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SHAPE RE-ENGINEERING BY PHOTOGRAMMETRY: FROM APPLIED RESEARCH TO INDUSTRIAL PRACTICE

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ABSTRACT

The past years our company was involved in the development of a novel ship hull design method, and corresponding software. Although this software was targeted on design work, the market appeared to be also interested in applying it for ship hull re-engineering. The first step in such a process is the measurement of the ship hull, so the first task in developing a re-engineering method was a survey into existing measurement methods. In order to choose the most appropriate measurement method several typical aspects of our object of measurement, such as its size, possible obstructions by scaffolding and poor accessibility, have to be taken into consideration, and we concluded that photogrammetry would be the most flexible method. One of the considerations in this respect was that with photogrammetry not only the 3D geometry can be measured, but that also topological properties will implicitly be taken into account, thanks to the fact that a human is interpreting and processing the photos. So a re-engineering system was developed, which consists of two major parts; the shape processing software and the photogrammetric measurement, which are tightly coupled. This system was applied successfully on a number of industrial projects. From the ship repair practice also the question arose for the measurement of flat construction elements. This led to the development of an alternative, much simpler approach for the measurement and further processing of flat steel parts. The current status is that four photogrammetric methods are available for re-engineering tasks; a) 2D with a single photo, b) 2D with a stereo photo, c) 3D with multiple single photos and d) 3D with a stereo photo. None of these is favorite over the others, it are the properties of a specific task which lead to the choice of the most appropriate method. This tutorial sketches the backgrounds and development of this practical approach, which grew out of the combination of applied research and industrial demand.

1. INTRODUCTION

Our company SARC, a consultancy and software manufacturer for the maritime industry, is involved in ship design and engineering. For this purpose we have developed, and are intensively using, software for the modeling of the shape of the hull. Although this software is mainly used for design activities, from time to time also questions related to the measurement and re-engineering of existing hulls reach our desks. Conventional manual measurements are time consuming, in the first place because the object may be rather large and have a complicated freeform shape, and secondly because creating a virtual model out of the measured 3D coordinates is in general not a trivial task. So we have been looking for a more efficient measurement method, which is preferable integrated with, or at least linked to, a data processing and modeling tool. For such industrial measurements several practical and technological aspects play a role. Practical issues are:

- The harsh shipyard environment, which inhibits the use of sensitive equipment.
- The fact that internal parts may be only accessible through narrow corridors or manholes, which inhibit the use of heavy or sizeable equipment.
- The (in-)availability of sufficient light.
- The possibility that parts of an object are covered by other parts, equipment or scaffolding, and therefore inaccessible by a ray of light or radiation.
- The sheer size of the object, which, for example, makes that large parts of it are inaccessible for a human (without auxiliary construction or equipment).
- The fact that measurements are not very frequently taken, depending on the size and nature of the shipyard typically once every week to once every month. Combined with the fact that it will not always be the same person who takes the measurements, this inhibits solutions which are very com-

plex, or have a long learning curve.

On the technological side important aspects are the correct processing of different shape features (such as discontinuities, or parts with *a priori* shape knowledge, such as their flatness) and the integration between measurement and modeling.
This market demand has, after research into and evaluation of the different possible solutions, led to the development of a dedicated photogrammetric hull measurement program, which is tightly connected to the modeling tools of our design software. The backgrounds and details of both aspects are the subject of this *industrial tutorial*, where in the next section the hull modeling roots will be discussed, in section 3 the hull shape re-engineering and measurement, while in sections 4 and 5 the practical aspects and the market acceptance will be the topics. Finally, some example pictures of real projects are presented.

2. SHIP HULL SHAPE MODELING

In some respect the shape of the hull of a ship is hard to qualify. Some authors have proposed a taxonomy of shapes and singularities, e.g. (Horváth & Vergeest, 1998), where first-order discontinuities as spikes and crests play a role in the division of a surface in more or less distinct regions. But, although ships may also have knuckles, or regions of sudden change of curvature, *in general* they tend to be rather smooth, see fig. 1 for a simple example. But the hull surface is strictly

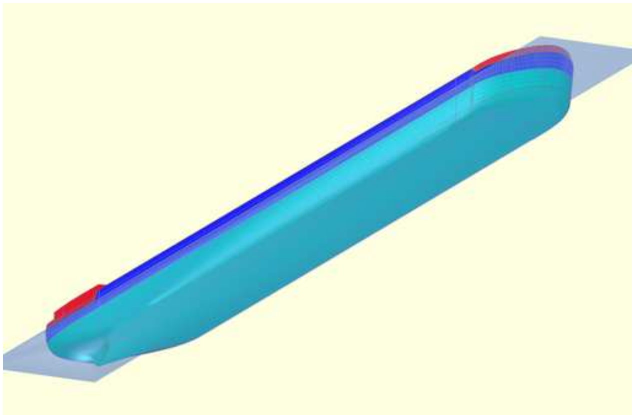

Figure 1 Quite simple inland waterway vessel

not free-form, in general the fore and aft regions are smoothly curved, but in the middle part the side and bottom of the vessel are exactly flat, with a cylindrical circular arc in between. Such a feature is quite common in our profession, but of course also more complex shapes can be encountered, such as shown in figs. 2 and 3.

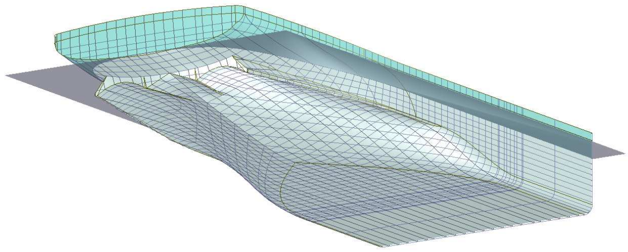

Figure 2 Aft ship with propeller duct

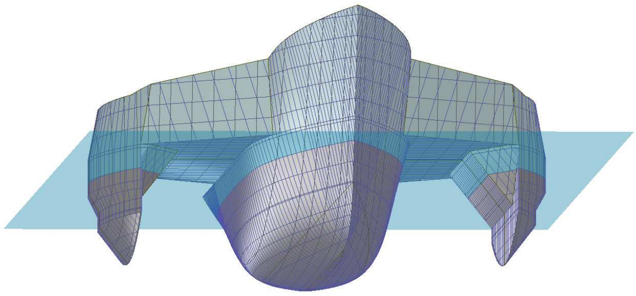

Figure 3 Trimaran hull form

Before we present the modeling method which we apply for this kind of shapes, we have to discuss a number of considerations:

- Traditionally the shape of the hull was man-drawn in orthogonal planes, the so-called waterlines (horizontal), buttocks (longitudinally vertical) and ordinates (transverse vertical). Such a human-centric approach might seem obsolete, because these days oblique planes, or arbitrary spatial curves can just as easily be employed with the aid of CAD. But the experience has shown that a representation in these orthogonal planes gives support to the mental image of the human, who is creating or interpreting the shape. So a network of curves lying in orthogonal planes is to be favored, but that results in an irregular network, see the example in fig. 4.

- Because such a representation of lines in orthogonal planes is quite common, it is also a requirement that it can be *imported* into the applied software. And because the most encountered formats in our industry are 3D DXF polyline and IGES NURBS surfaces, those should be supported.

- The exact representation of a simple midship section consists of the three parts, called flat of bottom, bilge and flat of side in the naval engineering jargon (fig. 5). It must be possible to model such a configuration exactly with the applied modeling method. Although this requirement seems simple, it rules out solutions with continuous spline or NURBS curves or surfaces, because those tend to smooth out the first-order discontinuities at both sides of the circular bilge.

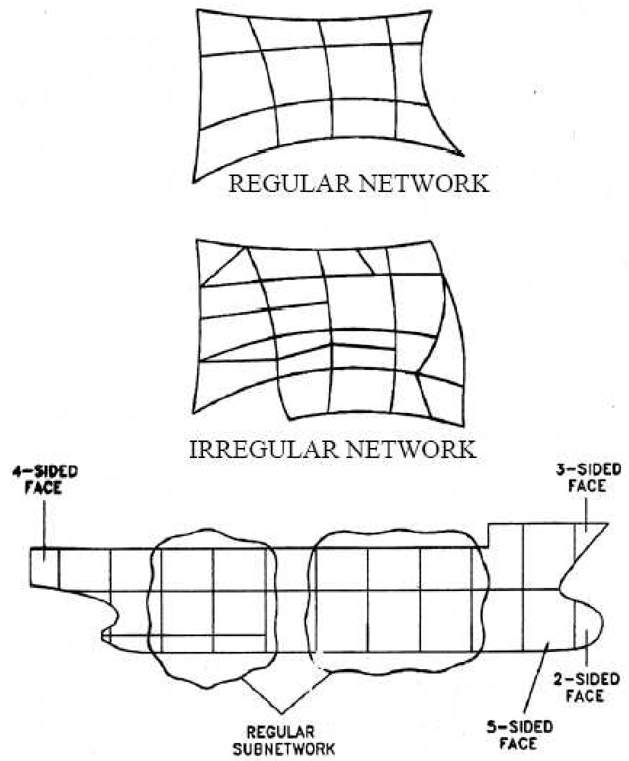

Figure 4 Irregular network

2.1. Applied modeling method

These considerations have led to the development of a hybrid representation of a solid model and curved geometry, the so-called H-rep method,which is proposed in (Koelman et al., 2001) and from which practical experiences are discussed in (Koelman, 2003). This method is aimed at the design and representation of a ship hull, but also on other application areas other authors have presented similar solutions, see e.g. (Congli & Tsuzuki, 2004). Basically, the H-rep approach contains the following elements:

- The topological elements of the conventional B-rep, which are the *vertex*, the *edge* and the *face*;

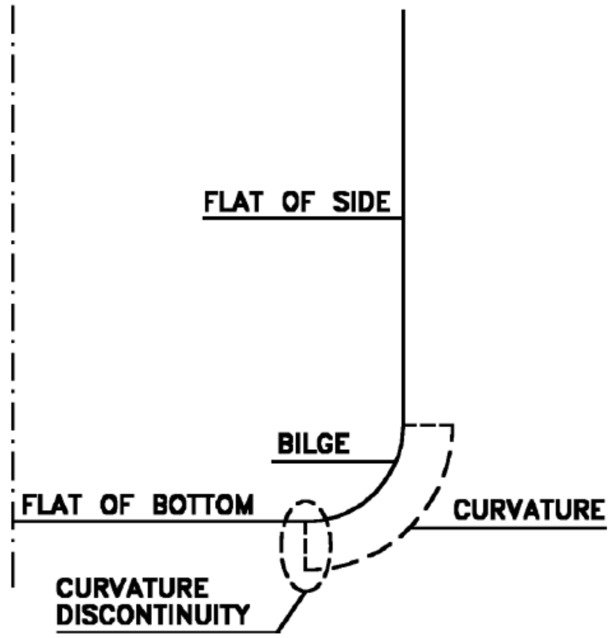

Figure 5 Typical miship section of a ship

- The (curved) *curve*, which consists of a topologically ordered sequence of edges, and which is geometrically shaped by means of a NURBS.
- The *polycurve*, which is an ordered sequence of curves.
- The (curved) *surface*, which is topologically a collection of faces, bounded and intersected by curves. The surface derives its shape by means of transfinite interpolation of neighboring curves.

2.2. The 'Fairway' computer program

This H-rep method has been implemented in a commercial computer program, called *Fairway*, see `www.sarc.nl` for further details. This program, which is used in abt. 40 companies and other organizations, can be employed for a number of tasks, such as:

- Hull form design, starting from scratch, or by distortion and of a previously defined hull form.
- Completion of partial lines plans.
- Shell plate expansions of developable and double curved plates including construction templates.
- Manipulations on multiple solids for hull, superstructures, bow thrusters, etc.
- Export of hull form data to a variety of CAD, CAE and CAM programs.
- Generation of lines plans and Rapid Prototyping models.

From a practical point of view it is interesting to note that the foundation of H-rep elements is only used *inside* the system, in order to maintain topological integrity. The program user only sees and works with curves and surfaces, so the look-and-feel of the User Interface is rather conventional (see fig. 6). For the user the *curve* is the main modeling entity, while the *surface* automatically derives its curved shape from the curves in the vicinity. Shaping and manipulating the hull form is done by manipulating the curves, either by means of moving the curve vertices, or by shifting curve points and a subsequent fairing step.

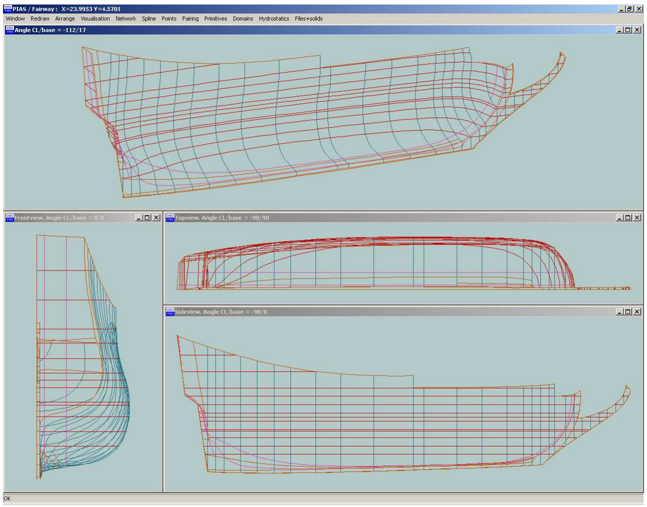

Figure 6 Curve-based User Interface

3. SHIP SHAPE RE-ENGINEERING

This ship hull modeling computer program is quite broadly employed in the dutch maritime industry for design and engineering tasks, which brought also the request for a wider application, in particular in the field of shape measurement and re-engineering. In order to investigate such an option, we must first survey potentially applicable measurement methods:

3.1. Measurement methods

From the available measurement methods we will discuss the four most commonly applied:

- Conventional manual measurement, with measurement tape or a laser distance meter. This method is rather flexible, it does not rely on expensive equipment or special skills, but is not very efficient. Furthermore, the size of object which can be measured accurately is limited to an order of magnitude of tens of meters.
- With a mechanical device, also called a *contact scanner* or a *coordinate measuring machine*, see `http://en.wikipedia.org/wiki/Coordinate_measuring_machine` for an example of a small device. An example of a larger apparatus, intended to measure yachts, is the 2D triangulation device of fig. 7, where the distances R1 and R2 are measured mechanically (as the length of the thin steel ropes). At the measurement point P a rod is attached, with which a human can touch points on the object. The advantages of this method are its modest costs, and the fact that measured coordinates are directly available in electronic form. The disadvantages are its 2D nature, as well as the limited size of objects (which in case of the 2D device can more or less be as large as the rod).
- With laser scanning, see e.g. `http://en.wikipedia.org/wiki/3D_scanner`, which functions on the basis of the time delay of a radiated and captured laser beam, which scans the environment in a high density.
- With photogrammetry, a method which is for many decades applied in areal surveying and architecture, but which finds application in many fields where it is required to determine to the spatial shape of an existing object. Photogrammetry belongs to the category of image-based modeling, a group to which also belong some more exotic technologies, such as *shape from shading*, *shape from silhouette* and *shape from texture*. In subsection 3.3 the technique is further explained, but summarized, with photogrammetry multiple photos of an object are made, and subsequently identical points of the object are identified on different photos, thus leading to a solvable system of equations.

The last two technologies, laser scanning and photogrammetry, are by far the most employed ones, which is the reason to discuss their merits in the next sub-section.

3.2. Laser scanning or photogrammetry?

Although laser scanning is a more recent development than photogrammetry, the latter is far from obsolete. The difference between the two methods is not only present in the measurement method itself, but also in derived properties:

- The order of magnitude of the measured points is

different, with typically a few hundred for photogrammetry, and up to millions for laser scanning.
- As a result of its large number of measured points, the *point cloud*, with laser scanning automated surface matching should be more reliable.
- A laser scanner is a significant investment, while photogrammetric equipment is more modestly priced.
- A laser scanner can only see those parts of the object which are in line-of-sight. In general, for a ship there will not be a single position from where the whole hull surface is visible, so that multiple scanning sessions will have to be performed. In this case it will be an additional task to merge the results of those different scans into a single model in one uniform coordinate system. With photogrammetry photos from different positions can, and should, be taken.
- With photogrammetry the same points must be marked on different photos, so the object should contain uniquely recognizable points, and if those are not naturally present (e.g. as corners or color markings) they should be attached, for example in the form of paint markings or stickers. With laser scanning this is not a prerequisite.
- With photogrammetry there is virtually no limit on the size and complexity of the object to be measured, while the range of a laser scanner is limited (albeit to tens or hundred meters).
- Photo equipment is easier to transport and to install than a laser scanner. This aspect plays an important role in the harsh industrial environment of a shipyard, and certainly in the confined spaces within a ship. On the other hand a photo requires *light*, which is not always sufficiently available.
- In general, laser measurements contain noise, which should be removed by additional processing. Of course photogrammetric measurements also have their inaccuracies, but these are smoothed out in the least-squares process which is applied to determine the 3D coordinates.

When observing a dense laser-scanned point cloud, a human may already 'see' the surface and its features in it. But it appears that the conversion of such a point cloud to a usable CAD model may seem easy, it is a challenging task, see e.g. (Vergeest et al., 2001), where some pitfalls are discussed. One aspect is that feature recognition is not trivial, so it may be necessary to perform a *segmentation*, which is the process of dividing a given point cloud into a number of separate surfaces, a process which is addressed in (Benkö & Várady, 2004), (Rabbani, 2006) and (Vieira & Shimada, 2005). Furthermore, the measured data might be noisy, so that a smoothing procedure might be necessary, or some parts of the object appeared to be obscured, in which case those holes need to be filled, a topic which is addressed in (Pernot et al., 2006). Finally, in recent years research has been devoted to the recognition of constituent elements, such as cylinders, tori, spheres and planes. In (Rabbani, 2006) different methods are proposed for the recognition of parts in industrial installations.

Not all these research topics also apply to photogrammetry, where on the one hand an automated segmentation is more difficult, due to the less dens point cloud, but on the other hand also less necessary, because the pictures are not only used to derive the 3D geometry, but also contain additional visual information which can serve as an aid in the manual segmentation and interpretation process. For automated element recognition the photogrammetric point set is too small, but just as a human can indicate the different segments, he can also specify the basic shape. *A priori* knowledge of the kind of shape of parts of an object can also assist in the photogrammetric measurements itself, in (van den Heuvel, 1999) a method is proposed which can utilize certain properties (planeness, straightness, parallelism etc.) of parts of the object, while (Remondino & El-Hakim, 2006) gives an overview of recent advances in this area.

In the literature on the core question *Laser scanning or photogrammetry?* mixed answers are given; in (Remondino & El-Hakim, 2006) it is concluded that human interaction will remain to play an important role in photogrammetric measurements and modeling. In (Remondino et al., 2005) an quantitative comparison was made between the two methods. For an example object of a church the photogrammetric measurement and modeling took 10 hours, compared to 7-8 hours for laser scanning (the latter only to obtain the point cloud model, the subsequent triangulation step was not further considered), while the accuracies for both methods are comparable. Another example, a small wooden statue, the laser scanning process took 15 hours, but the photogrammetric processing time was not reported, because the image resolution was reported to be too low. In (Milne & Pailing, 2007) a qualitative ranking is presented, where photogrammetry scores 23 points, and laser scanning 17 points.

Focussed on our application, the advantages of laser scanning are the accuracy of the measurements, and the fact that in a short time a large amount of 3D data can be gathered. Disadvantages are the required investment, and the property that with laser scanning a set of points is generated, a *point cloud*, but for our application it will especially be difficult to recognize the different features and discontinuities, which may be present in a ship hull form. So this method is not expected to deliver usable results without manual post-processing.
Advantages of photogrammetry are its flexibility, the equipment benefits (a modest investment, combined with its small size), and the property that there is virtually no limit on the size and complexity of the object to be measured. Disadvantages are the required manual processing, and the necessity of sufficient light. Furthermore, skilled personnel, or at least people with a good spatial awareness, is a requirement.
Considering these aspects we have selected photogrammetry as the most appropriate for the majority of cases, although there is one subject not yet addressed, which is the creation of a computer representation out of the measured data. With each measurement method, the result is a set of points in space, but what we need for our application is an H-rep solid model. Fortunately, there is already a method available to convert a wireframe representation into a solid, see (Koelman & Soede, 2002). So if we are able to generate or create such a wireframe, then all components are available.

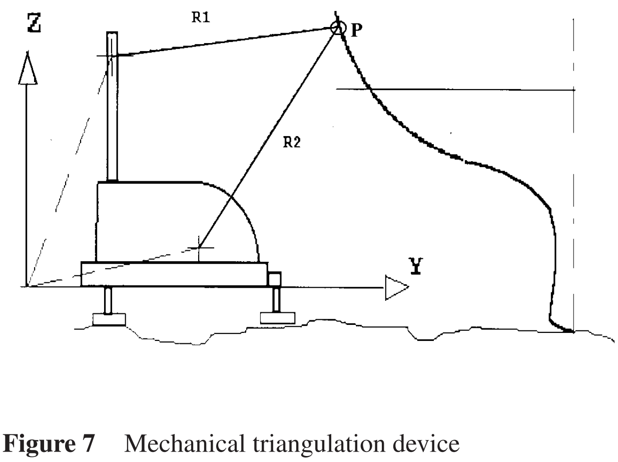

Figure 7 Mechanical triangulation device

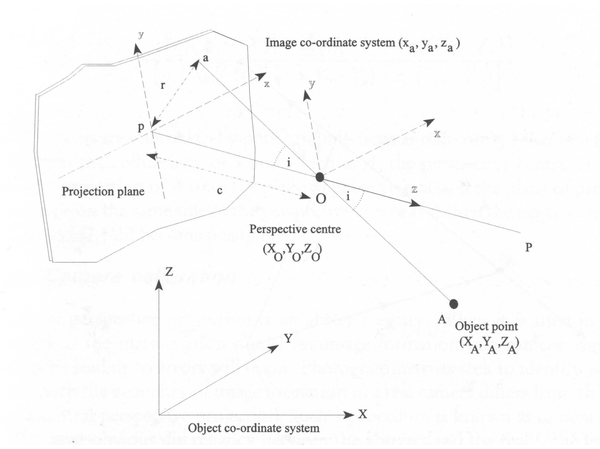

Figure 8 Object and image coordinate systems (from (Atkinson, 2001))

3.3. Background of photogrammetry

The roots of photogrammetry go back to 1859, when the first efforts were made towards object representation based on photographic images. Since 1923 this technology has been continually applied in practice, predominantly for aerial and terrestrial surveillance. Later on, it has been found useful also in close-range applications for the measurement of medical, archeological, architectural and industrial objects, see (Kraus, 2000) and (Kraus, 1997) for details.
The most complete measurement method is based on a plurality of photos, which, in their combination, form an over-determined system of equations, and which in photogrammetric parlance is called *bundle block adjustment*. The basis is formed by the central perspective projection, see fig. 8, where a light ray is shown from object point A, through perspective center O to image point a. The relationship between the coordinates of the object point, $\mathbf{X_A}$, and those of the image point, $\mathbf{x_A}$, is given by the vector equation

$$\mathbf{X_A} = \mathbf{X_0} - \mu \mathbf{R^t} \mathbf{x_a}, \qquad (1)$$

where μ is a scalar and $\mathbf{R^t}$ is the transpose of rotation matrix $\mathbf{R}$, a 3x3 matrix, with the elements functions of the camera rotation angles ω, ϕ and κ :

$$\begin{aligned}
r_{11} &= cos\phi cos\kappa \\
r_{12} &= sin\omega sin\phi cos\kappa + cos\omega sin\kappa \\
r_{13} &= -cos\omega sin\phi cos\kappa + sin\omega sin\kappa \\
r_{21} &= -cos\phi sin\kappa \\
r_{22} &= -sin\omega sin\phi sin\kappa + cos\omega cos\kappa \\
r_{23} &= cos\omega sin\phi sin\kappa + sin\omega cos\kappa \\
r_{31} &= sin\phi \\
r_{23} &= -sin\omega cos\phi \\
r_{33} &= cos\omega cos\phi
\end{aligned} \tag{2}$$

Assuming, for the time being, that the camera position $\mathbf{X_0}$ and the rotation angles are all known. For a single photo there are three equations and four unknowns (μ and the three components of $\mathbf{X_A}$), so this system of equations cannot be solved. However, if there are multiple cameras the system can be solved by *intersection*, as depicted in fig. 9, because now there are five unknowns (two μ's and $\mathbf{X_A}$) and six equations. So each photo (or each point on a photo) adds one unknown and three equations, while each unknown object point adds three unknowns. If N is the number of photo-points, and M the number of unknown object points, the number of unknowns is $N + 3M$, and the number of equations $3N$. In order for this system to be solvable the number of unknowns should be less than the number of equations, or $N > 1\frac{1}{2}M$.

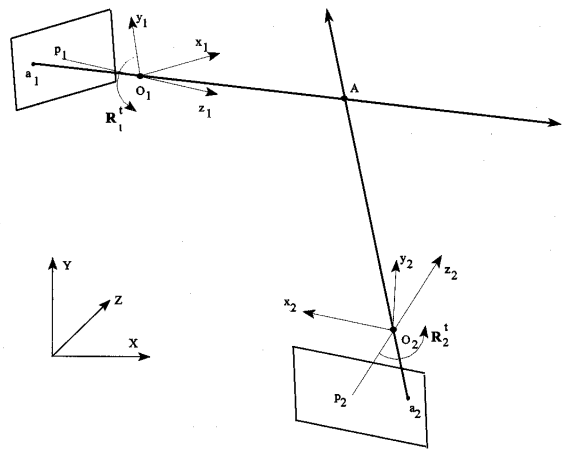

Figure 9 Object and image coordinate systems

However, in practice the assumption that camera position $\mathbf{X_0}$ and the rotation angles are known does not hold, after all a person is taking the photos out of the hand, and there is no way to determine the exact camera position in space, let alone the three camera rotation angles. But fortunately we are in the position to make the system of equations rather over-determined, by adding more photos or photo-points. With a sufficiently high N the μ's, camera position and camera orientation can also be treated as unknowns, and co-solved with the system of equations. With $N \gg M$ and all camera parameters assumed unknown, this system can be solved in least-squares sense, and because matrix $\mathbf{R}$ is non-linear, so is this system, which can be solved by an iterative non-linear least-squares method, e.g. by the *Levenberg-Marquardt* (LMA) algorithm (for which we refer to `http://en.wikipedia.org/wiki/Levenberg-Marquardt_algorithm` for further details).

A critical aspect is the initial estimation of camera positions and orientations; because LMS is an iterative procedure it starts with certain initial values, and in order to avoid that a local minimum is found as solution, the initial values should be properly estimated. For this task there exists a method called *spatial resection*, (Killian, 1955), which should be applied before executing the bundle block adjustment. However with this spatial resection method there is a pitfall, discussed in (Zeng & Wang, 1992), which may arise when we are taking photographs on a straight, circular cylinder through three reference points and its axis perpendicular to the plane through these points - that is sometimes called the 'danger cylinder' problem. If the camera position happens to be on, or in the close vicinity of the surface of this cylinder, the estimation of the camera position becomes ambiguous, which implies that multiple distinct camera positions are found, without the possibility to determine which of those positions is the correct one. Fortunately, in practice we have only seldom encountered this problem.

3.4. Application of photogrammetry in hull shape re-engineering

The method as just described is general, it can be applied on all kinds of objects. Photogrammetric applications in the field of shipbuilding are reported since the eighties, see (Atkinson, 2001) for an application where the shape of the hull of a container vessel was reported to be determined using 1500 landmark points, and some 140 photos. In (Milne & Pailing, 2007) photogrammetry is applied for determining the position and state of internal equipment, and for life-cycle support.

For our application not only the geometry of the points needs to be reconstructed, but also the topology, in the form of connections between the measured points, but with the photos at hand the operator has the required information to do so rather efficiently. The practical execution of the ship hull measurement method will be the subject of the next section.

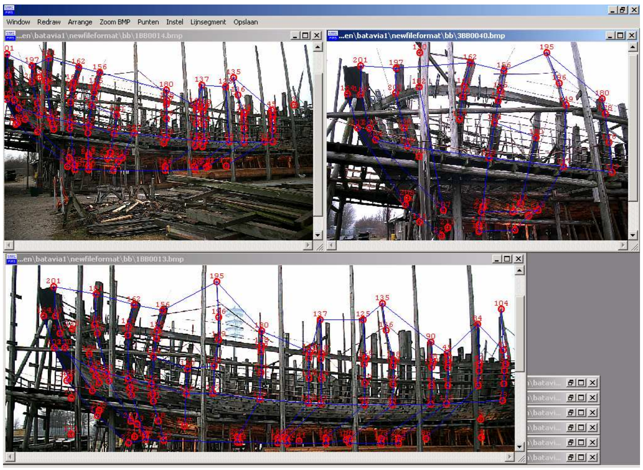

Figure 10 Ship with landmarks, marked and connected on the photo

4. HULL SHAPE MEASUREMENT IN PRACTICE

The typical sequence of actions in a photogrammetric process is as follows:

1. Choosing landmarks as points of measurement. In this step, first the necessary number of landmarks is determined, which is dependent on both the morphology of the object and the objectives of the measurements. It may be evident that in areas of high curvature more landmarks will be placed than in flatter parts. Similarly it will be beneficial to put landmarks on discontinuities or other features.
2. Placing landmarks on the object. For the measurements, various markings (spots, lines, symbols, etc.) are placed on the hull surface by e.g. chalk, paint or stickers, with the help of scaffolding or a crane, in particular, in the case of large-sized objects. In addition to the artificial markers, naturally distinguishable points such as corners or visible intersections between welds can be also used as marking points.
3. Obtaining the world coordinates of a limited number of landmarks, the so-called reference points. In order to fix the object in a Cartesian coordinate system for a limited number of reference points (typically four to six in total) the world coordinates must be established. These coordinates are usually obtained by traditional methods, such as measurement tape or laser distance meter. It is possible that for such a reference point not all three x, y and z coordinates are specified, but only those (x, or y or z) which can conveniently be measured, or, alternatively, measured distances between landmark points.
4. Taking photos from different positions. Photographs of sufficient resolution are taken. The spatial positions of the landmark points should be recognizable from the photographs. Furthermore, each landmark must be clearly visible on at least two photos.
5. Determining the position of each landmark on each photo. By *pinpointing*, which means that each photo is shown on screen, and each landmark on each photo must be pointed to with the cursor, so the processing software is able to determine the coordinates (in the coordinate system of the photo) of that point. Should a sticker with a unique pattern be applied as a landmark, it could be possible to identify the landmarks automatically, but that requires additional pattern recognition techniques.
6. Creating connections between landmarks. The purpose of this step is to create a connection between points that are 'naturally' connected because they form a distinctive feature on the hull surface, or are, more or less, in one of the orthogonal planes which play an important role in the mental representation of the hull shape. These connections are actually a constituent of the *wireframe model*, which is required, as discussed in subsection 3.1. Fig. 10 shows a screen dump of this stage, where on each photo all landmarks are indicated and connected.
7. Obtaining the position of each landmark point, with the method as discussed in subsection 3.3.
8. Now the positions of all landmark points are known, as well as their connections, so basically the shape retrieval process is completed, and a 3D model is available, see the example in fig. 11. Although this model is valid, it needs some postprocessing, because the choice and distribution of the curves on the surface is a 'coincidental' side-effect of the measurement process, and not as required to get a conventional and smooth picture. The final result is shown in fig. 12.

It should be emphasized that with this way of operation the photos serve a double goal; in the first place they are used as a measurement tool, to reconstruct the coordinates of the landmark points. But secondly they are used to create the topology of a network of typical curves on the hull surface. In this respect, the photographs are an aid to the human, albeit unconsciously, in the heuristic process of recognizing and fixing the character of the surface, and that of typical curves on the surface.

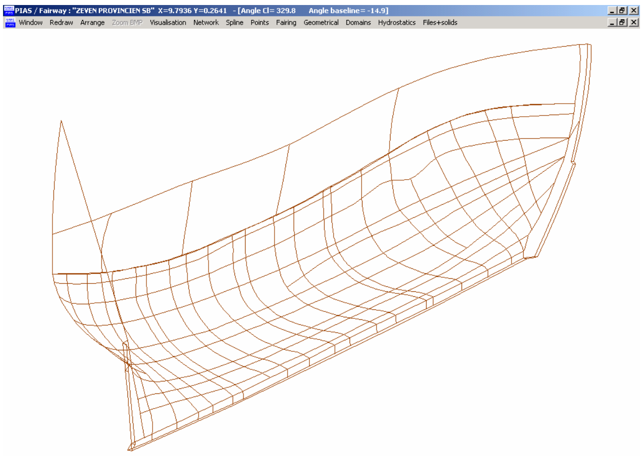

Figure 11 Hull shape before post-processing

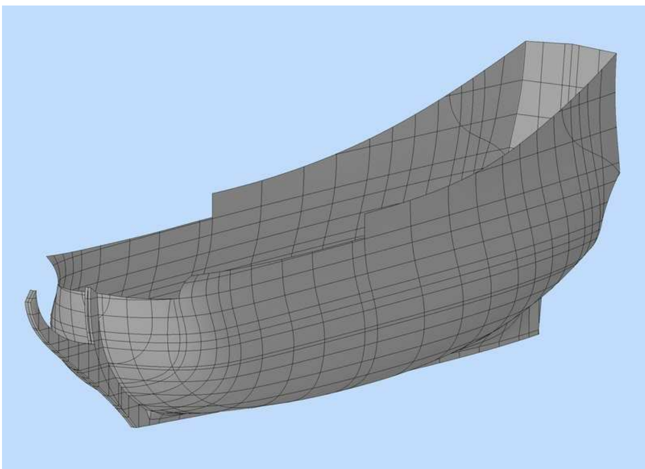

Figure 12 Final result after post-processing

5. MARKET ACCEPTANCE AND PRACTICAL CONSIDERATIONS

The photogrammetric method for the measurement of 3D objects, as described until sofar, exists for a couple of years, and has been applied on a number of projects, on hulls of varying size and complexity. In the market photogrammetry is often compared with laser scanning, and it depends on the nature of the object and the circumstances which method is preferred; recently we had a project at hand where from a motor yacht the hull shape was measured by photogrammetry, and the interior by laser scanning. Besides for the measurement of 3D objects, the market also showed interest in the measurement of simpler objects, which is the subject of the next sub-section.

5.1. Easier methods, for objects of lower complexity

Typical applications of photogrammetry are in the ship repair and conversion industry, and with this background a large south-European ship repair yard decided to investigate its merits. Two of our employees, both msc. level naval architects, went to the yard, in order to investigate and demonstrate the possibilities. It was our intention to focus on the 3D measurement of entire hulls, or parts of it, the latter being a typical ship repair issue, where the shape of damaged steel parts can be measured on the other, intact, side of the ship, and then be mirrored, see fig. 13 for an example worked out at that shipyard.
But it appeared that this 3D exercise was not *completely* what the yard required. Of course, whenever work on the 3D outer hull needs to be done it will prove to be handy, but on the other hand, in the ship repair business the majority of parts are *flat*; such as originally flat, but ruptured hull parts, or flat internal construction elements, such as brackets, floors and girders, which may need renewal because of damage or corrosion. This particular requirement for reconstructing the shape of 2D elements stroke us as a kind of odd; after all for an academic 2D is not more that a restricted kind of 3D. It took a while before we realized that our present 3D measurement and reconstruction method is powerful, but also laborious, while it also requires quite some skills from the people who apply it.
As soon as we realized the potential of the question, we started to develop simpler methods, for simpler elements, which are more robust and less sensitive to errors. The specific developed methods are:

- 3D stereo photography. With this method a dual photo can be shot, with 2 cameras on a beam, see fig. 14 for the principle. This method is intended for parts which are so small that they fit on a single photo, such as the plate of fig. 13. The advantage of this method is its simplicity, compared with

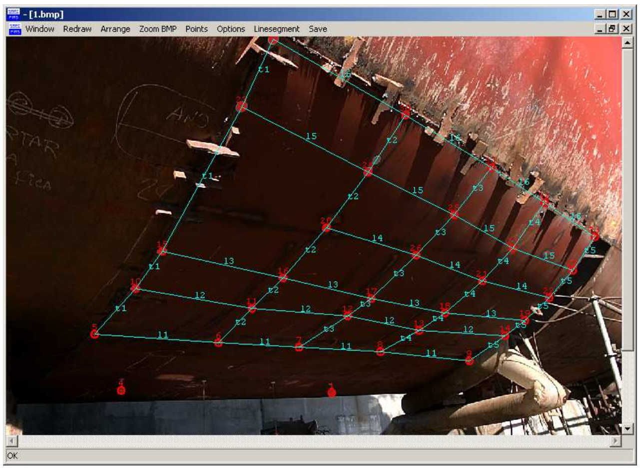

Figure 13 Measurement of single hull plate

the full-blown block bundle adjustment of subsection 3.3, the related fact that the camera positions and rotations do not play a role anymore, and consequently the fact that with this method the 'danger cylinder' is avoided.
Contrary to the block bundle adjustment method, this stereo method does not rely on conventionally measured reference points. This is an advantage, but the backside is that the stereo setup must be properly calibrated, in order to determine the distance and relative positions of the two cameras. Also a quite firm beam construction is required, so that differences in relative positions are minimized. Furthermore, there is a balance between accuracy and practicality; For a high accuracy the distance between the two cameras should be rather large, but a large beam is difficult to handle, and vulnerable with those delicate cameras at both ends.

- 2D stereo photography, which is similar to its 3D counterpart, but where coordinates are explicitly projected in the plane which fits best, in least-squares sense, through the measured points.
- 2D mono, where with a single camera a single photograph is taken. In order to determine the dimensions of the object, four reference points on the object should be measured, and processed. However, if this 2D mono mode is frequently employed, it might pay off to prepare a number of reference objects of known dimensions, which can quickly be sticked upon the object.

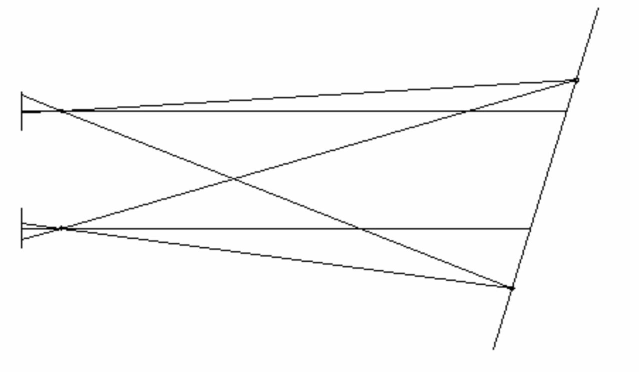

Figure 14 Principle of stereo vision

5.2. Cameras and calibration

The photogrammetric theory presented until sofar is *idealized*, but in the real world the light rays travel along a less ideal path. Each camera has some distortion, which can be modeled theoretically with calibration parameters. These parameters represent a mechanical non-perfectness (for example that the film or light-sensitive chip is not exactly located in the central axis of the lens), or an optical abberation (the well-known effect that with wide-angle lenses straight lines at the edges of the picture are not perfectly straight on the image). Specifically for photogrammetric application, the industry has developed special cameras where this distortion is as low as reasonably possible, these are the so-called *metric* cameras. But even with a metric camera some distortion remains, for which can be compensated with some theoretical compensation formulae, in combination with some camera-specific calibration coefficients. However, the recent years have shown the emerge of high-resolution amateur Single Lens Reflex (SLR) cameras, which are modestly priced. We have applied such an ordinary camera as well for photogrammetry, in combination with the same calibration procedure as applied for a metric camera, and have found the results to be comparable with our dedicated metric camera[1]. A condition for the application of an ordinary SLR is that a fixed-focus lens is used (because for zoom lenses the calibration factors are dependent on the focal length). Because it cannot be ruled out that the camera distortion varies over time[2], or with the circumstances, such as temperature or moist, the calibration parame-

[1]Where the remark can be made that this comparison is not strictly honest, because our metric camera is already a bit elder, and has a lower resolution than the SLR camera.

[2]Although the variation of calibration seems less likely with a metric camera, because it is more rugged.

ters should be re-determined on a regular basis. One possibility is to co-determine the calibration parameters with an ordinary bundle block adjustment measurement, because the system of equations can be quite over-determined, so there is room for a couple of additional unknowns in the form of the calibration coefficients. However, we never had really the courage to apply this method in a practical measurement, after all there are quite some possibilities for human errors (such as measurement errors with the reference points, or identifying the wrong landmarks) and with free camera calibration parameters such errors would be 'smoothed out' in the end solution, and therefore be less recognizable. For this reason we have made a calibration board, with known coordinates, which is used as object for a regular calibration.

5.3. Does photogrammetric ship measurement pay off?

The answer to this question is dependent on the particular constellation, e.g. how frequent are objects measured, what is the knowledge level of the personnel, are the objects good visible and accessible etc. Conventionally, in our industry the measurements are done on an *ad hoc* basis; by one or two men, with measurement tape, sometimes aided with a wooden frame or something alike. For different objects the costs involved with method is estimated in table 1, where also the payback period of the investment for photogrammetry is listed[3].
A second comparison is between photogrammetry and laser scanning. In subsection 3.2 a general comparison is given, but those subjects with a particular relevance for our application are summarized in table 2.

We end this sub-section with the remark that none of the two technologies can be considered as the absolute favorite. Each method has its own merits, and the choice also depends on the frequency of measurements, and the organizational structure of the applying company. Anyway, our company is quite satisfied with the capabilities of the photogrammetric method, with *flexibility* as prime reason.

6. PRESENT STATE

At this moment we now have four measurement methods fully implemented:

- 3D mono photography, the bundle block adjustment method of sub-section 3.3. This method is applied in practice on a regular basis, see e.g. the project in fig. 15, which shows a vessel with a large hole in its side (due to a collision), and where the shape of the area around the hole is reconstructed in order to re-engineer the curved shape of the missing part.
- 3D stereo photography, as discussed in sub-section 5.1, which is (much) easier to use than the 3D mono method, albeit only for objects which fit on a single stereo photo. With this method all landmarks points on both stereo photos need to be pinpointed, in order to establish their spatial coordinates.
- 2D stereo photography, which is the candidate method to be applied on a larger scale for flat construction parts, e.g.the bracket as shown in fig. 16. Compared with the 3D stereo method, this 2D

[3] With the investments including instruction and training, and the processing time including post-processing and input in a CAE system.

Object	Man-hours conventional measurement	Man-hours photogrammetry	Investment photogrammetry	Payback period photogrammetry
Complete hull (one side only, because of symmetry)	200	32	€25000	3 projects
A single curved shell plate	24	3	€15000	12 shell plates
A single flat bracket	1	1/2	€15000	500 brackets

Table 1 Estimated costs of different measurement methods

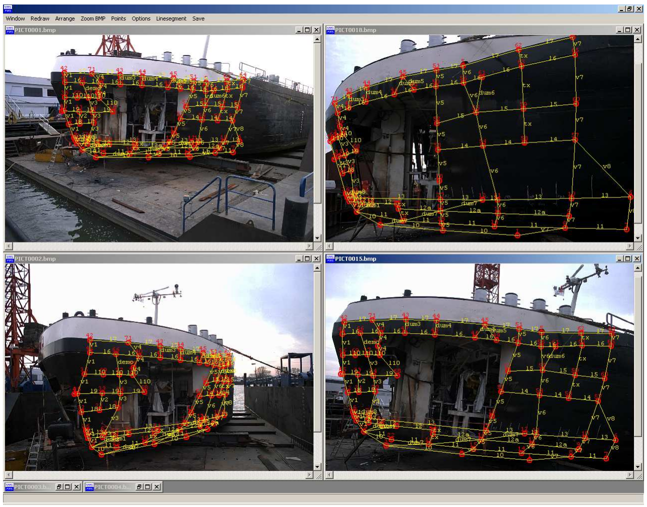

Figure 15 Hole after damage, to be re-engineered and repaired

	Laser scanning	Photogrammetry
Data acquisition	Automatically, without human intervention	With human intervention (attaching stickers, pinpointing on-screen). Sufficient light required.
Complexity of objects	Limited to objects within line of sight. Otherwise more complex composition of measurements, possibly with human intervention	No limitation
Accuracy	Sufficient (millimeters to centimeters)	Sufficient (millimeters to centimeters)
Feature or discontinuity recognition	Not guaranteed, possibly human intervention	Included in process
Investment	Significant	Modest
Equipment	Relatively large and vulnerable	Small, not particularly vulnerable, but not rugged
Requirements	Line of sight, proper distance to object, little obstruction (e.g. scaffolding)	Visible, more or less clean surface

Table 2 Qualitative comparison between laser scanning and photogrammetry, focussed on application in the shipbuilding industry

method is more efficient, because only a few (typically three or four) landmark points have to be pinpointed on both stereo photos, while all other points only need to be pinpointed on one of the two photos.

- 2D mono photography, which can be employed for flat items which are too large to fit on a single stereo photo, but which has the disadvantage that additional reference objects or measurements are necessary to determine the proper size of the object.

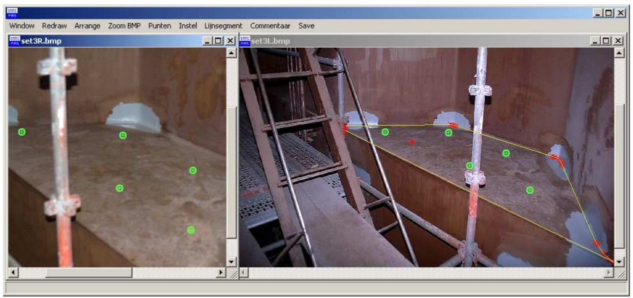

Figure 16 Flat bracket in a bulk carrier

7. CONCLUSION

In this industrial tutorial we have discussed the market demand for the measurements and modeling of a variety of objects which may be encountered in the shipbuilding and repair business, ranging from partial or complete ship hulls to flat construction parts. In particular we have evaluated laser scanning and photogrammetry, and found that, although laser scanning might potentially be more powerful thanks to its high resolution, in *general* the subsequent data processing and geometric modeling steps are too complex to be performed fully automatically. Photogrammetry also requires a human postprocessing step, but here the pictures not only serve the determination of the 3D coordinates, but are also an aid in the recognition of specific parts and features of the object. So, photogrammetry was chosen as our preferred measurement method, and as much as possible integrated within our existing H-rep-based design and modeling software.
For the measurement of flat objects dedicated approaches have been developed, where modeling plays a less important role (after all, this world is 2D), and where the measurement process is aided by the assumed flatness of the objects.
We hope these applications can serve as inspiration for similar industrial tasks.

REFERENCES

Atkinson, K. B. (2001). Close Range Photogrammetry and Machine Vision. Caithness, UK: Whittles Publishing.

Benkö, P. & Várady, T. (2004). Segmentation methods for smooth point regions of conventional engineering objects. Computer-Aided Design, 36(6), pp. 511–523.

Congli, W. & Tsuzuki, M. (2004). Representation of Curves and Surfaces in B-rep Solid Modelers. In J. C. Adamowski, E. H. Tamai, E. Villani, & P. E. Miyagi (Eds.), ABCM Symposium in Mechatronics, volume 1.

Horváth, I. & Vergeest, J. S. M. (1998). Natural Representation of Shapes with Singularities. International Journal of Shape Modeling, 3(4), pp. 127–140.

Killian, K. (1955). Über das Rüchwärtseinschneiden im Raum. Österreichische Zeitschrift für Vermessungswesen und Photogrammetrie, (43), pp. 97–107 , 171–179.

Koelman, H. J. (2003). Application of the H-rep Ship Hull Modelling Concept. Ship technology Research, 50(4), pp. 172–181.

Koelman, H. J., Horváth, I., & Aalbers, A. (2001). Hybrid Representation of the Shape of Ship Hulls. International Shipbuilding Progress, 48(3), pp. 247–269.

Koelman, H. J. & Soede, W. B. (2002). Construction of a Manifold Ship Hull Model, Derived from a Wireframe

Mesh. In I. Horváth, P. Li, & J. Vergeest (Eds.), the Fourth International Symposium on Tools and Methods of Competitive Engineering - TMCE 2002.

Kraus, K. (1997). Photogrammetry, volume 2. Köln, Germany: Dümmler.

Kraus, K. (2000). Photogrammetry, volume 1. Köln, Germany: Dümmler.

Milne, D. & Pailing, G. (2007). Photogrammetry, a picture of the future. In 13th International Conference on Computer Applications in Shipbuilding.

Pernot, J.-P., Moraru, G.-F., & Véron, P. (2006). Filling holes in meshes using a mechanical model to simulate the curvature variation minimization. Computers & Graphics, 30(6), pp. 892–902.

Rabbani, T. (2006). Automatic reconstruction of industrial installations using point clouds and images. PhD thesis, Delft, The Netherlands.

Remondino, F. & El-Hakim, S. (2006). Image-based 3D modelling: a review. The Photogrammetric Record, 21(115), pp. 269–291.

Remondino, F., Guarnieri, A., & Vettore, A. (2005). 3D Modeling of close-range objects: photogrammetry or laser scanning? In Videometrics VIII, Proceedings of the SPIE-IS&T Electronic Imaging, volume 5665 San Jose, CA, USA.

van den Heuvel, F. A. (1999). A line-photogrammetric mathematical model for the reconstruction of polyhedral objects. In El-Hakim & Gruen (Eds.), SPIE Proceedings, Videometrics VI.

Vergeest, J., Horváth, I., & Spanjaard, M. (2001). A methodology for reusing freeform shape content. In 2001 Design Theory and Methodology Conf., DETC'01/ DTM-21708 ASME, New York.

Vieira, M. & Shimada, K. (2005). Surface mesh segmentation and smooth surface extraction through region growing. Computer Aided Geometric Design, 22(8), pp. 771–792.

Zeng, Z. & Wang, X. (1992). A general solution of a closed-form space resection. Photogrammetric Engineering & Remote Sensing, 58(3).