The development of a contact-free 3D co-ordinate measurement machine

H. Rüther[1] and **D.H. Craigie**[2]
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The paper describes the design of a non-contact 3D co-ordinate measurement system for reversed engineering and quality control based on digital photogrammetry methods. The system projects a laser dot onto the surface of the object to be measured and employs machine vision algoritluns and photogranunetric models to automatically determine the 3D position of the surface point. The laser dot is then mechanically moved in a grid pattern and the object is rotated until the entire surface is captured. The paper gives details of the system design, the measurement procedure and reports test results. Accuracy estimates derived from measurements using a prototype system indicate accuracies better than 0.2 mms.

Introduction

Digital photogrammetry and machine vision have reached a level of development where it is possible to interface off-the-shelf cameras and computers with established algorithms for the design of customised 3D measurement systems. In an attempt to emulate the functions of expensive and difficult-to-maintain 3D co-ordinate measurement machines, a low-cost, easy-to-use, non-contact coordinate measurement machine (CMM) for reversed engineering implementation was designed in a joint project by the Department of Surveying and Geodetic Engineering and the Department of Mechanical Engineering at the University of Cape Town.

Criteria set for the design were the capability to

- determine 3D surface co-ordinates of sculptured objects with sub-millimetre accuracy,
- generate the co-ordinates in a format suitable for direct input into a computer numerically controlled (CNC) milling machine in a CAD/CAM environment,
- carry out the measurements in a non-contact mode.

CMMs are used extensively in industry for quality control purposes and reverse engineering. These systems typically rely on physical contact probes and there is a need for a non-contact measurement capability for non-rigid objects which deform on contact, such as car seat foam padding or upper shoe bodies. A less common area of application for a non-contact CMM is the measurement of works of art and archaeological artefacts. The often fragile nature of such objects, especially in the case of archaeological artefacts, requires contact-free measurements.

A secondary criterion was the cost factor and attempts were made to minimise costs by basing the design on PCs and low cost CCD video cameras of the type used for surveillance and security systems.

The measurement method

The system design is based on the automated measurement of a clearly visible dot on the object surface using photogrammetric models. To achieve this a single dot is projected onto the surface and its 3D co-ordinates are determined automatically. The laser dot is then mechanically moved and the object is rotated in a predetermined pattern until the entire surface is covered.

In order to provide the clearly visible dot, necessary for the automatic measurement, a laser beam projects a circle onto the surface of the object to be measured. Images of the dot are then captured by three CCD cameras and 3D co-ordinates of the surface point marked by the laser are determined employing digital photogrammetry algorithms and techniques. The dot is then moved to a new position on the object's surface until the entire area visible to the cameras and within the 'field of view' of the laser is recorded.

A rotation of the object gives access to a new area and the process is repeated sequentially until the entire surface area is completed. The procedure is based on three measurement processes, two mechanical and one photogrammetric, the former to quantitatively control the movement of the laser and the object, the latter to provide the 3D co-ordinates of the surface dot. Knowledge of the measurement sequence and angular rotation of the object are used in a post processing CAD environment to produce a three-dimensional point cloud in the form of a 'wire mesh' representing the surface of the object. The mesh resolution can be set prior to measurement, this choice depending on the curvature and general complexity of the surface. The process does only allow measurement of surfaces visible to the camera and the laser beam and no obscured areas or complex cavities can be captured by the system.

System components

The digital photogrammetry CMM was made up of the following components:

- point measurement system,

[1]Department of Surveying and Geodetic Engineering, University of Cape Town, South Africa.

[2]Department of Surveying and Geodetic Engineering, University of Cape Town, South Africa.

- motion control system, and
- additional system components.

The point measurement system

The point measurement system is based on digital photogrammetry and machine vision technology. It measures the position of the laser dot on the surface of the object. The system components are a standard PC equipped with a frame grabber, three analogue ITC-CCD cameras for image acquisition and software for image processing and digital photogrammetry algorithms. The specifications for the cameras are:

Chip size	7.95 mm (h) × 6.45 mm (v)
Pixel resolutions	795 (h) × 596 (v)
Pixel dimensions	11.86 μm (h) × 8.30 μm (v)
Nominal focal length	8.0 mm

A Matrox PIP-512B frame grabber card makes it possible to capture images of 512 × 512 pixel format. Frame grabber cards with higher resolutions and CCD cameras with direct digital output are available and would improve system accuracies and performance.

Allowance is made for the discrepancy between the resolution of the frame grabber (512 × 512) and the camera output (795 × 596) by re-sampling the analogue video signal in a horizontal direction from 795 to 512 and truncating the signal in a vertical direction after 512 lines.[6] This is an automatic function of the frame grabber which degrades the image and it would be preferable to have a frame grabber with user-selectable pixel formats which could then be set to coincide with the camera output.

A minimum of two cameras is required for the photogrammetric determination of space points. The measurement system uses a third camera to provide a redundancy for checking purposes and to increase system accuracy.

For the prototype of the system (Figure 1), the cameras were positioned at the corners of a frame, pointing at the object with a planar intersection angle of 90°, the deviation of the camera axes from verticality was about 30°. The cameras were located approximately 1 500 mm above the plane on which the object to be measured is placed. The camera positions described were constrained by the physical dimensions of the measuring machine itself.

- A Personal computer (80386 processor with 80387 math coprocessor with 8 MB RAM) was used to control the image capture and photogrammetric operations via the following software components:
  - least squares bundle adjustment program PHOTONET[8]
  - Digital Image Matching Software DIMS[7]
  - camera control routines
  - communication software (to interface with a motion control computer; see motion control system).

The relatively low processing power of the PC did not affect the overall system speed as the principal factors limiting the speed of the measurement were the mechanical movements of the laser and the object and not the time required for the photogrammetric computations.

The motion control system

The motion control system has a dual function:

- the movement of the laser target point in a two dimensional x/y grid pattern
- the rotation of the object

The optimal laser dot shape is obtained when the vertically projected laser beam intersects the object surface at a right angle. The rotation axis of the motion control system was oriented horizontally (Figure 1) to provide an optimal configuration for this condition.

The Motion Control system was operated via a second Personal Computer (80386 processor with 1 MB RAM) using software developed by Parbhoo.[5] The software provides a grid scanning capability for the translation of the laser target in the desired grid pattern and controls the rotation of the object through the rotary table.

The mechanical device used to perform the operations of the Motion Control system was designed and developed by the Department of Mechanical Engineering at the University of Cape Town.[5]

Additional system components

The two computers essential for the operation of the non-contact CMM system are mutually dependent and require a control link for the correct sequential execution of their respective operations: the object/target motion control and the photogrammetric analysis. The two PCs are linked via a standard RS232 communication port and software was written to provide an interface for data exchange. Details regarding the communication software are described in Parbhoo.[5]

The measurement procedure

The procedure for the object measurement can be divided into the following stages:

- calibration of the photogrammetric system
- measurement of the rotation axis
- measurement of the object
- generation of the three dimensional CAD mesh

Calibration of the photogrammetric system

Before the photogrammetric measurement of an object is possible, the measurement system must be calibrated. This is a procedure in which the orientation parameters of the cameras, i.e. their position and orientation in space, are determined. These parameters are then used for the photogrammetric determination of object point co-ordinates.

Out of a variety of mathematical models available for the determination of camera orientation parameters, the two most widely used are the Direct Linear Transformation (DLT)[2] and the bundle solution.[1] The bundle solution is mathematically more flexible and tends to provide more accurate results than the DLT. However, it requires good approximation values for the camera parameters to guarantee convergence of the iterative computation model. This disadvantage is not shared by the DLT. In the CMM system described here, the advantages of both models are exploited by evaluating provisional values for the camera parameters using the DLT and then introducing these as provisional values in a subsequent iterative least-squares bundle adjustment.

Both models require knowledge of the 3D co-ordinates of a number of object points (control points) for the determination of the orientation parameters. The control points used for the prototype CMM were 32 circular retro-reflective targets located on a control frame, which was positioned in the measurement region. Control point positions on the frame were established to sub-millimetre accuracy ($\sigma_{xyz} = 0.1$ mm) by means of an independent high precision photogrammetric system.

Images of the control frame were captured by the three cameras and processed to extract the centre positions of the control point targets with sub-pixel accuracy. The target extraction procedure used the following image processing techniques:

- application of an edge detector in the form of maximum gradient filter in the four principal directions for the identification of all – including target – edges in the image
- segmentation of the edge detected image by thresholding in order to create a binary edge image
- feature extraction to determine circular features on the binarised edge image
- sub-pixel, centroid determination of the circular features (targets) identified by the feature extraction process.

A full description of the image processing techniques may be found in Craigie.[3]

Once the targets have been found, a semi-automatic target identification procedure is implemented which requires an operator to manually identify 8 of the 32 control points on each of the three images for the first calibration of the system. Subsequent calibrations can be executed without operator support, provided the system configuration remains unchanged. A DLT based on the 8 manually identified targets is executed to determine first approximation values for the positions and orientations of the three cameras. The same mathematical model is then employed to automatically identify the remaining target points and, based on these, to further refine the approximations for the orientation parameters and increase the reliability of the solution. A final solution for the parameters is found by introducing the DLT-derived provisional values into a least-squares bundle adjustment.

The measurement of the rotation axis

Before the measurement process can be initiated and all-round object surface points determined, it is necessary to determine the position in space of the axis about which the object is rotated during the measurement process.

The rotation axis is calibrated by measuring a small spherical probe eccentrically attached to the rotary axis by means of a rod. The probe is rotated about the rotation axis in user-definable steps and the 3D co-ordinates of the probe in each position are measured. The probe will describe a circle around the rotation axis with its centre coinciding with that of the axis. Circle centre and radius

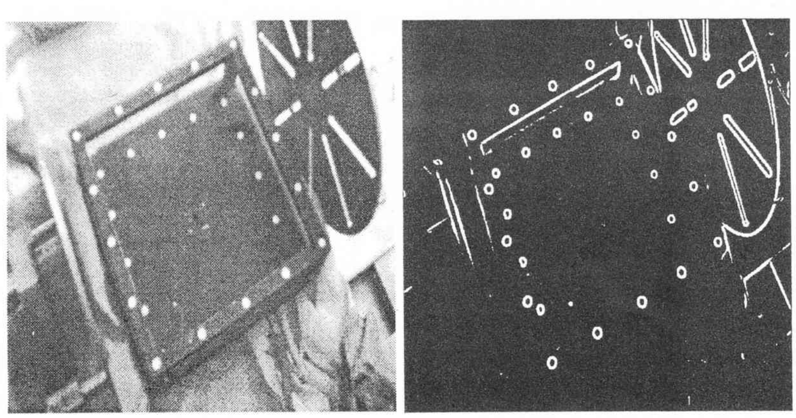

Figure 2 Edge detection and thresholding. The example shows the original image (left) and the binarised edge image after application of the gradient operator for edge detection and the thresholding function

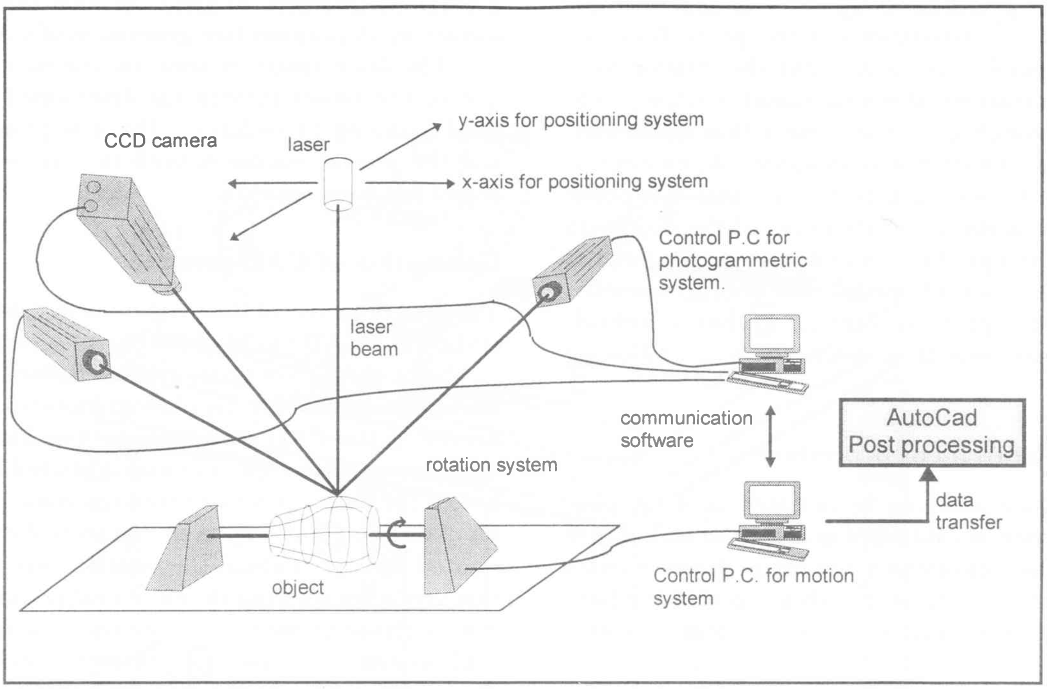

Figure 1 System design

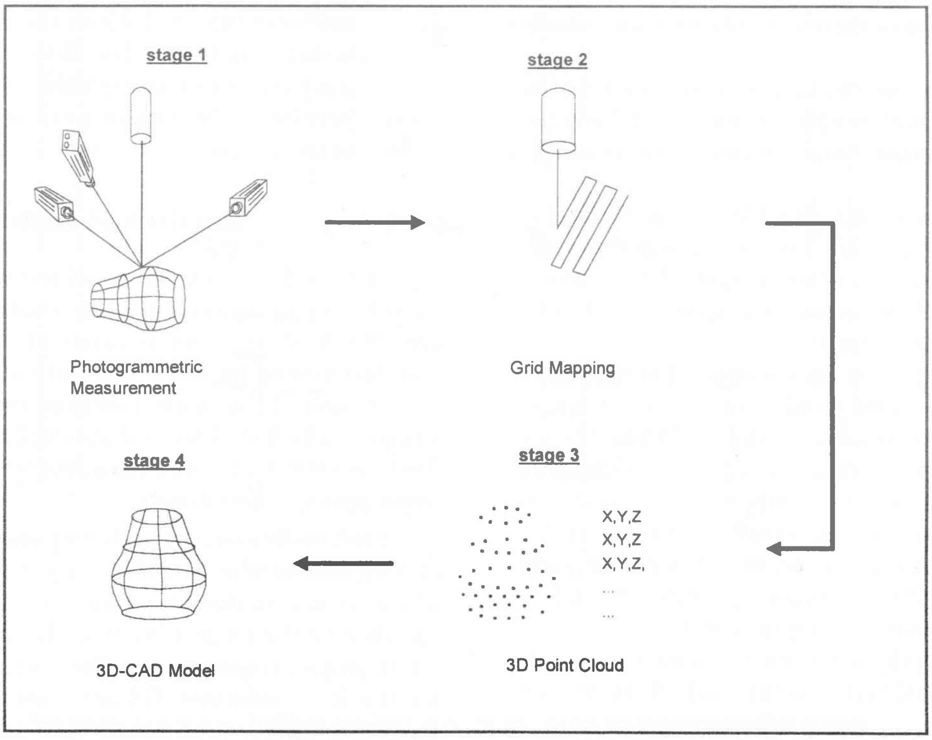

Figure 3 Development sequence of the surface model. Photogrammetric measurement of the laser dot on the objects surface, movement of the dot to a new position, sequential generation of 3D point cloud andcreation of the 3D meshed model

are determined in a best-fitting least-squares 3D circle adjustment. Repeating the measurement sequence with the probe in different positions along the axis and with different radii (different separations of the probe from the axis) leads to a number of points along the rotation axis. In a final step, a least-squares adjustment is employed to best-fit a line through the circle centres thus mathematically defining the rotation axis in space. Knowledge of the position of the rotation axis in space makes it possible to correct for asymmetric mounting of the object on the rotary table and produce an undistorted wire mesh of the object surface in a CAD model. The photogrammetric measurement of the probe is identical to that of individual laser dot measurement as described in the following section.

The object measurement procedure

The object measurement can be initiated once the photogrammetric system is calibrated as described earlier. For the duration of the measurement the entire device is veiled to control the light conditions in such a way that the laser target dot on the object surface is the only feature visible to the cameras.

In the first measurement step images of the laser dot on the object are captured by the three cameras, edge detection on one of the three images, the reference image, is performed, the edge image is binarised and the circular target feature extracted (as described earlier). Due to the controlled light conditions there will only be a single target in the image.

The centre of the circular target on the reference image is then computed and an epipolar line search[8] is implemented to locate conjugate target points on the remaining two images.

A Multi-Photo Geometrically Constrained Matching (MPGCM) routine[4,8] is then used to match the target points on the original grey-scale images of the cameras prior to the solution of the collinearity equations in a three-dimensional space intersection.

In the MPGCM process only a selected section of the reference image, a so-called window or patch is required. This is a small area surrounding and including the target point. In a search algorithm, windows containing the same target point are automatically detected on the images captured with the other cameras (target images). Due to their different perspectives the windows on the target images will have a different shape, orientation, and position and it is necessary to apply a shift, affine scales, shear, and rotation to the windows in a least-squares procedure until an optimal match is established. In this way the position of the target point is determined in terms of xy-image co-ordinates with sub-pixel accuracy on each of the images. These co-ordinates are, together with the calibration parameters, introduced into a least-squares space intersection to solve for the three-dimensional object space co-ordinates of the target point.

The three dimensional co-ordinates of the target point are cross referenced with the rotation angle of the rotary table at the instant of measurement and post processed in a CAD environment to yield the final three-dimensional surface mesh position (see generation of CAD mesh).

The laser target is then moved to a new position and/or the object rotated (as determined by the predefined scanning procedure). The new point is measured and the process continues until the entire surface of the object has been mapped.

Generation of CAD mesh

The final objective of the measurement process is the generation of a CAD model of the object surface. To this aim an object space co-ordinate system, defined by the control frame system used for the photogrammetric calibration, is defined in the CAD environment. The first set of three-dimensional surface co-ordinates is plotted in this system. Before the object is rotated through angle α and the next set of surface points captured, the plotted co-ordinates are rotated through α about the rotation axis; the position of this axis is known from the earlier calibration. This procedure is repeated until the entire object is captured in the CAD system. The resulting three-dimensional 'cloud' of data points represent the measured object's surface.

The next stage links the points of the cloud to form a 'wire' mesh based on the neighbourhood relationships of the individual points, where mesh links represent neighbourhood links. Knowledge of the sequence in which the data points were captured allows the mesh to be automatically generated in CAD. The three dimensional mesh is in a format that can be interpreted by a computer numerically controlled (CNC) milling machine to reproduce the surface of the measured object.

Results and analysis

A prototype device was built and tested to evaluate the design of the photogrammetric non-contact co-ordinate measurement machine. An estimate of the system accuracy was determined by using the system to measure the 3D co-ordinates of the target points on the control frame, positions of which are known to sub-millimetre accuracy. Differences between the two data sets were evaluated as root mean square differences (rmd).

First measurements and comparisons resulted in rmds of 0.05 mm in the X and Y object co-ordinates, values which fall within the sub-millimetre accuracy requirements specified for the project (an rmd of better than 0.1 mm was set as project requirement). However, the rmd of 0.13 mm for the Z co-ordinates did not meet these requirements. Further analysis of the results indicated that an accuracy deterioration was likely to have been caused by large rotations of the cameras (about their optical axis) with respect to each other. The initial three-camera configuration as installed for the test rotated the cameras about their optical axis resulting in rotated image geometry of the search images with respect to the reference image. This rotated

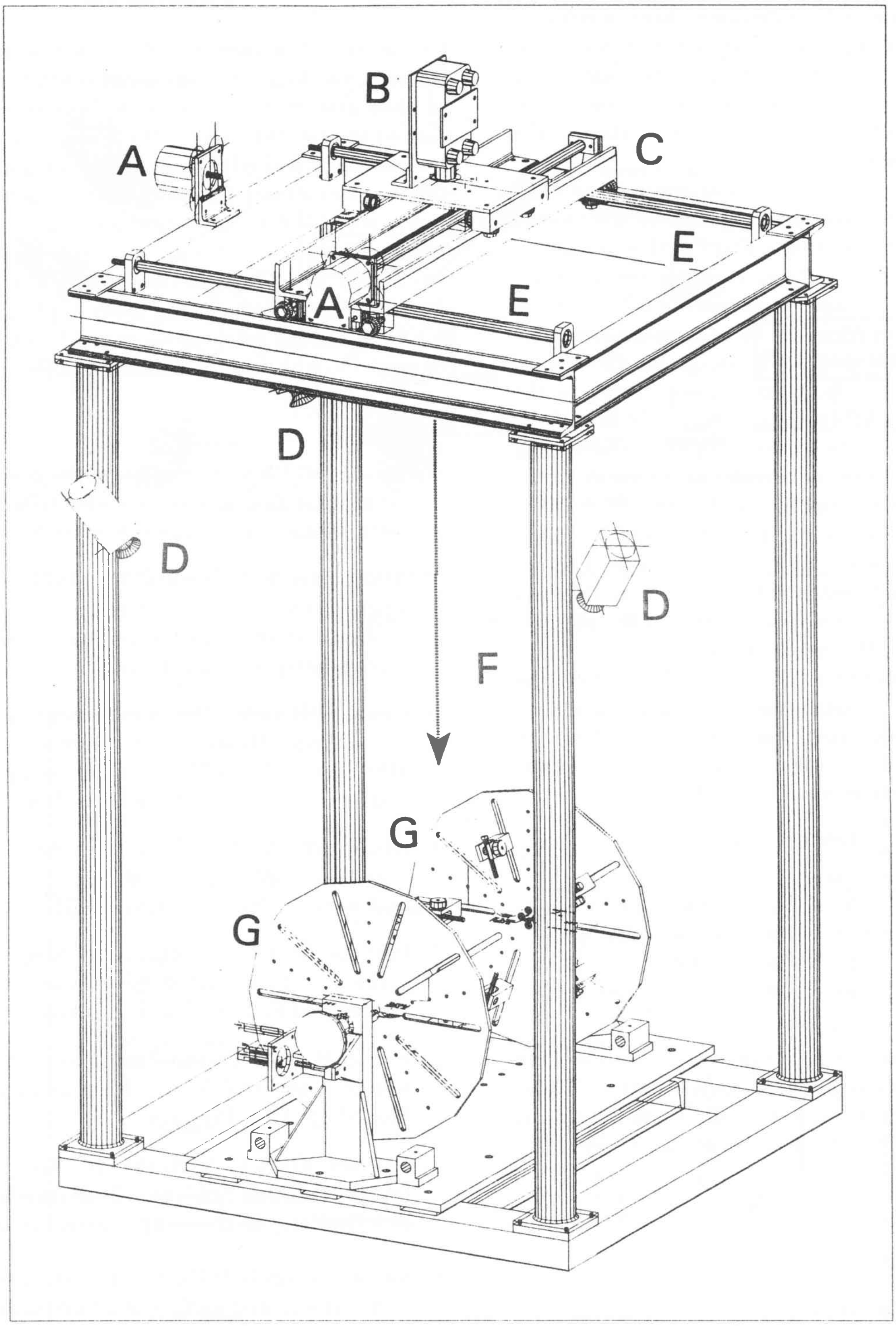

Figure 4 Laser positioning system and object positioning system hardware
A = drive motors for laser positioning system; B = laser
C = laser positioning system: x-axis guide rail; D = CCD camera positions
E = laser positioning system: y-axis guide rails; F = direction of projected laser beam
G = object motion system: rotation discs

configuration had not been allowed for in the mathematical modelling of the image matching procedure which lead to results of inferior accuracy. This phenomenon is of little theoretical interest in the mechanical engineering environment and shall thus not be discussed here; a detailed discussion is presented in Craigie.[3] However, it is of great practical relevance for the installation of the cameras in the CMM and care must be taken to mount the digital cameras in the system frame without much rotation of the cameras relative to each other.

Tests carried out with rotated and non-rotated cameras confirmed that rotated image geometry did indeed result in accuracy deterioration. The CMM was used to measure the known control frame co-ordinates using rotated and non-rotated image geometry. As a further improvement on the first test run, the target centres were determined to sub-pixel accuracy in all images and not, as was done in the first test, to single pixel accuracy in the reference image and to sub-pixel accuracy only in the two search images. The results of this test are presented in Table 1. They clearly show an overall improvement due to the sub-pixel centre determination and as the effect of rotated image geometry on the accuracy of the measurement system is minimal when sub-pixel accuracy is used to define the reference target centre. The results from this test fall within the sub-millimetre requirements of the project.

Table 1 gives the differences between the control point co-ordinates as determined with the CMM and with the high precision system. Listed are the root mean square deviation (rmd), the maximum absolute deviation between the two co-ordinate sets and the maximum range (largest positive − largest negative deviation value).

Table 1

	non-rotated			rotated		
(units: mm)	dX	dY	dZ	dX	dY	dZ
r m d	0.03	0.05	0.08	0.03	0.05	0.13
maximum deviation	0.12	0.10	0.28	0.12	0.10	0.46
range	0.17	0.18	0.42	0.17	0.18	0.65

In a final qualitative test series several objects were successfully measured using the prototype device. These objects were selected to provide a range of conditions under which to evaluate the capabilities of the device. The test objects were:

- a paper mask
- a mannequin head
- an outboard motor propeller

The paper mask provided a non-rigid object, the mannequin head a sculptured surface, and the propeller a discontinuous sculptured surface. The results of these tests could not be evaluated in any quantitative form as no reference data sets were available. However, a comparison of the original with the CAD model by inspection showed excellent agreement.

Conclusion

The design of a user-friendly, low-cost prototype non-contact co-ordinate measurement machine based on digital photogrammetry concepts has been successfully implemented at prototype level. The non-contact measurement method using a digital camera system, photogrammetric software and a laser targeting device has been tested and proved suitable for the measurement of non-rigid or rigid, sculptured objects with sub-millimetre accuracy. The system output is a 3D point cloud and a CAD model of the object surface suited, among other applications, for input to a CNC milling machine operating in a CADCAM environment to duplicate the measured object.

References

1. Brown DC 1958. A solution to the general problem of multiple station analytical stereo triangulation. RCA Data Reduction Technical Report No. 43.

2. Abdel-Azis Y & Karara HM 1971. Direct Linear Transformation from Computer Co-ordinates. *Proceedings of the Symposium on Close Range Photogrammetry*, Urbana, Illinois.

3. Craigie DH 1996. The development of a Non-contact Co-ordinate Measurement Machine. Unpublished MSc thesis. Department of Surveying and Geodetic Engineering, University of Cape Town.

4. Gruen AW & Baltsavias EP 1988. Geometrically Constrained Multiphoto Matching. *Photogrammetry and Remote Sensing*, **54**(5), p.633–641.

5. Parbhoo P 1995. Automated Non-contact surface mapping. Unpublished BSc thesis. Department of Mechanical Engineering, University of Cape Town.

6. Rüther H 1991. Digital Photogrammetry – Introduction to a new tool for the Photogrammetrist. ISPRS Workshop, V/4, Pretoria.

7. Van der Vlugt G & Riither H 1991. DIMS. Digital Image Matching Software. Department of Surveying and Geodetic Engineering, University of Cape Town.

8. Van der Vlugt G & Rüther H 1994. The development of an automated surface measurement system. *International Archives of Photogrammetry and Remote Sensing*, **30**(5), p.414–419.

9. Van der Vlugt G 1994. *PHOTONET* Bundle Adjustment Program. Department of Surveying and Geodetic Engineering, University of Cape Town.