Multi-Image Correlation for Digital Photogrammetric Measurement Systems

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ABSTRACT:

A multi-image correlation (MIC) method for determining image correspondences for digital photogrammetric systems is described in this paper. The MIC method was primarily developed as a robust algorithm for determining approximate parameters for the multi-photo geometrically constrained matching (MPGC) method. The MIC algorithm uses the a priori information of interior orientation parameters, distortion parameters and exterior orientation parameters of a multiple image set to geometrically constrain the correlation search area. As this paper will show, the use of multiple oriented (and calibrated) images not only reduces the search space of the correlation but also considerably strengthens the estimation of correspondences. Additional features of the method as well as its reliability are also outlined here. The results clearly demonstrate that MIC is significantly more effective than traditional stereo-correlation techniques (using epi-polar methods).

A typical photogrammetric application for this type of algorithm is the automatic measurement of surfaces. An outline of how the MIC and matching process fits into a surface measurement system is described. Two surface measurements, using standard resolution CCD cameras and the surface measurement software developed at the University of Cape Town, are reported and the results tabled.

1. INTRODUCTION

The efficiency of digital photogrammetric systems is mainly dependant on their level of automation for determining point or feature correspondences between the images. A multi-image correlation (MIC) method for determining correspondences between image patches/points in pre-oriented images is described in this paper. The MIC method was developed as a robust algorithm for determining approximate parameters for the well known multi-photo geometrically constrained matching (MPGC) method (Baltsavias, 1991). MPGC is a powerful least squares method for accurately matching small image patches in multiple image sets, however one of the principal difficulties in using this technique is the determination of good parameter approximations to ensure convergence of the least squares matching. The MIC algorithm uses the a priori information of interior orientation parameters, distortion parameters and exterior orientation parameters of a multiple image set to geometrically constrain the correlation search area. As will be shown, the use of multiple oriented (and calibrated) images not only reduces the search space of the correlation but also considerably strengthens the estimation of correspondences. In addition, the MIC method employs individual patch shaping in the various images to estimate the effects of perspective differences caused by the imaging geometry. This is useful for images which may be rotated by, for example, ninety degrees. The patch shaping in the MIC can then be successfully used as initial estimates for the patch shaping employed by the MPGC method.

A typical photogrammetric application for this type of algorithm is the automatic measurement of surfaces. Either natural texture or projected light can provide a dense set of surface features to measure. In the case of smooth surfaces, estimates of surface shape from neighbouring regions can be used to automatically compute approximations for the MPGC. However, to handle surface discontinuities and irregular surfaces a more robust method, such as the proposed MIC, needs to be employed. The important features of the developed MIC algorithm and an outline of how the MIC and matching process fits into a surface measurement system, are described. Finally, two surface measurements, using standard resolution CCD cameras and the surface measurement software developed at the University of Cape Town, are reported on and the results tabled.

2. HARDWARE

The hardware used for the development of the digital photogrammetric surface measurement system comprised a low resolution ITC CCD camera (795x596 sensor elements) with an 8mm lens connected to a Matrox PIP512B frame-grabbing card installed inside a 486 DX-33 PC. The cameras were calibrated using images of a point field of 101 retro reflective targets. Typically about 15 convergent images including some with 90 degree rolls around their optical axis were acquired for each calibration. Seven additional parameters modelling radial and decentering lens distortion, pixel spacing uncertainty and image shear (see Beyer, 1992) were always included as unknowns in a

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[1] This work was performed while the author was at the University of Cape Town

free network adjustment, with a single distance observation providing scale to the network.

For providing texture on the measurement surfaces, both a standard slide projector and overhead projector were tested for stability of the projected patterns. It was found that the slide projector was unstable (due to temperature changes and vibrations of the slide and projector due to the fan), whereas the overhead projector provided a relatively stable projection after allowing for a warm up period (one and a half hours in this case).

3. MATCHING PROCEDURE

Multiple images (usually four or more) of an object are acquired with a pre-calibrated camera. The matching of surface points in the multiple images is started once the exterior orientations of the various images has been computed. This orientation is achieved through the use of signalised points on a reference frame surrounding the object.

The following procedure was adopted for the image matching and surface measurement:

1. In a reference image, find a dense distribution of well textured reference patches on the object.
2. Determine provisional values for all image coordinates of the patches and the 3-D object coordinates of their associated surface point.
3. Perform MPGC matching for each set of patches to determine accurate image correspondences and 3D surface position.
4. Monitor the matching results with a run-time blunder detection process and also perform a post-measurement blunder detection.

In the first step it is possible to use any favoured interest operator, such as the Forstner Operator (Forstner and Gulch, 1987) or simple edge operators. The second step is the main subject of this paper, for which a combination of nearest neighbour extrapolation and MIC has been investigated. The third step is well documented as a high accuracy image matching and 3D position estimation technique. The blunder detection technique is also an important element of the procedure; here various parameters such as the *a posteriori* standard deviation of unit weight, the average correlation coefficient and the number of iterations (from the MPGC matching) are compared to absolute and relative thresholds to detect and eliminate blunders automatically at run-time and post-measurement stages respectively. For more details on all the aspects of this matching procedure see Van der Vlugt (1995).

The task of determining all provisional parameter values needed for the MPGC matching can be seen as the primary matching problem in that it is this task which actually determines the correspondence between the reference patch and the search patches, as opposed to the MPGC algorithm which provides the fine matching. The provisional values needed by the MPGC matching for a single match are: X,Y,Z object coordinates of the surface point; x,y image coordinates of the reference patch and all search patches and affine parameters for all search patches. The affine parameters are usually set to one for the two scales and zero for the shifts and shears. The other parameters can all be computed from the reference patch position (known) and only one other coordinate (image or object), using the known camera orientations and distortions. It is advantageous to use the depth coordinate (often defined by the Z object coordinate axis) from which to calculate all the others. The Z-coordinate is thus loosely defined here as the depth coordinate or height, which is more or less perpendicular to the general object surface. The provisional value problem thus reduces to finding the correct Z-coordinate given the reference patch position, much like adjusting the height of the floating dot onto the terrain surface in an aerial image stereo-pair.

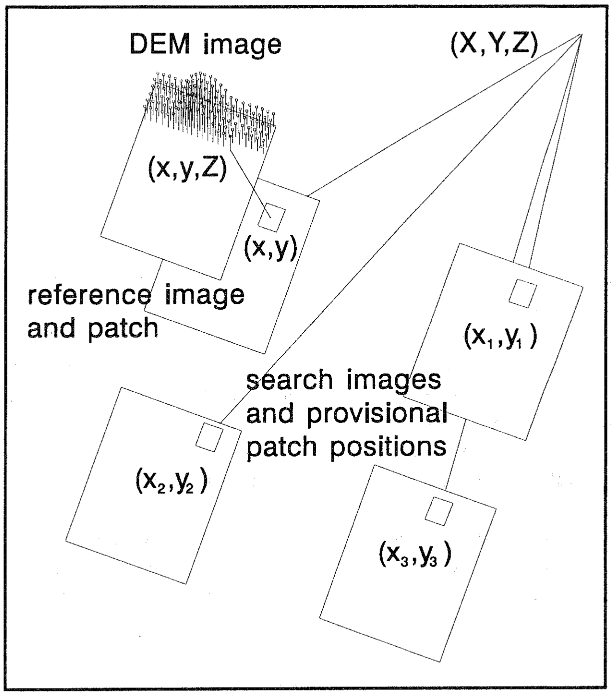

Figure 1. The DEM image and computation of provisional values for MPGC matching

The MIC search procedure has been developed for estimating the correct Z-coordinate. MIC is a reliable method of determining provisional values when multiple images are used, so it has been adopted as a back-up method for a less computation intensive (and less reliable) algorithm using surface height extrapolation. An initial surface match is obtained using MIC and subsequent surface point provisional Z-coordinates are then computed using the surface extrapolation technique until an MPGC matching failure occurs. When a matching failure occurs, the controlling routine assumes that an incorrect provisional value set was passed to the MPGC sub-routine. The MIC search is then called and a new set of approximations generated which are passed to the MPGC algorithm for a second matching attempt.

The height extrapolation is incorporated into the matching procedure as follows. A "DEM image" pixel-linked to the reference image is set up. Each pixel in the DEM image would ideally contain the height of the object point imaged by the corresponding pixel in the reference image. However as not every pixel in the reference image is matched and as the DEM image is still growing at any one time, the pixels in the DEM image either contain a height value indicating a successful match or a value defined as "no height" for a large number of unmatched pixels. When a reference patch with strong texture is extracted from the reference image, the Z-coordinate of the centre of this reference patch is calculated by extrapolating the height at this pixel from the nearest neighbour in the DEM image. In cases where the reference patches are distributed at regular and frequent intervals in the reference image the use of this simple method can be justified.

Once a height has been extrapolated for the current pixel the remaining provisional values must be computed (see figure 1). Firstly, the X and Y object coordinates are computed from the rearranged collinearity equations, using the known reference image orientation and all the calibrated additional parameters. In a second stage the computed X,Y,Z object coordinates are projected into all the search images to obtain x,y image coordinates (corrected for distortion). The image coordinates are then transformed into the original pixel coordinate system using the known transformation parameters. The provisional parameters are used by the MPGC routine and if successful (the matching results pass a run-time blunder test) the resulting height is stored in the DEM image. If the MPGC matching failed, the more reliable MIC routine is called to compute another estimate for the height of this current surface point.

4. MULTI IMAGE CORRELATION

Multi-image correlation (MIC) is an extension to the traditional grey level correlation technique. A correlation value, such as the normalized cross-correlation coefficient, describes the similarity between two patches, and can be used for solving correspondence problems between images. The basic steps of most correlation search procedures are:

1. Extract a reference patch from the reference image. The conjugate position of this reference patch in the search image must be determined.
2. Define a search area and specific sampling positions (search patches) for correlation, within the search image.
3. Compute the correlation values (with respect to the reference patch) at each of the defined sample positions.
4. Find the sample position with the maximum correlation value. This position indicates the search patch with highest similarity to the reference patch.

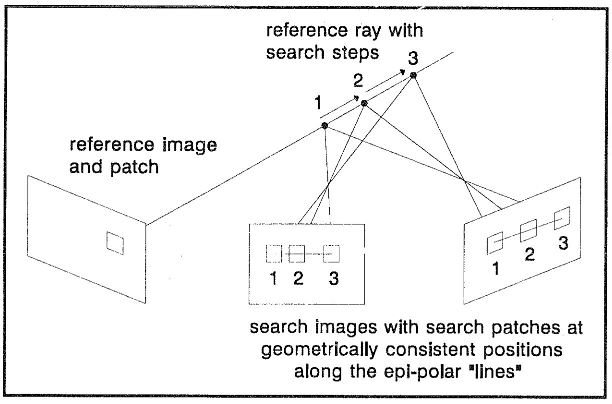

Figure 2. The multi-image correlation (MIC) search concept. A search step (sample) number is shown next to the search patches and their associated object point.

When no image orientation data is used, correlation search procedures correlate over an entire 2-D search area within the search image. When relative orientation between two images is known, the search patch centres can be restricted along the epi-polar "line" in the search image. This procedure is often used by photogrammetrists (see Wong and Ho, 1986; Claus, 1984 or Dowman, 1984) to determine correspondences between two images.

The feature which makes the developed MIC algorithm different and more reliable is the **simultaneous use of more than one search image**. The correlation search patch centres are not only constrained along the epi-polar "lines" of the search images but also to geometrically consistent positions within these "lines". Figure 2 shows both these constraints. A single correlation value describing the similarity of these search patches to the reference patch is computed at each of the search steps (samples). Again, the maximum correlation value of the samples indicates the search patch set with the highest similarity to the reference patch. This extension is a natural progression from stereo-correlation and shares many of the advantages of MPGC matching when more than two images are used.

4.1 Constrained Search Space

In order to create a geometric consistency between the search patches, it is appropriate to drive the search procedure by generating search patch image coordinates from a varying height coordinate along the "reference ray". The reference ray is defined here as the imaging ray passing through the centre of the reference patch. An example, using figure 2, is given here to the describe the search process. The search starts at height (Z-coordinate) 1 at point 1 along the reference ray. The X and Y coordinates of point 1 can be computed from the re-arranged collinearity equations. Both the search patch positions numbered 1 are calculated by back projecting point 1 into the two search images. Image distortions are taken into account during this computation. A correlation value, describing the similarity of these two search patches to the reference patch, is determined. The search height is then incremented to height number 2 and the process repeats itself.

This is therefore a one dimensional search in object space along the reference ray. The method ensures that all search patches are geometrically consistent and it also allows for the implementation of a reliable search Z-range. If relatively precise knowledge concerning the surface shape exists, the search Z-range could be strictly applied and even changed for each surface point. The search height increment (step) could simply be set to a constant value (say 1mm), however this might create an over or under sampling depending on the image scales and geometries. Rather, the height increment should be computed so that the search patches are moving at approximately constant steps in the search images. The computation suggested here is updated after each sampling by using a simple proportion calculation to approximate the required increment. The next height increment ΔZ_{i+1}, computed after the ith sample is given by:

$$\Delta Z_{i+1} = \frac{\Delta Z_i \, \Delta s_0}{\Delta s_i} \qquad (1)$$

where ΔZ_i is the height increment at sample i, Δs_0 is the required largest image step and Δs_i is the largest image step amongst the search images at sample i. This ensures that all the next search image steps are smaller than or equal to Δs_0. For most of the practical tests performed during this work a value of either 0.5 or 1 pixel for Δs_0 has been used.

4.2 Correlation Functions

To make a decision whether to accept or reject a group of conjugate search patches as possible matches to the reference patch, a suitable correlation (similarity) value needs to be computed from the grey values of the reference patch and all the search patches. This "combined" correlation value must be a function of the individual correlation values for each search patch. A number of possible methods for determining suitable individual correlation values could be used. The normalized cross-correlation function (see for example Wong and Ho, 1986, for the equation) can be used to calculate a correlation coefficient, p, ranging from +1 to -1; +1 indicates an exact similarity, zero indicates no similarity and -1 indicates that the search patch is a negative of the reference patch. The normalized cross-correlation function automatically allows for a radiometric equalisation of the mean and standard deviation of the two patches. The maximum correlation value indicates the most similar search patch position.

A second method is to compute the correlation value as the average of the absolute grey value differences between reference and search patch. The patches should be radiometrically equalised beforehand to obtain a more reliable correlation value. In this case the closer the correlation value is to zero the more similarity between the two patches. Thus, this correlation function needs to be minimised to find the most similar search patch position. Vollmerhaus (1987) describes the use of this function, which he calls the cross-difference-modulus-function, in some applications.

A combined correlation value must be computed from the individual correlation values of each search patch. The average of the individual correlation values has been used in this work as the combined correlation value. Only this combined (average) correlation value is used for determining the correct match. Both functions mentioned here have been investigated and both show similar results. The normalised cross correlation function has the advantage that the patches do not have to be radiometrically equalised beforehand. Assuming that the normalised cross correlation function is used, the sample with the maximum average correlation value is chosen as the matching sample.

4.3 Search Patch Shaping and Sampling

A square reference patch in the reference image is imaged as a non-square search patch in a search image due to different image positions and varying surface orientation and shape. The search patches used in MIC can be a priori shaped to model the effects of the known camera geometry, however as the surface shape is generally not known the second effect (due to surface orientation and shape variation) can not be modelled. To test the MIC routine, three methods of search patch shaping and sampling have been employed:

1. no search patch shaping, integer sampling.
2. no search patch shaping, sub-pixel sampling.
3. search patch shaping, sub-pixel sampling.

Using a rounded integer value for the search patch position introduces a further source of error (besides the error caused by unmodelled search patch shaping), but significantly speeds up the matching procedure as no grey level interpolation (resampling) is required. Sub-pixel sampling is employed to improve the reliability of the search but at a computational cost. Using rounded integer values is equivalent to resampling with nearest neighbour interpolation. In instances of highly convergent camera geometry or when cameras are rotated about their optical axis, the search patches should be shaped to eliminate the effects of camera geometry. As for the MPGC matching, an affine transformation of the search patch is used here. Three reference patch pixels (two corner pixels and the centre pixel) are projected through object space into the search images, using equal height values for each. The position of the centre pixel in the search image defines the position of both the shaped and unshaped search patch positions, while the positions of the two corner pixels define the orientation of the shaped search patch. Affine transformation parameters can thus be computed from the unshaped to the shaped search patch. All the unshaped search patch pixels are then transformed using these affine parameters and the search patch is resampled over this transformed grid at the sub-pixel positions. Bi-linear interpolation has been used in this work to compute the grey value at a sub-pixel position.

This shaping procedure eliminates the effects of camera geometry on the search patch shapes for flat surfaces parallel to the XY plane. Deviations of the surface patch from a constant Z-value plane will result in unmodelled patch shape distortions. If any of the pixels in the reference patch have reliable known heights, for example from previous matches, then these can be used to improve the affine shaping by assuming a slanted surface patch at this point. This could be used well in applications which have very dense sampling. As a by-product of the MIC search the computed shaping parameters of the correct match can be used as provisional values in the MPGC matching to ensure convergence.

4.4. Correlation Example

A number of tests were performed to investigate the reliability of the MIC process and to compare it to traditional stereo-correlation techniques. In one, a flat surface containing a highly repetitive grid pattern was imaged by the CCD camera in multiple positions. As a typical example, graphs of the correlation values versus sample height are depicted in figure 3 for three search images (nos. 2, 4 and 6) and their average for a single correlation search at one point. The reference image (no. 1) and the three search images were taken from camera positions forming a rectangle. Image 6 was rotated about 45 degrees around its optical axis to show the effects of patch shaping. The set on the left represents the correlation with patch shaping and the set on the right without.

The arrows in the figures depict the sample with the maximum correlation value in each of the search images and the average correlation values as well. As can be clearly seen from the patch shaped set on the left, the maximum of the average correlation values is far more unique (and thus more reliable) than for the individual correlation values (which would correspond to traditional stereo-correlation) which often have their maximum at the incorrect sample position. The two sets of graphs also show the improvement resulting from patch shaping which significantly improves the correlation results for image 6 and thus the average as well, however it does show that the use of multiple images significantly improves the reliability of the matching even when large errors caused by unmodelled shaping parameters still exist.

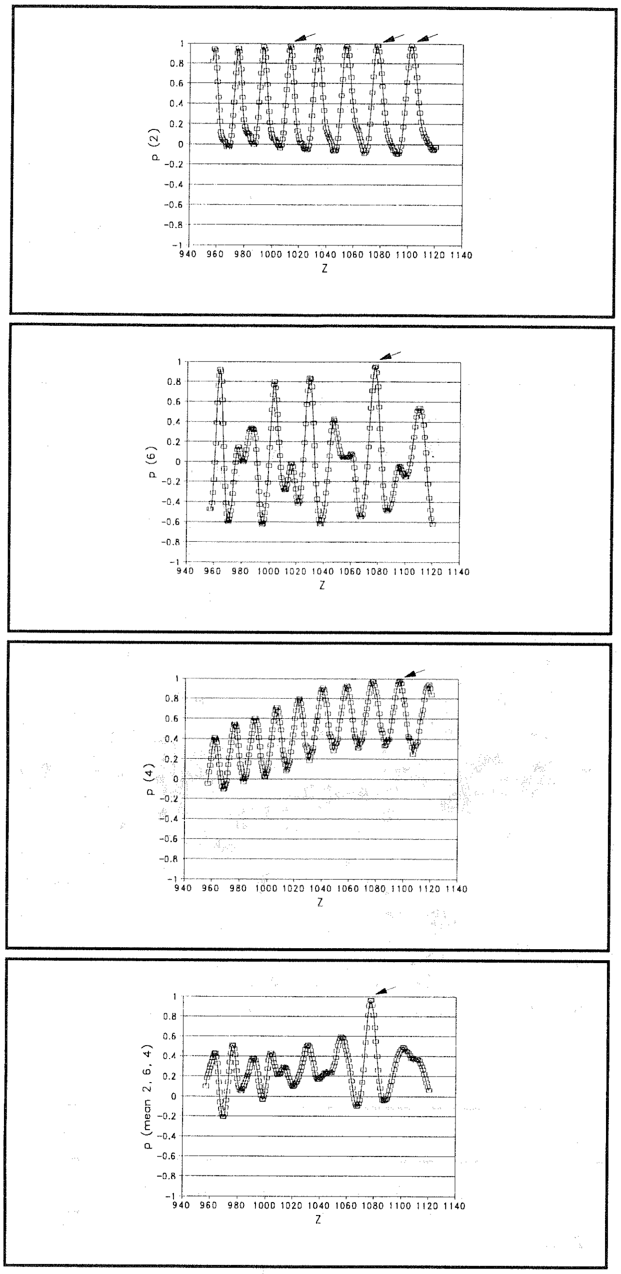

Figure 3a. MIC values of test search using images 1, 2, 6 and 4 ***with patch shaping.***

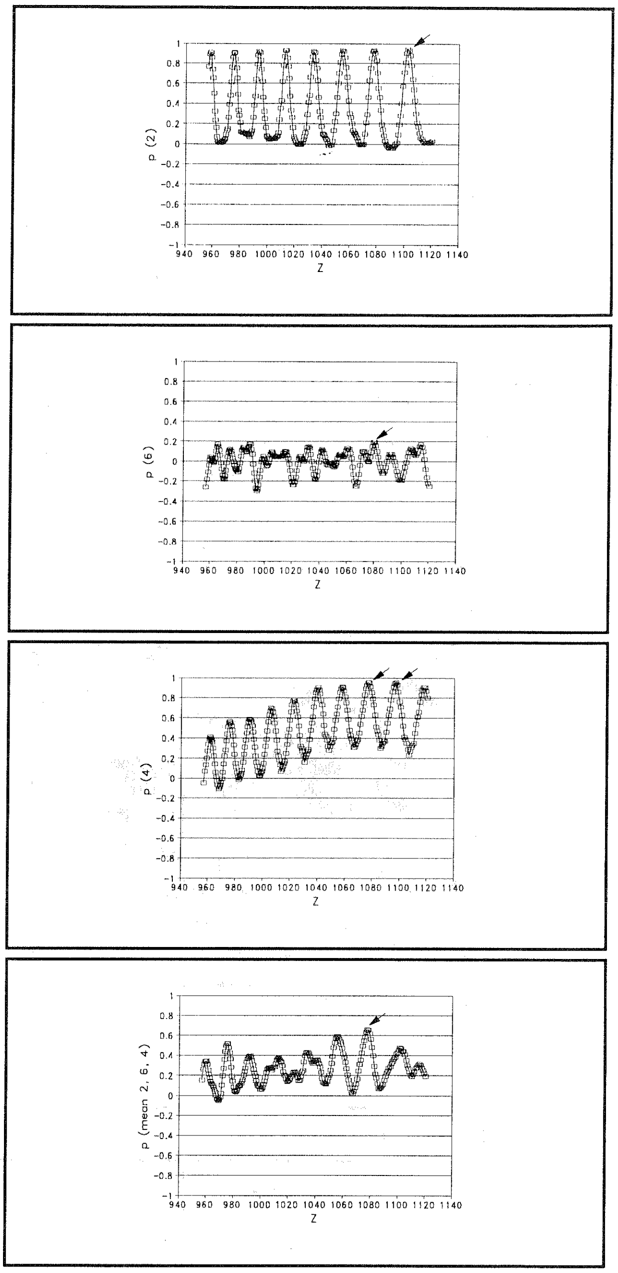

Figure 3b. MIC values of test search using images 1, 2, 6 and 4 ***without patch shaping.***

5. SURFACE MEASUREMENTS

Two examples are shown here, the first is the measurement of the blades of a propeller (see figure 4) and the second of a smooth curved plastic lid (see figure 5). As was to be expected the MIC procedure was called more often for the propeller measurement than for the smooth curved surface. The results from the MPGC matching are shown in table 1. The poorer precision in the depth coordinate (Z) is due to the fairly narrow camera base between the images employed in these measurements. A more convergent imaging geometry would increase the precision in the resulting Z coordinates. The resulting surface data was exported to a surface presentation package called SURFER and the perspective plots of the two surfaces are shown in figures 6 and 7.

6. CONCLUSIONS

The matching procedure presented here is flexible to the type of targeting used. In this work projected grids and hand-drawn lines have been employed for providing surface detail. Natural texture could also be used. The only restriction is that the surface detail is fairly dense and of sufficient contrast for matching.

A matching procedure has been designed, based on the MIC search procedure developed in this work and on the existing MPGC matching method. Some points concerning the MIC algorithm are listed below.

1. It can be applied to a theoretically unlimited amount of images.
2. The search space is constrained through the image geometries.
3. A method of shaping the patches to model the effects of camera orientation was described.
4. The search can accommodate (sometimes large) unmodelled shaping parameters of the search patches, caused by varying surface height.
5. The search steps within the search images can be controlled.

The MIC approach is significantly more robust and reliable than standard stereo-correlation algorithms due to the increased redundancy and geometric constraints. The technique is well suited not only for automated surfacing but also for interactive measurements providing specific object measurements such as 3-D coordinates, distances or volumes. The user only needs to identify the point of interest in a single image to obtain its 3-D coordinates. The MIC algorithm can be used for locating the point in all the other images with a high degree of reliability and efficiency.

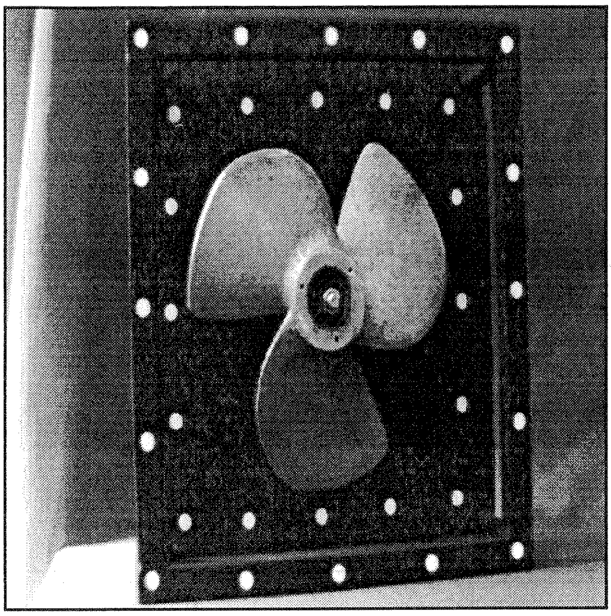

Figure 4. The propeller and control frame.

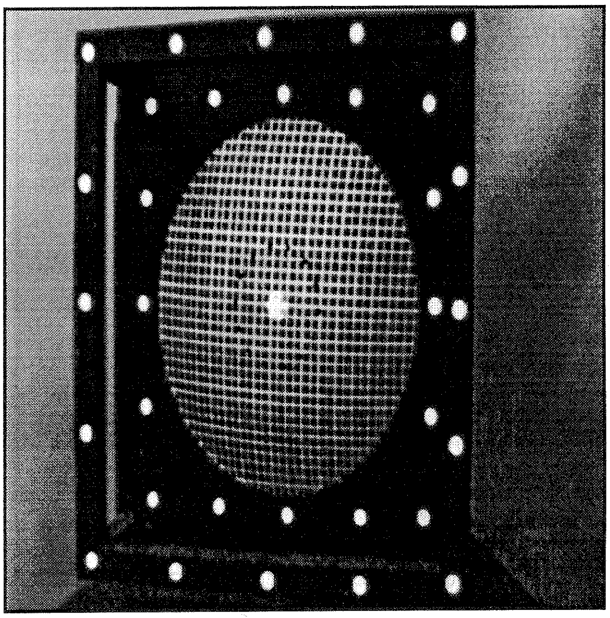

Figure 5. The plastic lid with projected grid.

Surface	RMS				
	σ_x (pels)	σ_y (pels)	σ_X (mm)	σ_Y (mm)	σ_Z (mm)
Propeller	0.05	0.05	0.04	0.04	0.17
Plastic Lid	0.03	0.04	0.03	0.03	0.14

Table 1. Results from the MPGC matching of both surfaces.

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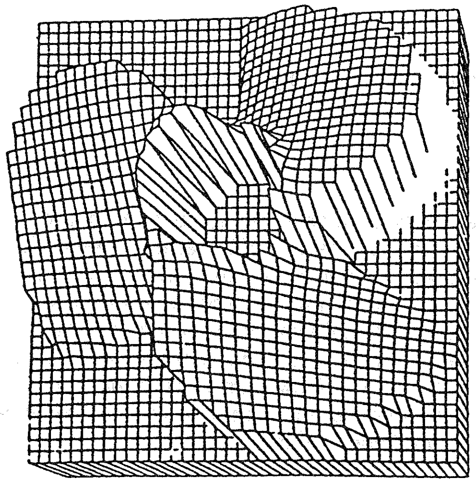

Figure 6. The perspective plot of the propeller surface.

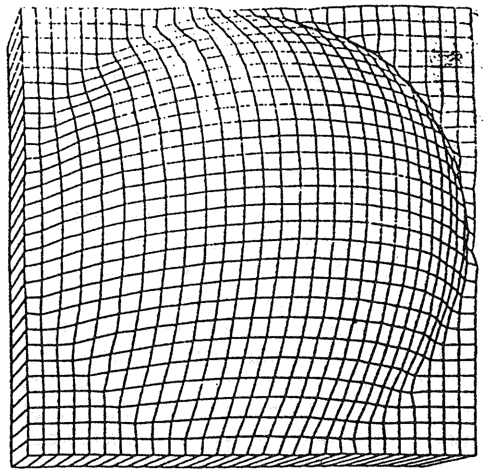

Figure 7. The perspective plot of the plastic lid surface.