# Large-volume photogrammetric deformation monitoring of the Bremen Cog

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**Key words**: *deformation; photogrammetry; accuracy; cultural heritage; ground control network*

**ABSTRACT**

This article will give an overview on the large-volume photogrammetric monitoring concept, the proposed analyzing methods on the geometric deformation estimation and results of a feasibility study of the conserved medieval ship "Bremen Cog" at the German Maritime Museum. The ship has a size of ~25m*8m*8m. Two main aspects of deformation have to be distinguished: rigid-body motion and the determination of strain. For the "Bremen Cog" size and kind of deformation are unknown. With knowledge from the Vasa ship monitoring at the Vasa museum in Stockholm, deformations of 1 mm within a year are detected. Therefore, the museum specified a deformation of ≥1mm to be estimated with the monitoring of the "Bremen Cog". The concept is based on a large-volume photogrammetric measurement. The measurements are referred to a ground control network which is established to the museums building structure and measured by a lasertracker network. For photogrammetry, reflective targets are glued to the ship which represent the object points to be monitored. Results are given for the ground control network with limitations induced by tides due to the museums location at the North Sea and for the photogrammetric measurements by a feasibility study. The findings of detectable deformation will be given with respect to the applied methods and the environmental conditions.

## I. Introduction

Long-term monitoring of conserved archaeological artefacts is an important issue in preserving their history and enabling their future presentation. Focusing on large-volumetric wooden artefacts, as historical ships, the monitoring can be separated into 1) conservation and preservation aspects, 2) geometric deformation estimation and analysis and 3) documentation and long-life retention.

Within the last decades digital monitoring of historical ships raised. (Colson, 2017) gives a review on the work on digital documentation of historical ships in Cultural Heritage within Europe. Laser scanning technology is applied to 3D ship reconstruction and analysis of hydrostatic and hydrodynamic characteristics of historical ships in Ireland and the United Kingdom (Tanner, 2013; Nayling *et al*., 2014). (Schofield et al., 2013) propose a real-time monitoring system based on total station and sensors placed on the hull of the Mary Rose, the warship of Henry VIII, exhibited in Portsmouth. Long-term monitoring is published from the Vasa in Stockholm, Sweden. (Jacobsen, 2003) refers to measuring system first established in the middle 1990s (based on a total station monitoring system) revealing movements of a millimetre per year. The data gives ability to long-term analysis and advanced mathematical modeling developments as it is published for the strain analysis by (Van Dijk *et al.*, 2016).

Geometric deformation estimation in general can be divided into issues of rigid-body displacement (motion) and deformation (strain, bending, torsion). A basic challenge for measurement concepts is given by the ability to separate both issues (Heunecke *et al.*, 2013). Displacement is strictly connected to the movement of a single point at different moments. Hence, the points to be monitored have to be identical and unique. Statistical tests are applied to the measurement data and its quality measure to allow for significance evaluation, e.g. of displacement given by coordinate differences. Strain analyses are standard approaches in geodesy or applied mechanics to enable predictions on deformation, referring to a segmentation of the object into parts of homogeneous deformation (Heunecke *et al.*, 2013; Van Dijk *et al.,* 2016). Typical approaches require same datum definition for all measurement epochs.

The estimation of deformation also relies on the choice of the measurement system with respect to the expected accuracy. For large-scale applications an overview is given in (Peggs *et al.*, 2009).

Focusing on the geometric deformation estimation and its analysis of the conserved medieval ship "Bremen Cog" at the German Maritime Museum, a photogrammetric monitoring concept is developed, prototypically implemented and evaluated.

## II. Medieval shipwreck "Bremen Cog"

The "Bremen Cog" is a medieval shipwreck presented at the German Maritime Museum in Bremerhaven, Northern Germany. The shipwreck from the 14th century was found in the River Weser in 1962 near Bremen during dredging works for the enlargement and deepening of the river bed. A dendrochronological analysis estimated the oak to 1378-1379, given a theoretical ship construction around 1380. Therefore, the ship dated from the Hanseatic League and made the find a crucial element for German maritime history.

The shipwreck was retrieved and stored at the German Maritime Museum to allow for a reconstruction which was conducted from 1972 – 1979. The reconstruction process intended the cog being the main exhibit for the museum. The cog was rebuilt in a building extension with three visitor floors that enable a good view on all parts of the vessel. Subsequently, a conservation treatment was conducted on the ship. Between 1981 and 1999 the "Bremen Cog" was submerged in a tank, enabling the conservation process using polyethylene glycol, a colourless and water soluble artificial wax. The first exhibition of the cog occurred in May 2000. But first movements were noticed one year later and a "reshaping" cradle was installed in 2006, its function is currently suspended.

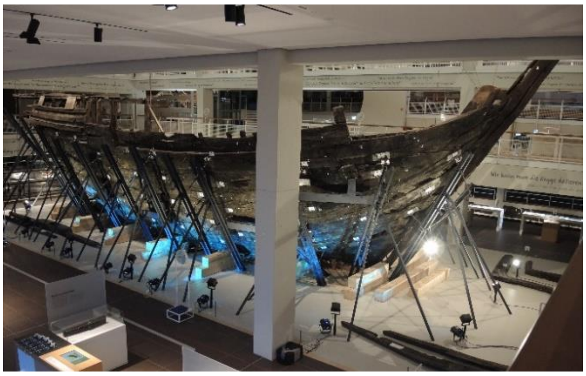

Figure 1. Medieval shipwreck "Bremen Cog" at the German Maritime Museum (side view from middle floor)

Figure 2. Medieval shipwreck "Bremen Cog" at the German Maritime Museum (view from upper floor)

The "Bremen Cog" has a size of ~25m*8m*8m and is on display at the German Maritime Museum (Figure 1, Figure 2). The influence of the relative humidity on the cog and its subsequent changes within time periods is unknown by now. Impact of daylight are eliminated by an automatically controlled sun protection system and UV filters on the windows.

The museum is located at the mouth of the river Weser to the North Sea and is situated on a small peninsula within the old harbour area, therefore directly influenced by the tides (Figure 3). By now, the tidal influence on the museum building and the cog is unknown. The impact of tides on geometric changes of comparable objects are known by the harbour authority in the order of 1-2mm. The resistance of changes on building structures or the ability to recover to its original state are unknown. In general, the water level inconsistently changes within a range of 5m between low and high tide.


Figure 3. Location of the museum (upper left: location within Germany; lower left: location at North Sea; right: location within harbour area of Bremerhaven)

## III. Monitoring concept

### A. *Objectives for the geometric monitoring*

For the "Bremen Cog" size and kind of deformation are unknown. From experiences of the Vasa ship monitoring in Stockholm, deformations of a millimeter within a year can be assumed. Therefore, the German Maritime museum specified a deformation of ≥1mm to be detectable with the monitoring system. This level of deformation has to be determined in order to provide information 1) about the size and direction of changes, 2) about critical sections in changes and 3) about interaction of sections.

Based on information theory, a significant movement can be identified by a signal-to-noise ratio of $q > 5$ (as approximation) if the movement is large relative to the technique's single point precision (Durpatz *et al.*, 1979). The signal-to-noise ratio is defined by (1):

$$q = \frac{|dl|}{s_{dl}} \tag{1}$$

The signal can be defined as the length $dl$ between a single point measured in different measurement epochs (vector length). The noise $s_{dl}$, which is the empirical standard deviation of the length of deformation, leads to a value of $s_{dl} < 0.2mm$ with $dl = 1mm$.

Assuming equal quality of all 3D points in all three coordinate directions within the measurement, with (2)( Luhmann *et al.*, 2014) a single 3D point precision of $s_{XYZ}$ = 0.15mm with a confidence level of 68% has to be achieved for the whole size of the object, and therefore for each point in any position within the measuring volume.

$$s_{XYZ} = \frac{s_{dl}}{\sqrt{2}} \quad (2)$$

In this case deformation estimation includes rigid-body motion of the artefact with respect to its stable surrounding as well as the determination of deformation of the artefact itself. Therefore, the measurements have to be placed within a ground control network to allow for the estimation of rigid body motion. With respect to the measurement's minimum single point precision, the ground control network needs to be estimated with a technique of higher accuracy and stable over time.

In order to achieve the high single point precision for each object point, a photogrammetric approach is chosen for the monitoring concept. In addition, this allows for short measurement time periods of about 2 hours for each measurement and for contact-less measurements of once signalised object points (non-destructive measurements for the medieval ship).

## B. *Ground control network*

The ground control network at the museum is based in the museum's building structure around the cog. 22 bolts are fixed to the struts of the exhibition hall on three different levels (see numbered positions in Figure 4). The female thread of the bolt can be used as socket for measuring adapters with a magnetic socket for targets of different measurement techniques. This is used with laser tracking, as measurement tool for the ground control network, and photogrammetry, as measurement technology for the monitoring.

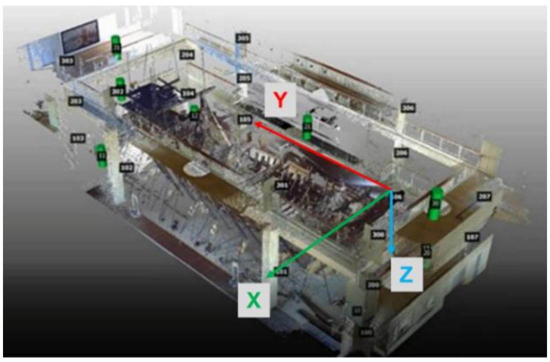


Figure 4. Ground control network, coordinate system and "Bremen Cog" in a scan visualisation

Unfortunately, the ground control network might be influenced by the inhomogeneous tidal changes. The ground control network was measured in July 2017 using a lasertracker. The network quality is estimated to 19µm in XY-direction and 27µm for Z-direction (1σ RMS, Schmik *et al.*, 2018). Therefore, the coordinates of the ground control network are of superior precision with respect to the recommended photogrammetric estimation.

## C. *Object representation*

For the deformation measurements around 120 reflective photogrammetric points are glued to the cog as main observation points. Japanese paper is used between the wooden structure and the sticky target to avoid any damage when removed from the artefact. Figure 5 shows the principle of object point distribution on the cog. The points are distributed irregularly 1) because of the local situations in visibility of targets due to the objects shape and the cradle and 2) to enable a good representation of the volume by applying a triangulation network over all object points for deformation analysis.

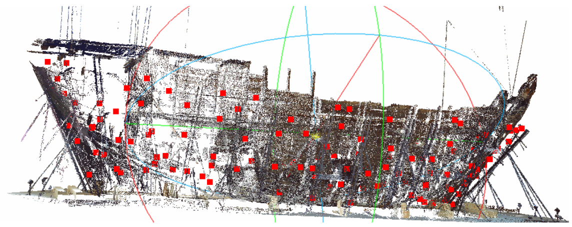

Figure 5. Principle of object point distribution on the cog

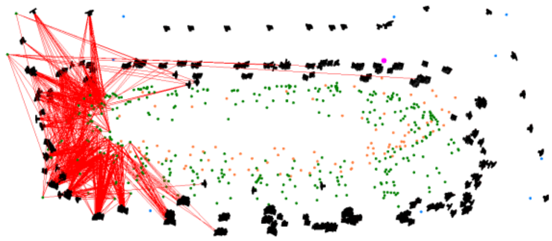

Figure 6. Principle acquisition scheme for large volume environment (green: object points, orange: points on Cog; red: exemplary image rays to object points, blue: control points)

## D. *Photogrammetric measurements*

For the photogrammetric measurements about 450 coded tie points are placed around the cog for automatic processing. 14 ground control points of the lower two exhibition levels are observed using interchangeable targets. The photogrammetric image bundle follows the principle acquisition scheme outlined in Figure 6. The use of a high-quality photogrammetric system with simultaneous camera calibration is expected to achieve the recommended single point precision for this large volume environment.

## E. *Photogrammetric bundle adjustment*

For the photogrammetric bundle adjustment, a datum definition with four ground control points on the lowest floor is used. The ground control points are introduced as pseudo observations with their related standard deviations to allow for lowest constraints in the adjustment. Figure 7 shows the location of the four control points. From a geodetic point of view, the use of the outer ground control points covering the whole object inside their volume is preferable. However, for photogrammetric purposes this is disadvantageous. The photogrammetric triangulation relies on the connection of all images using image measurements and good ray intersections. If points outside the main object volume are to be estimated with the same precision, different requirements have to be considered. For example, points have to be placed in-between or different viewpoints and viewing directions must be available for adequate ray intersections. For the present situation this is not satisfying and therefore the estimation of the outer ground control points by the photogrammetric measurements is of lowest quality. Hence, the photogrammetric measurement is based on the four ground control points that represent most of the object volume and fulfil the requirements of high-quality photogrammetric point estimation.

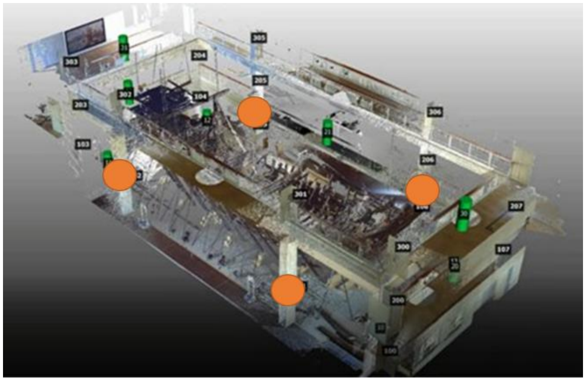

Figure 7. Definition of ground control points on lowest floor for the photogrammetric datum definition

### F. *Deformation analysis*

The analysis of deformation has to be divided into different tasks. Firstly, a test of the observed object points in two epochs is necessary in order to evaluate if a variation in coordinates is caused by measurement uncertainties or significant movements. Secondly, motion of single points or point groups within the object volume has to be identified and localised.

Applying a global congruency test, the general geometry of 3D measurements from two epochs is tested against changes by applying probability hypotheses and significance levels. Based on (Durpatz *et al.*, 1979) the resulting 3D object points of different epochs are tested against a t-distribution with $t_{f,1-\alpha/2} = t_{4,0.975}$ using (1). A quotient value of >2.78 indicates a significant movement of an object point with a significance level of 5%. Alternatively, a test of the signal-to-noise ratio (1) with $d_l$ as possible deformation vector and $s_{dl}$ as its noise (with consideration of full error propagation) with q>5 is applied to the results. With this, rigid body motion can be determined, vector fields can give an effective visualisation of the results.

A deformation of the observed object itself is determined by strain analysis. If deformation occurs homogenously for all parts of the object and is small compared to the size of the object, linear terms can be applied to the analysis. For the cog inhomogeneous deformation has to be expected. This is due to the different components of the wooden ship, the cradle and the existing deformation.

Therefore, a strain analysis based on (Heunecke *et al.*, 2013) is applied. The object is divided into finite elements of homogeneous deformation. In particular, a Delaunay triangulation is built through the observed object points on the cog to allow for equilateral triangles. Based on affine transformation theory, a strain analysis is defined to detect changes in dilatation and shearing of each triangulation patch. The results are statistically evaluated against a $\chi^2$-distribution.

## IV. Feasibility study

In order to evaluate the theoretical discussion on the objectives for the geometric monitoring, the applied ground control network and photogrammetric measurement technique, feasibility studies focusing on different aspects of the monitoring process were carried out. (Schmik, 2017) gives a summary on the whole process of geometric deformation monitoring with three exemplarily measured epochs between mid-July and end of August 2017. (Hastedt *et al.,* 2018) present a study on the measurement quality of different photogrammetric measurement systems, based on measurements in mid-July and end of December 2017.

Based on the feasibility study by (Schmik, 2017), the ground control network was measured in July 2017 (as described in section III.B), within 14 days to the first photogrammetric evaluations. A second measurement of the network in April 2018 yield to deviations up to 0.7mm for all coordinate components applying a best-fit transformation and 1.1mm for absolute deviations based on the same system definition. However, the two measurements just give an indication that it has to be controlled within shorter time periods and with respect to the possible influences of the North Sea tides.

For the photogrammetric measurements, all interchangeable targets for the connection to the ground control network are placed to the environment at least 30 minutes before start of measurements in order to accommodate for environmental influences. Image sets of 360-460 images are used for the object measurements and adjusted as described. For the study a standard DSLR-camera Nikon D4 was used with a Zeiss 35mm lens. The resulting single point precisions of the three epochs are summarised in Table 1. The RMS values show the ability of the photogrammetric evaluation to approach the recommended precision.

However, for this study different object points result in lower precision of up to 0.3mm.

Table 1. Single point precisions for three epochs in feasibility study by (Schmik, 2017)

| [mm] | E0 | E1 | E2 |
|---|---|---|---|
| $RMS_X$ | 0.15 | 0.13 | 0.08 |
| $RMS_Y$ | 0.13 | 0.09 | 0.08 |
| $RMS_Z$ | 0.10 | 0.08 | 0.06 |

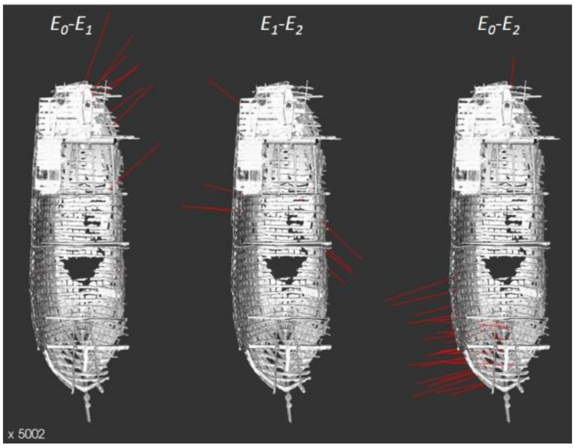


Figure 8. Statistically significant vectors of deformation (signal-to-noise ratio) for epochs E0, E1 and E2 with a maximum vector length of 1.3mm (Schmik, 2017)

The resulting object point coordinates are taken for an analysis with respect to the signal-to-noise test. The statistically significant vectors of deformation are visualised in Figure 8. All vectors remain lower than 1.3mm in length. In addition, their characteristics are non-linear over time and only valid for a subset of all points at the specific object part. Even though the image acquisition was done at nearly equal times during the measurement days and within same time periods of three hours, the influence of the tides is unknown and not taken into account. Therefore, the resulting vectors of possible movement might be affected by movement of the building, movement of the cog, an interaction of both or the measurement arrangement.

In order to allow for a closer insight to the volumes' behaviour, the results on dilatation and shearing are analysed. The congruency test of the strain patches in dilatation and shearing refer to statistically non-significant changes. Their results are exemplarily visualised in Figure 9 and Figure 10.

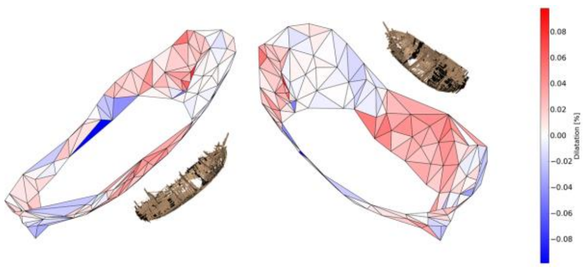

Figure 9. Resulting dilatation (statistically non-significant) between E2 – E0 (Schmik, 2017)

Figure 10. Resulting shearing (statistically non-significant) between E2 – E0 (Schmik, 2017)

The comparison of the statistically significant deformation vectors with the non-significant dilatation is shown in Figure 11. The vectors are located at the parts of lowest dilatation and shearing. Therefore, only a motion of that part would explain the vectors, but neighbouring parts of the strain analysis do not clearly indicate significant changes. Anyway, the results of the reconsidered epochs still deviate within their measurement accuracy.

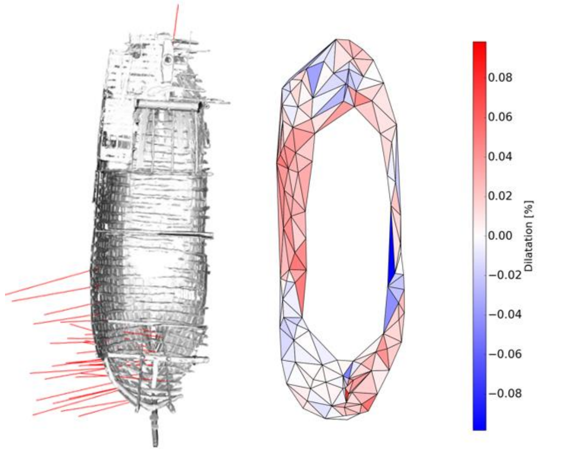


Figure 11. Comparison of deformation vectors and dilatation between E2 - E0 (Schmik, 2017)

Table 2. Single point precision using different photogrammetric systems (Hastedt *et al.*, 2018)

| [µm] | Nikon D4, 35mm | ALPA metric camera | | |
|---|---|---|---|---|
| | | 100 MP | 50 MP | 50 MP |
| | 12/17 | 07/17 | 12/17 | 12/17 |
| $RMS_X$ | 90.5 | 37.9 | 46.1 | 48.5 |
| $RMS_Y$ | 81.1 | 29.1 | 51.4 | 43.2 |
| $RMS_Z$ | 51.8 | 19.8 | 29.4 | 31.1 |

A second study on the measurement quality of photogrammetric systems applied to large-volume applications pick up on investigations on the quality assessment of camera systems and on datum definition (Reznicek *et al.*, 2016, Martin *et al.*, 2016).

Table 2 summarises the single point precisions of a selection of results given by the ALPA fps add|metric camera in comparison to results of a Nikon D4 camera. It can be identified that the large-volume measurements benefit from the use of a metric camera. The RMS values of single point precision show a high-quality level. Nevertheless, the results with the Nikon camera are of high quality but do not completely fulfil the requirements for precision set up by the Museum in the original objectives.

Investigations on the datum definition show the complexity of the photogrammetric adjustment, the influence of the unfavourable environment and the dependency on the quality and stability of the ground control network.

The data set with the Nikon camera from December 2017 is chosen for a comparative deformation analysis to E0 by (Schmik, 2017). The results remain almost the same. Statistical changes in coordinates indicate inverse characteristics to E2. Strain analysis remains statistically insignificant except for three tiny parts but are at critical sections of estimation and not unique in terms of reliability and precision.

## V. Summary and Outlook

A monitoring concept for the medieval shipwreck “Bremen Cog” is presented and supported by feasibility studies on the concepts’ processing and analysis as well as in measurement accuracy. General results are given and discussed with respect to the objectives.

It is evaluated which photogrammetric system fulfils minimum requirements in order to guarantee high quality precision within the large-volume metrology environment. Nevertheless, the studies just give a feasible insight, but have to be continued in order to evaluate all processes, the environmental influences and the deformation estimation over time. For the “Bremen Cog”, more object points have to be measured in order to allow for a better triangulation network and representation of deformation. It has to be evaluated which wooden parts should ideally be separated or consolidated for strain analysis.

It would be feasible to analyse the benefit of strain analysis based on tetrahedral meshes to describe in-plane and out-of-plane deformation as given by (Van Dijk *et al.*, 2016). Attention has to be taken on the ground control network as it is the main issue in datum definition. If the stability of the ground control network cannot be maintained as required for standard deformation analysis, an advanced deformation model has to be applied (e.g. given in Reinking, 1994).

## VI. Acknowledgements

The project was carried out in cooperation with the German Maritime Museum which partly funded the work. The investigations were supported by Jurij Schmik who spent high effort and commitment during his master thesis.

## References

Colson, A., 2017. Digital Documentation of ships in cultural heritage: a European review. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W5, 2017, 129-134

Durpatz, H., Niemeier, W., Pelzer, H. (1979): Analyse von Deformationsmessungen durch Klaffungszerlegung. Seminar über Deformationsanalysen, Schriftenreihe des Wissenschaftlichen Studiengangs Vermessungswesen an der Hochschule der Bundeswehr München, Heft 4, S. 45-66.

Hastedt, H., Rofallski, R., Luhmann, T., Rosenbauer, R., Ochsner, D., Rieke-Zapp, D. (2018): Prototypic development and evaluation of a medium format metric camera. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2, 2018, 441-448, https://doi.org/10.5194/isprs-archives-XLII-2-441-2018

Heunecke, O., Kuhlmann, H., Welsch, W., Eichhorn, A., Neuner, H. (2013): Handbuch Ingenieurgeodäsie – Auswertung geodätischer Überwachungsmessungen. 2.Auflage, Möser, M., Müller, G., Schlemmer, H. (Hrsg.)

Jacobsen, J., 2003. Measuring the Vasa. Transactions on the Build Environment vol. 65, WITpress, ISSN 1743-3509

Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2014. Close-Range Photogrammetry and 3D Imaging. *De Gruyter textbook*, 2nd edition, ISBN 978-3-11-030269-1

Martin O.C., Muelaner J.E., Dhokia V., Robson S., Kayani A., Maropoulus P.G., 2016: Comparative performance between two photogrammetric systems and a reference laser tracker network for large-volume industrial measurement. *The Photogrammetric Record* 21 (155), 348-360, doi 10.1111/phor.12154

Nayling, N., Jones, T., 2014. The Newport Mediaval Ship, Wales, United Kingdom. The International Journal of Nautical Archaeology 43.2, doi. 10.1111/1095-9270.12053

Peggs, G.N., Maropoulos, P.G., Hughes, E.B., Forbes, A.B., Robson, S., Ziebart, M., Muralikrishnan, B., 2009. Recent developments in large-scale dimensional metrology. *Proceedings of the Institution of Mechanical Engineers*, Part B: Journal of Engineering Manufacture. DOI: 10.1243/09544054JEM1284

Reinking, J., 1994. Geodätische Analyse inhomogener Deformationen mit nichtlinearen Transformationsfunktionen. DGK doctoral thesis Nr. C413

Reznicek, J., Hastedt, H., Ekkel, T., Luhmann, T., Jepping, Ch., 2016. Analysen zur Datumsfestlegung in photogrammetrischen Projekten großer Volumina. *Publikationen der DGPF*, Band 25, 259-270

Schmik J., 2017. Photogrammetrisches Monitoring und Deformationsanalyse der Bremer Hanse-Kogge. Master thesis at Jade University of Applied Sciences Oldenburg. Not published.

Schmik, J., Colson, A., Hastedt, H., Luhmann, T., 2018. Photogrammetrisches Monitoring und Deformationsanalyse der Bremer Hanse-Kogge. *Photogrammetrie, Laserscanning, Optische 3D-Messtechnik – Beiträge der Oldenburger 3D-Tage 2018*.

Schofield, E., McConnachie, G., Jones, M., 2013. Air drying of the Mary Rose hull. Proceedings of the 12th ICOM-CC WOAM Conference, Istanbul.

Tanner, P., 2013. 3D Laser Scanning for the Digital Reconstruction and Analysis of a 16th-Century Clinker Built Sailing Vessel. Underwater Archaeology Proceedings

Van Dijk, N., Gamstedt, E.K., Bjurhager, I. (2016): Monitoring archaeological wooden structures: Non-contact measurement systems and interpretation as average strain fields. Journal of Cultural Heritage, 17 (2016), p. 102-113