On the Feasibility of Using Large Scale Photogrammetry to Accurately Determine In-service Strain Distribution Across Three-Dimensional Textile Roofs

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Abstract

This paper presents the results obtained from a proof of concept simulation study into the feasibility of using a photogrammetric measurement system to accurately determine in-service strain distribution across full scale three dimensional textile roofs. The simulation has been carried out using synthetic images generated by photo-realistic raytracing software. Such a strategy allows for the incorporation of poor lighting and other potentially degrading effects. Particular attention has been addressed to the expected effects on measurement precision of image resolution; target shape, size, number and contrast; and operator access.

Surface Stressed Architectural Textile Structures

This work is concerned with the design of tensile membrane structures constructed from coated textile fabric. Such structures are characterised by their visually dramatic organic curves and light airy atmosphere. A rendering of a typical structure is shown in Fig. 1.

Design Procedures

In order to build a surface stressed textile roof the following design steps must be carried out: *Formfinding, Load analysis, Cutting pattern generation* and *Detailing* [5,6,7,8,9]. Typically architects will specify rough concepts of desired surface form together with geometric constraints on parameters such as height, curvature, mast radii and so on. The designer must then determine a smooth surface which satisfies these constraints, while additionally satisfying structural constraints. To this end equilibrium modelling software tools are now routinely used to generate force-equilibrant surfaces, as well as perform geometrically non-linear load analysis. Through judicious variation of membrane prestress specification the structures load resisting qualities can be optimised for the critical applied load. It is a common misconception that constant surface prestress will be optimal. In reality it is invariably desirable to use variable stress fields, especially in radial high point forms. Having determined a suitable form through a sequence of *Formfinding/Load Analysis* cycles, it is necessary to create cutting patterns for each of the individual fabric cloths and to dimension the various connections, masts, cables and so on. The creation of high quality cutting patterns is a very complex problem requiring sophisticated tools to help convert the original non-developable surface into planar strips with a minimum of distortion. Once this procedure has been carried out it is necessary to compensate the geometry to allow for the required prestrain. It is with this aspect of the design procedure that the following work is most concerned.

Figure 1: Rendering of a typical stressed membrane surface structure.

Cutting Pattern Compensation

In practice pattern compensation is typically achieved through the application of orthogonal scaling to the generated pattern. The reduction values used being determined according to a mixture of membrane material data, specified cloth prestress level, and designer experience.

It is well known that the textiles used in the construction of architectural stressed membrane surfaces exhibit highly non-linear anisotropic elastic behaviour. Due to this situation, in order to be able to accurately generate cutting patterns for such structures, it is necessary that a large number of simplifications to the material model be made. This still requires that very high quality material elasticity data is available to the engineering team so that they can make the best choice for prestress compensation values.

Once a design is finished and the structure erected, it is extremely difficult to assess the efficacy of the compensation strategy adopted. If wrinkling occurs then the site prestressing is varied to alleviate the problem, but no simple system exists to measure the strain over the membrane surface. With respect to the measurement of in-situ membrane stresses in full-scale doubly curved structures only very limited work has been carried out using contact mechanical techniques. In addition to requiring complex calibration such a strategy suffers from being slow and requiring operator access to the membrane. Consequently it is infeasible to measure more than a few representative areas.

Measurement of the Elasticity of Textiles for Architectural Membrane Structures

To date most investigation of textile elastic behaviour has been conducted using small test samples loaded in either uni- or bi-axial machines. Traditionally, in such systems strain measurement has been determined mechanically at the sample limits. Recently, this procedure has been extended through the use of two dimensional optical strain measurement systems [3]. Such a procedure offers many advantages over mechanical systems. Firstly measurement can be made at positions distant from, and therefore unaffected by, the disturbance of the clamping system. Additionally, many more observations can be achieved in a two dimensional field resulting in better sampling.

Requirements for Better Cutting Pattern Compensation

It is clear that the quality of textile elastic property measurement as well as modelling of the micro-structure itself is now very high. Unfortunately, it is extremely difficult for this knowledge to be applied in engineering practice. This is in part due to the complexity of the models, and lack of a standardised membrane property database between the various fabric manufacturers. Until it is possible to accurately assess the accuracy of the complex elastic models through comparison of predicted with real strains, no progress can be made in this direction. There is, therefore, a large requirement for a low cost yet comprehensive system for measuring membrane strains in three dimensional membrane surfaces. To address this need the use of *Large-scale Photogrammetry* is proposed.

Large-scale Photogrammetry

Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images, patterns of electromagnetic radiant energy and other phenomena. Geometrically, the measurement of image coordinates corresponds directly to the measurement of direction vectors in space with a theodolite. Triangulation methods can therefore be used to derive three dimensional information such as location, orientation, size, and form of objects in space for numerous purposes.

General Principles

Photogrammetry is a non contact method which has many advantages. These include; short object occupation time, fast acquisition of data (images), high flexibility, high accuracy, permanent record, and documentation of the present state of objects. Sophisticated mathematical camera models and advanced algorithms are used to improve the precision, accuracy, and robustness of photogrammetric evaluations. Redundancy (many images from many views) is used to improve reliability.

The basic principle in photogrammetry is the pinhole camera or the collinearity condition. The collinearity condition expresses that a point in object space, its corresponding point in the image plane and the centre of perspective lie on a straight line. It thus assumes an ideal imaging geometry. Real cameras do not have the properties of the pinhole camera. Consequently, some deviations from this simple model are required. In photogrammetry the pinhole model has traditionally been extended with a distortion correction term that models difference in scale and lack of orthogonality between the image axes as well as radial lens distortion.

Originally photogrammetry used analogue, mechanical instruments and later changed to analytical methods. In the last few years the field of photogrammetry has become increasingly digital; first through the use of scanned analogue images, and then through the introduction of digital cameras directly. The digital approach has many advantages. Since environmental changes do not affect the images, they are geometrically stable. Digital image processing techniques can also be applied leading to better and more precise results.

The most precise and reliable three dimensional results are obtained using the bundle adjustment technique. Bundle adjustment uses measured image coordinates, control point information, distances in object space and other additional observations to simultaneously determine the exterior orientation of the images (position and direction at exposure time) and three dimensional object coordinates of new points in one step. Additional parameters can be applied for camera calibration.

Typical Applications

Close range photogrammetry is used in various types of application fields such as

- Architecture
- Industrial inspection
- High precision point determination (targeted or natural points)
- Surface measurements (cars, aeroplanes, industrial goods,...)
- Quality control
- Non destructive testing (deformation analysis)
- Biomechanics
- Camera calibration

PICTRAN

In this investigation the **PICTRAN** digital photogrammetric system [12]. This state-of-the-art system incorporates all the necessary features for photogrammetric measurements and object reconstruction in a user friendly windowed interface. It can be used with scanned analogue imagery as well as with digital cameras.

Bundle adjustment is a very non linear procedure which in general needs good quality approximate values for the object points and the parameters of exterior orientation. The bundle adjustment system implemented in **PICTRAN** uses a sophisticated technique to automatically provide approximate values [4]. It also allows the calibration of cameras.

Proposal for Experimental Research in the Monitoring of Textile Roof Strain.

Objectives

It is envisaged that two fundamental objectives can be addressed with the following proposed system. Firstly to be able to compare the design strains specified and those actually existing in a realised textile structure. Secondly, to perform long term monitoring of membrane strains in order to investigate creep effects. Through the establishment of such a capability the efficacy of more complex non-linear elastic models can be assessed. Ultimately it is hoped that membrane structure design systems will be able to accessing rich elastic parameter sets provided by the membrane manufacturers in a routine manner.

Strategy

A distinction should be made between structures built specifically for the proposed research programme, and conventional textile structure projects which are monitored. In the latter case it is clearly unacceptable to permanently mark the membrane in a visible manner. Targets must therefore either be attached temporarily or projected optically. Since the use of identical targets during successive measurement epochs is a requirement for worthwhile long term creep deformation analysis, this would seem to rule out monitoring of real structures. It would, however, be possible to permanently mark membranes in such a way that the marking was invisible from all human viewing distances, yet permit temporary targets to be accurately applied at known positions.

In the case of dedicated test structures, since no constraints exist on the visual appearance of the membrane surface, permanent targets may be used. Indeed it would be both cost effective and technically desirable to have a target pattern printed into the fabric itself.

Feasibility Study

In order to test the feasibility of using photogrammetry to determine membrane strain using synthetic images the following steps needed to be done. A computational model of a test structure had to be generated and converted into a format suitable for rendering in a raytracing system. From this, two series of images needed to be created. The first set were used to determine the overall structures form, while the second were taken at a close distance and determined the small scale membrane geometry. Additionally, a calibration of the raytracer camera was required.

Problem Specification

The design configuration chosen for the feasibility study was a 6m x 6m x 4m hyperbolic paraboloid shade structure (See Fig.). This type of structure is extremely common and exhibits all the features of a typical design.

Generation of Synthetic Images

Photo Realistic Renderer

The renderer chosen to generate the synthetic images used in the following simulation was the *Persistence of Vision Raytracer* **POVray** version 2.2.

Structural Model

The fundamental geometric model data was generated using the **Easy** surface structure design system's force-density formfinding tool **Fofin**. The data so obtained was composed of nodes and links. A triangulated surface representation was additionally obtained using the **Easy** tool **Masgen**. The usual technique for preparing photorealistic renderings of structural models developed using **Easy** is to export the data as an **AutoCAD** DXF format file. This can then be read by any third party renderer. In order to exploit the higher level design information available in the **Easy** data, the basic data was converted to **POVray** format using the dedicated **Easy** tool **EIN2POV**.

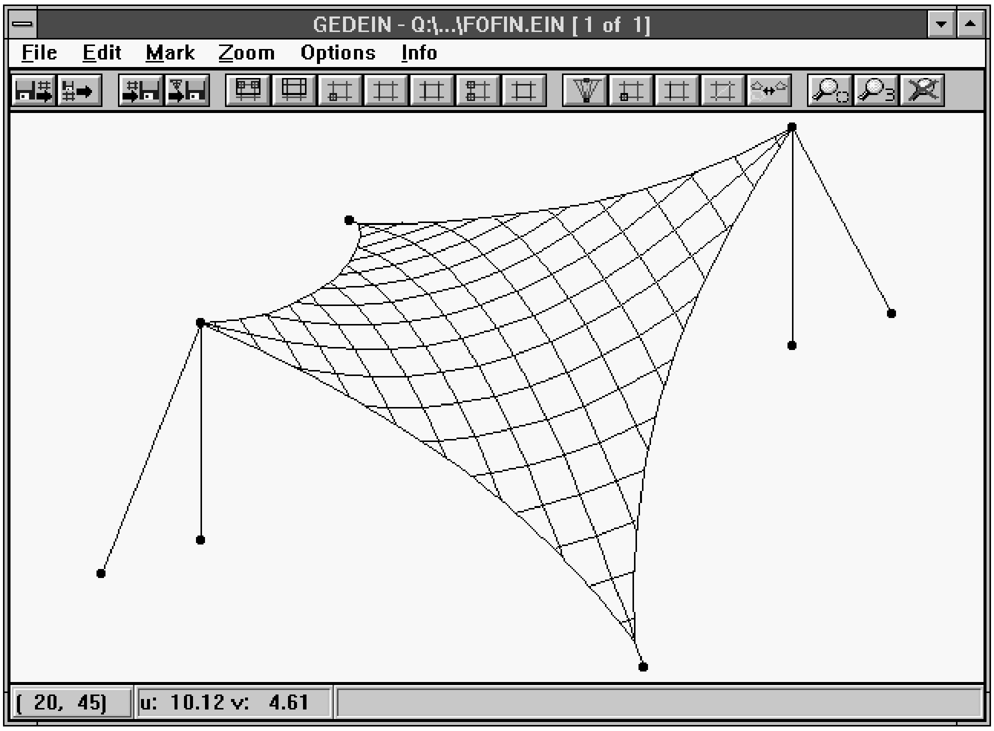

***Figure* 2**: Easy model of 6m x 6m x 4m hyperbolic paraboloid shade structure.

Target design
Targets needed to be created over the membrane, at the tops of the masts and on the ground. Due to the location and viewing angle requirements the mast targets were modelled using spheres. In order to model the planar disk shape of both the ground and membrane targets, low aspect-ratio cylinder objects were used. The membrane targets were aligned with the membrane through calculation of the surface vector normals. Target thickness was determined in such a way that the intersection of the membrane triangles and the targets never extended to the top or bottom surface of any target. The resulting targets have a thickness greater than would be expected in a real situation. The distance between the centre of the targets top and bottom surfaces is therefore larger than would occur with real membrane. A small modelling error is consequently introduced.

Colour, Lighting and Texture
Due to the overwhelming predominance of white textiles in architectural membrane structures, black was chosen for the target colour. White point light sources were used for preliminary image generation. Subsequent to determination of appropriate camera positions, White area lights were substituted in order to introduce soft shadows in the final images, and thereby more accurately represent realistic conditions. As an alternative to the use of dark targets on light membrane, the simulation of the use of retroreflective targets in dark conditions can be investigated through the use of white targets on dark membrane and dark environment. Target and ground textures were modelled with a dull matt finish. In order to introduce realistic and potentially degrading specular reflective effects all other surfaces were considered shiny.

Cameras and Image Resolution
The **POVray** camera uses a simple pinhole model. Focal length is fully variable, as is image aspect ratio and resolution. There is, however, no ability to model limited depth of field and resulting out of focus effects, or motion blur. While the latter is of no relevance for this study, the unreal perfect focus throughout the model space could in some situations prove significant. The focal length specified is approximately 40 mm and the corresponding image area is 56 x 42 mm^2 with a resolution of 800x600 pixels.

Calibration of Renderer Camera

In order to determine exact values for the focal length and principal point, a camera calibration was performed. The values for the focal length and principal point determined are used in the subsequent photogrammetric camera model.

Geometrical Setup (Target Points and Camera Positions)

The camera calibration was done by bundle adjustment with a set of 9 images of a predefined point field. These are reproduced in Figures 6(a)-(i) of the Appendix. 36 target points on a regular grid with a spacing of 1 m were used. The targets used were circular black dots on a white background with a diameter of 0.06 m.

Photogrammetric Analysis

The targets were measured in the images with an accuracy of 0.03 pixel (0.002 mm) using **PICTRAN**'s semi-automatic measurement mode. This uses a digital image matching techniques (Least Squares Template Matching) [1]. The actual focal length resulted in 39.898 mm (±0.002 mm). The principal point lying in the centre of the digital image.

Measurement of Overall Geometric Form

Geometrical Setup (Target Points and Camera Positions)

In order to determine the overall geometric form of the surface, 30 targets on the membrane were used. As a reference some control points on the ground were targeted as well as two points at the mast tops. For the membrane and the ground targets black circular disks with a diameter of 0.06 m were used. The mast top targets were black spheres of the same diameter.

Ten images from an approximate distance of 6 m were used to adequately cover the membrane surface**.** These are reproduced in Figures 7(a)-(j) of the Appendix.

Photogrammetric Analysis

As with the calibration test field, the targets were measured in the images using **PICTRAN**'s semi-automatic measurement mode where possible. Many of the targets could not be measured automatically due to their small inclination relative to the viewing direction distorting their shape. These targets had to be measured manually. Manually measured points can be expected to have an accuracy of 0.3 pixel (0.02 mm) whilst automatically measured points are in the range of 0.03 pixel (0.002 mm). The overall accuracy for these measurement averages at 0.15 pixel (0.01 mm) in the image.

Typical screen shots obtained from **PICTRAN** during the digitising and target measurement stages are shown in Figures 3 and 4.

The object points on the membrane were determined with an accuracy of 1-2 mm. The internal accuracy measures of the bundle adjustment showed very good correspondence to the differences between the determined and the predefined points.

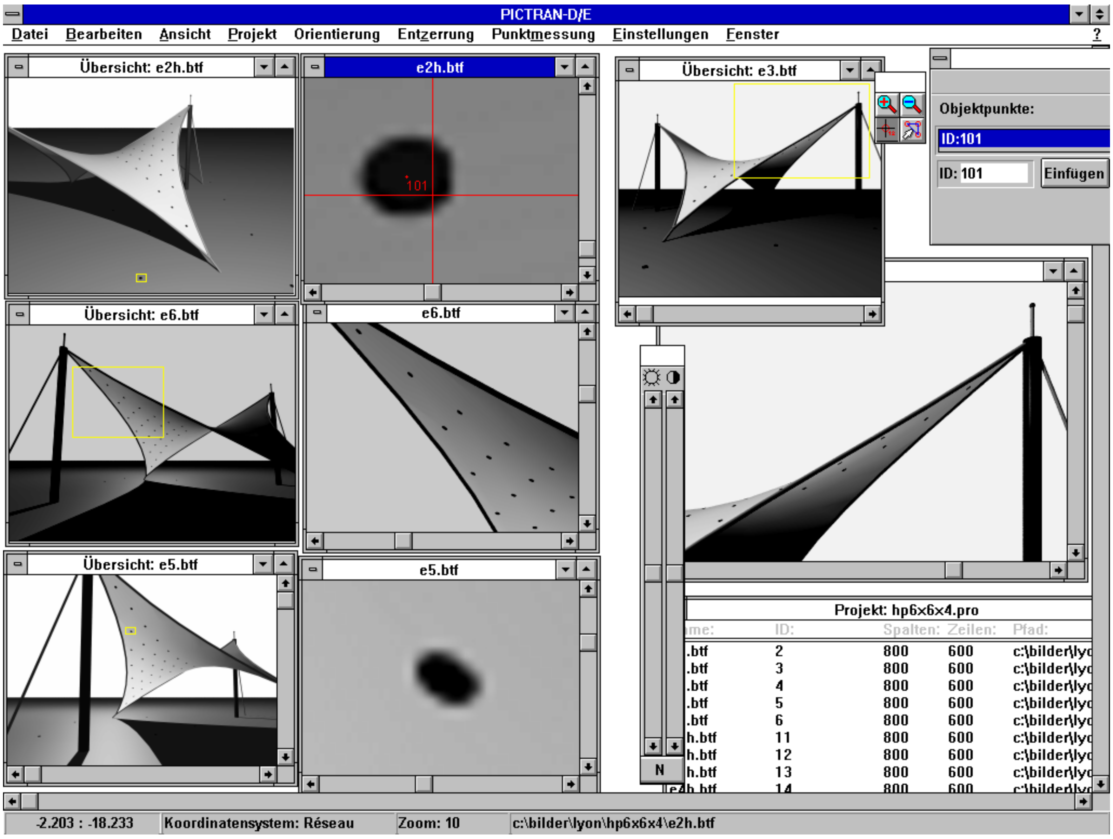

Figure 3: Screen shot from **PICTRAN** during the digitising and target measurement.

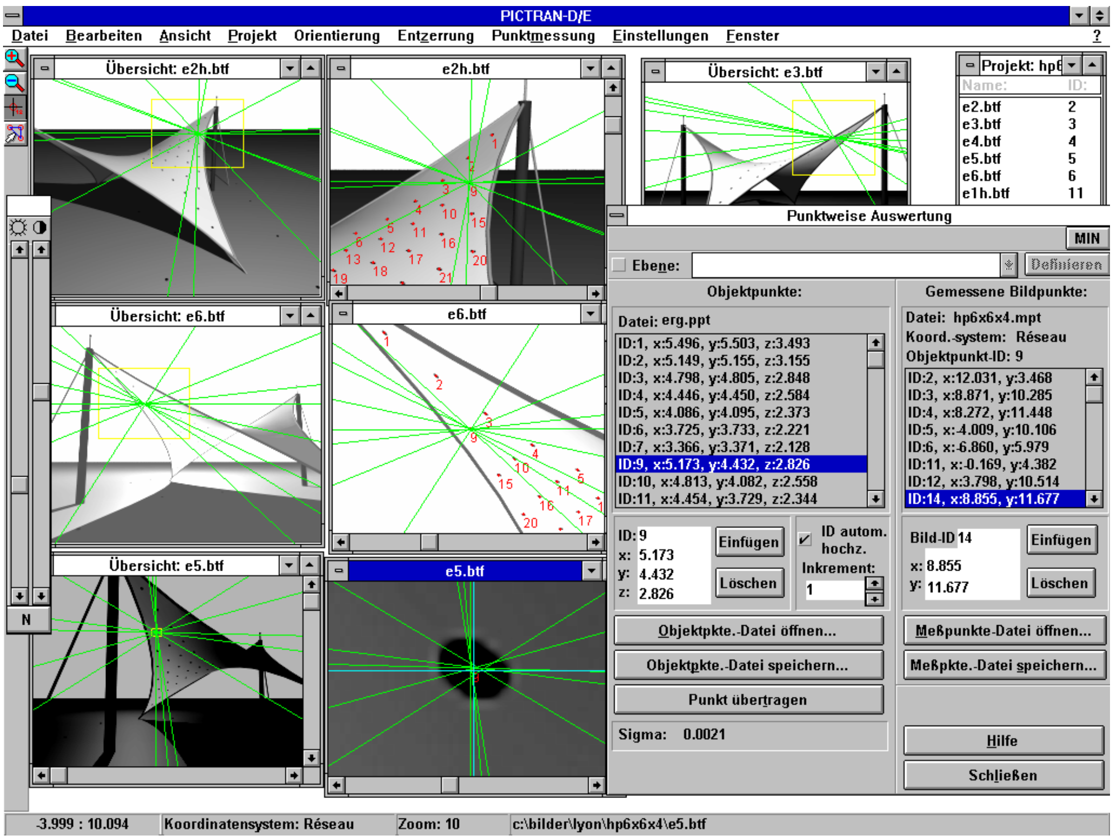

Figure 4: Screen shot from **PICTRAN** showing epipolar lines.

The goal of this type of measurement is mainly to get information on the strains in textile structures. The distances between target points have to be determined as accurately as possible.

Geometrical Setup (Target Points and Camera Positions)

A photogrammetric bundle block (multiple images from different views) describes a three dimensional point field. There are seven degrees of freedom: three location, three rotational, and one scale. These parameters can be determined by using control points with known coordinates.

For the closeup investigation the points of the overall form determination can be used as control points. However, since they have only an accuracy of between 1 and 2 mm, they can only be used for positioning the point field in the context of the whole membrane structure. As we want to determine lengths between the targets, the correct scale is very important. Therefore a scale bar with accurately known distances between its target points is used to determine the scale. This scale bar is placed somewhere in the area of investigation and may not be moved during the capturing of the different images.

Five images were taken from a distance of 1 m to the membrane surface covering an area of approx. 1x1 m²; These are reproduced in Figures 8(a)-(e) of the Appendix. Circular dots with diameters of 0.01 m were used for the small targets on the membrane and the scale bar.

Photogrammetric Analysis

The small targets were measured with an accuracy of 0.04 pixels (0.003 mm), the big targets of the overall form determination (diameter 0.06 m) with 0.3 pixels (0.02 mm) in the image. The accuracy of the points in object space is 2 mm. This reduced accuracy results directly from the accuracy of the control points used and describes the accuracy of the points with respect to the whole membrane structure; so, when the datum is not very accurate, the result cannot be expected to be. However, the relative accuracy between the points - which is important for the length measurements - is 0.1 mm. The scale does not depend on the control points but on the distances between the points on the scale bar and therefore is also in the range of 0.1 mm over the area of 1 m x 1 m.

A screen shot from **PICTRAN** during the digitising and target measurement stages is shown in Figure 5.

The accuracy σ_s of a distance *s* calculated from the point coordinates (with σ_{coord}) will be $\sigma_s = \sqrt{2} \cdot \sigma_{coord}$ (0.15 mm). If we sum up *n* distances to an overall length *l*, the accuracy of this length will be $\sigma_l = \sqrt{n} \cdot \sigma_s = \sqrt{2n} \cdot \sigma_{coord}$.

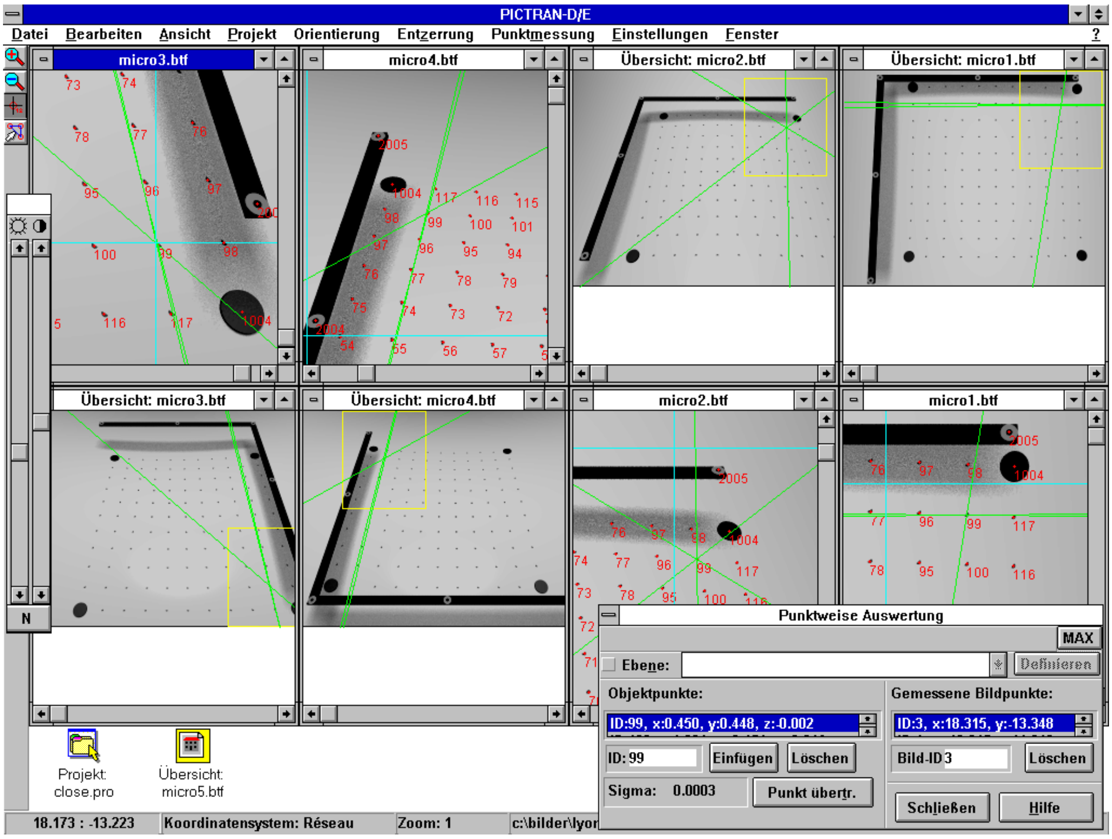

Figure 5: Screen shot from **PICTRAN** during digitising and target measurement for close up investigation.

Analysis of Measurement Accuracy

Accuracy of image coordinates, image errors

The accuracy of the image coordinates can be expressed in relative terms with respect to the image format. For the renderer camera the relative accuracy is in the range 1:8000 - 1:20000. It must be remembered that the renderer camera is an ideal camera with no influences from lens distortion, film deformation, scanning error, or other deficiencies. With real cameras these “image errors” do exist and can be partly corrected using a sophisticated camera model and an appropriate calibration procedure. Part of the errors will still remain in the image coordinates. On the other hand, digital images which are used for photogrammetric purposes, obtained either through film scanning or directly from digital cameras, usually have a resolution better than the 800x600 pixels used for the rendered images in this study.

What can be expected with real cameras?

A Rollei 6008 semi-metric camera [10] and a Kodak DCS 420 digital camera [2,10] are used as examples for a comparison of the expected results.

The Rollei 6008 uses an image format of 60 mm x 60 mm. Lenses are available with various focal lengths. The semi-metric camera uses a Réseau grid, therefore image errors due to film deformation can be corrected. The images can be scanned with a pixel size of 0.02 mm. Even by using image matching techniques, the accuracy of the images will not be much better than

0.1-0.3 pixel because of the remaining image errors. This accuracy leads to an image accuracy of 0.002-0.006 mm. This relative accuracy of 1:10000-1:30000 is in the same range or slightly better than with the renderer camera.

The Kodak DCS 420 is a digital camera with an image format of 14 mm x 9 mm. It is used with lenses between 17 mm and 35 mm focal length. The pixel size of the CCD sensor is 0.009 mm, the resolution is 1524 x 1012 pixels. Since CCD sensors are very stable and in general of good quality, there is no such influence as film deformation or scanning errors. The image coordinates can be measured with an accuracy of 0.1 pixel (0.0009 mm); this corresponds to a relative accuracy of 1:15000.

The relative accuracy of these real world cameras is in the same range as the renderer camera used in the simulation. If the lenses of the real cameras are chosen so that the field of view (aperture angle) is the same as with the renderer camera the geomtric setup can be the same as in the simulation and the expected accuracies of the three dimensional point coordinates can be expected to be in the same range.

Conclusions

On the basis of the simulation study conducted, it can be concluded that the use of digital photogrammetry for the precise measurement of realistic textile roof structures is entirely feasible. Provided sufficient care is taken in the conception and execution of the image acquisition, a high quality photogrammetric system, such as **PICTRAN**, is quite capable of measuring membrane geometry extremely accurately. Consequently, the objective of monitoring real strain can be efficiently and thoroughly achieved. It is hoped that a comprehensive programme of full scale tests will therefore be initiated soon using such technology in order to address this extremely important gap in the current understanding of textile structure behaviour.

References

[1] Ackermann, F., (1984), `High Precision Digital Image Correlation,´ *Schriftenreihe des Instituts für Photogrammetrie, Universität Stuttgart* **9**, 231-243.

[2] Beyer, H., (1993), `Performance Analysis of CCD-Cameras for Industrial Inspection,´ *The society of Photo-Optical Instrumentation Engineers, Vol. 1989, International Symposium on Electronic Imaging Device Engineering*.

[3] Bonnel, P., Di Natale, E. and Hamelin, P., (1993), `Characterisation of Textile Structural Composites by Combined Numerical-Experimental Method,´ in Proc. *Studiedag-Seminaire Textielstrukturen Architecture Textile*, Vrije Universiteit Brussel, 25th May 1993.

[4] Gründig, L., Bühler, W., (1985), `Zur Näherungswertbestimmung und Bündelausgleichung von Konvergentaufnahmen,´ *Bildmessung und Luftbildwesen* **53** 6.

[5] Gründig, L. and Bahndorf, J., (1988), `The Design of Wide-Span Roof Structures Using Micro-Computers,´ *Computers & Structures* **30**, 495-501.

[6] Gründig, L. and Bäuerle, J., (1990), `Automated Cutting Pattern Determination and Control for Prestressed Membranes,´ *Proceedings of Textile Composites in Building Construction,* Part 2, Pluralis, Lyon, 1990.

[7] Gründig, L. and Moncrieff, E., (1993), `Formfinding of Textile Structures,´ in Proc. *Studiedag-Seminaire Textielstrukturen Architecture Textile*, Vrije Universiteit Brussel, 25th May 1993.
[8] Gründig, L. and Moncrieff, E., (1993), `Cutting Pattern Generation of Textile Structures,´ in Proc. *Studiedag-Seminaire Textielstrukturen Architecture Textile*, Vrije Universiteit Brussel, 25th May 1993.
[9] Linkwitz, K., Gründig, L., Bahndorf, J., Neureither, M. and Ströbel, D., (1988), `Optimizing the Shape of the Roof of the Olympic Stadium, Montreal,´ *Structural Engineering Review* **1**, 225-232.
[10] Luhmann, T., (1990), `Image recording systems for close-range photogrammetry,´ *The society of Photo-Optical Instrumentation Engineers Vol. 1395, Close-Range Photogrammetry Meets Machine Vision*, 86-95.
[11] Krzystek, P., Petran, F., Schewe, H., (1995), `Automatic Reconstruction of Concept Models by using a Digital Photogrammetric Measurement System,´ *International Archives of Photogrammetry and Remote Sensing* **30**, Part 5W1, 176-185.
[12] Technet GmbH, (1995), *PICTRAN-B*, User manual for integrated photogrammetric analysis software, Technet GmbH, Briesingstr. 13, D-12307 Berlin, Germany.
[13] Technet GmbH, (1995), *EASY*, User manual for integrated surface structure design software, Technet GmbH, Briesingstr. 13, D-12307 Berlin, Germany.

Appendix: Synthetic Images used in Feasibility study

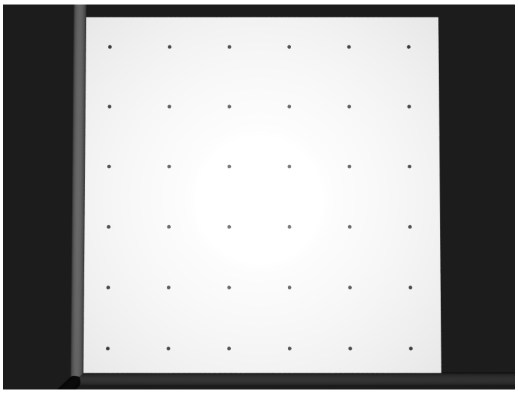

Figure 6(a): Camera calibration image 1

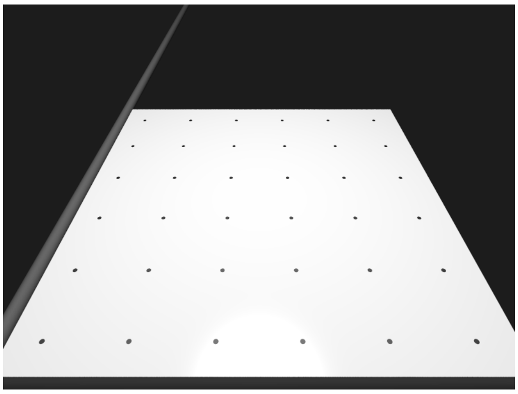

Figure 6(b): Camera calibration image 2

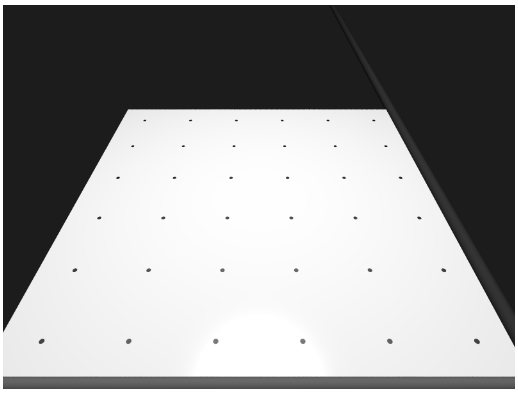

Figure 6(c): Camera calibration image 3

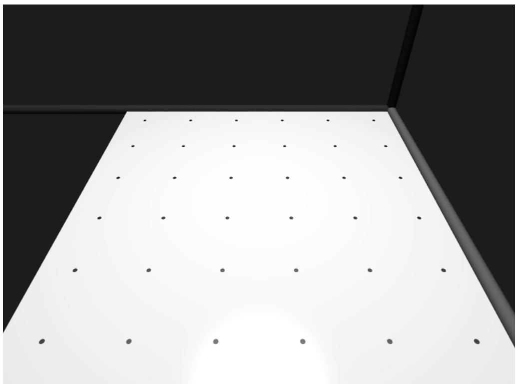

Figure 6(d): Camera calibration image 4

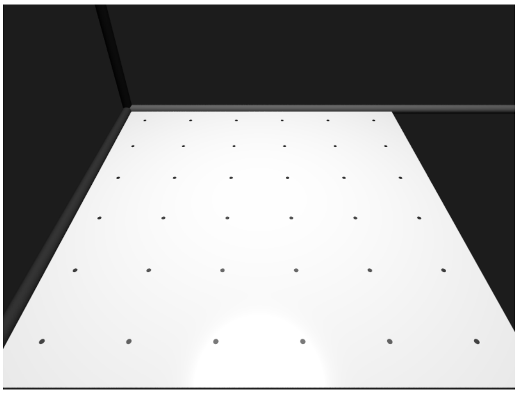

Figure 6(e): Camera calibration image 5

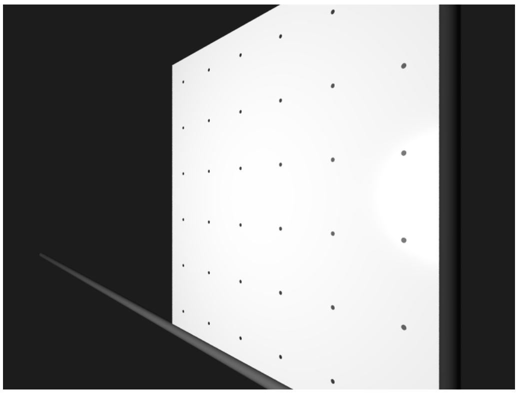

Figure 6(f): Camera calibration image 6

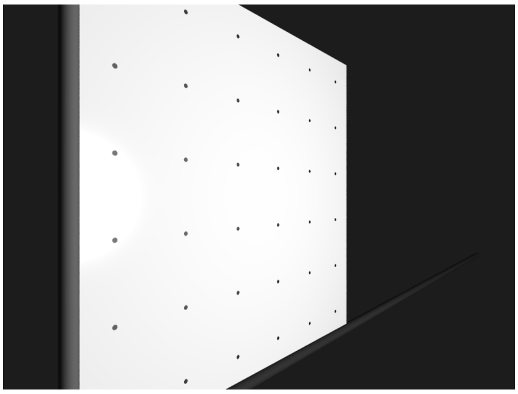

Figure 6(g): Camera calibration image 7

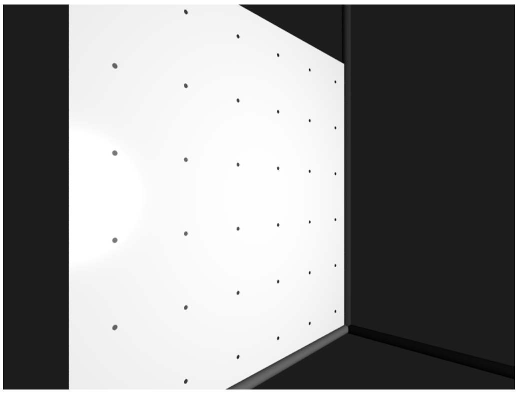

Figure 6(h): Camera calibration image 8

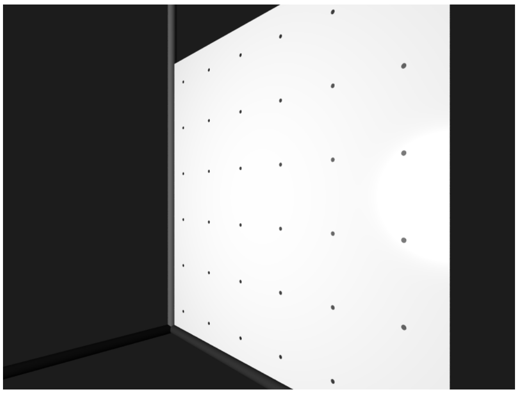

Figure 6(i): Camera calibration image 9

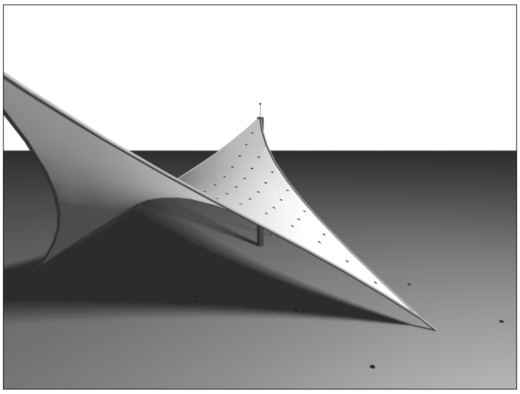

Figure 7(a): Overall image 1

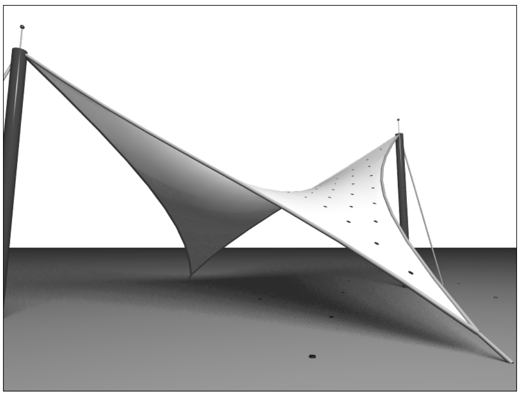

Figure 7(b): Overall image 2

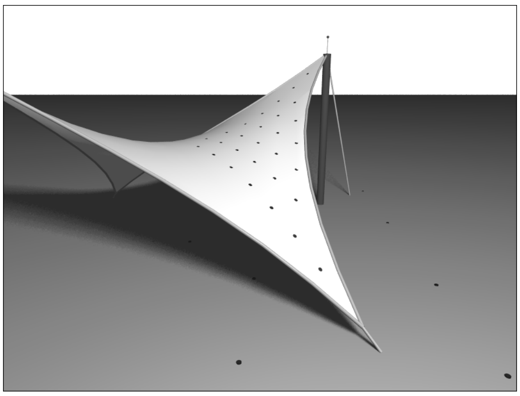

Figure 7(c): Overall image 3

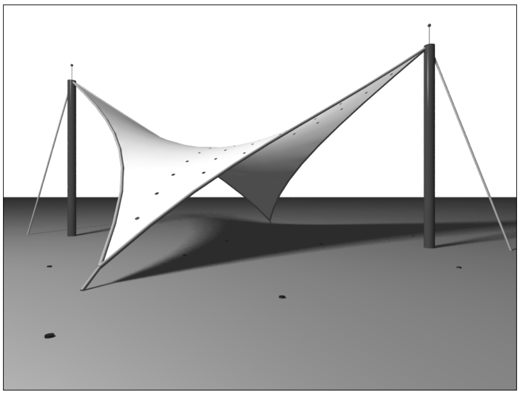
Figure 7(d): Overall image 4

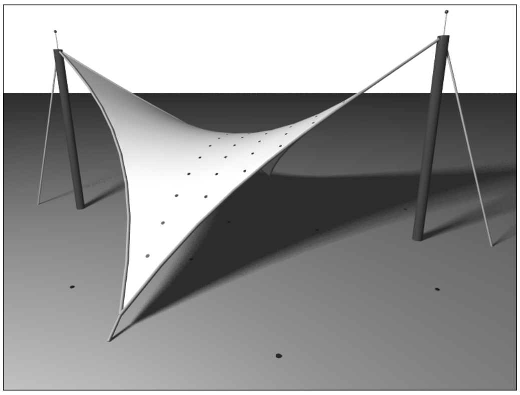
Figure 7(e): Overall image 5

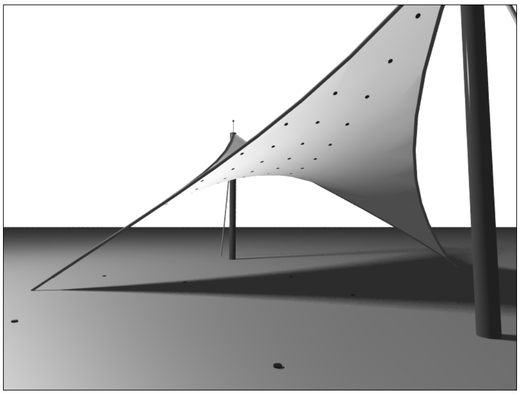
Figure 7(f): Overall image 6

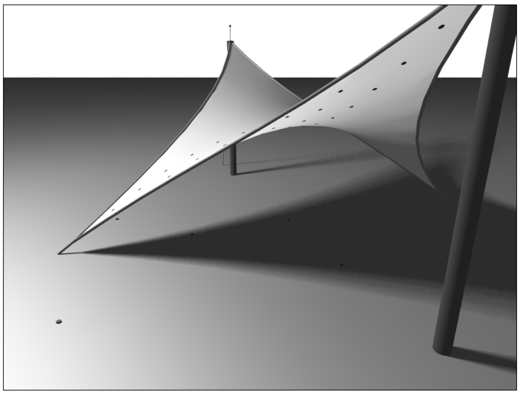
Figure 7(g): Overall image 7

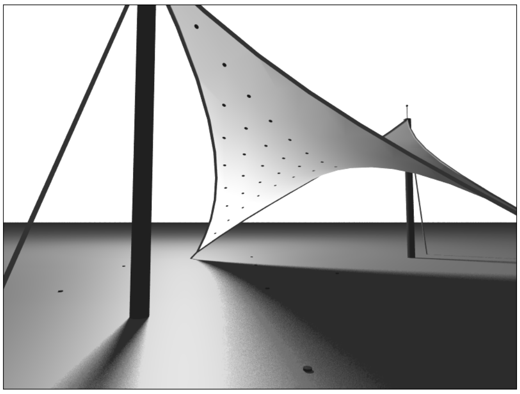
Figure 7(h): Overall image 8

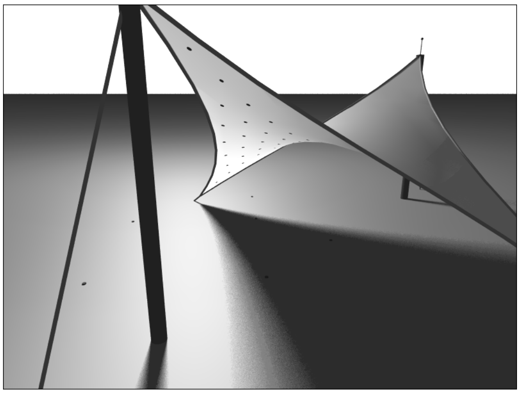
Figure 7(i): Overall image 9

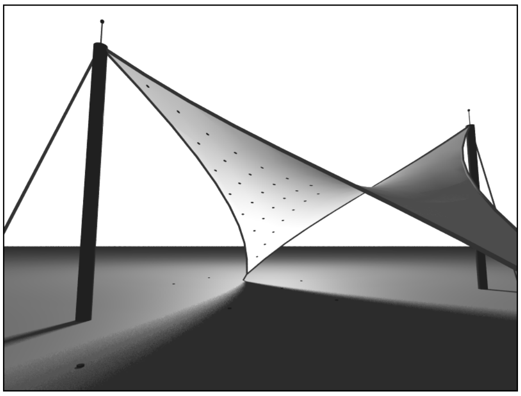
Figure 7(j): Overall image 10

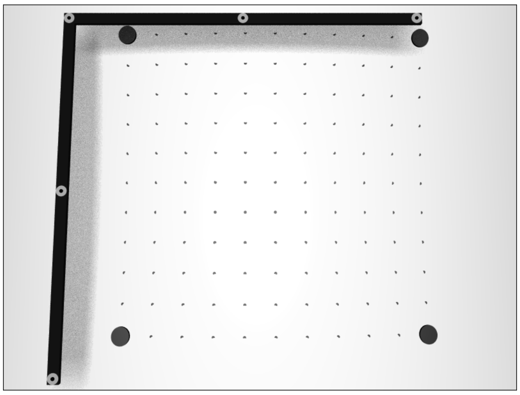
Figure 8(a): Close up image 1

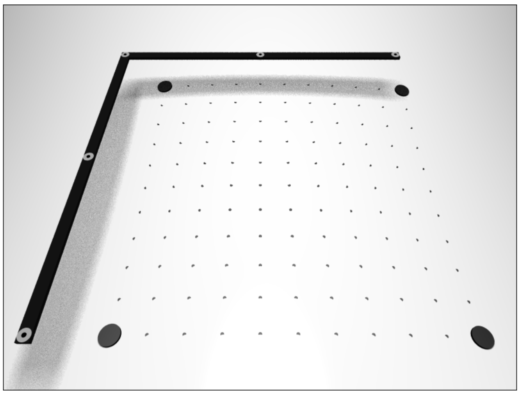

Figure 8(b): Close up image 2

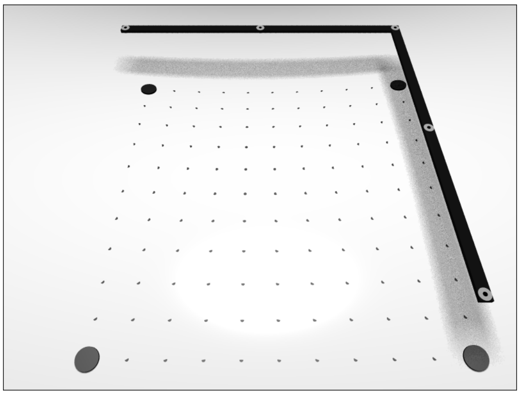

Figure 8(c): Close up image 3

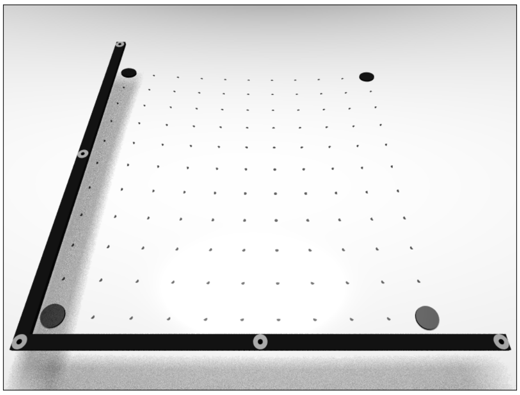

Figure 8(d): Close up image 4

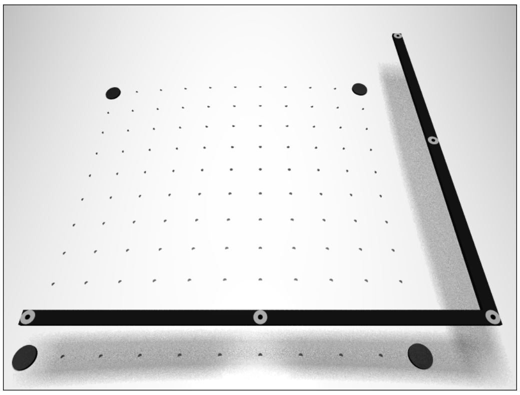

Figure 8(e): Close up image 5