The digital wireframes (.3DM files) were first simplified by refining the coordinate data that dealt with overall geometry, fastener location and fastener angles. The simplified wireframe models were then surfaced to create watertight digital solids. These watertight digital solid models, complete with fastener holes, were saved in a .STL format and scaled down to 1:10. They were then sent in batches to a rapid prototyping facility that used Selective Laser Sintering additive manufacturing technology to make physical models of each digital solid model. The manufactured pieces were then cleaned, checked for accuracy and sent to the back to the ship centre. A total of 10 separate builds were commissioned over an 18 month period. A database was used to track the status of each modelled timber as it progressed from digital file to physical scaled model piece. Upon receipt of the scaled physical models, the CT identification numbers (or function codes) on each piece were checked against the packing list, and then released for use on the construction of the model.

The next phase of the project involved the assembly of the physical scaled model pieces in order to create a physical scaled research model that could be analysed in an effort to determine original hull form. Special micro-fasteners were used to fasten the model pieces together, using the modelled locations of the original fastener holes. This assembly process was experimental, and attempted to follow the perceived order of original construction. The changing size and shape of the scaled physical model was documented using time lapse photography, contact digitising and laser scanning. The following sections detail the process of creating physical solid models from 3D digital solid models and assembling the individual pieces in order to create a composite model of the articulated original hull remains.

Rapid Prototyping Technology and Equipment

There are many manufacturing options available to make a physical part from a digital model. At the most basic level, the rapid prototyping process involves removing (subtractive rapid prototyping) or adding (additive manufacturing) material until a desired three dimensional shape is achieved. The material(s) can be added or removed in a variety of ways, involving the use of physical agents including temperature, chemicals and friction. Unlike more familiar laser cutting or multi-axis milling machines, where material is removed from a solid block until the desired geometry is achieved, selective laser sintering is an additive manufacturing process whereby material is added or built up in thin layers, until the desired geometry is achieved. The laser sintering process utilised lasers to melt successively deposited layers of finely ground plastic particles, a type of nylon called Polyamide-12, into complex shapes. Mechanical or aesthetic properties like strength, flexibility, elasticity, texture, and colour are all important factors to consider when choosing a modelling material and method.

The locally based Manufacturing and Engineering Centre (MEC), at Cardiff University in Wales, had a rapid prototyping division, which investigated and tested various innovative manufacturing technologies. In a collaborative effort between the University of Wales Trinity Saint David (at the time University of Wales Lampeter), the MEC, and the Newport Medieval Ship project, a pilot project was run to see which parameters, settings and materials would produce the most accurate and cost effective part.

Several factors had to be considered when selecting an appropriate rapid prototyping technology. The various commercially available prototyping technologies had specific advantages and limitations. Some related to properties of the model part material as produced, such as flexibility, durability and surface finish, whereas others relate to the maximum size of part that can be manufactured or the resolution with which fine features, like small holes, can be consistently created.

Investigations into rapid prototyping technology and experimental trials showed that the selective laser sintering additive manufacturing process was the most cost effective and accurate way of creating physical solid models of the ship timber digital solid models. Polyamide-12 was chosen because the sintered (melted and fused) product was strong and flexible, and being a thermoplastic, capable of being reshaped when gently heated.

An EOS P700 Selective Laser Sintering machine (LS model with two 50W CO2 lasers) was identified as the ideal tool to create the physical solid models of each ship part. The build chamber on the machine was capable of accommodating a maximum part size measuring 700mm x 380mm x 580mm (Figure 114). The decision to build the model at 1:10 scale was certainly influenced by the size of the build chamber.

Figure 114. Selective Laser Sintering (SLS) machine at the Manufacturing and Engineering Centre at Cardiff University. The machine was capable of producing several hundred scale model ship parts in each batch. Toby Jones.

Materials

Polyamide-12 nylon was chosen as a sintering material because the finished model pieces appeared to have broadly similar mechanical properties to wood (a traditional modelling material), in terms of strength, flexibility and elasticity. The flexibility of the model pieces depended on the scantling of the overall part and the thickness of the shelling (see Process section below), number and position of fastener holes and orientation of the forces acting on the component. Further research in this area, quantitatively comparing the physical properties of the modelled parts in different materials, might identify an ideal material, with the findings being useful for inputting parameters for advanced digital modelling into engineering analysis software programmes, like SolidWorks.

At £50/kg, the material was also cheaper than other alternatives, like Polyamide-11. A full build (using the entire available area within the build chamber) would typically cost £2000-£3000. Un-sintered Polyamide-12 particles could also be recycled (reused) to a limited extent, lowering the cost of the build (Soe et al., 2012: 448). Typical costs for the Newport Medieval Ship Project were around £10 per piece, with the entire model costing in the region of £8000 to manufacture, however, this amount does not take into account the cost in terms of time and money to create the digital solid models, or the assembly of the physical scaled model.

Test pieces: Identifying and Refining Ideal Production Parameters

In order to determine accuracy and precision in the manufactured hole diameter and ensure consistency between the numerous builds, a series of test pieces were created by the author in order to evaluate the performance of the laser sintering machine. These test pieces consisted of flat and triangular (in section) blocks with a series of vertical through holes in a variety of diameters (Figure 115).

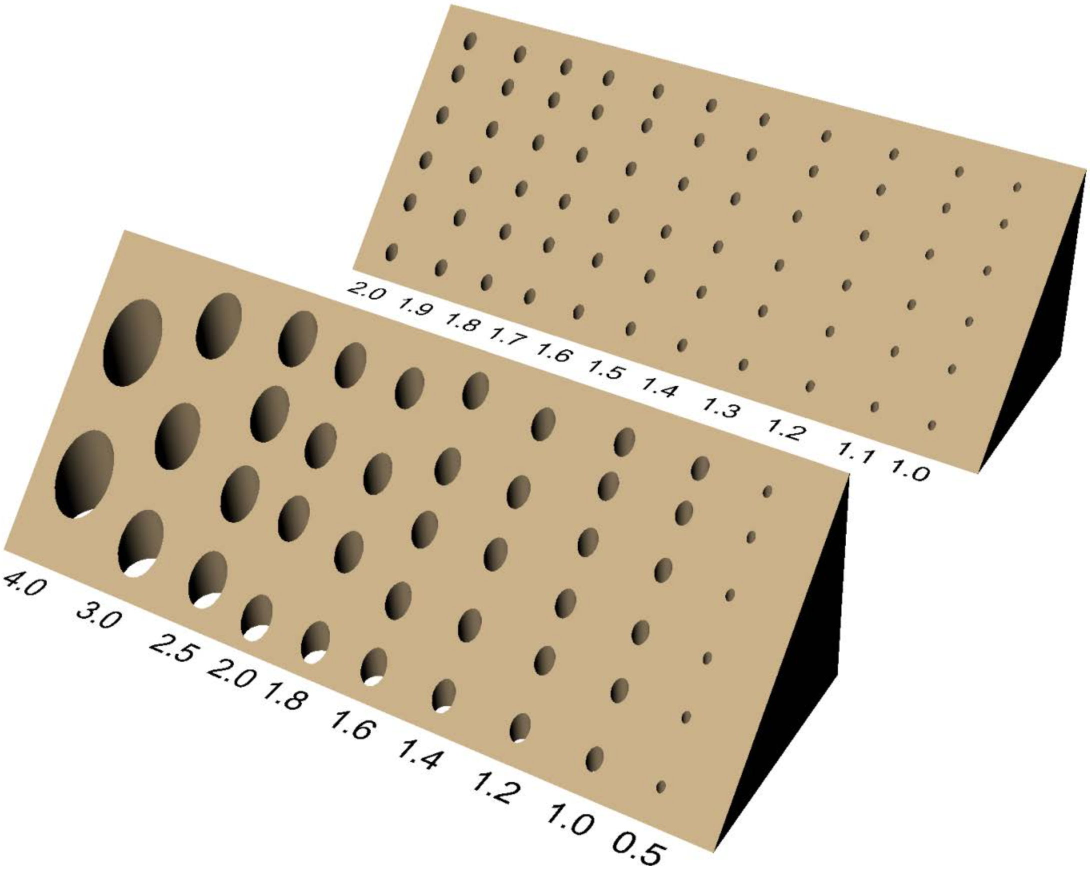


Figure 115. Test blocks were created in order to test the precision and accuracy of the selective laser sintering machine. Comparisons were made between the manufactured hole diameter and the nominal hole diameter (above in mm). These test parts were included in each batch. Toby Jones.

These blocks were arranged around the build chamber to test the ability of the machine to accurately and consistently create small features (the fastener holes) at the extreme edges of the build area (Figure 116). The diameters of the holes in the test blocks were measured after manufacture, and compared to the actual modelled values. This process helped to establish the relationship between the diameters of the holes as modelled and as built. The slight difference led to a refinement in the digital modelling process (see digital solid modelling fastener section above), with archaeologists creating fastener holes that were slightly larger than originally recorded (but with the same fastener centre). These test blocks were manufactured by the laser sintering machine prior to each build, to ensure that the machine was operating within the tolerances necessary to create consistent and accurate physical solid models of the scaled ship parts in each build session (Soe et al., 2012: 448).

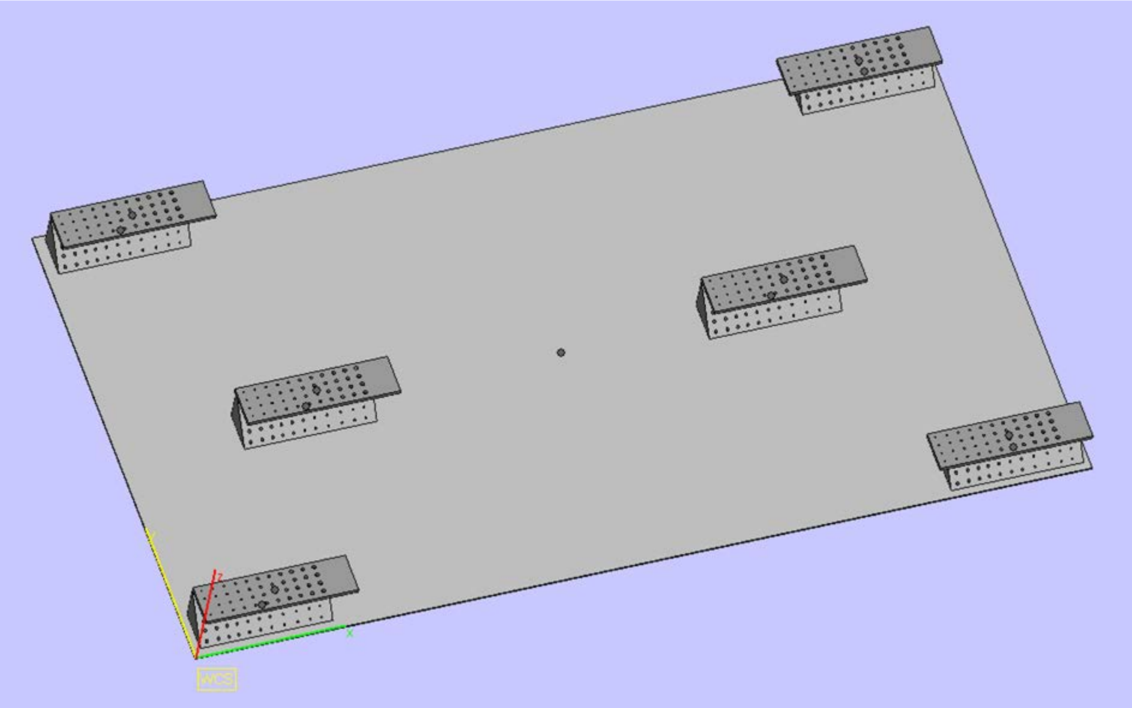


Figure 116. These blocks were arranged around the build chamber to test the ability of the machine to accurately and consistently create small features (the fastener holes) at the extreme edges of the build area. Shwe Soe.

Additive Manufacturing: The Selective Laser Sintering Process

After several months of tests and adjustments, a consistent and repeatable manufacturing process was developed and batches of digital solid models in .STL format were sent via email to the MEC, where they were then analysed, manufactured and posted back to the ship centre. The individual laser sintered models of the ship timbers had the overall geometry, lands, scarfs, and major fastener holes recreated at the desired scale with exacting precision.

The digital solid model files were received by the MEC in batches of similar timbers (planking, framing etc.). The individual digital solid models were checked once again, using the commercial version of Materialise Magics software, for any defects that might compromise the part’s ability to be physically manufactured. Special attention was paid to areas where the part was very thin. Any defects could potentially cause the SLS machine process control software to crash in the middle of a build.

During this phase of the manufacturing process, a shelling technique was developed to impart some flexibility into each part. Shelling or part-hollowing involved modifying the digital solid model so that it contained internal areas of un-sintered material. In practice this meant fusing the finely ground plastic only near the edges of the part and around fastener holes. The process involved selecting a shell thickness, which was projected inward, leaving the part with the original overall geometry. The thickness of the shelling could be adjusted, allowing for the desired degree of flexibility to be obtained through trial and error experimentation.

Several different wall thicknesses for the shell were tested before a satisfactory thickness was found. Thinner walled parts (1mm-2mm) cracked when subjected to moderate stress, while parts shelled with 4mm thick walls displayed negligible flexibility. Given that as the shell thickness increased, the flexibility decreased, the Newport Ship project used 3mm shelling on all the framing and other larger timbers (Figure 117). The application of shelling also reduced the build time, which, in turn, lowered the build cost because of the energy savings. The un-fused Polyamide-12 within the shelled walls of each part could have could have theoretically been reused, but it would have required a small hole to be drilled in each part to allow the powder to be removed. Parts less than 6mm thick (i.e. those timbers from the ship less than 60mm in thickness) were not shelled, as they were deemed to already have the right balance of strength and flexibility. This category included all of the planking, tingles, and many of the stringers (Soe et al., 2012: 443-450).

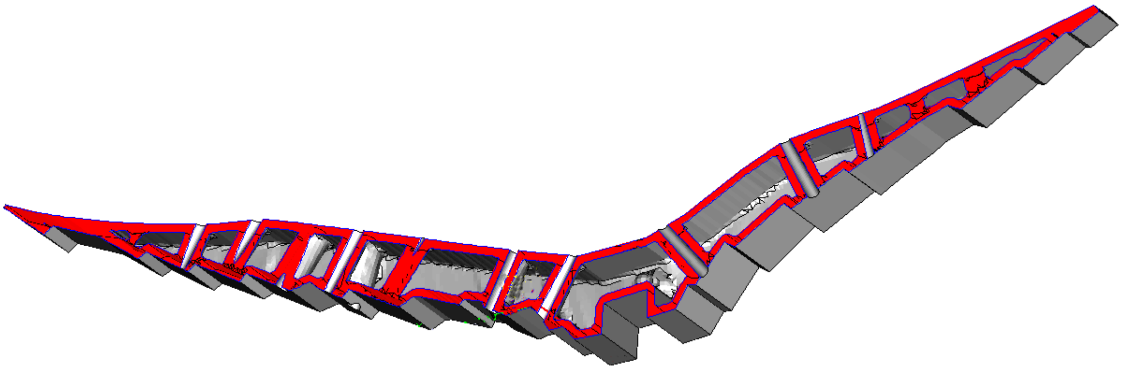


Figure 117. Cross-section of shelled floor timber model. Note the shelling around each treenail hole. Shelling reduced the manufacturing time. Shwe Soe.

Digital solid models were arranged within the build area in order to use the space efficiently (Figure 118). Digital models could be placed in any orientation within the build chamber, however, as many of the ship timber models were similar in shape and size, it was possible to logically nest them in layers in the build chamber in order to utilise the available space most efficiently. This layout process was conducted by the operators of the laser sintering machine. Once the parts had been satisfactorily arranged within the digital build chamber, the machine was set to run overnight or over the weekend.

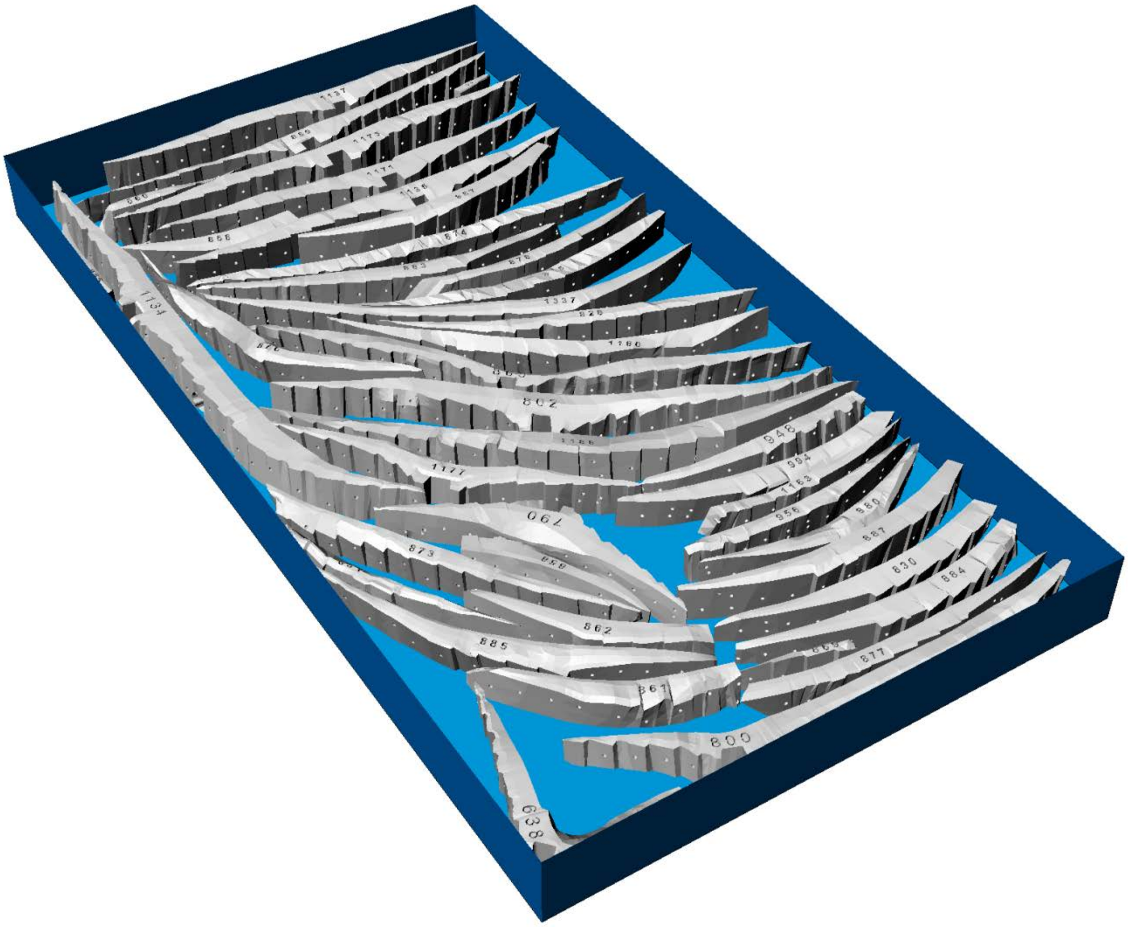


Figure 118. Typical layout of a layer of modelled ship timber models in the selective laser sintering machine. Each build comprised multiple layers of model pieces. Toby Jones.

During the building process, the Polyamide-12 powder was laid down in 0.15mm layers and levelled. The ambient temperature of the build chamber was set at 177 degrees C, just below the melting point of the plastic. The focused beams of the two lasers systematically travelled across the bed of powder at a rate of 3000mm per second. Wherever a solid area was desired, the lasers would activate, melting the plastic particles in a small area and fusing these to the previously deposited layer. The machine created holes and voids in the part by turning off the laser momentarily in predetermined areas. The active working plane would be lowered each time a new layer of powder was added, keeping the upper surface of the build at the same relative height throughout the process (Soe et al., 2012: 443-450).

After the build had been completed, the entire block, consisting of sintered and un-sintered Polyamide-12 powder, was allowed to cool. During this time, cracks would appear through areas where the powder was un-sintered. After the build reached a cooler temperature, parts were removed by tapping on the block and working the existing cracks until they opened further. Loose powder was collected for reuse, while parts were cleaned by tapping or using compressed air to clear the holes filled with un-sintered powder. The dimensions of the finished parts were selectively spot-checked against the original digital models. Physical model parts would be sent by post in batches, and were checked against a database before being readied for attachment to the model (Figure 119).

Figure 119. Completed framing timber scale model pieces. Digital solid models of each timber were emailed to the Manufacturing and Engineering Centre at Cardiff University. The finished physical model pieces from each batch were packaged and then posted back to the ship centre. Toby Jones.

Assembly of the Physical Scaled Model

The physical scaled model piece production and assembly phase of the Newport Medieval Ship Project occurred between 2008 and 2011. While the digital modelling process was continuous, the physical production of these parts was divided up into sequential batches, with a conscious decision to try and have the digital production and physical manufacture and assembly occur simultaneously. To this end, timbers needed first for building the model, like the keel and garboard planks, were selected first for digital solid modelling and physical manufacture (Figure 120).

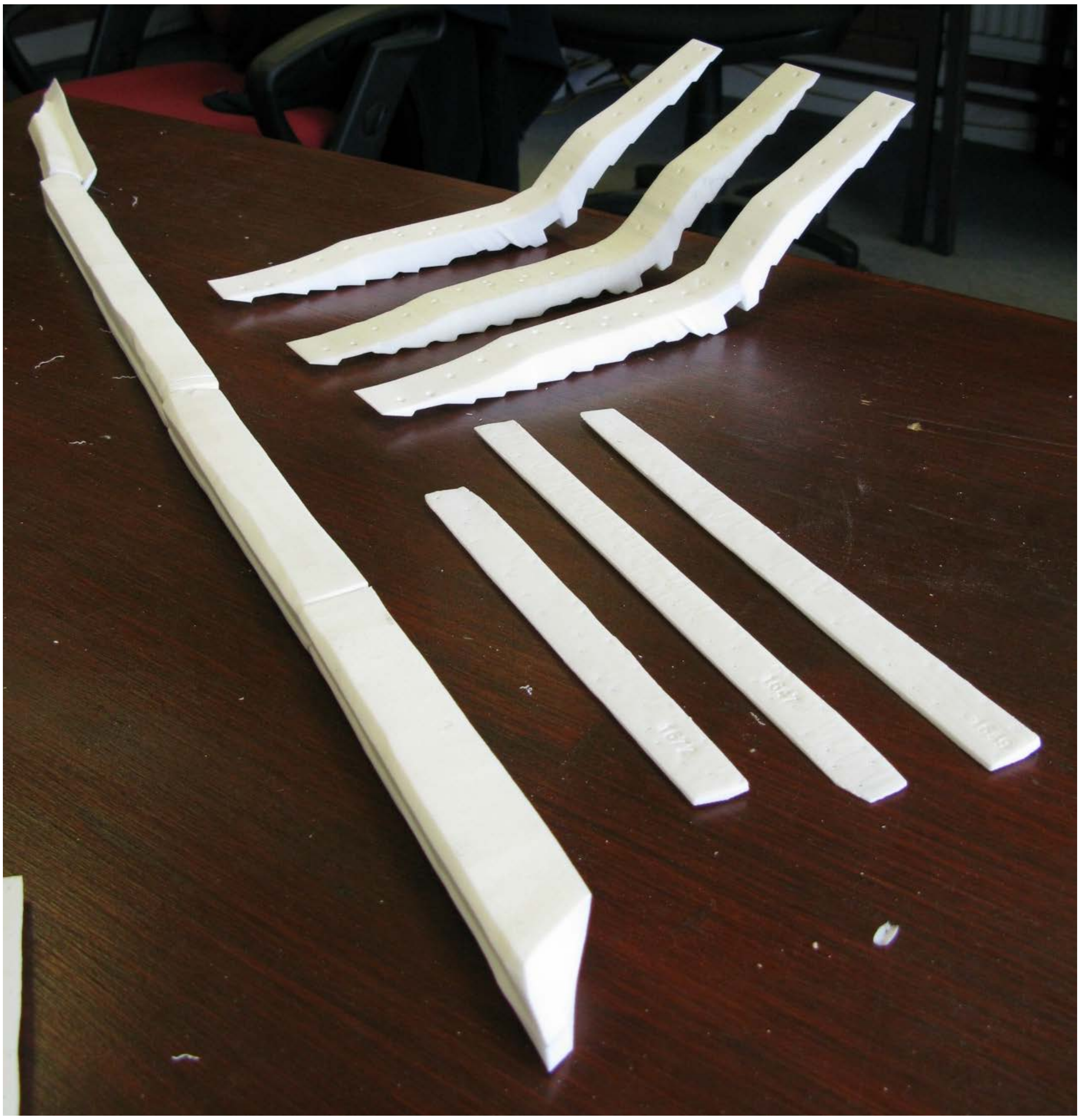


Figure 120. The first batch of modelled pieces are prepared for assembly. The 1:10 scale model pieces were held together using threaded metal micro-fasteners. Toby Jones.

A sturdy modelling table, suitable for model construction, documentation and display, and complete with rolling castors and a removable cover, was designed by the author in 2008 (Figure 121). A clear perspex shield protected the model from damage and dust, while allowing for close inspection. This shield was removed during periods of active model assembly and documentation.

Figure 121. Modelling table with protective shield in place. Members of the public were able to view the assembly of the model during open days. Toby Jones.

The physical scaled model of the articulated remains of the Newport Ship was assembled in the perceived original order of construction for lapstrake vessels, beginning with the keel (Crumlin-Pedersen, 2004: 47). The keel was laid down on the centreline of this table, but not fastened firmly to it (Figure 122). The model was only firmly anchored to the table after all the articulated model pieces had been attached. In all cases, the focus was on letting the assembled model timbers (especially the hull planking) determine the original form, with no reshaping input from the model builders. Archaeologists documented the changing shape state of the model at numerous points in time through a series of time-lapse photographs, laser scanning, and contact digitising.

Figure 122. The author assembling strakes of planking. The sequence of construction of the 1:10 scale model was visually documented using time-lapse photography. Newport Museums and Heritage Service

The process of adding additional timbers continued with the garboards being attached to the keel, followed by more hull planking through to the turn of the bilge. Selected floor timbers were added at this point followed by additional planking through strakes P16 and S16 (Figure 123). First futtocks were added on both sides in selected areas, followed by more hull planking (Figure 124). Upon completion of the shell, the remaining framing was inserted.

Figure 123. Planking was added to the model until reaching strake 16 on both the port and starboard sides. Toby Jones.

In all cases, the planking was inserted before any overlying framing timbers were attached. After all the outer hull and framing (including frame fillers) had been attached, numerous internal timbers were fitted, including the mast step/keelson and associated braces, followed by stringers and riders. Hull planking patches, known as tingles, were modelled and dyed red for contrast and attached in their various correct locations on the outer hull (Figure 125). After all of the articulated material had been fitted, disarticulated timbers, including beam knee complex and deck elements were experimentally fitted into the hull (Figure 126).

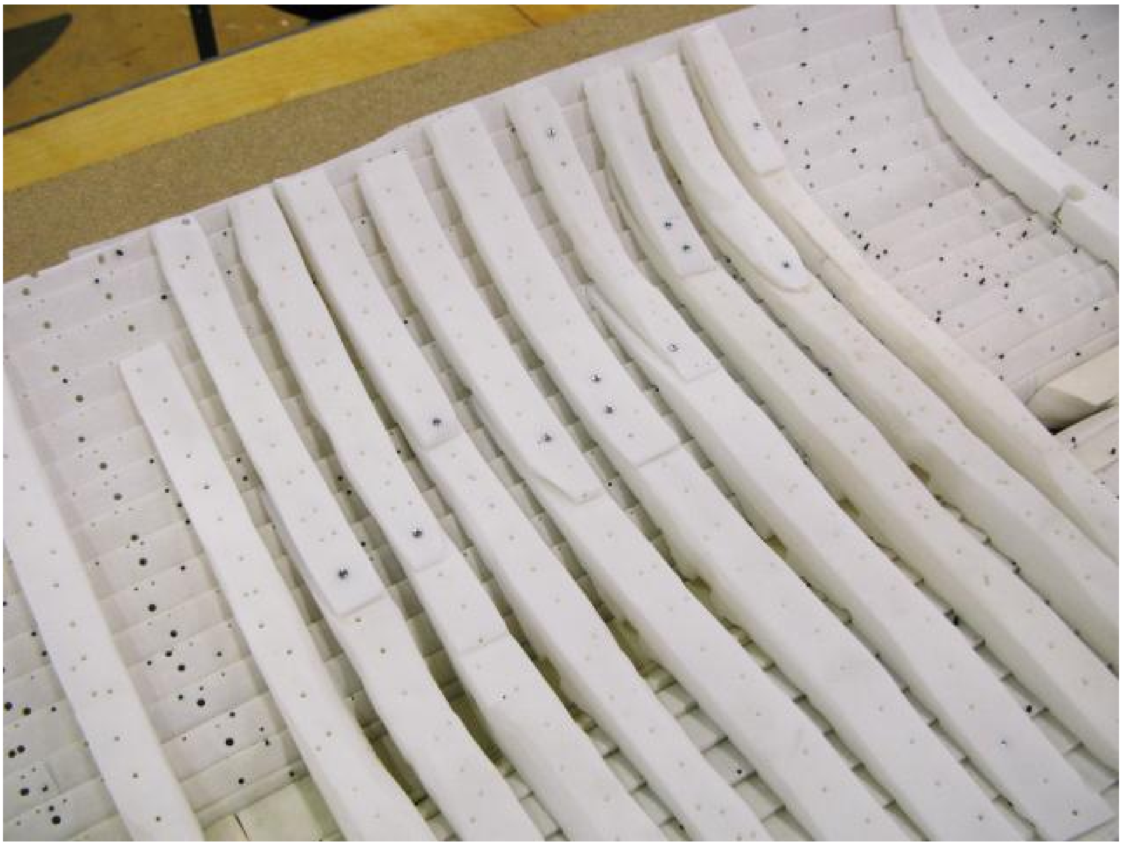


Figure 124. Framing timbers attached to the model up to the turn of the bilge. The bow is to the right. Toby Jones.

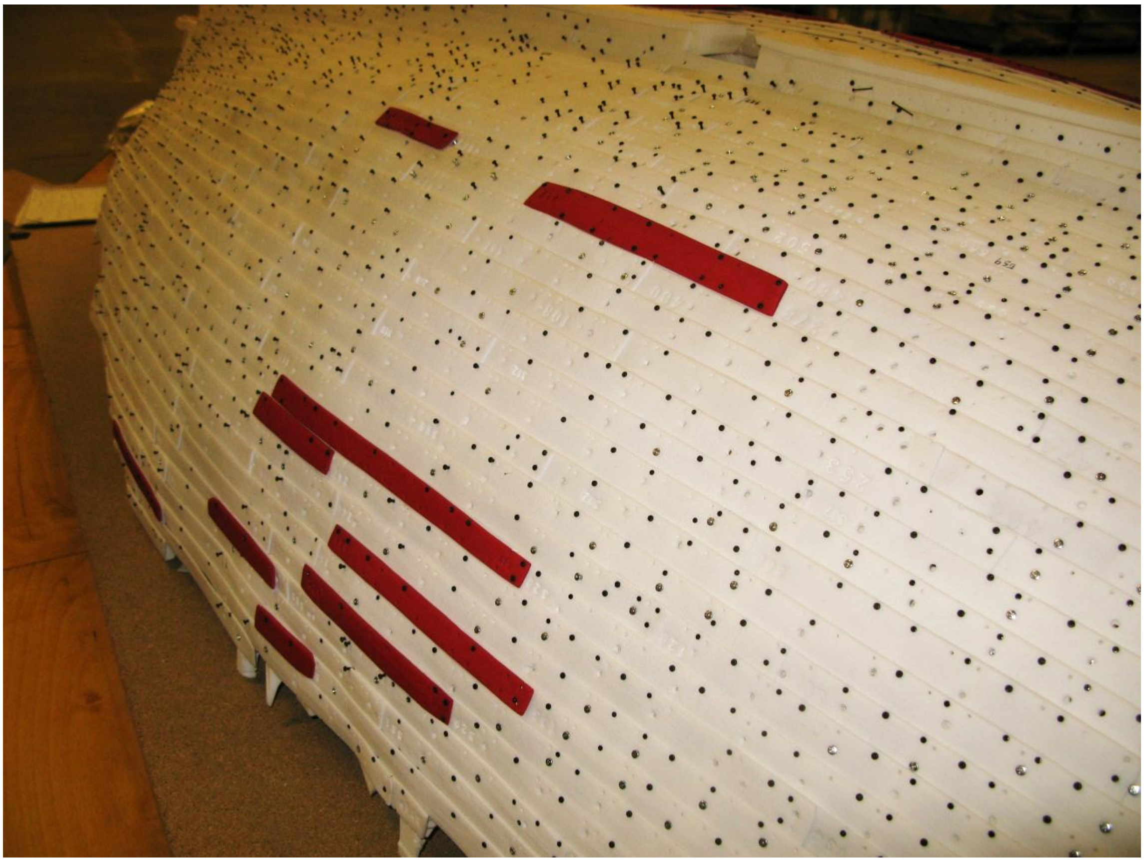


Figure 125. Outboard starboard surface of the inverted model. Note the tingles (patches) modelled in red. Toby Jones.

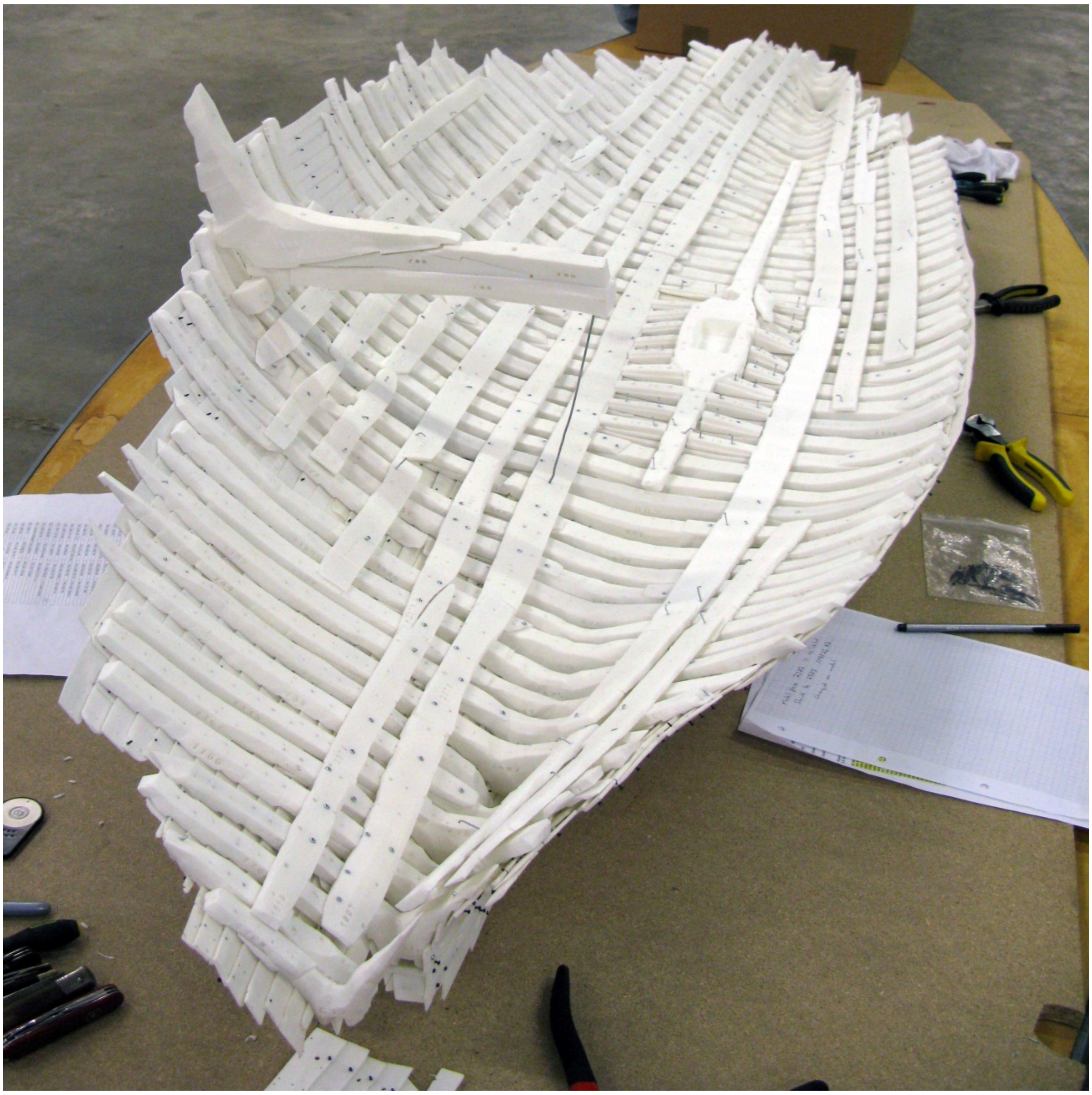


Figure 126. Completed laser sintered 1:10 scale model of the extant articulated structural hull timbers. The ceiling planks and bilge boards were digitally recorded, but not modelled, as they were not considered to affect the hull form. Note the disarticulated composite beam/knee struture, which has been tentatively placed. The bow is in the foreground. Toby Jones.

The model was assembled one piece at a time, and fastened together using threaded steel micro-fasteners (Figure 127). These small metal screws were purposely designed to cut threads into thermoplastics like Polyamide-12. These non-permanent fasteners were ideal in several respects. Micro-fasteners were chosen due to their availability and economy and for their ability to be readily removed from the model, an important consideration if there was a need to disassemble part of the model to add a missing part or correct a mistake.

Figure 127. Threaded micro-fasteners used to assemble the hull form model. The smaller black screws were used in clench nail holes, while the larger silver screws were used in treenail holes. Toby Jones.

Two diameters of screws were used, with 1.7mm screws being used to fasten the hull planking together through the original clench nail holes. These screws (large Pan Head Phillips Tri-Plas black plated) came in two lengths, 8mm and 5mm. Larger screws, with a diameter of 2.6mm were used in the original treenail fastening holes to fasten the planking to the framing. These screws (small Pan Head Tri-Plas zinc plated) were 12mm in length. All of the screws were driven into the model using manual micro-screw drivers with ‘00’ Phillips tips.

Planking was added to the model by lining up the clench nail holes along the lower land of the plank to the holes along the upper land on the next lower strake. Planking was added from the aft most surviving plank and worked forward, plank by plank. Some experimentation was also done by attaching a complete strake together at the scarfs and then holding this entire strake up to the model before aligning and fastening it to the previous strake. Both methods worked well (Figure 128).

The timbers recovered from the severed bow section were also digitally modelled and physically manufactured. These model planks and framing timbers were fastened together, forming a panel. This panel was aligned and added to the existing model using small metal clamps (Figure 129).

Figure 128. Archaeologist attaching framing model pieces to the planking shell. Note the camera and tripod set up in the background to take time-lapse photographs. Toby Jones.

Few problems were encountered when fastening the planking together. However, there were areas of considerable distortion, with humps and hollows visible in selected areas of planking on the model. Many of these disappeared with the insertion of the framing. It was occasionally necessary to use pins and metal rods to lever the hull planking and framing around (a matter of a few millimetres) in order to make the respective fastener holes align. Fasteners would be used at fairly evenly spaced intervals. It was not necessary to put a fastener in every single hole along each strake of planking. It was found that a fastener used in every fifth hole along a strake would

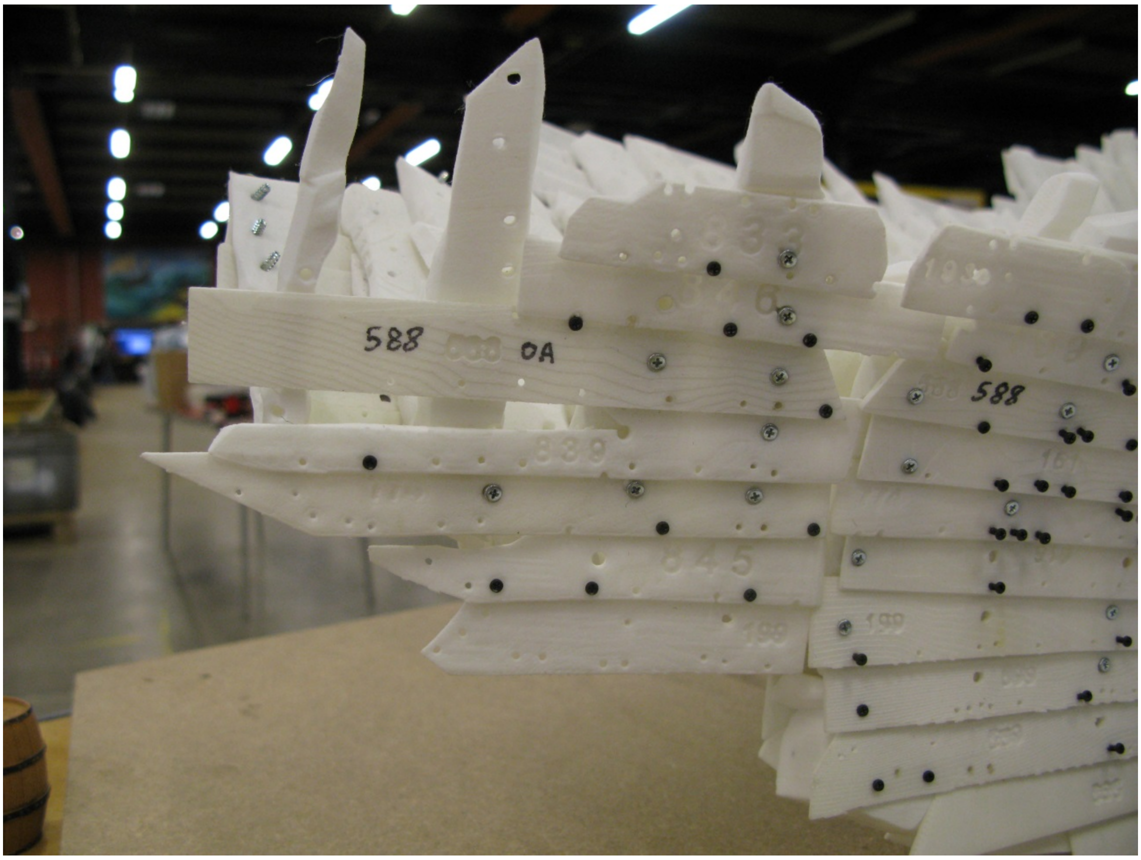


Figure 129. Attaching the severed port bow section to the model. Toby Jones.

be more than adequate to fasten the model pieces together. This saved time and money, as the screws were expensive. Model pieces of the tingles were added to the outer hull using the shorter (5mm long) 1.7mm diameter screws.

It was necessary to use more screws to fasten the hull planking to the framing. In these areas, the stresses of making the planking and framing fit together required that nearly every treenail hole be filled with one of the larger diameter micro-fasteners. It was possible to strip out the fastener holes when driving in some of the micro-fasteners. This could be prevented by ensuring that the whole diameter was correct. If it was too large, then a shim (plastic shaving) could be inserted with the screw, causing it to bite. Another occasional problem would be stripping out the head of the fastener or breaking the tip of the screwdriver off in the head of the fastener. Both of these problems could be prevented by pressing firmly and evenly turning the screwdriver. Sudden, jerky, movements were much more likely to damage the screw head or driver.

The assembly of the model was documented using time-lapse photography. After every new piece was fastened to the model, the archaeologists would remotely take a colour digital still photograph of the progress. The camera was mounted on a fixed tripod with the modelling table and tripod being kept in the same position relative to one another. The photographs (over 1600 in total) were later sequenced in a movie making programme and turned into a video. The movie file, (Newport_Medieval_Ship_Project_Movie_2012), can be viewed on the ADS website at the following address: http://archaeologydataservice.ac.uk/archives/view/newportship_2013/downloads_excavation.cfm?archive=movie. The movie also contains summaries of other aspects of research and conservation that have occurred during the course of the project (Nayling and Jones, 2014b).

The similarities between the model and the actual remains are striking, when comparing the parts of the vessel to the same sections of the model (Figure 130, Figure 131). The model has helped both members of the public and visiting archaeologists to understand the size and complex construction sequence of the actual ship, and in the future will hopefully serve as a 3D blueprint when reassembling the original conserved hull remains in a museum.

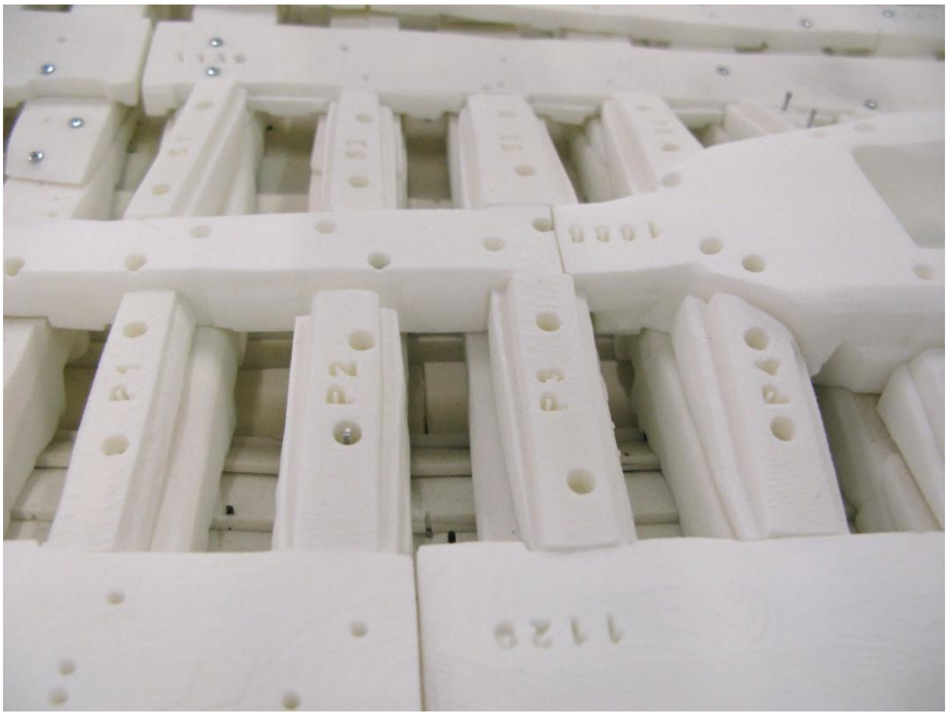


Figure 130. Detail of the mast step/keelson and forward-most braces on the scale model. Compare to Figure 131. Bow is to the left. Toby Jones.

Figure 131. Detail of the *in situ* mast step/keelson and forward-most braces. Compare to Figure 130. Bow is to the left. Newport Museums and Heritage Service.

Documentation of the physical model shape during and after assembly

The 1:10 scale research model took several years to build, and the changing hull form was documented at various stages during the assembly process, in an effort to quantify the changing shape and to try and correlate this change to the addition of specific timbers. This documentation took the form of contact digitising, laser scanning, and digital photography and videography. In addition to being a research tool, the model served several other purposes, including providing an interactive display for helping with public understanding and engagement, which was especially important as the ship timbers had entered the conservation phase and were no longer available for public viewing.

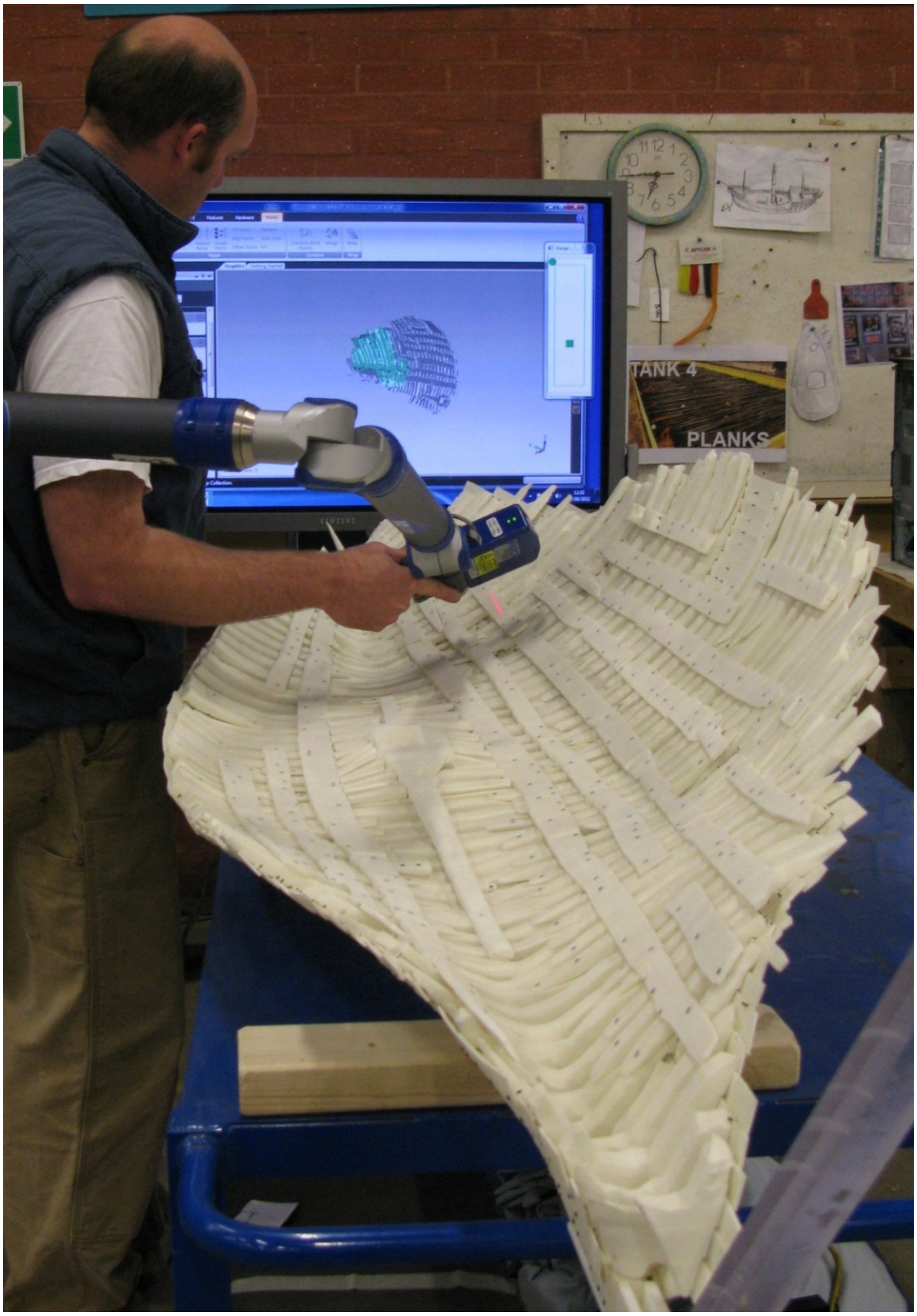


Figure 132. The author laser scanning the inner surface of the completed 1:10 scale hull model. Newport Museums and Heritage Service.

The shape of the evolving hull form was primarily documented using laser scanning (see laser scanning the scale model section below) and contact digitising (Figure

132). Both of these methods produced accurate and useable data sets, which could be directly compared. Contact digitising occurred at various intervals, with archaeologists taking coordinate data along selected frame stations or planking strakes (Figure 133)(File on DVD: NMS_Scale_Model_Doc_WF_Data _Meshes.3DM). This data, while deemed useful at the time of capture, was later found to be superseded by the comprehensive laser scanning of the entire model. One challenge recognised by those performing the documentation was the tendency of the contact digitising probe tip to slightly deflect the hull form when the probe tip made contact with the model, effectively changing the hull form shape, even if only slightly.

This problem was bypassed by using the non-contact laser scanner to collect shape data. The contact digitisation did have some advantages however, as the informed collection of coordinates from certain areas could be repeated at intervals and easily compared, whereas the laser scanning offered no interpretation, and required extensive post-processing to make the data useable.

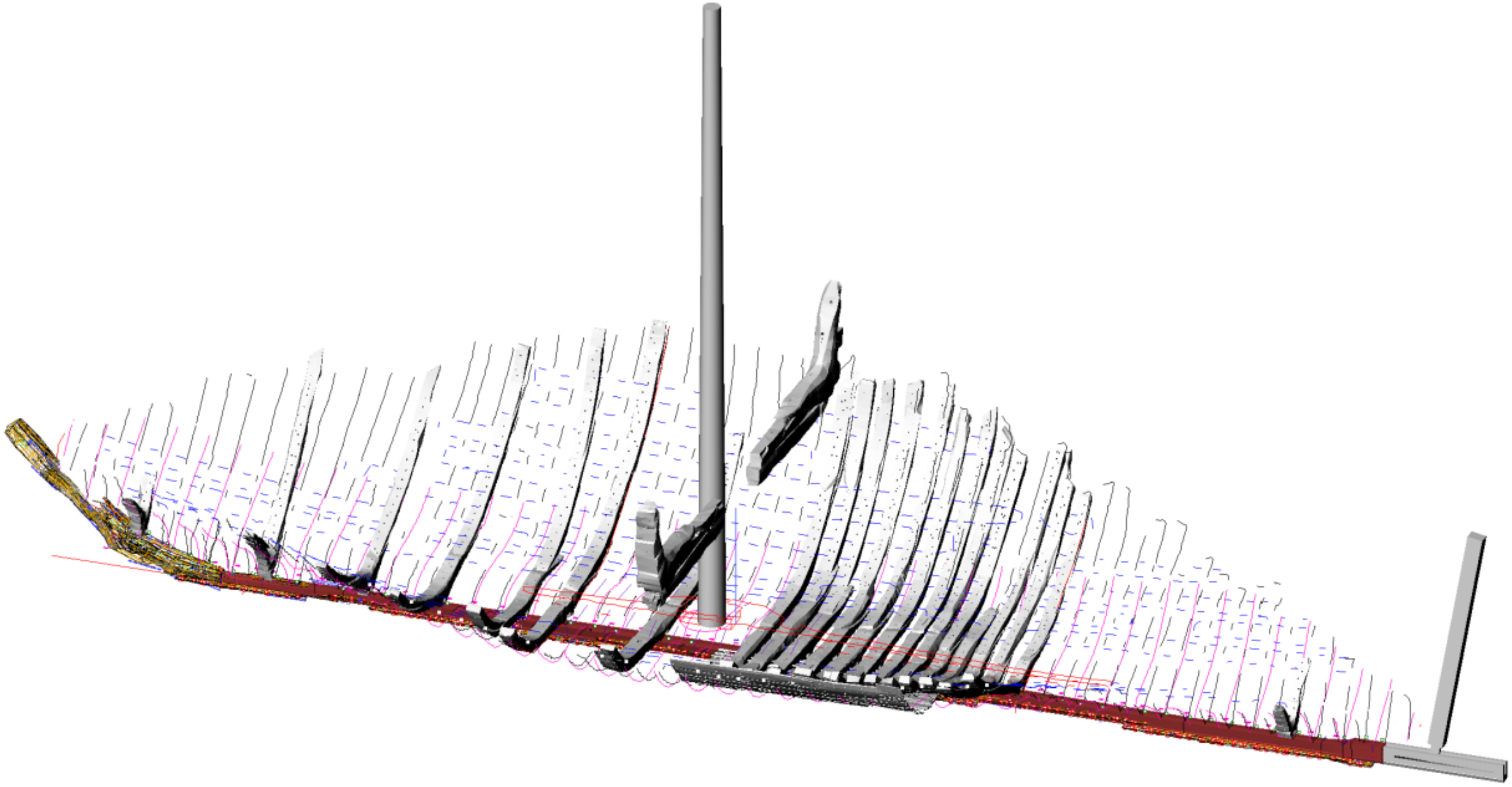


Figure 133. Experimental fitting of digital solid model pieces into the digitally documented scaled physical hull form shape. Toby Jones.

Laser Scanning the Physical Scale Model

The scaled physical research model was documented using laser scanner technology when the planking shell had been completed up to strake 16 on both the port and starboard sides (Figure 134). The interior of the hull was then documented after all of the articulated model pieces had been fitted, followed by a similar laser scan of the exterior of the hull. These inner and outer hull laser scans were then fitted together to create a composite digital version of the hull form model (as a point cloud), to which the severed bow portion of the hull model was then digitised and added (Figure 135). It was important to note that at this phase of the project, the model of the articulated hull remains, although complete, had not yet been firmly fastened to the modelling table, and the shape recorded did not represent a faired hull form, as no attempt had been made to actively reshape any of the pieces.

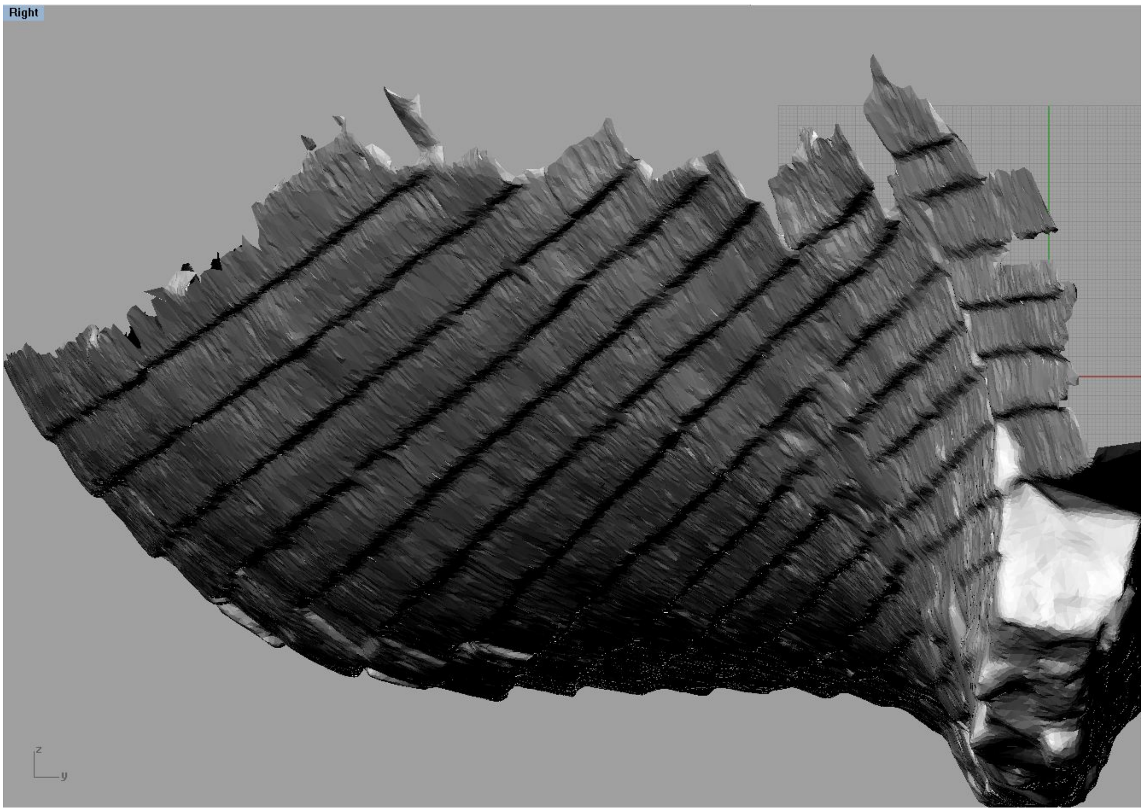


Figure 134. Digital mesh model produced from laser scanning the 1:10 scale hull form model when the planking had reached the 16th strake on both the port and starboard sides. Note the twist in the keel. Toby Jones.

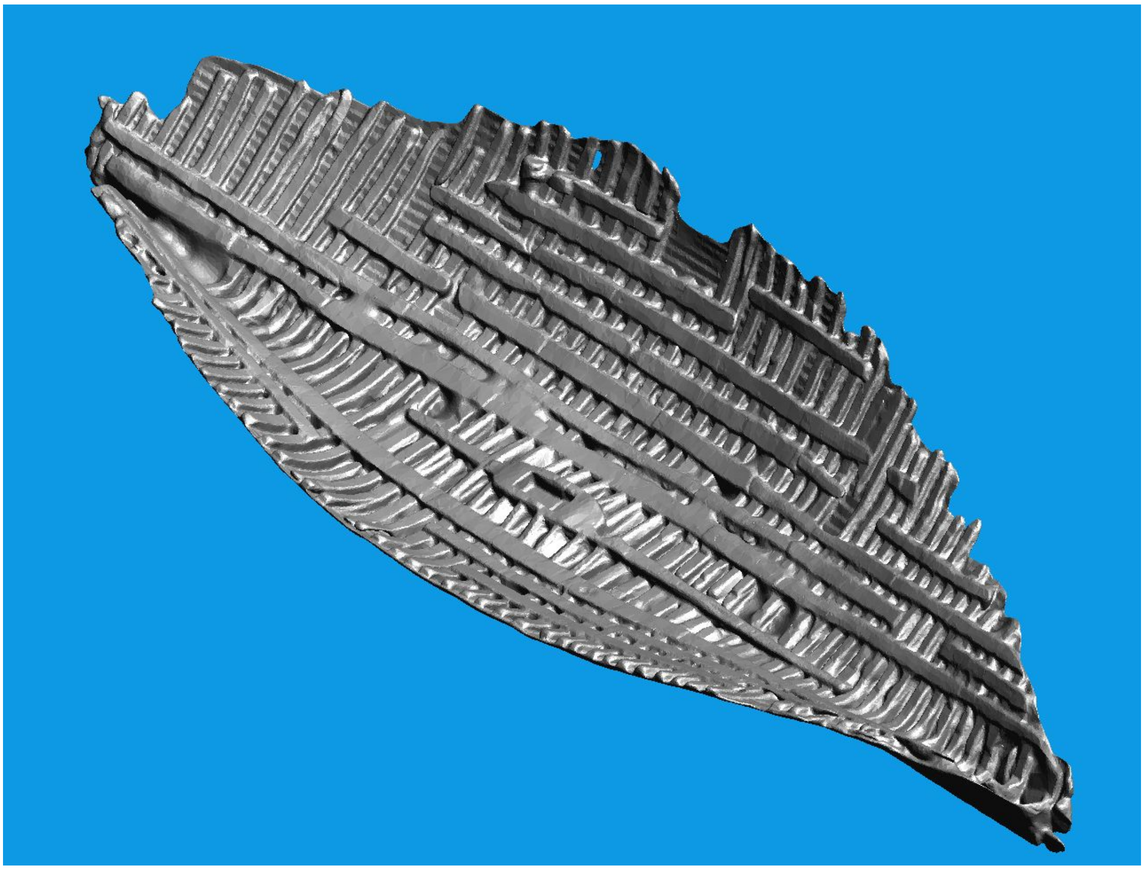


Figure 135. Perspective view of the digital mesh model produced from laser scanning both the inner and outer surfaces of the scaled physical hull form model. Bow is in the upper left corner. Toby Jones.

Laser Scanning Equipment and Methodology

There were numerous types of 3D laser scanning technology available during the documentation phase of the ship project with many companies and some universities offering commercial scanning services. Certain systems were designed to record large scale objects, including architecture, quickly, whereas other systems could record smaller objects, like sculpture or small finds, in a higher degree of detail. Laser scanners might be hand held or tripod mounted, and connected to a computer via USB cables or wirelessly. Some laser scanning systems came with proprietary software, while others had the ability to interface with a variety of software packages (Barber, 2011: 9). The Newport Ship Project, having previously invested in FaroArm contact digitisers, decided to purchase a laser scanning system that could be integrated with the existing style of contact digitiser. A FaroArm Laser Line Probe V2 (also known as a LLP or ScanArm V2) was mounted at the distal end of a 7-axis 10 foot Fusion model FaroArm.

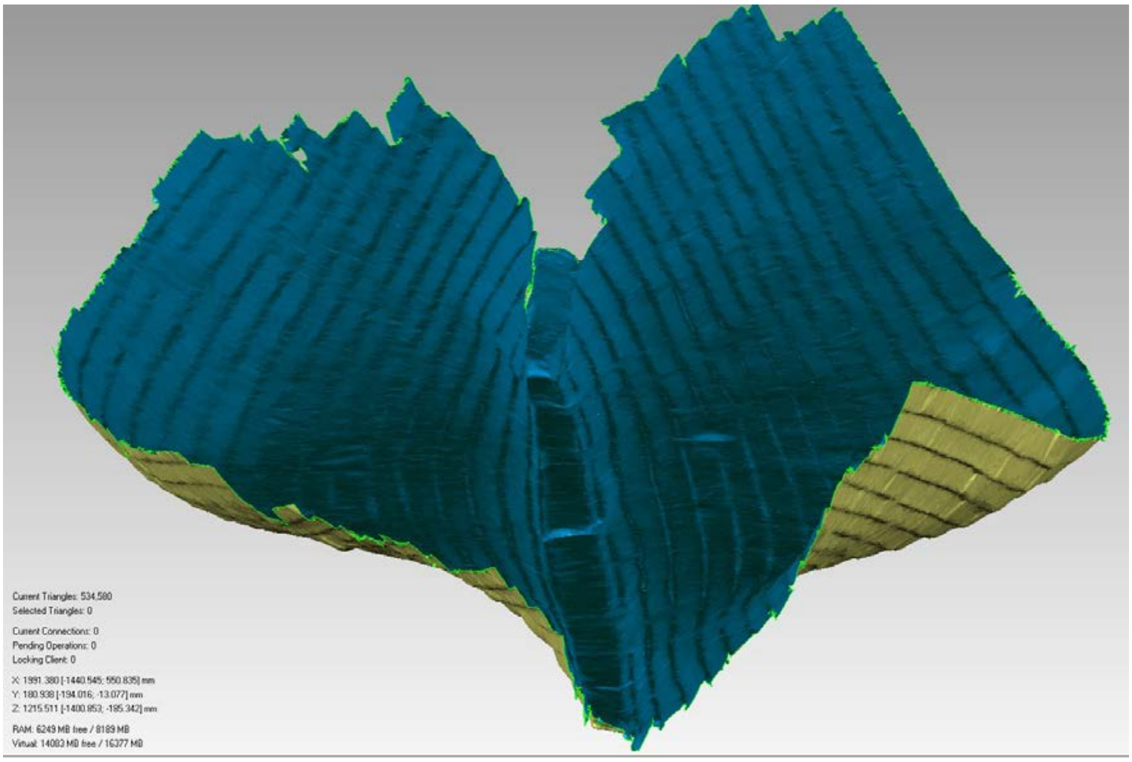
The LLP could take up to 19,200 x,y,z points per second along a 34-60mm scan width, with an accuracy of 50 microns. The ship project invested in Geomagic Studio software to capture, store and display the resultant point cloud data (Note: the software, while sophisticated, was exceptionally expensive to buy and there were on-going costs associated with licensing fees that should be factored in when budgeting for such a project in the future. Other long-term costs included warranty renewals on the contact digitising and laser scanning hardware). The volume of data generated by the laser scanner necessitated the use of a powerful workstation-style computer with dedicated high specification graphics card.

The non-contact FaroArm LLP scanner worked by emitting a low-power laser swath. The laser bounced off of an object’s surface, with the reflections being picked up by an off-axis digital camera. The device and associated software were able to triangulate the position of the points because the laser emitter and camera locations were known. The system readily captured detailed surface geometry, but also created large files consisting of millions of points. The scanning of the scaled physical model was successful, as the surface was relatively smooth, dry and light in colour. Fine features, such as the position of the scarf joints and identification numbers in the model pieces, were clearly visible and recorded in great detail.

Limitations of the laser scanning system described above included object size and shape, with the limited reach of the scanning arm and necessity of line-of-sight access restricting the shape or complexity of candidate artefacts. However, objects that were too fragile to be contact digitised were often ideal candidates for laser scanning. Overall, laser scanning was a highly effective tool for capturing complex surface geometry, but one significant drawback was the lack of interpretation of the artefact. The recording process, while relatively rapid, required substantial post-processing and the need to still analyse or interpret the object. There were a limited number of relevant and applicable case studies examining the archaeological applications of laser scanning, but the situation will likely change as laser scanning (and contact digitising) become the established standard for the three dimensional documentation of artefacts and objects, including ship models (Barber, 2011: 16-17).

Documentation Results

The physical scale model was laser scanned in four stages, beginning with the partially completed planking shell, followed by scans of the complete model, and a scan of the separate bow section. All of the later laser scan data was incorporated into a single model, which was used as a starting point for the 3D advanced digital modelling efforts. All of the 3D digital data files referred to below are available on a data disc appended to this thesis. The data is available in a variety of formats, including .PDF, .WRP, .STL and .3DM formats.



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Current Triangles: 534,580
Selected Triangles: 0

Current Connections: 0
Pending Operations: 0
Locking Client: 0

X: 1991.380 [-1440.545; 550.835] mm
Y: 180.938 [-194.016; -13.077] mm
Z: 1215.511 [-1400.853; -185.342] mm

RAM: 6249 MB free / 8189 MB
Virtual: 14083 MB free / 16377 MB
```

Figure 136. Digital mesh model produced from laser scanning the interior surface of the assembled hull planking (through p16 and S16). Toby Jones.

The interior of the planking shell was laser scanned when the planking had been added up to the 16th strake on both sides (Figure 136) (File on DVD: 001_P16_S16_interior_hull_planking_final.pdf). Numerous localised distortions were visible, which largely disappeared upon insertion of the framing timber pieces. The completed model was then laser scanned in three phases, with the outer hull surface being laser scanned by Pat Tanner in May 2011 (File on DVD: 003_full_exterior_hull.pdf), with the author scanning the inner hull in September 2011 (File on DVD: 002_full_interior_hull.pdf). The exterior scan contained 112.8 million points, while the interior hull scan contained 15.6 million points. The separate bow section contained 3 million points (File on DVD: 004_bow_decimated.pdf). The three scans together contained 131.4 million points. At this point, the inner and outer hull laser scans were integrated, aligned and combined to form a single point cloud, which was then wrapped (surfaced with a polygon mesh) and edited to create a watertight solid (File on DVD: 005_Total_Hull.pdf) (Jones, Nayling & Tanner, 2013: 123). This new digital model of the physical scaled model was used in a variety of ways, including the creation of further scaled physical models and as a starting point for advanced digital modelling and reconstruction efforts.

The digital model of the 1:10 scale hull form model was decimated to reduce the file size and scaled to 1:30 (when compared to the original vessel). The resulting file was then sent to the MEC at Cardiff University as a .STL file. Two physical copies of the digital model were manufactured using Polyamide-12 nylon powder and laser sintering technology (Figure 137). The models were formed as single pieces, resulting in a ‘scaled model of the ship model,’ which measured 642mm long x 150mm wide. This model, although of fairly low resolution, still had discernible framing and planking strakes, and was useful as a readily portable model which could be taken to offsite lectures and meetings about the ship, with one of the copies being used as part of a travelling exhibit about the Newport Ship. Several 1:30 scale adult size human figurines were also manufactured, to help people understand the relative size of the model (Figure 138).

The digital point clouds of the model were converted into .3DM, .STL, and .3D PDF files, as well as the proprietary Geomagic .WRP (Wrap) format. The 3D .PDF files were useful as they could be readily shared with other researchers and easily accessed by the public using free .PDF viewing software. Archiving had become an area of increased focus as ever larger data sets were being produced. The ship project internally archived the laser scan data as .STL meshes which could be converted back into a point cloud. Unedited raw point cloud data, which was saved in .WRP file format, was not accepted for public archive deposition, but remained internally archived within the Newport Museum (for a discussion of open source data formats and archiving see Barber 2011: 15 (Barber, 2011), or review the guidelines on the ADS website (Archaeology Data Service, 2012b).

The model has encouraged public engagement by making the archaeological data visually accessible and readily understood. The use of scale model human figurines manufactured at the same scale as the various ship models has helped the visitors relate to the size of the original vessel. The model has always been on public display,

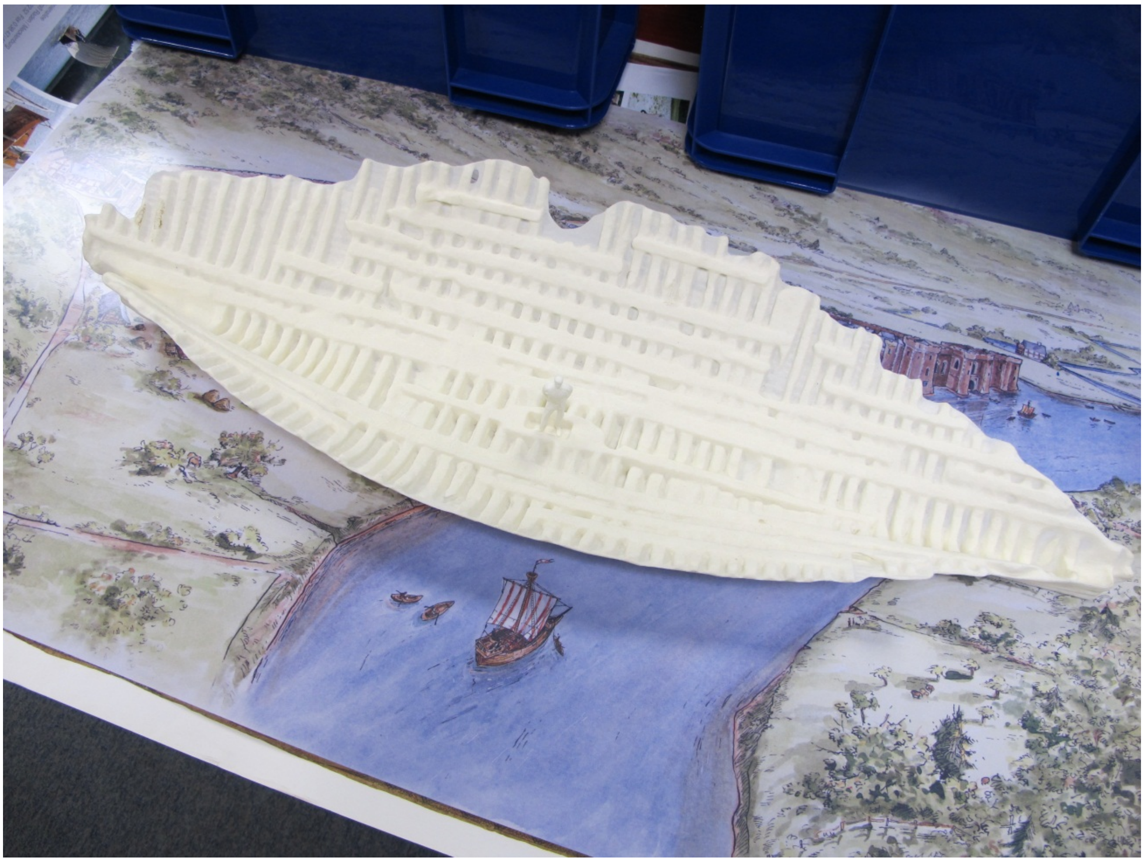

Figure 137. 1:30 scale laser-sintered model of the articulated hull remains. Bow is to the left. Toby Jones.

and the members of the public were able to see the progress made on successive open days and the watch the hull change shape as pieces were added. The physical hull form construction was, by design, publically accessible, and generated a considerable number of questions and observations. Visiting archaeologists and other specialists were shown the model and they offered detailed feedback. Some were even able to assist in identifying and placing disarticulated timbers.

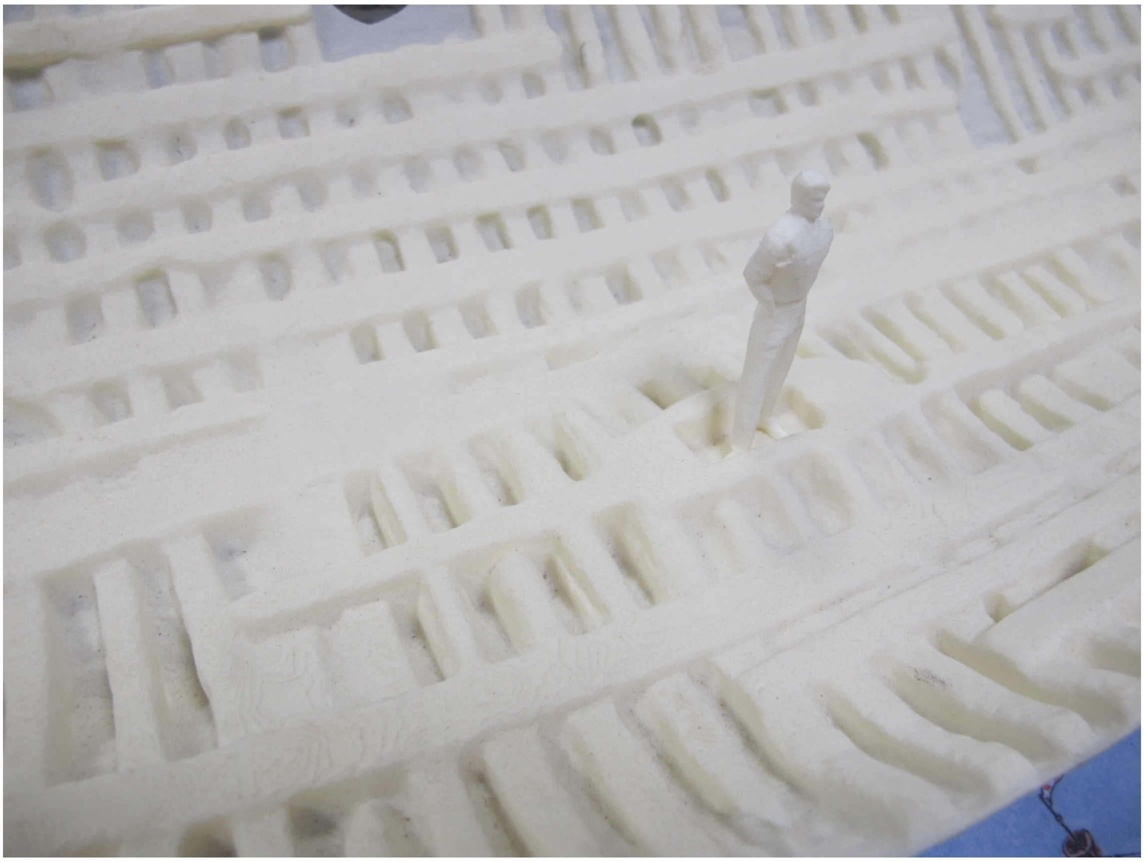

Figure 138. Detail of the 1:30 scale laser-sintered model of the articulated hull remains. Note the removable human figure standing in the mast step rebate. Bow is to the left. Toby Jones.

The use of Ribbands to Ghost in the Missing Areas of the Original Hull

The next phase in the hull reconstruction effort was to ghost in the missing portions of the model, in an effort to determine the overall size and form of the original vessel. This was accomplished by attaching thin and flexible plastic (polycarbonate or Plexiglas) ribbands to the model (Figure 139).

Figure 139. Author fitting plastic transverse ribbands to the model. Newport Museums and Heritage Service.

The installation of the ribbands began in September 2011, shortly after the laser scanning of the 1:10 scale hull model had been completed. These strips were extended along every existing fourth strake on the port and starboard side of the model. Transverse ribbands were threaded through the inter-frame spaces, under the stringers (and keelson in amidships area), near every fifth frame station (Figure 140).

Figure 140. Transverse ribbands were threaded through the inter frame spaces, under the stringers (and keelson in amidships area), near every fifth frame station. Newport Museums and Heritage Service.

In all cases, extra-long ribbands were added to the model, to be trimmed back at a later point (Figure 141). The process was a trial and error attempt to use the curvature present in the existing hull and project, by eye, reasonably faired curves into areas where the hull no longer existed (Figure 142).

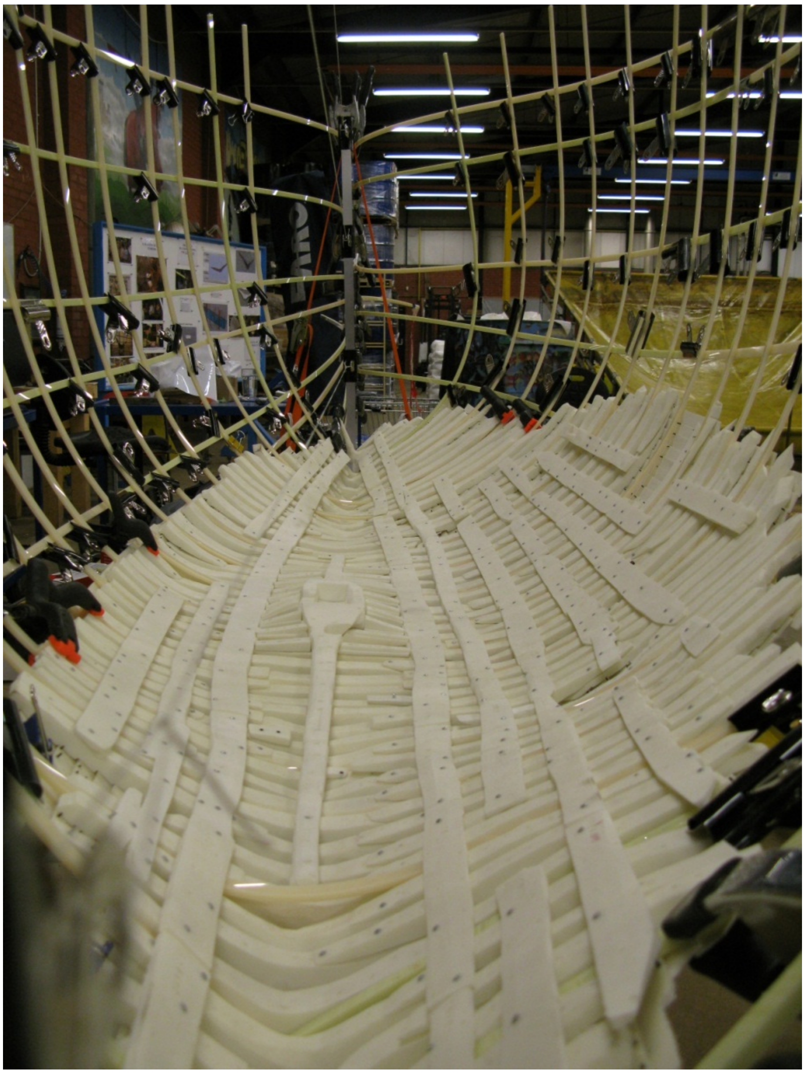

Figure 141. Transverse and longitudinal ribbands tentatively fitted to the model. The metal 'bulldog' clips were used during the fairing process and were later replaced with more permanent plastic cable ties. Toby Jones.

Figure 142. The plastic ribbands were aligned to existing strake runs on the outer hull surface of the scaled physical model. Newport Museums and Heritage Service.

As the sternpost was not recovered during the original excavation, a model stern post (arbitrarily the same width as the keel) with an adjustable rake was designed and tested. The two piece model consisted of a slotted keel extension, which attached to the extant keel and extended aft, and an upright post that fit into the slotted keel. The post could be moved fore and aft in the slotted keel section and pivoted forward and aft to accommodate various rake angles. The extended slotted keel worked well, but the first version of the sternpost, made from Polyamide-12 using selective laser sintering technology, was found to be too short (Figure 143).

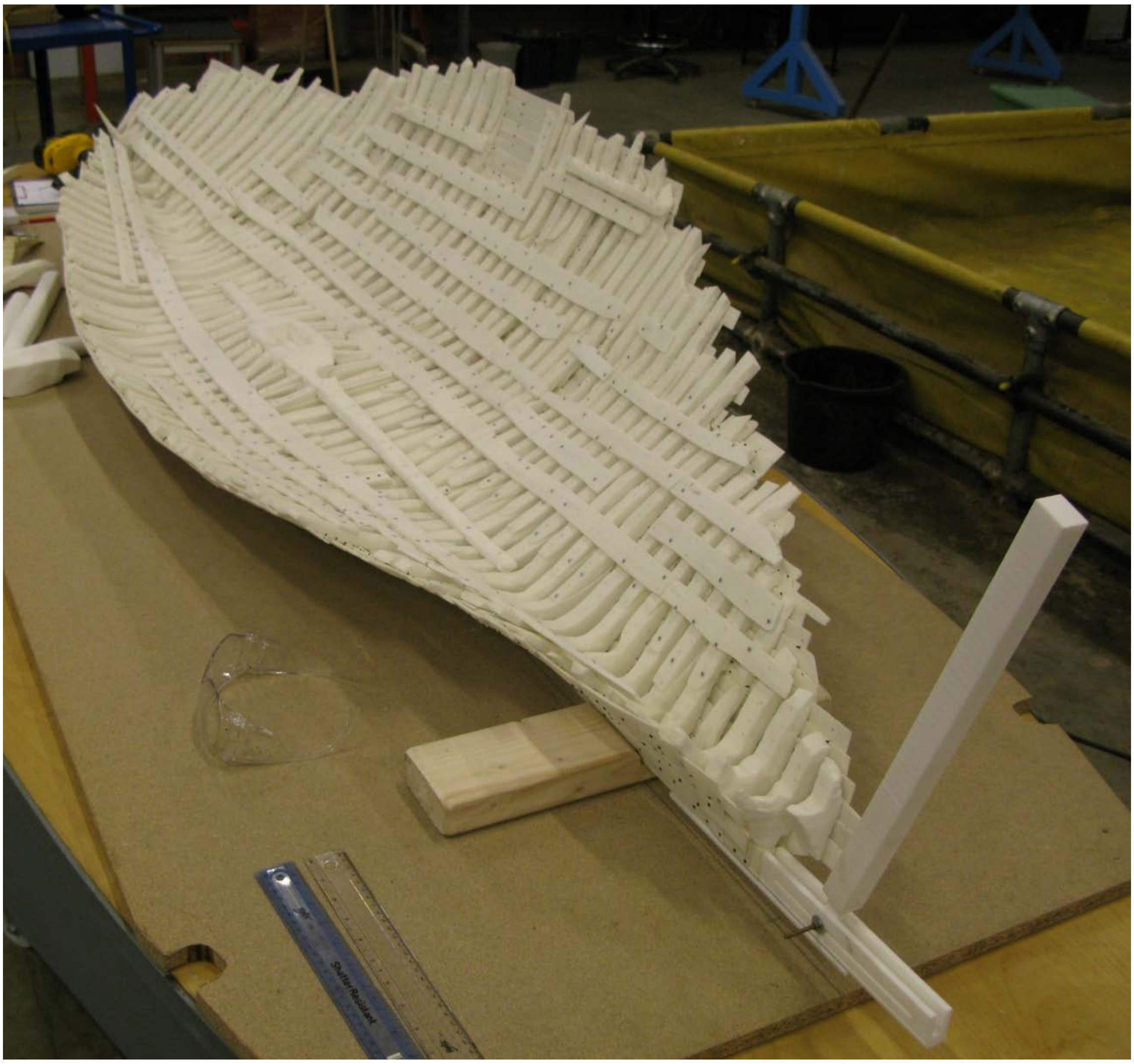

Figure 143. The first attempt to create a keel extension and adjustable stern post. Toby Jones.

Figure 144. The second attempt to create a suitable adjustable stern post. Toby Jones.

The next sternpost was identical in dimensions to the first, except for being taller (Figure 144). This version was made from polycarbonate, but was found to flex too much at the keel-stern joint. These adjustable systems were superseded by designing and installing a large solid polycarbonate sheet (Figure 145). A similar polycarbonate sheet was used in the bow area of the vessel. The polycarbonate sheets, measuring 900mm x 400mm x 22mm, were similar in thickness to the keel and fragment of the stem, and, being transparent, allowed ready comparison between strake runs on the port and starboard side of the vessel.

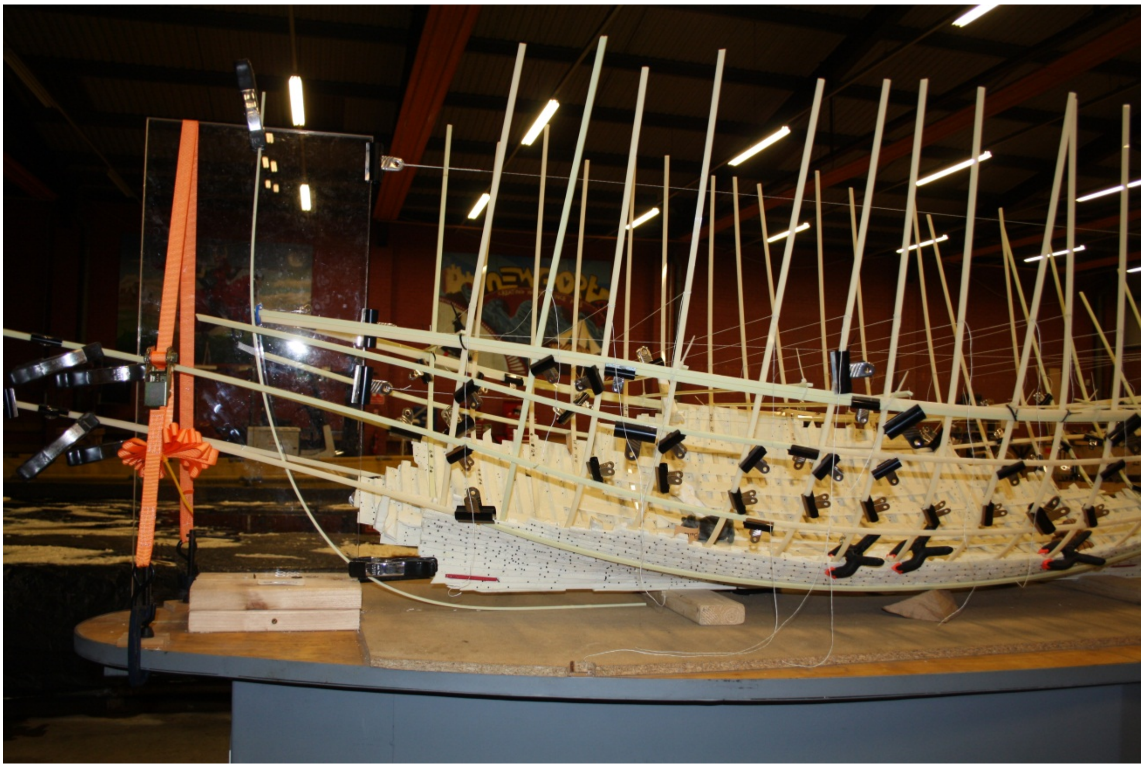

Figure 145. Polycarbonate sheets were eventually used in both the bow and stern to provide adjustable attachment points for the ends of the ribbands and planking strakes. Bow is to the left. Toby Jones.

The polycarbonate sheets served as attachment planes to which the ends of the strake runs could be attached tentatively using duct tape. The use of these large plates allowed for infinite adjustments to the position of the posts and their respective rakes. Dry-erase markers were used to draw on potential posts and planking termination points (Figure 146). These tentative lines were later reinforced by using steel flat stock clamped to the polycarbonate plates, providing firm anchor points for the ends of the ribbands.

Figure 146. Dry-erase markers were used to draw on potential posts and planking termination points. These tentative lines were later reinforced by using steel flat stock clamped to the polycarbonate plates, providing firm anchor points for the ends of the ribbands. Newport Museums and Heritage Service.

The experimental approach to ghosting in the missing areas began with basic research into investigating ideal material types to use as ribbands. A range of plastics, metals, composites and wood were all tested to see which material offered the best mix of strength, flexibility and rigidity. Plexiglas, various acrylic plastics and polycarbonates were tested, along with composites made from a layer of rubber sandwiched between sheets of aluminium. Plywood was considered as an alternative, but suitable lengths were not readily available.

Polycarbonate was found to be an ideal material, but it was not available in lengths exceeding 2.4m. A solution to this problem was found by carefully scarfing and gluing two strips together to obtain the necessary length (~3.0m to 3.5m) to run between the posts at the estimated sheer line. However, the scarf joints were weak, and care had to be taken not to break the lengthened ribbands. It helped to reinforce these areas using metal binder clips or bulldog clips. The ribbands measured 5mm x 10mm, and were fastened to the model using plastic cable ties. Where transverse ribbands intersected longitudinal ribbands on the model, they were fastened together using bulldog clips. After preliminary fairing work, these bulldog clips were replaced with plastic cable ties. Every intersection was eventually fastened together using a single small cable tie, with certain important intersections being locked or reinforced with two or more cable ties.

The transverse ribbands were installed first, and then restrained using a single ribband running forward and aft at the extreme top of the polycarbonate sheets. This allowed the transverse ribbands to extend vertically while still allowing fitting and adjustments lower down on the model. These control ribbands were later removed as the lower ribbands were systematically clamped or tied together, creating a more rigid structure that would hold its shape. The two ends of the same ribband were sometimes temporarily tied together using fishing line. Attempts were also made to drill and tap the ribbands, in an effort to integrate them directly into the hull structure using the existing fastener holes, however the plastic ribbands were found to be too brittle, and shattered frequently.

The initial attachment of ribbands to the model and polycarbonate plates assumed that the vessel was originally double ended with a straight raked stern post and a curved stem. The curved stem was based on the perceived slight curvature present in the fragments of the stem that were recovered. No evidence of the stern post was recovered, but there was an assumption that a medieval clinker-built vessel of this large size and late date would have had a stern-mounted rudder and therefore a straight raked sternpost. The initial angle of the straight raked sternpost was determined by looking at contemporary archaeological and iconographic evidence.

Close parallel archaeological evidence showed that the Aber Wrac’h 1 model had a sternpost rake of 65 degrees (measured by the author), while the Baltic Copper Wreck had a stern post angle of 70 degrees (based on unpublished drawings seen by the author). The early 15th century Drogheda wreck had and angle of 72 degrees, while the later carvel built *Mary Rose* and San Juan vessels had stern post angles of 73 degrees and 69 degrees respectively (Tanner, 2013: 144, McElvogue, 2009: 88, Loewen, 2007: III-144). A figure of 70 degrees was chosen as a starting point, as it fell midway between the other contemporary sternpost angles (subsequent research was to show the probable presence of a transom stern, however estimating the sternpost angle was still a useful and relevant exercise). An adjustable transom stern was designed and attached to the model (Figure 147).

Figure 147. The transom stern fitted to the physical scaled model. Toby Jones.

The position of the sternpost/keel joint was determined by running fair curved ribbands from the lower strakes of planking aft into the missing areas and recording where they naturally intersected with the polycarbonate plate. A similar technique was used in the bow, with ribbands curving upwards and twisting slightly out as they intersected the polycarbonate sheet. The lower strakes of planking and their associated ribbands generally ran straight and level, terminating into the posts with little or no rising. The upper strakes, however, displayed more rising and flaring, but still ran in a fair curve to the rebates on the post.

This real world modelling exercise led to a basic tentative minimum physical reconstruction, with the sheer ending at the top of the last surviving strake (S35) on the starboard side. At this point no attempt was made to add castles, super structure, decks or other any internal structure. Longitudinal ribbands on the port and starboard side were compared and adjusted by eye before the bulldog clips were replaced with plastic cable ties. The end product represented a reasonably fair hull form which served as the beginning point for a new phase of advanced digital modelling.

Advanced Digital Modelling

The next phase in the modelling process involved simultaneously working with the digital and physical hull form models. This was an interactive process where data and measurements would be taken from one model and compared or applied to the other model, and vice versa. The goal was to create a digital version of the hull form model that could be modified, faired and eventually fully reconstructed (both minimally and capitally) within a digital work space using CAD software (a process explained in full in Pat Tanner's 2013 article on the Drogheda Boat (Jones, Nayling & Tanner, 2013: 123-130, Tanner, 2013: 137-149). The results of the digitally modelling efforts would be compared against the basic physical hull form model and also used to create reconstruction drawings and lines plans.

The polygon mesh, created from the laser scan of the 1:10 scaled physical hull model, was used as a starting point for a digitally-based hull form modelling approach. This work was commissioned by the Newport Medieval Ship Project and was undertaken by Pat Tanner, and was supported by grants from CyMal: Welsh Museums, Archives, and Libraries Innovation and Development Grant Project No. 2012-m-027-023, along with the Arts and Humanities Research Council, Newport City Council, The Friends of the Newport Ship, and the University of Wales Trinity Saint David (The advanced digital modelling methodologies and process developed by Pat Tanner will form part of his PhD thesis at the University of Southampton in the UK).

The freeform closed polygon mesh of the physical solid model was initially imported into Rhinoceros3D version 5.0 modelling software and oriented to the standard horizontal work plane, with the keel being level and floor of the vessel/inboard face of the keel parallel with the horizontal work plane. Curves were projected on to the mesh at every fifth frame station and along every fourth strake. These curves were faired using the curvature analysis tool in Rhinoceros3D. Areas of localised and global distortion in the mesh model were noted, with a substantial amount of starboard twist in the bow and stern (measuring 4.2° and 8.4° respectively). These problems were eventually rectified by twisting the mesh in the opposite direction.

The next step was to study the existing scantlings from different areas within the hull in detail and extrapolate averages, which could then be applied to missing areas of the hull. The extant plank widths at every fifth frame station were measured, and this data was used to calculate overall average plank widths at each selected frame station and eventually create an estimated sheer line height (Jones, Nayling & Tanner, 2013: 124).

A preliminary sheer line was created using a combination of the average plank widths projected along a faired section curve at every fifth frame station. As starboard strake 35 was the highest recovered, this number of strakes was used at other frame stations to effect an evidence-based minimum reconstruction. By projecting 35 equal widths at each respective frame station, and drawing curves connecting the frames at selected strakes, a network of curves representing the hull form was created.

With a tentative sheer line in place, attention was turned towards the ends of the vessel. The surviving fragments of the stem post, although badly fragmented, revealed that the vessel had a curved stem, at least in the lower part of the bow. This curve was projected along the existing data in a faired curve up to the tentative sheer line, as determined by the average hull planking sections.

The stern was not recovered during the excavation, while a large part of the stem had been removed in antiquity. Initial estimates of the stem and stern location, based on the narrowing of framing timbers in the bow and stern, suggested that several more metres of hull was lying outside of the confines of the cofferdam. In order to determine the likely location of the stern (and stem) post, the overall plank lengths along each strake were measured and a minimum, a maximum and an average plank length were recorded. This data was then used to create a probability box, or likely range, for the length of the final plank on each strake. This probability box was projected aft from the forward part of the last extant plank scarf joint. It was thought that the stem or stern would likely pass through this area (Jones, Nayling & Tanner, 2013: 124). This process was repeated on each strake, with a series of probability boxes stacked on top of each other. It was assumed that the shipwrights would not have used an exceedingly short length in this area as it would have presented difficulties in bending the short length to match the hull curvature, whereas a longer plank could be more easily handled.

The probable angle of the sternpost, as mentioned above, was based upon parallel archaeological evidence and relevant iconography. An aft rake of 70 degrees was settled upon, and a model sternpost was fitted at this angle within the aft probability boxes. With the posts tentatively in position, the frame station (section) and strake (longitudinal) curves were faired and a simplified surface fitted. This surface represented a smooth and faired outer hull form. At this point, the twists in the mesh model were eliminated by transforming the affected areas until they lined up with the faired surface.

An attempt was then made to transfer the modifications that were made to the digital model over to the scaled physical model. The physical scaled model was, for the first time, firmly attached to the modelling table and the aforementioned starboard twist in the bow and stern was largely removed by using clamps, screws and braces to force the physical model into a more correct shape (Figure 148). It was clear that there was still a minor amount of lateral distortion or twist in the bow and stern of the physical scaled model, probably caused by the lack of posts to anchor the ends of the planking strakes to, as well as the lack of framing to provide shape control. To try and eliminate it completely, the large polycarbonate plates in the bow and stern were used as anchor points. Duct tape was used initially to temporarily hold the ends of the ribbands in place. Later, holes were drilled through the polycarbonate sheet to provide anchor points for cable ties, which were used to firmly hold the ends of the ribbands, once there correct position had been determined.

Figure 148. The physical scaled model was firmly attached to the modelling table and the starboard twist in the bow and stern was largely removed by using clamps, screws and braces to force the physical model into a more correct shape. Toby Jones.

Vertical measurements were then taken at the points where the longitudinal and section ribbands intersected on the digital model (vertical measurement from the working plane). These dimensions were used to modify the position of the ribbands on the physical scaled model (Figure 149). The controlled distortion (twisting) of the physical model and alignment of the ribbands had the effect of bringing the digital and physical models into close agreement, with the physical model beginning to approximate a fair original hull form. This iterative process helped to refine the hull form shape in a controlled and measureable way. The digital modelling process was validated by checking the digital curves against the physical model ribbands. The real world constraints imposed on the physical model were useful reality checks against which the digital model could be assessed. The final physical scaled model of the Newport Ship was created through an iterative process that relied on the simultaneous utilisation of digital and physical modelling methodologies (Figure 150).

Figure 149. Final fairing of the model was achieved by comparing corresponding measurements on the port and starboard sides of the model. Newport Museums and Heritage Service.

Figure 150. The completed 1:10 scale physical hull form model of the Newport Medieval Ship with ribbands ghosting-in the missing areas of the hull. Toby Jones.

Similar approaches on other projects

Several other ship reconstruction projects have recently been using variations and derivations of the physical and digital modelling processes mentioned above. The Prince's Channel Wreck reconstruction project has utilised a combination of digital solid modelling, additive manufacturing, and more traditional paper and card modelling to reconstruct a fragmented hull form. Similar techniques were used by the Norwegian Maritime Museum to reconstruct the Sørenga 7 shipwreck. In terms of documentation and modelling methodologies, the closest parallels to the Newport Ship Project are the Drogheda wreck reconstruction project, and the on-going Doel Kog reconstruction effort. The following section provides brief summaries of these projects and their respective methodologies.

Prince's Channel Wreck

The Prince's Channel Wreck (also known as the Gresham Ship) was discovered in 2003 in the Thames estuary in the United Kingdom. The remains of the late 16th century AD vessel consisted of several major pieces, including a portion of the bow and several large fragments from the port side. These disarticulated fragments were raised intact and recorded using a total station. The resulting 3D digital data was then used by Thomsen to create a single physical composite model, in order to create a set of hull lines and reconstruct the original hull form (Thomsen, 2010).

The forward part of the model, comprising the bow, forward most framing timbers and stem, was digitally modelled from the total station data and created using selective laser sintering at a 1:10 scale (Thomsen, 2010: 55-56). Shape data from the other fragments (and individual timbers) was extracted from the total station data and used to create traditional 2D projections and printouts, which were affixed to wood or cardboard. These blanks were overlaid with the projection and then physically shaped to make a 3D model of each piece. These pieces were then fastened together into the larger original fragments and placed within an adjustable framework containing all of the major recovered sections of the hull in physical scaled form. This model was then modified and adjusted, using wooden ribbands as guides, until damaged and missing areas were ghosted in and a reasonable hull form was achieved. This scale model was then recorded with a total station and a set of lines extracted (Thomsen, 2010: 93-94).

Norwegian Maritime Museum – The Sørenga 7 shipwreck

The lapstrake hull of the Sørenga 7 vessel was discovered in Oslo, Norway in 2006, and dendrochronologically dated to after 1665. The excavated hull remains were digitally recorded and selectively digitally modelled. Like the Prince's Channel Wreck reconstruction methodology, the team at the Norwegian Maritime Museum created a composite physical scale model, with the framing created using additive manufacturing technology, and the planking created by printing the plank shape onto paper and affixing this to card. The resulting model was documented using a contact digitiser and a set of lines created, suitable for traditional publication (Figure 151). The digital set of lines from the physical reconstructed hull form were subsequently analysed using the Rhinoceros3D Orca Marine plugin (T. Falck 2014, pers. comm., 5 May).

Figure 151. Composite scaled physical hull form model of the late 16th century Barcode 6 shipwreck at the Norwegian Maritime Museum. The 1:5 scale model was created using a combination of laser sintered framing and hand-cut cardboard planks. The same methodological processes used on the Barcode 6 shipwreck were used to record and model the Sørenga 7 vessel. Toby Jones.

Drogheda Boat Recording, Modelling and Reconstruction

The Drogheda Boat, a well-preserved 16th century lapstrake vessel, was excavated, disassembled, and raised from the River Boyne in Ireland in 2007. The timbers from the vessel were digitally documented, with these records being used to create digital solid models of each part of the hull. The digital models were physically made using additive manufacturing technology. The resulting parts were assembled into a 1:10 scale hull form model (Schweitzer, 2012: 225-231). The physical model was laser scanned and a set of faired hull lines created for use in hydrostatic and hydrodynamic calculations. The resulting data was used to help reconstruct the rig of the vessel and estimate hypothetical load capacity and sailing characteristics (Tanner, 2013: 137-148).

The Doel Kog and the Roskilde Wrecks

Several other archaeological ship recording and research projects, including the Doel Kog and the Roskilde ships (Viking Ship Museum in Roskilde, Denmark), are beginning to experiment with digital solid modelling and additive manufacturing technology to produce reconstructions. The Doel Kog project is currently modifying some of the digitally produced 3D records in order to create digital solid models, which are in turn being made using additive manufacturing technology (Figure 152). The project is in the early stages of this work, but there are plans to assemble a scaled physical model of the Doel Kog hull remains based on the contact digitising and digital and physical solid modelling of the entire ship timber assemblage. Similar experimental work is currently underway at the Viking Ship Museum, where the use of ‘Direct Digital Manufacturing’ is being trialled alongside the traditional cardboard modelling techniques for the building of experimental ship reconstructions (Ravn, 2012: 316).

Figure 152. The first batches of additively manufactured scaled model parts from the Doel Kogge project. Toby Jones.

Chapter 6: Conclusions

The Potential of Digital Documentation and Modelling Approaches in Nautical Archaeology

This thesis, while primarily focussed on the digital recording and modelling methodologies developed at the Newport Medieval Ship Project, has also traced the development of traditional nautical archaeological recording and modelling over the last two centuries. The inclusion of numerous case studies has helped to place the recording methods used and developed during the Newport Ship Project into a broader context, and illustrates how the project has been influenced by other major nautical archaeology projects. In turn, the section of the thesis covering the growth of digital recording shows how the Newport Ship project has directly influenced subsequent projects.

The digital research and reconstruction methodologies presented in this thesis represent a stage of development at a given point in time. Given the nature of fast-changing digital technologies like laser scanning and CAD modelling, it is likely that new documentation tools will be available in the near future. As new tools become available, new methodologies will need to be developed or modified to aid in the effective application of technology to archaeology. However, the underlying philosophy of documentation will likely remain unchanged. The requirement for accurate, comprehensive and versatile 3D data will become a standard. Innovation will likely come in the form of increasingly affordable technology that is ever more accurate and portable.

One of the tangible products of the development of digital recording at the Newport Medieval Ship Project has been the creation, by the author, of the Newport Ship Timber Recording Manual, which has served as a training guide and reference manual for Newport Ship project staff. Relevant sections of the manual have been adopted by other nautical archaeological projects, ensuring continuity in templates and layering.

The possibility also exists to apply the contact digitising technology (and digital and physical solid modelling methodologies) to previously studied sites, in an effort to extract more information. The conserved remains of ancient vessels can be digitised, modelled and digitally reassembled prior to undertaking the actual reassembly of the physical remains. If adequate pre-conservation drawings exist, 3D/digital or otherwise, it may be possible to identify and quantify any shrinkage or distortion. Custom-made cradles and display spaces can also be designed based on the documentation and modelling of the conserved material.

The scale and scope of the digital recording undertaken at the Newport Ship Project has proven the viability of this technology and methodology for documenting large and diverse assemblages of waterlogged archaeological remains. There will also undoubtedly be opportunities to apply contact digitising, digital solid modelling and scaled physical solid modelling to archaeological finds beyond those of a nautical nature. Although previously used primarily on waterlogged wood assemblages, digital documentation methodology, in the form of contact digitising, has the potential to be utilised across the archaeological spectrum. As the range of sophisticated recording tools available to archaeologists continues to increase, care should be taken to ensure that proper training in both archaeological method and theory keeps pace (To paraphrase Fred Hocker, ‘a well-trained expert with a pencil, paper and tape measure will trump an idiot with the latest digital technology every time’). It is important to recognise that the varying levels of technology used to record archaeological material are simply a means to an end. However, digital approaches to nautical archaeological recording and modelling are seemingly here to stay.

The following section will examine the impact of the revolution in hull documentation that the Newport Ship Project represents. The final sections of this thesis will explore the future potential of digital documentation by looking at how technological innovation will affect *in situ* documentation and post-excavation documentation of nautical archaeological remains.

Digital documentation and the Newport Ship: The production of a trustworthy and versatile dataset

Through the use of digital documentation, The Newport Ship project has created a primary data set of unparalleled detail and accuracy. It is the first large (measured in 1000s of timbers) archaeological ship timber recording project to have created a 3D digital data set describing the recovered hull timbers. All of these drawings and associated records have been digitally archived in open source formats and made freely accessible to anyone with a computer and internet connection.

For the first time, it is possible for another archaeologist to easily access and download all of the primary 3D drawings and ship timber models at full scale. They can then independently attempt to analyse and/or reconstruct the vessel using the exact same primary source data in its original, unaltered state and at full resolution. This is the exact same raw data that the project’s own archaeologists used to create their reconstructions. Using this data, any researcher can investigate or challenge the original interpretation on any level, from a detail as small as an individual fastener or inscribed line to the reconstructed lines of the original hull form. This has not been possible before.

To help illustrate the point, one can look back at previous marine archaeological projects and assess the accessibility and utility of the original site record. For example, is it possible to go back to the Skuldelev ships archive, access the original full-scale timber records, and attempt a re-analysis or reconstruction? Even if it is possible, is it practical or affordable to attempt this? Is there enough detail present in the publications or timber catalogues to make an independent attempt at reconstruction? The point is not to criticise the work of the previous archaeologists, just to demonstrate the advantageous aspects of new methods of capturing, storing and disseminating the basic details of a digitally recorded ship find.

It is neither practical nor affordable to publish a traditional ship timber catalogue containing scaled drawings of all the Newport Ship timbers. By publishing the timber catalogue digitally as 3D vector graphics files, we have created a dataset of unparalleled detail and utility, readily accessible and open to infinite interrogation.

This data set contains much new knowledge and may hold the key to answering new research questions. When looking at the master composite files or hull form reconstructions, is a system of geometric hull form control visible? Are there clues about the design of the vessel hidden in the minutiae of tiny additional nail holes, or in the patterning of inscribed lines recorded across the hull? The ability to order and view all of the timbers displaying the desired features, at any chosen scale, will prove to be an increasingly powerful analytical tool, and aid in our understanding of how and why ships were designed and constructed.

It may be possible to test or examine areas of the reconstructed hull, comprising the digitally recorded and modelled components, using software like ORCA Marine and finite element analysis. This research may determine if there were any inherent weaknesses or hidden flaws in the design and construction of the ship.

Future generations of scholars will be able to readily access a vast and versatile Newport Ship timber catalogue, and compare this with other digitally derived (as well as traditional) data sets. Assuming in the future that additional contemporary ships will be discovered and digitally recorded, one can envision being able to import typical hull planks from several vessels into a single file, making analysis and comparison convenient.

The trustworthy reconstructions that have been created using the accurate Newport Ship primary data can help provide a better understanding of the capabilities of late medieval merchant vessels operating in Western Europe. This information can be used by historians to flesh out economic details of trade routes and determine contemporary navigation capabilities, as well as contributing to our general understanding of the changes in society mirrored by the changes in shipbuilding.

The Future of *In Situ* Documentation

Nautical archaeologists today have a range of tools and techniques to choose from when excavating the remains of ships found in terrestrial settings. Numerous factors must be considered when selecting the most effective and efficient documentation methodologies. The two basic phases of documentation, during the initial excavation and during the post-excavation research phase, should be considered together, as decisions made during the initial documentation will directly influence research objectives and practices in the second phase of detailed recording. Archaeologists should consider a variety of possible recording methods, and chose the most appropriate.

A flexible and open-minded approach to selecting a recording methodology is necessary, given the unique nature of each set of hull remains. Factors that need to be considered include the extent and condition of the remains, issues of access, finances, available time, weather or adverse environmental conditions, available equipment, and availability of staff with the necessary expertise or relevant experience. The decision to retain or discard the remains after initial excavation work will also influence the level and type of recording selected.

In anticipation of the next major terrestrial nautical archaeology find, it can be useful to think about the best ways to record waterlogged hull remains found on a typical terrestrial site. If the Newport Medieval Ship had been found today, what would be the ideal methodology to document the *in situ* remains of the vessel? If the same ship was disassembled and raised, what would be the best way to document the individual timbers? If money and time constraints were set aside, what would the ideal documentation programme look like?

If the hull remains of the Newport Medieval Ship had been found today, the excavators would probably rely on high resolution digital documentation technology, including total station survey, laser scanning, and digital photography and videography to document the *in situ* hull remains. A series of laser scans could be made of the entire site, capturing the initial shape of the vessel and position of any disarticulated material. Following removal of the loose timbers and cleaning of the hull, a second phase of laser scanning could commence. Additional laser scans could be taken at selected intervals, in order to document the shape and structure of the vessel as it was being dismantled. A minimum of three laser scans would be needed to show the post deposition *in situ* shape state of the inner hull, framing, and outer hull. Because the laser scanner relies on line of sight to capture surface geometry, the scanner would have to be moved to several different vantage points, to ensure comprehensive coverage. However, all of the individual scans could be combined to create a single point cloud for each stage of the documentation.

The ability of the modern laser scanners to incorporate colour information into the point cloud data helps to create a readily understandable 3D visual image of the site. The use of such laser scanners would replace the more traditional utilisation of stereo photogrammetry. Global site layout and general geometry of individual timbers could be readily extracted from the 3D point cloud in CAD software, either through manually tracing lines along edges and around fasteners or by using automatic surfacing and section commands available within the relevant software.

One of the key philosophical differences between laser scanning and contact digitising is the lack of interpretation present in the former. Although the laser scanner might be ideal for capturing accurate geometry or *in situ* shape data on a global level, it may not be possible for the device to register certain fine features, like scarf joints or fastener holes. It might be necessary to augment the digital data set produced using ‘broad-brush’ laser scanning with selected point data generated using a total station, which gives the operator the ability to deliberately record only that 3D point data which is deemed significant, as opposed to the laser scanner, which captures all the surface texture data that is visible. Given that both data sets are digital and contain simple coordinate data, it is possible to readily merge the data sets into a single CAD file, with a layering system to help differentiate the data sets. A useful check against the digital documentation of the *in situ* hull shape would be the manual acquisition of selected direct measurements, which could be compared to the digital data set.

The selective (or comprehensive) use of a total station to document highly complex areas of an excavated hull would be an ideal method for simultaneously measuring and interpreting whilst in the field. If detailed recording (in the form of contact digitising) was included in the post-excavation phase of the project, then the insertion of at least three stainless steel control points (wood screws) into the visible faces of the *in situ* timbers would aid in the digital reassembly of the wireframe records and solid models. Each control point would be labelled and its position recorded using a total station. The label would stay attached to the control point all the way through the post-excavation digital recording phase, where its position would be documented with a contact digitiser and the point labelled in the CAD software programme.

Such a method was used during the recovery of the bow timbers of the Newport Medieval Ship in a separate excavation in April 2003. By using exact coordinates to align the modelled timbers with the point cloud framework created by the total station, an accurate digital model of the site could be recreated. The use of the Termite plugin for Rhinoceros3D would help to ensure the fast and accurate transfer of point data from the total station directly in the Rhinoceros3D CAD software.

Hiring a total station is undoubtedly cheaper than hiring a laser scanner, and would likely be the ideal way to record *in situ* hull remains, especially if time was not a factor. If only one advanced survey/documentation tool was available, a total station, because of the ability to discriminate (and, therefore, provide interpretation) when taking coordinate points, would probably be the best choice. Artefact and environmental sample locations could be quickly and easily plotted in 3D as they were uncovered. Additional benefits include smaller file sizes that can more easily be processed and converted into something useable in the field. A laser scanner can rapidly collect a tremendous amount of surface data, but the lack of interpretation will result in a considerable amount of post-processing to separate the valid and superfluous data. The point clouds produced by laser scanners are still useful, and can provide frameworks into which solid models and wireframes of individual timbers can be manually fitted. A belts-and-braces approach would see both techniques, laser scanning and total station survey, used during an excavation, ensuring maximum primary data capture.

High resolution digital photography (and videography) is another valuable *in situ* documentation tool in the field. High level plan view digital photography of a site at several stages would be useful when identifying and coding timbers prior to removal. The photographs can be used to create a quick and accurate 2D site plan, which can then be laminated and used in the field. This system has been used to great effect on the Barcode wrecks in Oslo, Norway, where time pressures dictated a rapid approach to documentation, coding and removal of the various ship timbers from within the confines of an active construction site (Vangstad, 2012: 305-324).

Using a series of overlapping 2D digital photographs it is now possible to create and disseminate 3D digital models of a site. The development of inexpensive digital stereo photogrammetry programmes, like Agisoft Photoscan, has enabled the creation of 3D surface models of sites both above and below water. Legacy data sets (individual digital photographs from previously constructed 2D photomosaics) can be effectively reprocessed in order to create a 3D site plan. It is even possible to capture stills from a digital video and use these images as the basis of a 3D surface model. The resulting point clouds can be incorporated into a site plan in 3D GIS programmes, aiding in the comprehension of complex shipwreck sites.

Obviously, as new digital tools become available for *in situ* documentation of ship finds, they will need to be evaluated for suitability before full scale use on site. It might be necessary to trial the new technology alongside existing methods, and compare the results, as was done during the early recording trials for the Newport Ship Project. Dissemination of the results should be a priority, with research networks like the FRAUG group encouraging members to test and develop new tools and techniques.

The Future of Post-Excavation Documentation

Regardless of the survey and documentation methods used in the field, the post-excavation phase of detailed recording can currently best be accomplished using a contact digitiser like a FaroArm, or one of the recently developed ‘armless’ hand-held contact digitisers like the *Créaform 3D* HandyPROBE, which allow the user to collect coordinate point data with fewer mechanical restrictions. The use of contact digitisers and CAD software like Rhinoceros3D, to document ship timbers, has grown substantially in the last decade. Numerous nautical archaeological projects are now using the technology to efficiently create accurate 3D digital records. Contact digitisers are currently the preferred tool for documenting archaeological ship timbers.

Contact digitisers are ideal tools to record 3D shape information, along with fastener holes, toolmarks and inscribed lines. They are especially suited to efficiently recording material that is linear, specifically ship planking and framing. The five metre long recording stations used on the Newport Ship Project were ideal for facilitating this work. However, there are limitations or disadvantages that crop up when trying to record material that is non-linear or oversize. These obstacles can be overcome by recording a timber in sections and moving the digitiser, or timber, in order to reach the unrecorded areas of the timber, although this is time consuming. The high initial cost of the equipment is another disadvantage, with many digitisers being potentially cost-prohibitive, although the savings in time and labour costs would not be insignificant. Time saved during the initial documentation phase would need to be considered in the context of any additional time spent during the post-processing phase. Such post-processing for data gathered with a contact digitiser was found to be minimal on the Newport Ship Project. However, a substantial amount of post-processing time was needed when editing data acquired via the laser scanner. Whilst laser scanners were quick to capture data in the field, the post processing could take hours. However, the increased utility of the digital data sets created many opportunities for organising, analysing and disseminating the data which would not have been possible with more traditional analogue records.

The Newport Medieval Ship Project represents the first large scale application of this technological concept, with the project exploring the possibilities and limitations of creating digital models to aid in the understanding of the complex assemblage. The Newport Medieval Ship reconstructions that have been attempted would not have been possible without the abovementioned application of contact digitising to record the individual elements of the hull. The creation of hull form master composite files also facilitated the creation of the final hull form reconstructions by checking and ordering the massive data set.

The Future of Digital Modelling and Analysis

There are exciting opportunities ahead for the increasing use of sophisticated digital modelling of original hull form performance. The preliminary set of lines taken from the physical 1:10 scale model of the Newport Ship was faired and turned into a digital model representing the minimally reconstructed original hull form and then analysed in the Rhinoceros3D modelling software plug-in called Orca3D, which was used to determine the hydrostatic and hydrodynamic characteristics of the modelled hull form (Figure 153). The use of the abovementioned advanced digital modelling software has allowed archaeologists to accurately characterise the estimated capabilities, capacity, and seaworthiness of the original vessel (Jones, Nayling & Tanner, 2013: 123-130). The advanced digital modelling work by Tanner promises to revolutionise the visualisation and archaeological analysis of reconstructed ancient hull forms (Tanner, 2013: 137-149). The use of software programmes like Orca3D allow archaeologists to input, test, and then easily change numerous parameters relating to the hull form. The ability to quickly modify and test myriad aspects of the reconstruction are of great importance and utility, and hitherto only possible using powerful computers or by hand using laborious equations. The ability to perform numerous sophisticated iterations will change the way we analyse ancient hull forms.

A three-dimensional digital data set is the fundamental starting point for advanced modelling and analysis. Digital solid models, master composite models, and physical solid models are some of the outputs made possible by the digital documentation of the individual ship timbers that comprise the hulls of ancient boats and ships. The creation of an accurate digital primary record of each timber’s geometry and construction features has enabled the establishment of a variety of research tools to study the construction and design of ancient vessels in general and the Newport Medieval Ship in particular.

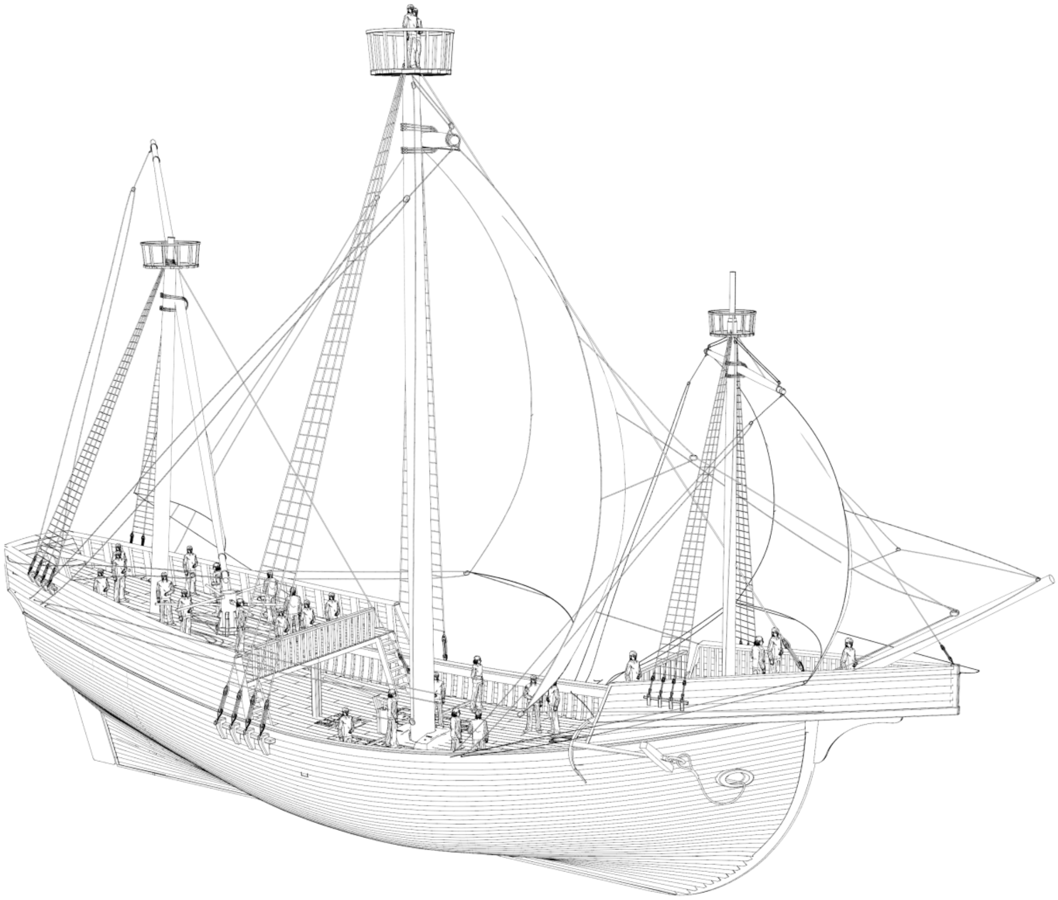

Figure 153. Perspective view of the minimum reconstruction of the Newport Medieval Ship. The minimum reconstruction consists of a single deck, castles, and three masts. Pat Tanner.

A series of minimum reconstruction drawings of the Newport Medieval Ship have been created using the shape data taken from the physical scaled model as a starting point. The individual digital solid models and wireframe drawings of each timber in the master composites have been fitted to this shape in order to create a detailed digital solid model of the original vessel.

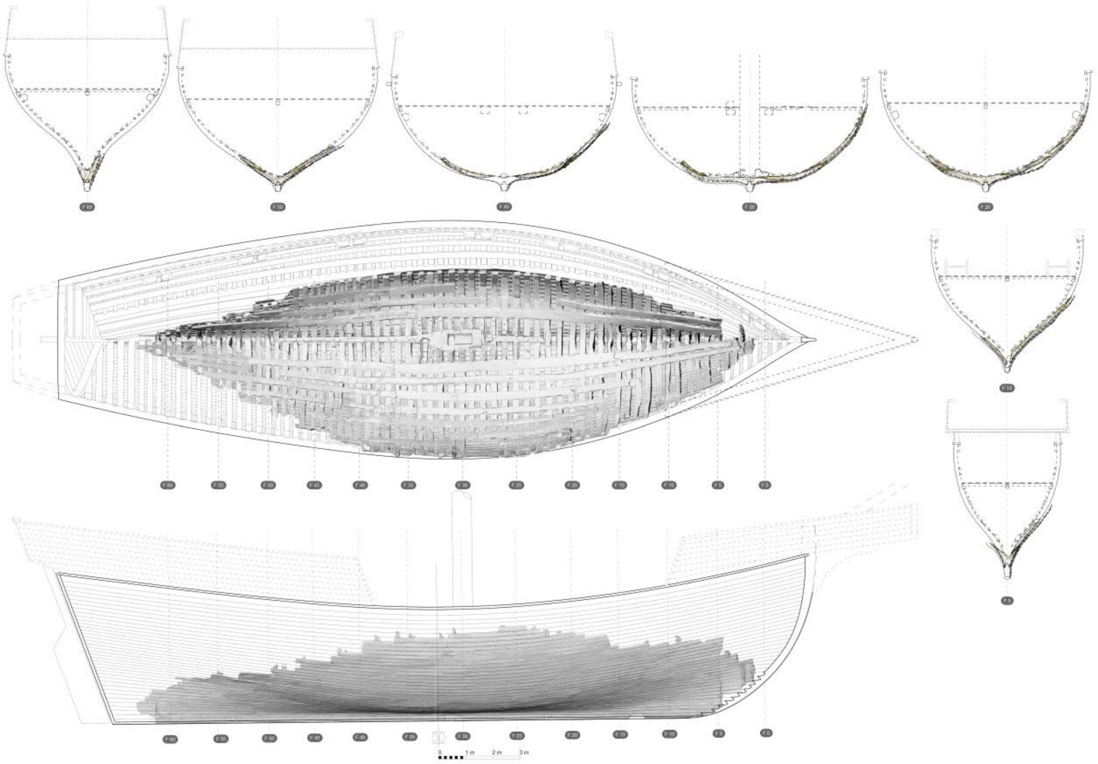

Figure 154. The advanced digital modelling has allowed for the formulation of detailed drawings showing a laser scan of the completed physical model fitted into the reconstructed hull form, graphically contrasting the recovered elements of the hull against those that were missing. Pat Tanner.

The minimum reconstruction models have, in turn, been used as a starting point for creating capital reconstructions of the Newport Ship. The advanced digital modelling has allowed for the formulation of detailed drawings showing a laser scan of the completed physical model fitted into the reconstructed hull form, graphically contrasting the recovered elements of the hull against those that were missing (Figure 154). Other drawings show the relationship between archeologically recovered material and those parts of the vessel that have been reconstructed from indirect evidence with varying degrees of confidence (Figure 155). A principal or capital reconstruction of the vessel was created by building on the minimum reconstruction data (Figure 156).

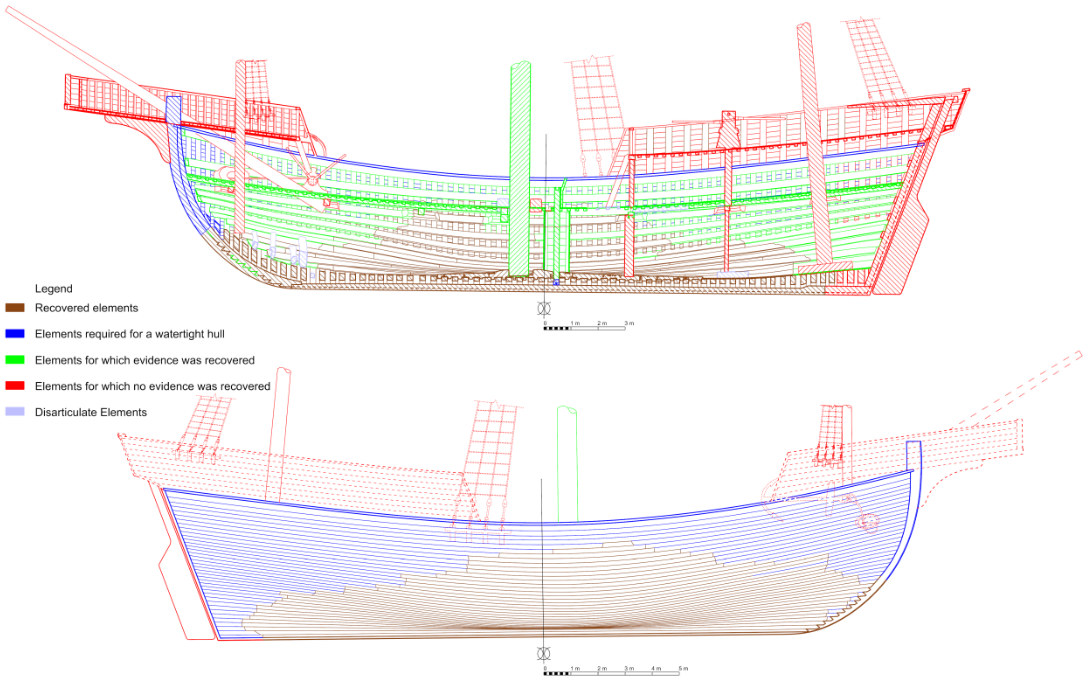

Figure 155. Drawing showing the relationship between the archeologically recovered material and those parts of the vessel that have been reconstructed from indirect evidence. Pat Tanner.

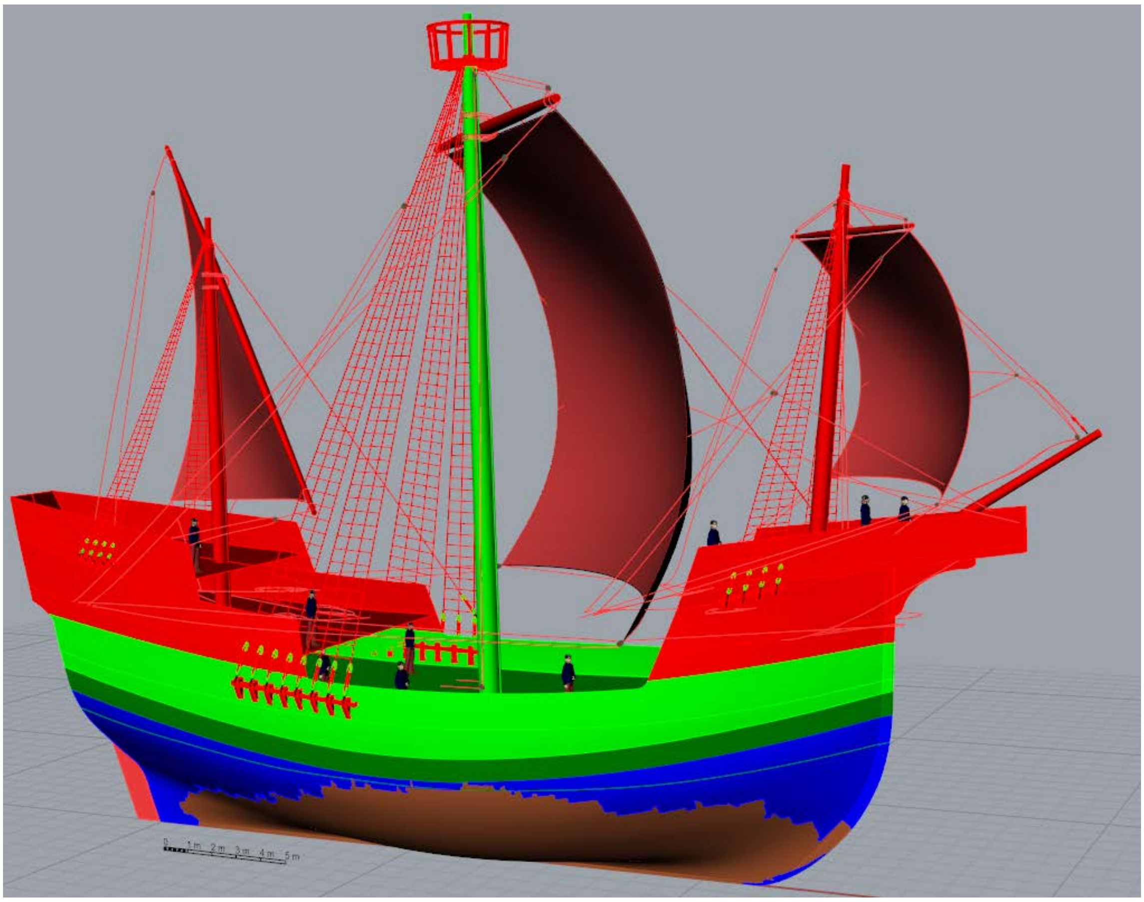

Figure 156. Capital or principal reconstruction of the Newport Medieval Ship. The reconstructed vessel has two full decks, three masts, and a total displacement of 393 tons. Pat Tanner.

Digital documentation and analysis are powerful tools to answer question about construction sequence and especially design considerations. The creation of digital master composites, with their organised schematic layouts of adjacent timbers used in the hull, allow for the trained archaeologist to detect patterns amongst even the smallest details. Full-scale detailed three-dimensional records of adjacent timbers can be brought together side-by-side for analysis. Fine details might be lost on scaled drawings, while working with full size 2D tracings would be cumbersome and, in many cases, impractical. Having a three-dimensional digital record of the timber or timbers is like having the actual timbers laid out in front of you, with the added advantage that the visually displayed digital data has been interpreted, distilled, and categorised by the archaeologist.

For example, recent analysis of the outer hull master composite revealed the presence of a series of drain holes along starboard strake S19, important features which had remained undetected by archaeologists for over 10 years. The significance of these holes was only realised by recognising their location and spacing on the outer hull master composite drawing and comparing this to the location of the framing timbers. The ability to highlight certain layers and hide others has become a powerful tool for visually detecting patterns and determining fastening patterns and construction sequence. While the master composite files can be difficult to open on standard computers, it is likely that they will become increasingly accessible in the next few years. Digital files of individual timbers and those covering discrete sections of the ship are currently readily opened by most computers.

The reshaping and fitting of the digital models of the individually recorded timbers into a reshaped hull form has opened up new analytical possibilities. The use of transparency and visualisation commands in the render settings have allowed for variable amounts of detail to be displayed, with the resulting ability to simultaneously see a complete timber as well as see through to an adjacent one. The effect is like slowly flying in a miniature helicopter through the reconstructed ancient vessel, with the ability to stop, hover, pan around, and zoom in and out of areas of interest. This is a powerful tool for examining the relationship between timbers and their mutual fasteners, as well seeing the inscribed lines and tool marks on the surface of the models. Linear measurements can be taken from any point within the model to any other point, along with angle measurements, and volume measurements on closed mesh solids. One can simultaneously view the shape and complexity of the entire reconstructed vessel while contemplating the interpretations of the archaeologists who recorded the fine details on each piece. Construction sequence can be deduced by looking for blind or hidden fasteners, and reverse engineering sections of the vessel, in an effort to understand the ship as a whole. Experimental animations can be created that can test the perceived construction sequence.

Additionally individual components of the ship's equipment or sections of the hull can be modelled in high levels of detail for visualisation or analytical purposes. These models are useful for helping the public, as well as specialists, to understand complex devices like the ship's pumps (Figure 157). Such digital models can also be used for animations and as the basis for creating interactive digital activities for children and adults.

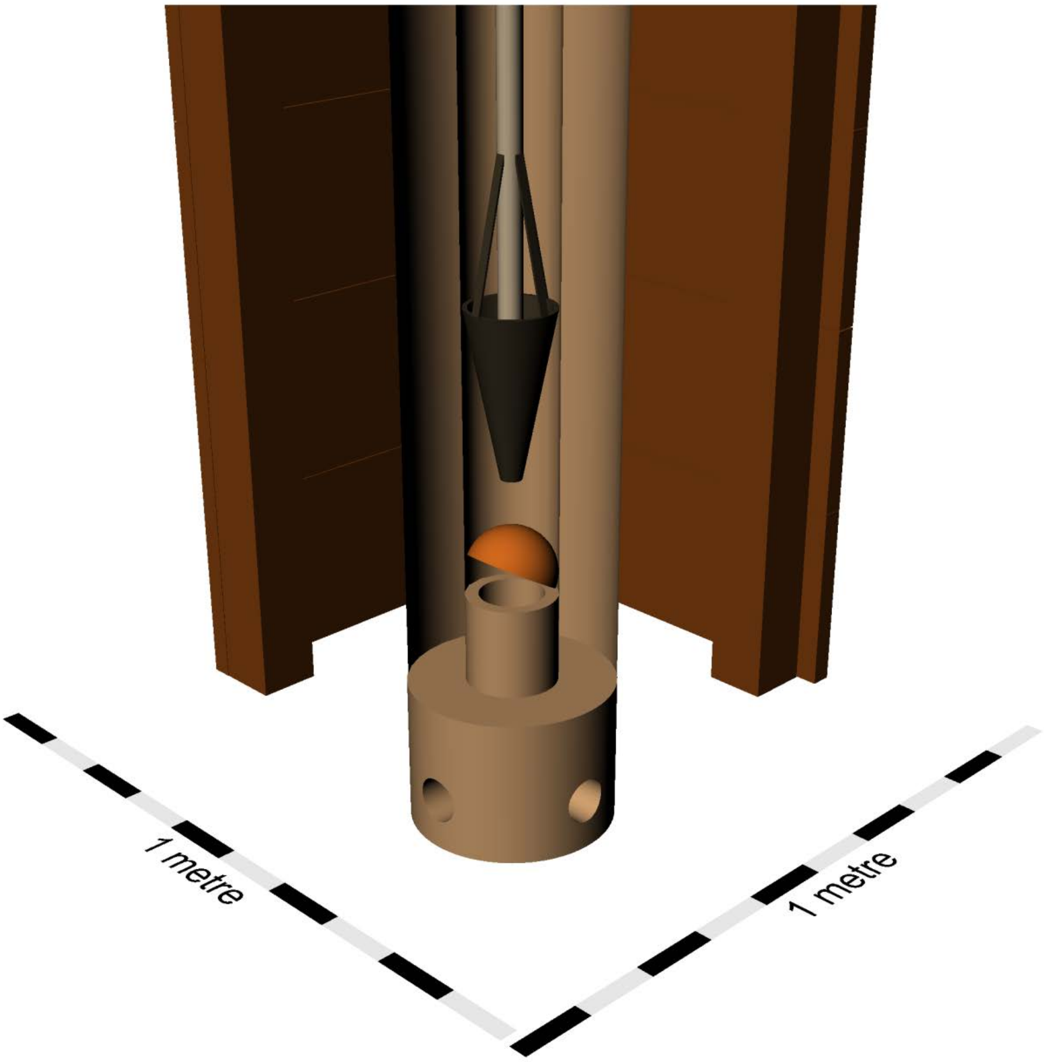

Figure 157. Screen capture of the 3D digital model of the composite bilge pump found during the ship excavation. There were at least four pump locations in use at various times during the ship's working life. Toby Jones.

The digital records of individual timbers can also be examined for clues about forest management and timber conversion. The detailed recording of wood grain, especially knots and end grain, in a wireframe drawing, can be analysed and used to reconstruct the parent tree, helping to inform about conversion practices. For example, side branches that have been trimmed and healed over can be indicative of active management of the forest resources long before the harvest of the timber.

Information from multiple timbers can be collated and an image of medieval forest management deduced. The angle of these side branches can be measured and the crown or base of the tree determined. Additionally, the size and shape of the crown can be determined if enough side braches are documented, allowing for the reconstruction of the type of canopy, leading to insights into the nature of the woodland.

It is also possible to use recorded wood grain to provide additional supporting evidence that two individual timbers came from the same parent tree. On the Newport Ship, both STRS1_2 and STRP1_2 are stringers that lie parallel with, and adjacent to, the keelson/maststep (although separated by the braces). These two stringers are nearly identical in length and are in almost mirrored positions along the centreline axis. When the digital wireframe drawings of these two timbers are combined and oriented, it is possible to trace the wandering centre of the tree, as indicated by the grain pattern, off of one timber and on to the next, suggesting that they were originally converted from the same tree. It would be useful to analyses these timbers using dendrochronology to confirm that they are from the same parent tree (as well as examining other possible mirrored stringer pairs).

This type of analysis would have been difficult, if not impossible, using unwieldy 2D full-scale tracings. On scaled drawings, the wood grain, visible as sections, would be nearly invisible at the reduced scale. It is clear from these examples that the 3D digital nature of the recorded data allows for readily understandable and convenient comparisons.

Conclusion

The Newport Medieval Ship Project has served as a test bed for the development of 3D digital approaches for the documentation and modelling of nautical archaeological finds. The successful refinement of a credible alternative form of documentation, in the form of 3D contact digitising, has enabled a wide range of digital and physical research outputs. The development of a successful digital solid modelling methodology has been used to create scaled physical parts of each structural hull component. Innovative additive manufacturing technology, specifically laser sintering, has been used to convert the digital solid models to accurate physical solid models. Tangible outputs, including the scaled physical research model of the original hull form, have been complemented and enhanced by extensive and detailed corresponding digital data sets.

The digital nature of the produced data sets, coupled with appropriate interpretation, has allowed for widespread public access to and dissemination of the accumulated knowledge, through a series of reports, articles, and an extensive online archive. Additionally, the digital and physical 3D reconstructions are designed to serve as guides for the eventual reassembly, reshaping and display of the conserved vessel. The digitally produced data sets have a wide variety of potential uses beyond purely academic research.

The 3D digital reconstructions can be used in the creation of animations and games, and as key parts of future interactive museum displays. These 3D reconstructions can be used to illustrate the central role of ships in medieval society by providing engaging and readily understandable content to the general public. The various 3D digital and physical reconstructions of the Newport Medieval Ship will be used together to increase public awareness of this unique and internationally significant archaeological find.

For example, the British Museum is currently hosting the Vikings: Life and Legend temporary exhibition which includes the reconstructed Roskilde 6 long ship. The exhibition incorporates video animations of the vessel which are based on models created using Rhinoceros3D software. Such animations, showing construction sequence and the ghosting-in of missing areas, will allow the visitor to gain a better understanding of the otherwise fragmented physical remains.

Such models can also be posted online, enabling widespread access outside the confines of a museum. The availability of the project archive online will enable researchers around the world to freely access all of the pertinent records relating to the excavation and post-excavation research phases of the project. Hosted by the Archaeological Data Service and made available on the Internet, the project archive contains over 12,500 digital files. These files have been formatted to ensure longevity and organised by record type (photograph, site drawing, 3D model etc.) as well as being searchable using timber identification numbers.

The deposition of this data set represents a milestone in the development of accessible archaeological archives for so-called ‘big data’ projects. The original creation of the bulk of the data set in a digital format, and the conversion of the extant analogue data sets into digital forms, has enabled the archive to be hosted online. The archive has been constructed within an open access framework model, with the hosted data being made available in perpetuity.

The existence of research networks, like FRAUG, has enabled archaeologists to provide feedback and constructive criticism, in an on-going effort to create ever more robust and useful methodological tools for documenting and reconstructing ancient vessels. The networks serve as forums where the latest templates, toolbars, and layering systems can be widely shared. The creation of a common visual language for the documentation of ship's timbers has made it possible for nautical archaeologists to understand, in detail, the fine and complex construction features on a variety of vessels.

The rapid growth of contact digitising and digital solid modelling in nautical archaeology has created a growing digital data set of different vessels. As the number of digitally documented and modelled ship (and ship timber) finds increases, so does the potential for meaningful and efficient comparative research and analysis. The use of logical and thoughtful digital recording and modelling methodologies, as presented here, will help to ensure that the raw digital data from a well-recorded ship find will remain accessible, useful and relevant into the future.

Finally, the digital documentation and modelling methodologies presented in this thesis are consciously transparent and have been freely shared to all interested parties. It is hoped that future advancements in the field of digital documentation in nautical archaeology will follow suit, allowing for ever more thorough documentation of ancient hull remains and the subsequent creation of comprehensive archives/catalogues. The resulting data can be used to craft convincing reconstructions, helping us to understand the role of ships and shipbuilding in wider society.

References

Archaeology Data Service (ADS), 2012a. *Guidelines for Depositors.* Archaeology Data Service. Available from: http://archaeologydataservice.ac.uk/advice/depositCreate2#section-depositCreate2-2.2.1.OverviewOfPreferredDataFormats.pdf, [viewed 28 May 2014].

Archaeology Data Service (ADS), 2012b. *Preparation of Files for Deposit with the ADS.* Archaeology Data Service. Available from: http://archaeologydataservice.ac.uk/attach/depositCreate2/depositor_guidelines.pdf,[viewed 28 May 2014].

Auer, J. and Maarleveld, T., 2013. *Skjernøysund Wreck 3: Fieldwork Report 2011.* Esbjerg: Maritime Archaeology Programme University of Southern Denmark

Barber, D., 2011. *3D Laser Scanning for Heritage: Advice and Guidance to Users on Laser Scanning in Archaeology and Architecture.* Swindon: English Heritage Publications

Bass, G. 1975. *Archaeology Beneath the Sea: A Personal Account*. New York: Walker and Company.

Bischoff, V., 2010. Hull Form of the Oseberg Ship. *Maritime Archaeology Newsletter from Denmark*, vol. 25, pp. 4-9

Bischoff, V. and Jensen, K., 2001. The Ship. In: A. Sørenson, V. Bischoff, K. Jensen and P. Henrichsen eds., *Ladby: a Danish ship-grave from the Viking Age.* Roskilde: Viking Ship Museum, pp. 181-248

Broadwater, J., 2012. *USS Monitor: A Historic Ship Completes its Final Voyage.* College Station: Texas A&M University Press

Brøgger, A. and Shetelig, H., 1971. *The Viking Ships : Their Ancestry and Evolution.* Oslo: Dreyers Forlag

Bruce-Mitford, R., 1974. *The Sutton Hoo Ship Burial: Volume 1, Excavations, Background, the Ship, Dating and Inventory.* London: British Museum

Brunning, R., Nayling, N. and Yates, A., 1998. The Boat. In: N. Nayling ed., *The Magor Pill Medieval Wreck.* York: Council for British Archaeology, pp. 45-111

Bruseth, J. and Turner, T., 2005. *From a Watery Grave: The Discovery and Excavation of La Salle's Shipwreck, La Belle.* College Station: Texas A&M University Press

Carver, M., 2005. *Sutton Hoo : A Seventh-Century Princely Burial Ground and its Context.* London: British Museum

Cederlund, C., 2006. *Vasa I: The Archaeology of a Swedish Warship of 1628.* F. Hocker ed., Sweden: National Maritime Museums of Sweden

Christensen, A., 1997. Oseberg Ship. In: J. Delgado ed., *Encyclopaedia of underwater and maritime archaeology.* London: British Museum, pp. 302-303

Civil War News, 2003. *Major Steps Taken in Conservation of USS Monitor.* Historical Publications Inc. and The Civil War News. Available from: http://www.civilwarnews.com/archive/articles/monitor_conserve.htm,[viewed 28 May 2014].

Coates, J., McGrail, S., Brown, D., Gifford, E., Grainge, G., Greenhill, B., Marsden, P., Rankov, B., Tipping, C. and Wright, E., 1995. Experimental Boat and Ship Archaeology: Principles and Methods*. International Journal of Nautical Archaeology*, vol. 24, no. 4, pp. 293-301

Cronyn, J. and Robinson, W., 1990. *The Elements of Archaeological Conservation.* London: Routledge

Crumlin-Pedersen, O., 1995. Experimental Archaeology and Ships—bridging the Arts and the Sciences*. International Journal of Nautical Archaeology*, vol. 24, no. 4, pp. 303-306

Crumlin-Pedersen, O., 1997. *Viking-Age Ships and Shipbuilding in Hedeby/Haithabu and Schleswig.* Roskilde: Viking Ship Museum

Crumlin-Pedersen, O., 2002. Documentation, analyses and dating. In: O. Crumlin-Pedersen and O. Olsen eds., *The Skuldelev Ships I: Topography, Archaeology, History, Conservation and Display.* Roskilde: Viking Ship Museum, pp. 49-68

Crumlin-Pedersen, O., 2004. Nordic Clinker Construction. In: F. Hocker and C. Ward eds., *The Philosophy of Shipbuilding: Conceptual Approaches to the Study of Wooden Ships.* College Station: Texas A & M University Press, pp. 37-63

Crumlin-Pedersen, O. and McGrail, S., 2006. Some Principles for the Reconstruction of Ancient Boat Structures. *International Journal of Nautical Archaeology*, vol. 35, no. 1, pp. 53-57

Crumlin-Pedersen, O. and Olsen, O., 2002. Archaeological fieldwork. In: O. Crumlin-Pedersen and O. Olsen eds., *The Skuldelev Ships I: Topography, Archaeology, History, Conservation and Display.* Roskilde: Viking Ship Museum, pp. 23-48

Crumlin-Pedersen, O. and Rieck, F., 1993. The Nydam Ships: Old and new investigations at a classic site. In: J. Coles, V. Fenwick and G. Hutchinson eds., *A Spirit of enquiry : Essays for Ted Wright.* Exeter: Wetland Archaeology Research Project Nautical Archaeology Society National Maritime Museum with the support of Fenland Archaeological Trust Somerset Levels Project, pp. 39-45

Crumlin-Pedersen, O. and Trakadas, A., 2003. *Hjortspring : A Pre-Roman Iron-Age Warship in Context.* Roskilde: Viking Ship Museum

Delgado, J., 1997. Nydam Boat. In: J. Delgado ed., *Encyclopaedia of underwater and maritime archaeology.* London: British Museum, pp. 300-301

Engelhardt, C. 1865. Nydam Mosefund 1859 – 1863. Copenhagen: G. E. C. Gad. Available from http://reader.digitale-sammlungen.de/en/fs1/object/display/bsb10361315_00013.html, [viewed 4 April 2015].

Evans, A., 1994. *The Sutton Hoo Ship Burial.* London: British Museum

Evans, A. and Fenwick, V., 1978. Chapter 1: Discovery, Excavation, and Recovery of the Remains, Part 2: Excavation, Phase II. In: V. Fenwick ed., *The Graveney boat : a tenth-century find from Kent : excavation and recording, interpretation of the boat remains and the environment, reconstruction and other research, conservation and display.* Oxford: British Archaeological Reports, pp. 7-16

Falck, T., 2013. *Documenting Archaeological Boat Finds Digitally in 3D.* Norwegian Maritime Museum. Available from: http://www.marmuseum.no/no/arkeologi/dokumentasjonslaboratoriet/Documenting+archaeological+boat+finds+digitally+in+3D.d25-SwJvMWa.ips, [viewed 28 May 2014].

Fix, P., 2007. *Doel (Doelse) Cog: Artifact Evaluation & Preliminary Conservation Planning ,Stabilization, Reconstruction and Display.* Brussels: Vlaams Instituut voor het Onroerend Erfgoed (VIOE) Flemish Heritage Institute

Gøthche, M., 1997. The Roskilde Ships. *Maritime Archaeology Newsletter from Roskilde*, vol. 8, pp. 3-8

Gøthche, M., 2002. The Roskilde Ships and the Documentation Technique. *Maritime Archaeology Newsletter from Roskilde*, vol. 19, pp. 16-17

Gøthche, M., 2006.The Roskilde Ships. In: Blue, L.K., Hocker, F.M. and Englert, A., eds. *Connected by the sea: Proceedings of the Tenth International Symposium on Boat and Ship Archaeology*. Roskilde, pp. 252-258

Grenier, R., Stevens, W. and Bernier, M., 2007. *The Underwater Archaeology of Red Bay: Basque Shipbuilding and Whaling in the 16th Century.* Ottawa: Parks Canada

Grille, A., 2013. *Rapport Final D'opération : Epave De l'Aber Wrac'h 1.* Bretagne: Association Avena

Gundersen, J., 2012. Barcode Project: Fifteen Nordic Clinker-Built Boats from the 16th and 17th Centuries in the City Centre of Oslo, Norway. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 75-80

Hocker, F., 2000. New Tools - for Maritime Archaeology. *Maritime Archaeology Newsletter from Roskilde Denmark*, vol. 14, pp. 27-30

Hocker, F., 2001. Projects Involving Technical and Natural Scientific Investigations at the Centre of Maritime Archaeology in Roskilde. *Maritime Archaeology Newsletter from Roskilde Denmark*, vol. 17, pp. 16-22

Hocker, F., 2003. *Faro Manual V.2.* Copenhagen: National Museum of Denmark

Institute for Archaeologists., 2008. *Standards and Guidance: Nautical Archaeological Recording and Reconstruction.* London: Institute for Archaeologists

Jones, T., 2005. Recording the Newport Ship: Using Three Dimensional Digital Recording Techniques with a Late Medieval Clinker-Built Merchantman. *Institute of Nautical Archaeology Quarterly Journal*, vol. 32, no. 3, pp. 12-15

Jones, T., 2008. Newport Medieval Ship Project Update. *Archaeology in Wales*, vol. 48, pp. 85-88

Jones, T., 2009a. The Newport Medieval Ship: Her Three-Dimensional Digital Recording and Analysis. *Skyllis Journal: Zeitshrift Für Unterwasserarchäologie*, vol. 9, no. 1, pp. 36-41

Jones, T., 2009b. The Three-Dimensional Recording and Digital Modelling of the Newport Medieval Ship. In: E. Laanela and J. Moore, eds. *Advisory Council on Underwater Archaeology Proceedings*. Toronto, pp. 111-116

Jones, T., 2013. *The Newport Medieval Ship Timber Recording Manual: Digital Recording of Ship Timbers using a FaroArm 3D Contact Digitiser, FaroArm Laser Line Probe and Rhinoceros3D Software, with Additional Sections on Digital Modelling and Metrical Data Capture.* Newport: Newport Medieval Ship Project

Jones, T. and Nayling, N., 2011. ShipShape: Creating a 3D Solid Model of the Newport Medieval Ship. In: F. Castro and L. Thomas, eds. *Advisory Council on Underwater Archaeology Proceedings.* Austin, pp. 54-60

Jones, T., Nayling, N. and Tanner, P., 2013. Digitally Reconstructing the Newport Medieval Ship: 3D Designs and Dynamic Visualisations for Recreating the Original Hull Form, Loading Factors, Displacement, and Sailing Characteristics. In: C. Breen, and W. Forsythe, eds. *Advisory Council on Underwater Archaeology Proceedings.* Leicester, 123-130

Jones, T., Nayling, N. and Tanner, P., Forthcoming. Physical and Digital Modelling of the Newport Medieval Ship Original Hull Form. In: Editors to be announced, *Proceedings of the 13th International Symposium on Boat and Ship Archaeology*. Amsterdam

Kocabas, I., 2012. Hull Characteristics of the Yenikapi 12 Shipwreck. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 115-120

Kocabas, U., 2008. *The `Old Ships' of the `New Gate', Vol. 1 Yenikap'Nin Eski Gemileri, Cilt I.* Istanbul: Yayinlari

Kocabas U., 2012a. The Latest Link in the Long Tradition of Maritime Archaeology in Turkey: The Yenikapi Shipwrecks*. European Journal of Archaeology*, vol. 15, no. 2, pp. 309-323

Kocabas, U., 2012b. Byzantine Shipwrecks at Yenikapi. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 107-113

Kocabas, U., 2015. The Yenikapı Byzantine-Era Shipwrecks, Istanbul, Turkey: a preliminary report and inventory of the 27 wrecks studied by Istanbul University. *International Journal of Nautical Archaeology,* vol. 44.1 pp. 5-38.

Krueger, B., 2010. 21st Century Steamboat Archaeology: Three Dimensional Digitalization of the Red River Artifact Assemblage. *Center for Maritime Archaeology and Conservation: News & Reports*, vol. 2, no. 2, pp. 36-38

Lemée, C., 2006. *The Renaissance Shipwrecks from Christianshavn: An Archaeological and Architectural Study of Large Carvel Vessels in Danish Waters, 1580-1640.* Roskilde: Viking Ship Museum

Lenaerts, T., Vermeersch, J., Haneca, K., Deforce, K., Van Camp, L., Seurinick, J., Rijmenants, S. and De Bie, M., 2011. *Kogge Rapportage 1: Internal Report on the Doel Kogge.* Antwerp: Flemish Heritage Institute and Archeologische Dienst Waasland

L'Hour, M. and Veyrat, E., 1989. A mid-15th Century Clinker Boat Off the North Coast of France, the Aber Wrac'H I Wreck: A Preliminary Report*. International Journal of Nautical Archaeology*, vol. 18, no. 4, pp. 285-298

L'Hour, M. and Veyrat, E. , 1994. The French Medieval Clinker Wreck from Aber Wrac'h. In: C. Westerdahl, ed. *Crossroads in ancient shipbuilding: Proceedings of the Sixth International Symposium on Boat and Ship Archaeology*. Roskilde, pp. 165-180

Loewen, B., 2007. The Square Tuck Stern: A Renaissance Innovation? In: R. Grenier, W. Stevens and M. Bernier eds., *The underwater archaeology of Red Bay : Basque shipbuilding and whaling in the 16th century.* Ottawa: Parks Canada, pp. III-132-III-148

Marsden, P., 1978. Chapter 2: Recording: Part 1: Preparing a measured drawing of the boat *in situ*. In: V. Fenwick ed., *The Graveney boat : a tenth-century find from Kent : excavation and recording, interpretation of the boat remains and the environment, reconstruction and other research, conservation and display.* Oxford: British Archaeological Reports, pp. 23-27

Marsden, P., 1994. *Ships of the Port of London: First to Eleventh Centuries AD.* London: English Heritage

Marsden, P., 2003: *Sealed By Time: The Loss and Recovery of the* Mary Rose. Portsmouth: The Mary Rose Trust.

McElvogue, D., 2009. The Hull. In: P. Marsden ed., *Mary Rose : your noblest shippe : anatomy of a Tudor warship.* Portsmouth: Mary Rose Trust, pp. 81-105

McGrail, S., 1992. Replicas, Reconstructions and Floating Hypotheses*. International Journal of Nautical Archaeology*, vol. 21, no. 4, pp. 353-355

McGrail, S., 2003. How Were Vessels Designed before the Late-Medieval Period? In: C. Beltrame, ed. *Boats, ships and shipyards: Proceedings of the Ninth International Symposium on Boat and Ship Archaeology*. Venice, pp. 124-131

McGrail, S., 2007. The Re-Assessment and Reconstruction of Excavated Boats. *International Journal of Nautical Archaeology*, vol. 36, no. 2, pp. 254-264

McKee, E., 1978. Chapter 2: Recording: Part 3: Recording Details of the Hull. In: V. Fenwick ed., *The Graveney boat : a tenth-century find from Kent : excavation and recording, interpretation of the boat remains and the environment, reconstruction and other research, conservation and display.* Oxford: British Archaeological Reports, pp. 35-46

McNeel, R., 2008. *Non-Uniform Rational B-Spline (NURBS).* Robert McNeel & Associates. Available from: http://4.rhino3d.com/4/help/Information/NURBS_About.htm, [viewed 28 May 2014].

Myrhoj, H., and Gøthche, M., 1997. The Roskilde Ships. *Maritime Archaeology Newsletter from Roskilde*, vol. 8, pp. 3-7

Nayling, N., 1998. *The Magor Pill Medieval Wreck.* York: Council for British Archaeology

Nayling, N., 2004. *Newport Medieval Ship Recording Trials: Comments on FaroARM and Tracing Methods.* Unpublished Report. Newport

Nayling, N. and Jones, T., 2012. Three-Dimensional Recording and Hull Form Modelling of the Newport (Wales) Medieval Ship. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 319-324.

Nayling, N. and Jones, T., 2013. The Newport Medieval Ship, Wales, United Kingdom. *International Journal of Nautical Archaeology*, vol. DOI: 10.1111/1095-9270.12053, [viewed 28 May 2014].

Nayling, N. and Jones, T., 2014a. *Newport Medieval Ship [Data-Set].* Archaeology Data Service. Available from: http://archaeologydataservice.ac.uk/archives/view/newportship_2013/, DOI 10.5284/1020898. [viewed 28 May 2014].

Nayling, N. and Jones, T., 2014b. *Newport Medieval Ship [Data-Set].* Archaeology Data Service. Available from:

http://archaeologydataservice.ac.uk/archives/view/newportship_2013/downloads_excavation.cfm?archive=movie , DOI 10.5284/1020898. [viewed 28 May 2014].

Nayling, N. and McGrail, S., 2004. *The Barland's Farm Romano-Celtic Boat.* York: Council for British Archaeology

Nestorson, M., 2004. *Reconstruction of the Technical Properties of the Gota Wreck. Report no. X-04/155.* Goteborg: Department of Naval Architecture and Ocean Engineering, Chalmers University of Technology

Nicolaysen, N., 1882. *The Viking-Ship Discovered at Gokstad in Norway.* Oslo: Alb. Cammermeyer

Parham, D., 2011. The Swash Channel Wreck. In: Castro, F. and Thomas, L., eds. *Advisory Council on Underwater Archaeology Underwater Archaeology Proceedings*. Austin, pp. 103-106

Pulak, C., Ingram, R. and Jones, M. 2015. Eight Byzantine Shipwrecks from the Theodosian Harbour Excavations at Yenikapı in Istanbul, Turkey: an introduction. *International Journal of Nautical Archaeology*, vol. 44.1 pp. 39-73.

Ranchin-Dundas, N., 2012. *Three-Dimensional (3D) Recording of Recovered Shipwreck: A General Presentation and Comparative Analysis of Digital Recording Tools Recently used in Nautical Archaeology, Along with a Case Study regarding the use of a C-Track to Record the Arles-Rhone 3 Shipwreck.* Esbjerg: University of Southern Denmark

Ravn, M., 2012.Recent Advances in Post-Excavation Documentation: Roskilde Method. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 313-318

Ravn, M., Bischoff, V., Englert, A. and Nielsen, S., 2011. Recent Advances in Post-Excavation Documentation, Reconstruction, and Experimental Maritime Archaeology. In: A. Catsambis, B. Ford and D. Hamilton eds., *The Oxford Handbook of Maritime Archaeology*. Oxford: Oxford University Press, pp. 232-249

Redknap, M., 1998. Reconstructing the Magor Pill boat. In: N. Nayling ed., *The Magor Pill Medieval Wreck.* York: Council for British Archaeology, pp. 129-142

Rice, W., 1824. XIII. Account of an Ancient Vessel Recently found Under the Old Bed of the River Rother, in Kent: In a Letter from William McPherson Rice, Esq. F.S.A. Late of the College of Naval Architecture at Portsmouth, Addressed to Henry Ellis, Esq. F.R.S. Secretary. *Archaeologia*, vol. 20, pp. 553

Rieck, F., 1994. The Iron Age Boats from Hjortspring and Nydam - New Investigations. In: C. Westerdahl, ed. *Crossroads in Ancient Shipbuilding: Proceedings of the Sixth International Symposium on Boat and Ship Archaeology*. Roskilde, pp. 45-54

Rieck, F., 1995. Institute of Maritime Archaeology – the beginning of maritime research in Denmark. In: O. Olsen, J. Madsen and F. Rieck eds., *Shipshape: Essays for Ole Crumlin-Pedersen on the Occasion of His 60th Anniversary, February 24th 1995.* Roskilde: Viking Ship Museum, pp. 19-36.

Rule, N., 1989. The Direct Survey Method (DSM) of Underwater Survey, and its Application Underwater*. International Journal of Nautical Archaeology*, vol. 18, no. 2, pp. 157-162

Schweitzer, H., 2012.Drogheda Boat: A Story to Tell. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 225-231

Soe, S., Eyers, D., Jones, T. and and Nayling, N., 2011. The application of Laser Sintering for archaeological model-making. In: P. Bártolo, ed. *Innovative Developments in Virtual and Physical Prototyping*. Leiria: CRC Press, pp. 757-762

Soe, S., Eyers, D., Jones, T. and Nayling, N., 2012. Additive Manufacturing for Archaeological Reconstruction of a Medieval Ship*. Rapid Prototyping Journal*, vol. 18, no. 6, pp. 443-450

Sørenson, A., Bischoff, V., Jensen, K. and Henrichsen, P., 2001. *Ladby : A Danish Ship-Grave from the Viking Age.* Roskilde: Viking Ship Museum

Starr, M., 1996. Measuring Mystic Seaport's Half-Model Collection the Electronic Way*. The Log of Mystic Seaport*, vol. 48, no. 3, pp. 69-72

Steffy, J., 1994. *Wooden Ship Building and the Interpretation of Shipwrecks.* College Station: Texas A&M University Press

Tanner, P., 2013. 3D Laser Scanning for the Digital Reconstruction and Analysis of a 16th-Century Clinker Built Sailing Vessel. In: C. Breen and W. Forsythe, eds. *2013 Underwater Archaeology Proceedings*. Leicester, pp. 137-149

Terve, A., 2002. Happiness is a 20 M upside-down Cog at Doel (Belgium). In: P. Hoffman, J. Spriggs, T. Grant, C. Cook, and A. Recht, eds. *Proceedings of the 8th International Council of Museums (ICOM) Wet Organic Archaeological Materials (WOAM) Conference*. Stockholm

Thomsen, C., 2010. *Reconstructing the Lines of the Princes Channel Ship.* Esbjerg: University of Southern Denmark

Tremain, B., 1978. Chapter 2: Recording: Part 2: Photography. In: V. Fenwick ed., *The Graveney boat : a tenth-century find from Kent : excavation and recording, interpretation of the boat remains and the environment, reconstruction and other research, conservation and display.* Oxford: British Archaeological Reports, pp. 29-34

Valsecchi, M., 2010. *2,500-Year-Old Greek Ship Raised Off Sicilian Coast.* National Geographic. Available from: http://news.nationalgeographic.co.uk/news/2008/08/080811-greek-ship.html,[viewed 28 May 2014].

Van Doorninck, F. 1972. Byzantium, mistress of the sea: 330 – 641. In Bass, G. ed., *A History of Seafaring Based on Underwater Archaeology*. London: Thames and Hudson, pp. 133-158.

Van Hove, R., 2005. *De Doelse Kogge(n) Maritiem Erfgoed Van Europees Formaat.* Antwerp: Archeologische Dienst Waasland

Vangstad, H., 2012.Development of an Adaptive Method for the Rescue of 15 Shipwrecks from a Construction Site in Oslo Harbour: Need for Speed. In: N. Gunsenin, ed. *Between Continents. Proceedings of the Twelfth International Symposium on Boat and Ship Archaeology*. Istanbul, pp. 305-311