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PROCEDURE FOR RECONSTRUCTION OF GAJETA HULL FORM USING PHOTOGRAMMETRIC MEASUREMENT METHOD

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Summary

Traditional shipbuilding is an important part of Croatian cultural and national heritage that needs to be preserved. This refers to the importance of documenting and transmitting knowledge and skills and preserving the authenticity of the shapes, dimensions, materials and technology of building traditional boats. One of the problems that arises in the revitalization and reconstruction of traditional boats is the lack of documentation, so it is necessary to make line drawings and show the details of traditional construction solutions. The paper presents a procedure for reconstruction of the hull form of a traditional boat using the photogrammetric method. In the preparation phase of the procedure the activities of recording and analysis of photographs are necessary. The SfM approach was used in this phase. The result of the processed data with this method is a cloud of measured points. These points were used in the next step of the procedure for the creation of the preliminary mesh to describe the hull form. In the final phase of the procedure the exact 3D hull model was created using combination of mesh refinement in specialized software and measurement updates from the boatbuilders. The advantages in use of photogrammetric measurement method, in combination with the SfM method for photo analysis, for the reconstruction of the hull form of a traditional boat are highlighted in the conclusion.

Key words: maritime heritage; reconstruction; documentation; photogrammetry; SfM method

1. Introduction

Traditional shipbuilding is the construction of any historic vessel that includes preservation of the authentic shape, dimensions, materials and production technology. Croatian traditional shipbuilding, thanks to its longevity and significance from the cultural-historical, artistic, ambient, ethnological and scientific point of view, is an important part of Croatian cultural and national heritage [1].

Traditional shipbuilding is based on small-scale craft production in smaller shipyards where traditional materials and technologies are used. Shipbuilders acquired and developed their skills mostly by passing knowledge from generation to generation [2]. Traditional shipbuilding today usually involves the construction of wooden vessels for recreation or tourist purposes.

Recently, more and more attention has been paid to the preservation of traditional ship designs. This is carried out thorough projects of reconstruction and revitalization of individual historic vessels and projects of research of historical and technological aspects of that part of shipbuilding. Fundamental activities for the preservation of shipbuilding heritage include re-establishing the functionality of the vessel as well as adaptation and modification of parts of the structure in order to achieve new value and integrity [3]. An equally important component is the preservation of knowledge and skills as well as the transmission of knowledge to future generations.

One of the problems that arises in the revitalization and reconstruction of a traditional boat is the lack of documentation, so it is necessary to make line drawings. The drafting of the lines is preceded by the measurement of the hull form of a traditional boat. A fast and reliable measuring method is required that will enable a sufficient number of points for the quality definition of the boat's hull lines.

In practice, traditional and modern measurement methods are used. The advantages of traditional methods are the simplicity of the procedure and the use of simple tools. The disadvantages are the long duration of the measurement process and the unreliable accuracy [4]. Wei and authors point out that traditional measurement methods could hardly meet the shipbuilding requirements [5]. With the development of optics and electronics, modern optical methods and measuring instruments appear in the field of measurement. The possibilities of measurement, storage, processing and analysis have increased. Zong and Wan present advanced 3D scanning method for container ship cell guide accuracy check [6]. The shortcomings of traditional methods are being reduced, particularly the duration of the measurement process and the accuracy of the results. Measurement accuracy and reliability of the results depend on the precision of a measuring device, the knowledge and skills of measurer, the stability of instruments and the measuring object. Proper handling of the instruments is required when measuring. Carelessness can cause mechanical damage to the device or block the measurement process. Most of the optical instruments are sensitive to moisture, dust, temperature differences and operating conditions at the measurement site. The optical measurement methods in shipbuilding, such as photogrammetry, have been used as acceptably reliable and fast methods for controlling dimensions and shapes [7], [8]. Photogrammetric technique could be used for dimension and shape measurement and to control any stage of building a ship hull. In the ship production phase of element cutting and shaping, photogrammetry could be used to control dimensions and shape of elements. In the subassembly stage, it enables the control of dimensions and shape of sections. The control on the building berth includes the dimensional and shape control of the assembly stage [9]. Photogrammetric methods can be applied in any situation where measured object can be photographed. The quality of the results depends on a number of factors at site, such as contrast, weather conditions, light sources and the surface properties of the object. One of the most significant advantages of using the photogrammetric method in relation to traditional measurement methods is the possibility of obtaining a large number of measuring points. Then the analysis of object shape and dimensions can be done better than traditional measurement methods. Compared to optical measuring instruments, the photogrammetry method is less sensitive to environmental influences, such as the vibrations of the floor at the measuring site. Another advantage of the photogrammetric method, when compared to existing procedures, is the use of computers and specialized software. In addition to computers, the digital cameras, software packages and photo processing capabilities, speed of analysis and display of measurement results are being developed, which further speeds up and facilitates measurement. The application of photogrammetry is usually associated with expensive measuring equipment, and the development of the method has the effect of reducing the cost of equipment and the entire measurement process.

Martorelli and authors use photogrammetry and reverse engineering methods to define the hull form of a traditional boat. In the process, they use markers placed on the frames to define the position of other measuring points. Measurement accuracy was compared with laser scanner measurement results, and the average deviation was 1.25mm [10]. An important parameter in the application of the photogrammetric measurement method in some objects is the accuracy of measurement results. Ackermann and the authors [11] point out that the photogrammetric method can achieve a measurement accuracy of 0.1 mm. Koelman considers optimal placement of minimum number of landmarks [12]. Ahmed and authors use photogrammetric method to survey small boat hull [13]. Menna, Nocerino and Scamardella emphasize the importance of preserving cultural heritage and use photogrammetry and laser scanning in the measurements [14]. The development of the photogrammetric method for underwater imaging was presented by Menna and authors [15]. The application of underwater surveys and a reliable method of measurement is important in another important segment of heritage preservation under the sea, and that is the reconstruction of wreck forms. Examples are presented in the works of Baletti and authors [16], Drap and authors [17], Costa and Guerra [18].

2. Photogrammetry measurement method

Photogrammetry is an optical measurement method where 3D coordinates of observed object points are determined from photographs taken with a camera [19]. The recorded distinguished measuring points are used for reconstruction of optical rays.
The mathematical model for reconstruction of a light rays uses two sets of coordinates, i.e.:

- OBJECT (X, Y, Z) – coordinates of an object points,
- IMAGE (x, y) – position of an observed point projection in a photograph.

Equations of image coordinates are:

$$x = f(c, Xo, Yo, Zo, \omega, \psi, \kappa, X, Y, Z, x_o, \Delta x)$$

$$y = f(c, Xo, Yo, Zo, \omega, \psi, \kappa, X, Y, Z, y_o, \Delta y),$$

where:

c – coefficient of the camera, value close to focal length
Xo, Yo, Zo – coordinates of the lens origin in auxiliary coordinate system
ω, ψ and κ – turning angles of the camera coordinate system
x_o, y_o – image coordinates
X, Y, Z – object coordinates
Δx, Δy – deviation from the central projection. Due to lens imperfection, position of the point which is not on a central projection axis has to be corrected. In corrections, parameters like radial distortion, disparate scale of the photograph, perpendicularity and deformity of the photographs are considered.

Reconstruction of an optical straight-line consists in establishing a functional relation between the object and image coordinates. This model is sufficient for considering measurement in the plane with two unknown values of the object coordinates X and Y, (Z=0), and they could be calculated using two equations of image coordinates (x, y).

A 3D measurement includes three unknown values of object coordinates X, Y, Z. Two equations of image coordinates are not enough for calculation of three coordinates. Additional equations of image coordinates are necessary to solve the problem. The object point has to be recorded from another position, which gives additional two equations. System of the equations is predefined. The system of nonlinear equations redefined in this way is solved iteratively by an error minimization method, and the outputs of this analysis are 3D coordinates of measuring points and other parameters of the mathematical model [19].

The optical measurement techniques for calculation of point position in space are based on stereoscopic effect. A 3D position of a point is determined by triangulation, as shown on Figure 1. The position of a point is determined from an intersection of straight lines determined by a point on object P and its projections on photographs.

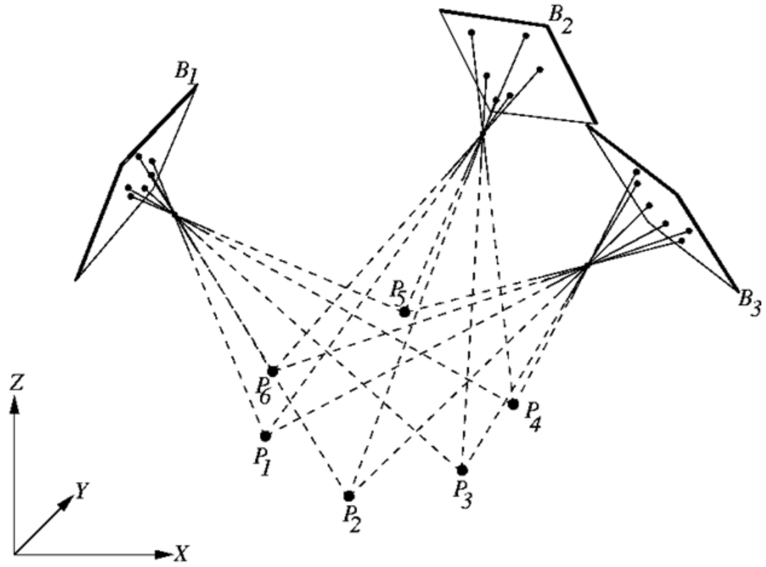

Fig. 1 Triangulation principle

An important condition for reliable measurement using the photogrammetric system is availability of measuring points with sharp contrast. White points on black background or black points on white background are used. The measuring points are divided into coded and uncoded. Dedicated software recognizes the coded points by the defined bar code and they are used to determine position of a camera in space. Uncoded points are placed in characteristic points on the object, the position of which must be determined. A software automatically determines position of an uncoded point, and to the measuring point is attached an identification number which later facilitates the analysis of the results and reconstruction of characteristic lines, edges, and holes. The uncoded points are usually equal in size to the coded points.

Increased power of computer processors has enabled the application of many different algorithms that approach 3D modelling in a new way. In the field of optical measurement methods, the processing of measurement results has been facilitated, and a new Structure from Motion - SfM method has been developed, based on the phenomenon by which human visual systems can reconstruct three-dimensional structures from 2D images projected on the retina. Eltner and Sofia point out that the SfM method in photogrammetry is a simple, inexpensive and widely available measurement method [20]. Granshaw defines characteristics of SfM method [21]. Westby and authors point out that the SfM method can be used to analyse topographic measurements more easily and cheaply, which are more organizationally demanding and expensive using traditional methods [22]. Isteni̇č and authors use SfM technique for underwater image-based 3D reconstruction with use of automatic scale accuracy estimation framework [23].

By applying the SfM method, it is possible to obtain a dense cloud of measuring points from the image collection. It is not necessary to calibrate the camera, and it is possible to analyse photos taken with different cameras at different recording times, which facilitates the process of processing the measurement results. The paper describes the procedure for reconstructing the hull form of a traditional gajeta boat using the SfM method in photogrammetry.

3. Reconstruction of the hull form of the traditional gajeta boat

The procedure for reconstructing the hull form of a traditional boat is shown in the article on the example of a gajeta. It is implemented in 5 phases:

- overview of the condition of the traditional boat,
- measuring the hull form of a traditional boat,
- analysis of photographs and definition of a preliminary 3D model,
- making the final 3D model of a traditional boat,
- drafting the hull form of the traditional boat form.

3.1 Overview of the condition of the traditional boat

An overview of a traditional boat includes an inspection of the shape and condition of the structure at site. An example of condition of the gajeta is shown in Figure 2. Gajeta is a traditional fishing boat with a more rounded shape and a wider bow. It was mostly used for transporting people, various cargoes and even cattle, and for fishing with nets. Gajeta usually have a sharpened underwater part of the hull and a wide deck on the bow or stern for handling nets. The traditional drive was mostly oars and sails. Their length ranged between 4 and 10 meters, and most often between 6 and 8 meters. According to the data from the research of the dimensions of traditional boats, the width of the gajeta must be more than a third of the length of the boat. Gajeta was built in all parts of the Adriatic, so in Croatian traditional shipbuilding there are several significant different designs, such as gajeta Lovranka or Lovranski guc, Komiška falkuša, Korčula gajeta and Betina gajeta. It can be seen that the elements of the structure mostly need to be replaced by new elements, but the shape is well preserved. Enough size measures are taken as preliminary guidelines for modelling. These include overall length, breadth and height of the boat as well as keel height and breadth. Depending on a type of a boat other dimensions of interest can be checked in this phase. At the end of this phase a plan for taking photographs must be made. After planning and when the desired conditions are met the phase of measuring can start.

Fig. 2 State of form and structure of the traditional boat

3.2 Measuring the hull form of a traditional boat

The hull form of the gajeta was measured in the field by the photogrammetric method using a digital camera. The SfM method was used to process the measurement results. The photographs were analysed and selected for processing. The result is a cloud of measuring points of the hull of gajeta. Multiple cameras and even cameras of modern mobile devices can be used in the recording process. Most of the photographs were taken with a professional digital camera with the use of different lenses for different recording conditions. For comparison, many photos were taken with a hi-end mobile phone camera. The chosen technique is very suitable for recording considering conditions found in the field. The gajeta was not placed on a flat surface. Access was blocked on starboard side. The necessary distance, required to apply other, more complex and expensive methods, was not provided. The boat was inclined to starboard side and was close to heavy objects that could not be easily removed. For the application of other measurement methods, it would be necessary to adequately position the boat, clean the location and the area around the boat so that recording would be possible. In addition, when recording with more advanced methods, it is often necessary to clean the surface so that measuring instruments can be used. To apply the recording technique used here, objects do not have to be on a flat surface or cleaned, and the environment may contain some objects that even partially block the view or access. When recording smaller objects, it is advantageous that there is enough distance to be able to capture the whole object in one frame with the camera. This will often not be possible with larger objects such as bigger ships where the cameraman cannot move away far enough to capture the entire object. In such situations, the object is recorded largely with photographs that overlap. This could be analyzed and corrected in software but requires additional time to process the model. It is also possible to use flying drones to record a video from which a series of non-overlapping photos are later extracted. This approach requires additional investments in equipment and staff training. In the case of gajeta, most of the photos covered the entire boat in the frame. Exceptionally, parts of the interior are shot from a smaller distance and not all elements are in one frame. When recording, good lighting of the object should be considered. It is recommended to record object in daylight, but not in strong sunlight that can produce a lot of reflection.

Fig. 3 Shooting condition of the traditional boat

In such conditions better surface contrasts are obtained, which enables computer programs to better discern the shape of the object. In this case, the gajeta was recorded in daylight, with lightly cloudy weather, as seen on Figure 3. Another important condition for the successful application of this technique is that the environment of the object does not change during the recording. This means that the cameraman, or other persons, must not move objects, tools, etc. that are in the recorded frame, even if they block part of the hull when viewed from different angles. If the subject was moved for a better view, and it was previously taken in all the photographs, there would be a problem in the computer program for recognizing the shape. This could lead to the need to repeat the recording because the software would not be able to generate correct shape of the object. The third important recording parameter is the condition of the boats themselves, and it is related to lighting. The recorded surfaces should not be smooth and shiny, precisely because of the reflection of light.

The recording must be carried out so that all sides (surfaces) of the boat are visible on photographs, including the deck and bottom. Therefore, it is always better to have the boat raised on slightly elevated girders. This makes it easier for the cameraman to record from a suitable distance by capturing the whole boat or at least as much as possible in one photo. Recording is performed in a sequence, planned in the first phase, so that each subsequent photo shows the boat from a different angle. The cameraman makes a full circle around the boat and records the so-called a belt of photographs composed of a series of photographs of the shape of a boat at the same height. For the gajeta in the example, four photo belts were taken: the bottom belt, the deck belt, and two belts in height between the bottom and the deck as schematically shown in Figure 4.

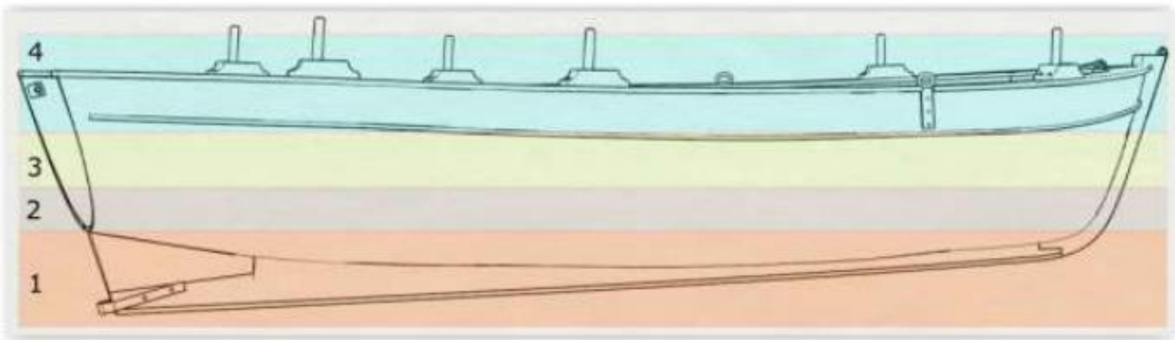

Fig. 4 Levels of recording the hull form of a traditional boat

3.3 Analysis of photographs and definition of a preliminary 3D model

The captured photos are processed in Autodesk Recap software [24]. The program is used to convert photographed or scanned objects into high-resolution 3D mesh. Although theoretically two photographs are sufficient to determine the position of one measuring point, in practice many more photographs are taken to obtain reliable readings. About 150 photographs were taken to create a computer 3D model of an object the size of the traditional gajeta boat. The photos were first reviewed on a computer and all that had any flaws, e.g., were out of focus or a person was in the frame, were discarded. A selection was made for the gajeta, leaving about 100 quality photographs that covered the entire hull form. The photos were then loaded into software that analyses them and by applying triangulation and finds the position of the measuring point on them from different camera positions. With a well-prepared photography plan one such boat can be recorded in two to three hours.

Once the photos have been uploaded, it sometimes takes several hours for the program to create a preliminary 3D version of the object. This is followed by model processing. First, the so-called textured models are created. Textured models connect captured photos and a preliminary mesh. They are used to determine redundant objects and remove them. It can be seen in the pictures that it was necessary to manually, in the program, delete all elements that are not part of the boat, such as supporting wooden carriers and other objects. Photo processing can be more demanding if it is necessary to correct deformations or gaps in the model shown on Figure 5. The cause of deformations is the uneven arrangement of cameras during shooting. The gaps in the model are in places that could not be well captured. Work on model correction can take several days.

Fig. 5 An example of deformation and insufficiently covered model of a traditional boat

In addition to textured models, the programs also enable the creation of mesh models of boats. These are mesh of lines that describe 3D models and are necessary for preliminary fairing of the hull form. The measured reference dimensions of the boat in the field are entered into the model, e.g., length over all, breadth in some positions and keel length and height. Too many dimensions are not recommended because it could "confuse" the programs into making more deformed mesh models. Fine refinement of the model is conducted in the next phase of the procedure where all the necessary measures are checked and the precise model is generated.

3.4 Making the final 3D model of a traditional boat

In this phase, the fact that most of the traditional boats are symmetrical can be used, so it is enough to refine one half of the recorded model. The side of the model that is less deformed and has fewer gaps is usually more suitable for work. This half of the model is inserted into advanced 3D modelling programs.

In the image processing program, the form of the model is defined by a set of small areas (polygon mesh). It is actually a set of vertices, edges, and geometric shapes, mostly quadrilaterals and triangles. For this boat, the polygon mesh consisted of triangles.

The quality of the model and the amount of detail are contained in the set and arrangement of surfaces. Figure 6 shows an example with $3 * 10^5$ polygons. In order for the model to be detailed, as many small areas as possible are connected into one large area. The more polygons, the more detailed the model, but the process of making the final model is slower because the denser network needs to be inspected and the response of the computer is slower. With a larger number of polygons, the size of the file exported from the program also increases, which can affect further work in other programs. It is necessary to find the optimal ratio of the number of polygons and quality. This means to reduce the number of polygons, but to pay attention to the loss of details on the model. A very detailed grid is important mainly when rendering to visually improve the model for presentation, but it does not affect the accuracy of the measuring points of the boat hull form.

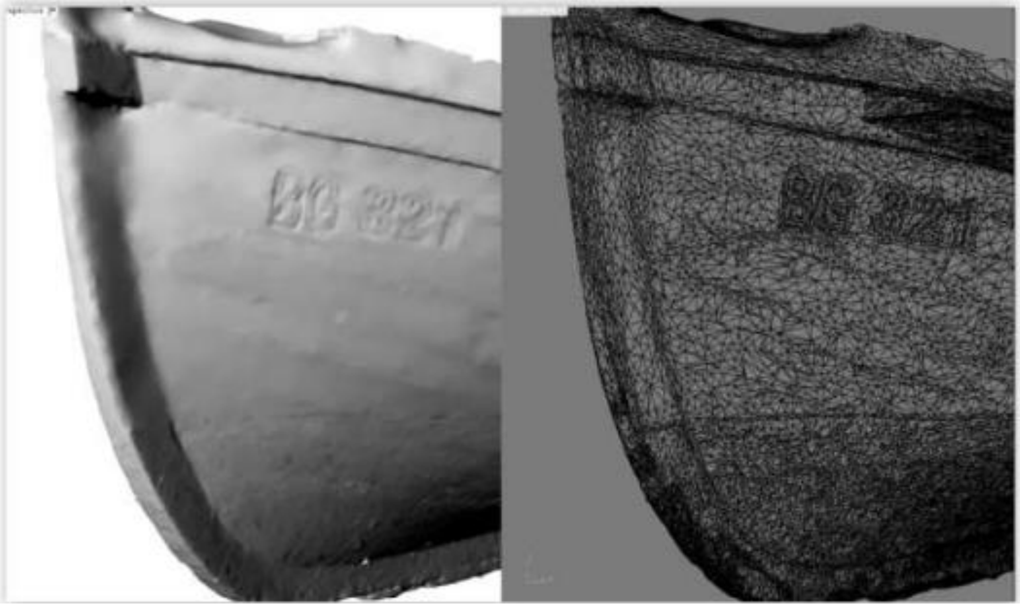

Fig. 6 Quality of the model in relation to the number of polygons

A set of equally spaced planes was used to draw the lines in the scale. After positioning the planes along the length of the model the grid was divided into segments. Segments can be hidden to get better visibility while focusing on a specific modelling task. Two section curves can be obtained from each segment, so that the program, in the first iteration, automatically draws them using built-in mathematical polynomial functions (NURB splines). The technique and choice of the type of curves, as well as the size of the mesh, the number of control points, the degree of the polynomial, the stiffness of the curve, for application to a particular part of the form is a matter of knowledge and experience.

After drawing the lines of the form, they need to be inspected in detail using various tools in a 3D modelling program. This phase of hull form development is critical. Below are some examples of mesh deformations that have been processed to obtain a fair gajeta form in scale. The detail of network damage is shown on Figure 7.

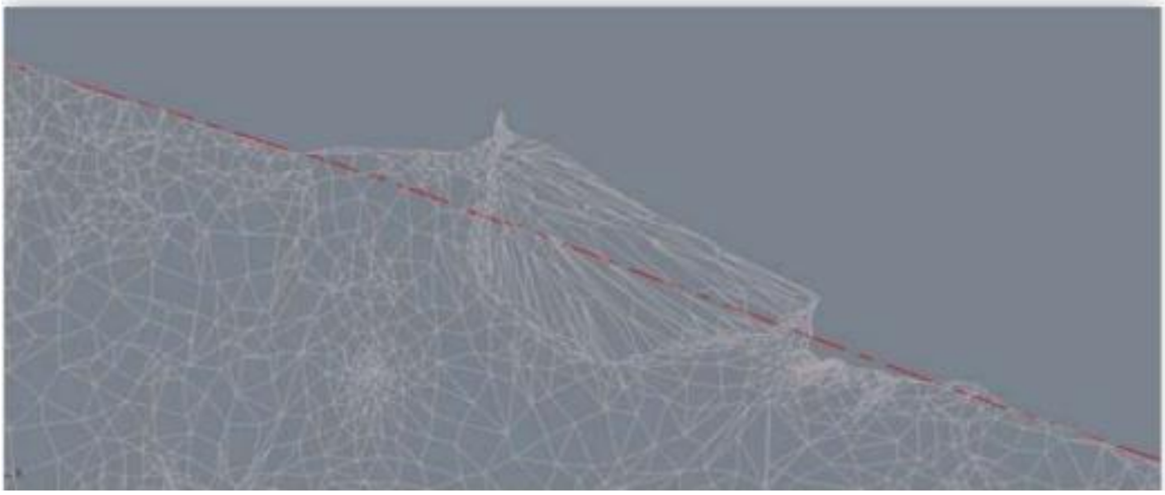

Fig. 7 The detail of mesh damage

The finally obtained model is the result of processing and refinement of all contours of the form and is noticeably more precise than the preliminary model.

Fig. 8 Fine and basic model of a traditional boat

From the fine model, a mesh of curves and preliminary drawings of frames, longitudinals and waterlines can be extracted. The generated grid of curves is the basis of a fair 3D model. The lines should be further checked and corrected once more in all projections so that a hull form drawing as shown on Figure 9 can finally be obtained.

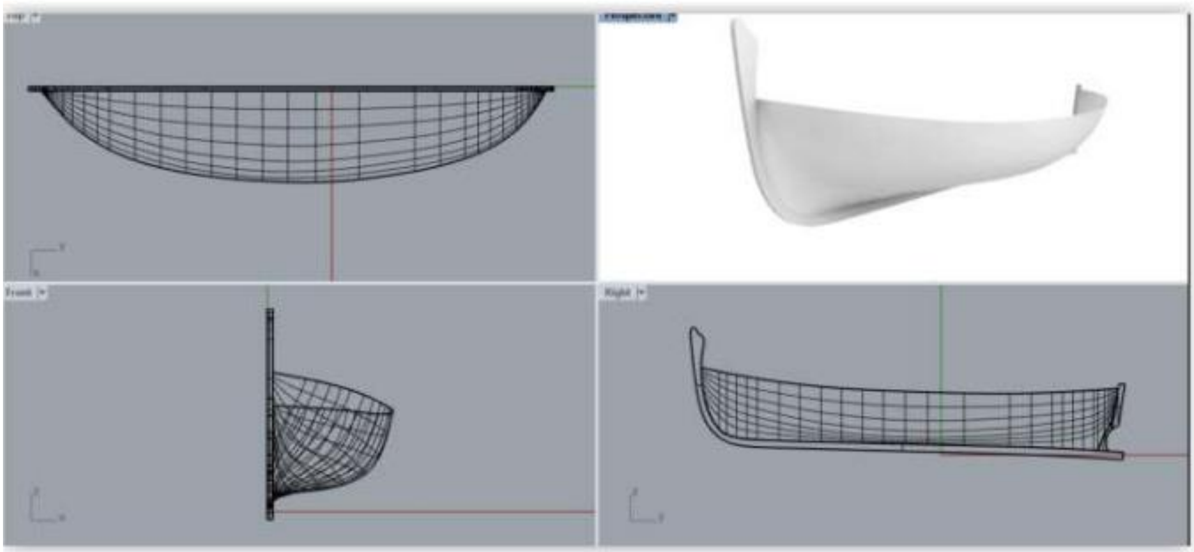

Fig. 9 Final 3D model of a traditional boat

In this last phase of the procedure, it is necessary to compare the final 3D model of gajeta to the real boat after reconstruction through inspection and measurement. The various dimensions in final 3D model, including length, breadth and height of the gajeta, were compared to the measurement data of the boat builder. It was concluded that the applied measurement method gives sufficiently precise results for the reconstruction of the hull form of smaller traditional boats such as the gajeta.

The 3D model of the gajeta then can be used to design the arrangement and size of the longitudinal and transverse structural elements.

4. Conclusion

Traditional shipbuilding is an important part of the national heritage. Its preservation is one of the fundamental goals that has been talked about a lot lately and implemented through revitalization projects. It is not just about ships, but also about the knowledge that needs to be preserved and passed on to new generations. Old shipbuilding masters have passed on the knowledge and experience of making traditional wooden boats, which in recent times have been largely replaced by those made of fiberglass.

Knowledge and experience are often not documented and important segment of preserving traditional shipbuilding is preparation of documentation of traditional boats that contain features of the hull form of boats and details of construction solutions. The drafting of the hull lines is preceded by the recording of the form. A simple measuring method with reliable measurement results is desirable to record the hull form.

The scientific contribution of the paper is presentation of the five phase procedure for recording the shape and defining the lines of a small traditional wooden boat. The procedure needs appropriate and reliable measuring method. The photogrammetric measurement method using the SfM method in the analysis of photographs met all main requirements. The scientific contribution is application of modern photogrammetric method which facilitates the overall process, because the preparation of the recording is much simpler. It is not necessary to set measuring points on a boat hull. It is important advantage of applying this method because boats can be in a very poor condition, which is often the case when it comes to traditional wooden boats. It is not required to have a large number of prerequisites as is the case with measurements by traditional measurement methods. No specific or expensive equipment is required during the recording process. A modern digital camera is enough. Photos taken with a mobile phone can also be analysed. Programs that generate a preliminary 3D mesh model from a series of photos are often free for a limited number of photos, usually around 150, which is enough for gajeta-sized objects shown in the paper. The result of the photo processing is an extensive cloud of measuring points on the outer hull of the boat that were used to define the preliminary 3D model. This model displays all the deformations and visible damage of the hull. It is necessary to correct it in the form of a 3D mesh model from which the final 3D model is formed, suitable for drafting the hull lines of boats. By comparing the values of the measurements of the 3D model and the reconstructed gajeta, it was concluded that good accuracy of the results was achieved.

The procedure defined in the paper can have wide application along the Adriatic coast where the construction of traditional boats developed. It is extremely important to document and transfer knowledge and skills and preserve the authenticity of the hull form, dimensions, materials and technology of building traditional boats.

The presented method proved to be successful in reconstruction of small boats and presents a good balance regarding overall costs of the procedure and time spent for the reconstruction, which is acceptable both for the boat owners and performers. As presented here the only limitations for the procedure could be the weather conditions or close obstacles to an object, which block the view. Further applications should be focused on the reconstruction of larger boats. The one approach could be to use air-drones equipped with cameras. In that case the drones should have to be pre-programmed to cover all angles and views of a larger boat. This would result in more complex procedure and would take more time for preparation phase, which will increase the costs. However, the precision of the method would be proper for 3D models and reconstruction even in that case.

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