

Report

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**A review of industrial
capabilities to measure
free-form surfaces**

**Gordon Rodger, David Flack
and Michael McCarthy**

January 2007



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A review of industrial capabilities to measure free-form surfaces

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ABSTRACT

An industrially orientated review of the current capabilities for measuring free-form surfaces has been undertaken with the aim to establish traceability requirements and potential designs for free-form verification artefacts. Encompassing non-contact and tactile measuring techniques, this report draws on published literature and information gained from visits to industry, academic institutes, International Organisation for Standards and systems manufacturers. Finally, the report summarises industrial free-form measurement capabilities, the requirements for published standards and system verification metrology artefacts.

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1 INTRODUCTION

An industrially orientated review of the current capabilities for measuring free-form surfaces has been undertaken with the aim to establish traceability requirements and potential designs for free-form verification artefacts. Encompassing non-contact and tactile measuring techniques, the review summarises presently available commercial instruments, software and related research.

As a deliverable for the Free-form Verification project, (see section 1.2) this report draws on published literature and information gained from visits to industry, academic institutes, International Organisation for Standards and systems manufacturers.

This report is in three sections: chapters two and three look at current free-form measurement systems, technologies and related design and analysis software. Chapters four and five concentrate on the research effort by universities and other National Measurement Institutes (NMIs). Finally, chapter six details the contacts made from some twenty visits to industry as part of the information gathering process.

The authors do not promote or endorse any product or system contained herein and no inference should be made from the non-inclusion of any institution, product or publication.

1.1 DEFINING A FREE-FORM SURFACE

No precise definition for a free-form surface was found as part of this review. ‘Free-form’ suggests a surface with non-prismatic shape and form. VEECO [83] describe asymmetric and spherical optical components as ‘free-form optics’. When trying to describe a free-form surface, even the use of ‘asymmetry’ can be misleading, as it may be argued that if one axis of a surface can be described mathematically as a geometric shape, it cannot form part of a truly free-form surface. However, there are a countless number of components and artefacts that combine a series of varying shapes and geometries. Whilst discrete regions of an artefact such as this may be described mathematically, the whole artefact has a complex form and is therefore very difficult to describe mathematically. This report will employ a simpler definition for a free-form surface thus:

A surface, the shape of which, cannot be described by a simple mathematical expression.

1.2 THE PROJECT (2.01 FREE-FORM VERIFICATION)

The proposed project to develop free-form verification processes is designed to support industries with free-form manufacturing capabilities, where traceability and quality control are issues due to lack of traceable verification artefacts. The development of free-form artefacts will extend capabilities beyond the National Measurement System (NMS) boundaries that currently offer basic support for components such as those having prismatic form (for example, cubes or cylinders). New machining techniques make it possible to manufacture a range of advanced free-form components and, with appropriate metrology, higher precision (sub-micrometre) can potentially now be achieved, combined with increased productivity levels and lower costs. However, it has

been observed that the application and advanced development of such manufacturing techniques has a lack of suitable traceability, where depending on the application and component size, measurement uncertainties in the range from tens of micrometres to one micrometre are required. Investments in related UK manufacturing facilities, and more importantly measurement systems for quality control, are increasing year on year.

Free-form components include moulds, turbine blades, camera lenses, prosthetics, anthropometric parts such as hips and limbs, and large automobile and aerospace panels. In the case of turbine blades, Internet based research conducted by one of the authors suggests that one UK company alone has 30% of the world market and its annual sales in the civil market alone are in excess of £2.3 billion. Metrology advances in this area alone could enable the UK to capture more of an annual £7.6 billion, growing worldwide market.

Established free-form measurement techniques do not provide the required measurement accuracies or traceability needed to verify the performances of, for example, modern high precision multi-axis manufacturing centres. Thus, current applications and advanced developments of such emerging free-form manufacturing techniques are being hindered by a lack of supporting metrology. New generations of both non-contacting and contacting free-form measuring systems are now being developed. Although these take advantage of recently developed higher-resolution probes, which can collect large data sets and benefit from phase measuring techniques, they nevertheless still require verification and traceability routes.

The NMS free-form verification project aims to establish a free-form measurement infrastructure supported by portable verification artefacts. These artefacts will assist significantly in the characterisation and provision of measurement traceability for commercial complex free-form measuring systems, thus supporting the UK's engineering base in the rapidly growing field of advanced free-form machining. In collaboration with industry, measurement capabilities will be developed and free-form verification artefacts will be designed. These designs will be presented *via* NPL's Dimensional Metrology Awareness Networks (EMAN/DMAC [80]), free-form measurement user groups, through active project contributors and *via* knowledge transfer (KT) aspects of the Engineering Measurement Programme. Free-form transfer artefacts of comparable sizes to the available measuring facilities will be manufactured from these designs and used for verifying industrially based systems. A variety of commercially based and existing NMS facilities, operating in a volume of nominally 550 mm × 500 mm × 150 mm, with dimensional measurement uncertainties in the range of 1 µm to 30 µm, (dependant upon volume and application,) will be targeted. The technology developed will be disseminated to equipment manufacturers and industrial end users.

The project objectives are:

- To carry out a literature search and industrially based surveys determining the current industrial capabilities and traceability requirements including discussions with members of ISO/TC 213 *Dimensional and geometrical product specifications and verification*.
- To optimise NMS based static tactile and non-contacting facilities for measuring surfaces up to 550 mm × 500 mm × 150 mm, collaborating with commercial or industrially based facilities.

- To design and manufacture free-form artefacts in the range 20 mm to 500 mm and develop measurement strategies, and models, as required.
- To implement a measurement comparison between at least five systems using industrially based collaborator's facilities.
- To disseminate the technology developed by way of publications, for example through Measurement Science and Technology (MST), The European Society for Precision Engineering and Nanotechnology (**euspen**), The American Society for Precision Engineering (ASPE), and presentations to key industrial audiences *via* the Engineering Measurement Awareness Network (EMAN), Dimensional Metrology Awareness Club (DMAC) and trade exhibitions and seminars.

1.3 PREVIOUS RELATED WORK AT NPL - NON-CONTACT STANDARDS FOR ANTHROPOMETRY AND INDUSTRIAL IMAGING SYSTEMS

The free-form verification project follows on from a project that formed part of the NMS Programme for Length Metrology, (2002 to 2005), entitled Non-Contact Standards For Anthropometry And Industrial Imaging Systems. The aim of the project was to develop standards and mobile calibration facilities for verifying non-contacting measuring systems used for industrial inspection and measuring the human body form (anthropometry).

1.3.1 Rationale

During the earlier project the use of high-speed, non-contact measurement systems in many manufacturing sectors was identified. Few such systems were traceable to the NMS because the relevant two-dimensional (2D) and three-dimensional (3D) reference artefacts and non-contact calibration facilities were not available. There was also widespread concern among users that measurements made using commercially available contact and non-contact systems rarely correlated. These discrepancies needed to be investigated using specialised dual-purpose artefacts that reflected shop-floor requirements, without compromising on the disseminated metrology. If non-contacting systems were going to be employed effectively, it was essential to demonstrate that they measure, not only reproducibly, but accurately too.

1.3.2 2D reference materials

As part of the earlier project, the traceability routes required for non-contact target metrology were investigated in conjunction with industry. As a result of this investigation, some prototype verification artefacts were manufactured. These included grid plates (see Figure 1) and scales up to 650 mm in size. These artefacts were measured using NPL facilities and by some industrially based measuring machines. Grid plates like this will have a direct use in the free-form verification project as structured light systems routinely use 2D grid plates to calibrate their imaging components.

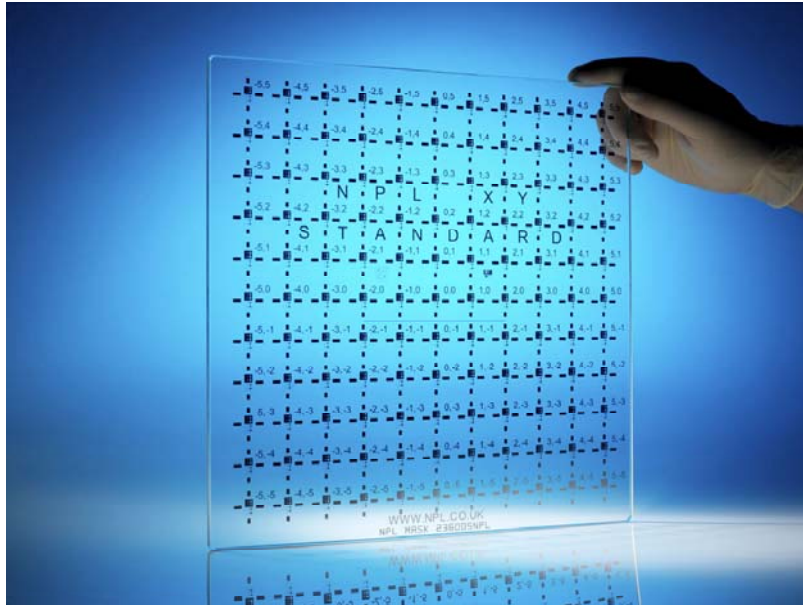


Figure 1: NPL 2D grid plates for calibrating vision-based instruments

1.3.3 3D reference materials

With respect to anthropometric and 3D image systems, two human sized geometrical models (as shown in Figure 2) and eight engineering orientated transfer artefacts (as shown in Figures 3 and 16) were manufactured and calibrated using NPL's co-ordinate measuring machine (CMM) facilities. These artefacts have been measured by a number of industrial collaborators whose businesses range from human body scanning metrology and turbine blade production to high-speed photogrammetric and laser scanning non-contact measuring equipment. Some collaborator's equipment performed well once calibrated using the NPL verification artefacts. This indicated that their equipment was working well as a 'comparator', but only working well over a given range or for similar surface textures. Few instruments were able to directly measure all of the artefacts reliably. The overall outcome of the collaboration was that the industrially based non-contact facilities tested did not perform as well as the users had expected. NPL was able to offer advice and in some cases to help overcome some of the measurement discrepancies.

1.3.4 Tactile and non-contact instruments

Measurement discrepancies between commercial contact and non-contact systems were investigated. Clearly the two technologies are very different and for general engineering applications, contact metrology is invariably a more sound approach to providing traceable dimensional metrology. However, non-contact systems are superior where high-speed measurements are essential, sterile conditions are needed or where large data sets are required. Two of NPL's CMMs (Leitz contact machine and Mitutoyo vision machine) were modified to work in both contacting and non-contacting modes. The outcome was positive, with both machines working nominally to specification, but clearly there were significant discrepancies in terms of speed and machine flexibility. It is envisaged that both instruments, together with an upgraded Zeiss CMM, will be used in the latter stages of the free-form verification project to provide measurement data.

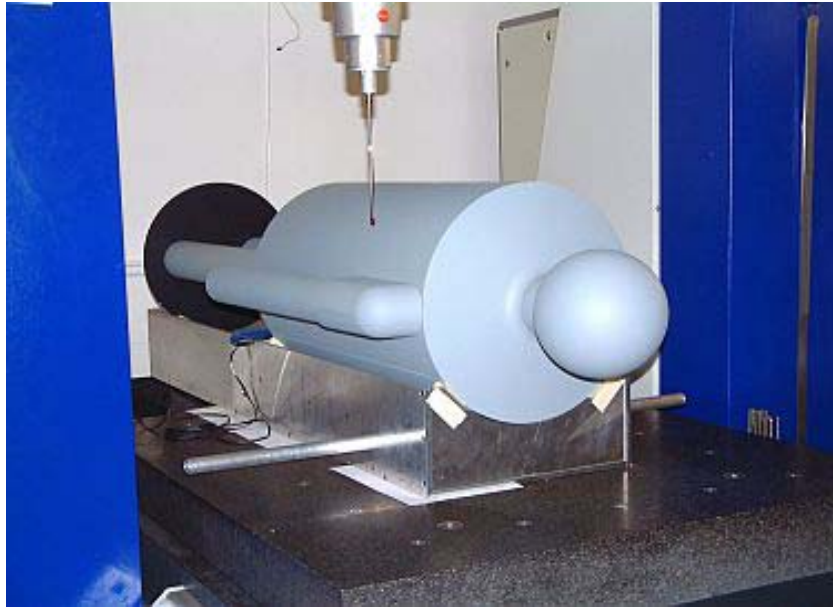


Figure 2: NPL Phantom, anthropometric dimensional metrology

1.3.5 Collaboration and further research opportunities identified

There was significant interaction between NPL and Technical University of Denmark (DTU) [81] who acquired an NPL 2D grid plate and who themselves produced a mechanical 2D hole-plate. Rolls Royce used some of the smaller 3D artefacts shown in Figure 3 to develop and verify the performance of their new non-contact facility for measuring the form of gas-turbine blades. These artefacts have also been measured using non-contact scanners at Heriot-Watt University (see section 6.5), whilst the larger anthropometric artefact has been measured by Wicks and Wilson (see section 6.20), GOM UK Ltd (see section 6.4) and the University of Birmingham (see section 6.1).

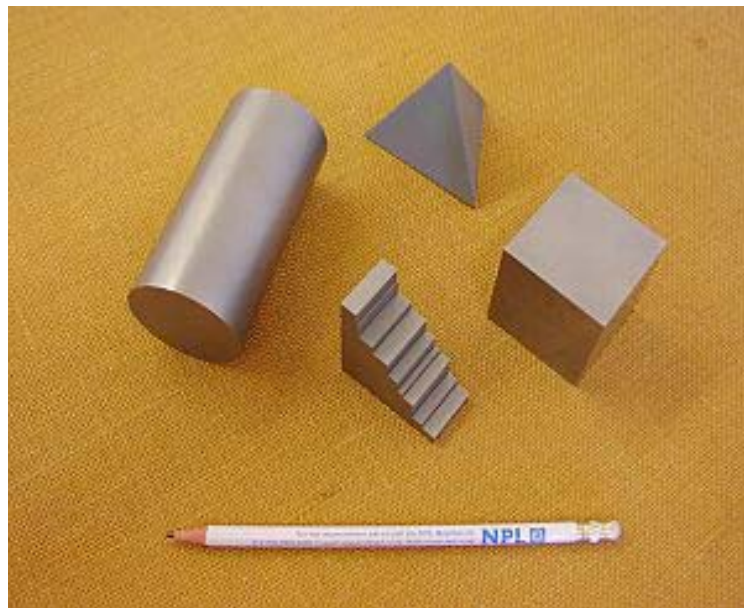


Figure 3: Engineering-orientated dimensional transfer artifacts

The NMS programme for length metrology (2002-05) identified in project 3.3 [84] that there is an industrially driven demand for increasing the diversity and range of reference artefacts. Specifically, 3D (volumetric) free-form artefacts were developed to

support the surface-form metrology community, with these artefacts also being suitable for use in target-type metrology instruments.

2 FREE-FORM MEASUREMENT SYSTEMS AND TECHNOLOGIES

A broad range of metrology systems and technologies with free-form measurement capabilities have been investigated. They have been classified as either tactile or non-contact and are reported on in the following sections.

2.1 TACTILE SYSTEMS – COORDINATE MEASURING MACHINES

There are numerous types of CMM commercially available. Some types and manufacturers include:

- Hexagon Metrology Ltd (now including Leitz) [1,2] (see Figure 4), Mitutoyo [3] and Zeiss [4]. CMM types include Bridge, Gantry, Column and Cantilever (for example see Figure 5).



Figure 4: The NPL Leitz CMM



Figure 5: Zeiss cantilever CMM demonstrated at Carl-Zeiss based in Rugby

- Laser tracker co-ordinate measuring systems (for example, Faro [5], Leica Geosystems, now also part of Hexagon Metrology Ltd [6] and NDI [7]). Figure 6 shows a demonstration of a Leica tracker being used to measure the free-form shape of a car at Control-2006 and Figure 7 shows the associated hand-held Leica six-degree of freedom (6DOF) probe that was demonstrated at Hexagon Metrology Ltd in Telford.



Figure 6: Leica laser tracker in operation at Control-2006



Figure 7: Leica 6DOF probe demonstrated at Hexagon Metrology Ltd in Telford

- Horizontal arm and portable (or articulated) arms, such as those available from Cimcore[77] and Faro[5]. Examples of such arms were demonstrated at Inspex (see section 6.19) and are shown in Figure 8 and Figure 9.



**Figure 8: Example of Cimcore articulating arm promoted at Inspex 2005
(Courtesy of Europac [77])**



Figure 9: FARO articulating arm CMM shown at Control 2006

Typical CMM accuracies are shown in Table 1. However, they all operate using the same principle; by moving a spherical ended stylus to contact the object to be measured at appropriate points. For each contact of the stylus with the object, coordinates of the sphere centre are recorded. In order to calculate the position of the point of contact between the sphere and the surface being measured, the direction of the local normal to the surface that passes through the sphere centre is required. This can be calculated trivially for simple, geometric surfaces, but is difficult to obtain for free-form surfaces. The surface point is calculated by shifting a distance equal to the sphere radius away from the sphere centre in the direction of the normal – a process known as radius correcting. In this basic mode, a CMM is unsuited to perform measurements on an unknown free-form surface.

Type	Indicative Errors
Bridge	$\pm <5 \mu\text{m}$
Gantry	$\pm 10\text{s } \mu\text{m}$
Column	$\pm 10\text{s } \mu\text{m}$
Cantilever	$\pm 10\text{-}50 \mu\text{m}$
Articulated	$\pm 50\text{-}250 \mu\text{m}$
Tracker	$\pm 10 + 5 \mu\text{m/m}$

Table 1: Typical CMM accuracy

2.1.1 CMM scanning probes

Traditionally, CMMs are generally used to measure single points on a surface, and the shape is inferred from a best-fit substitute element to those points. In order to increase the density of data and to extend the capabilities of CMMs, some have the ability to scan the surface at high speed, whereby the machine is driven from one surface point to another keeping the probe in contact with the surface at all times. This can produce a series of closely spaced measurements along the line. Normally the line of a scan is straight if projected into one of the coordinate planes. From this, CMM software can provide information about the form of features, as well as their size and location.

Scanning probes can also be used to acquire discrete points in a similar way to touch-trigger contact probes.

Scanning is useful for measurement applications where the form of a feature is specified, or where complex surfaces must be inspected. For the best results, it is necessary to keep the deflection of the probe stylus within the measurement range of the probe. This demands significant control effort to link sensor and machine, as well as computational effort to convert the measurement data into information about the surface. The control algorithms can also respond dynamically to the shape of the part, for example taking less data on flatter surfaces and taking more data where the surface form changes rapidly.

The Renishaw SP25M is a typical scanning probe and uses a lightweight passive mechanism, making it suitable for high speed scanning [8]. Such a probe was demonstrated on a DEA (now trading as Hexagon Metrology S.p.A, Italy) CMM at Hexagon Metrology Ltd in Telford, where a complex surface was measured (see section 6.6 for information on Hexagon Metrology Ltd). A photograph of the probe and the artefact measured is shown in Figure 10.

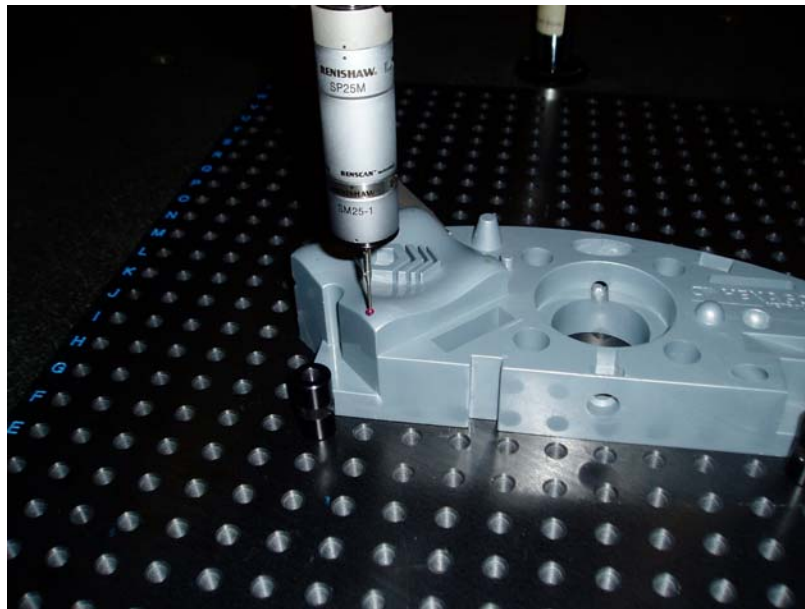


Figure 10: Renishaw SP25M on a DEA CMM at Hexagon Metrology Ltd Telford

To enable better accuracy and a faster dynamic response, the deflection of the stylus is sensed directly by isolated optical systems. A range of probes is available, suitable for all sizes and configurations of CMM. The Mitutoyo Legex 322 CMM [9] claims an accuracy of $0.8 + 0.2L/100 \mu\text{m}$, where L is in millimetres, equating to $1.4 \mu\text{m}$ over its full range of 300 mm using the SP25M scanning probe and TP6M fixed probe. Mitutoyo also have their own scanning probes, the MPP-100 and 300 series. Stated accuracies are $\pm 3 \mu\text{m}$ for the MPP-100 when used with a CRYSTA-APEX700/700 system, $\pm 1.0 \mu\text{m}$ for the MPP-300 when used with a RV-II system and $\pm 0.5 \mu\text{m}$ when used with a LEGEX system [10].

The latest offerings from Renishaw in the scanning probe market are the Revo™ and the Renscan5™ [11]. The Renscan5™, which is shown in Figure 11 is only available for use with the Renishaw UCC2 Universal CMM Controller. The more universal Revo™ probe, which is shown in Figure 12 and has recently been released, was

demonstrated measuring the form of an engine block at Control-2006 at Sinsheim, Germany (see Figure 13).

The Revo™ probe is designed to maximise CMM throughput whilst maintaining high system accuracy. Scanning speeds up to 500 mm s^{-1} are possible without accuracy penalties. The Revo™ measuring head is articulated with 0.08 second of arc high-resolution encoders providing fast ultra-high accuracy positioning. It is able to quickly follow changes in the part geometry without introducing dynamic errors due to its better frequency response and low mass. The CMM is then able to operate in its most efficient mode, namely moving at constant velocity along a single vector while the probe is measuring.



Figure 11: Renishaw Renscan5™ [8]



Figure 12: Renishaw Revo™ [8]

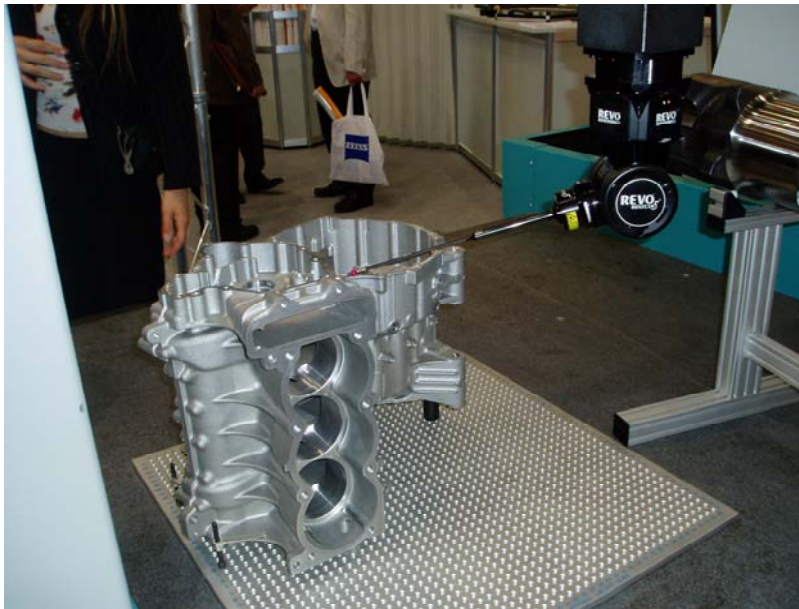


Figure 13: Renishaw Revo Probe demonstrated at Control 2006

Carl Zeiss Industrial Measuring Technology have introduced the VAST XXT [12] fast scanning probe (see Figure 14) into their product line as a replacement for touch trigger probes. It offers scanning capability on Carl Zeiss CMMs equipped with an articulating probe holder and is suited for applications where maximum accuracy and flexibility are key. The VAST probe was demonstrated by Carl-Zeiss at their contract measurement

and demonstration facility in Rugby and also at Control-2006 (see section 6.18). An example of the probe is shown in Figure 15.



Figure 14: Zeiss VAST XXT demonstrated at Rugby



Figure 15: Carl-Zeiss (Rugby) facility including VAST scanning probe on a CMM

2.1.2 CMM touch probe free-form measurement

The University of Padova and Technical University of Denmark (DTU [81]) have conducted significant research in the free-form field using CMMs and have developed artefacts and methods for traceable free-form measurement [13,14]. The work is based around a Modular Free-form Gauge (MFG). The MFG is based on physical modelling of a given free-form surface by a combination of artefacts with regular geometry. The items are calibrated for dimension and form. The authors conclude that the MFG is a practical solution to establish the traceability of free-form measurements for a specific application (the measurement of turbine blades). They were also able to quantify the free-form measurement uncertainty at the 10 μm level. The limitations are that by using

this gauge it is impossible to simulate extensive and continuously varying shapes, in particular concave surfaces.

The modular free-form gauge described could be something that is applicable to this project. It is composed of items of simple geometry that are easily measured by conventional means. The calibration of the MFG was carried out using a conventional CMM.

Savio and De Chiffre of the DTU [81] have also presented work detailing the validation of calibration procedures for free-form parts on CMMs [15]. This paper is relevant for our work and describes a new method for the establishment of traceability of free-form measurements made on CMMs. The technique is based on the draft of ISO/TS-15530-6 – *GPS – Co-ordinate Measuring Machines: Techniques for determining the uncertainty of measurements. Part 6 Uncertainty assessment using uncalibrated workpieces and a multiple of measurement strategies*.

It is of interest that the work was published in 2003 and yet the draft standard has not yet been published. This should perhaps be followed up through ISO TC213. The basic idea is to perform the uncertainty assessment by means of experiments where uncertainty contributions are varied. This involves measurements at different positions and orientations and variation in number and distribution of points and scanning speed. A final calibrated length standard is used to get scaling. The method has been tested on a turbine blade, a screw compressor and a bevel gear using two different CMMs. Using the data collected, the estimated uncertainty of free-form measurement was 2 μm to 3 μm for one CMM (high accuracy) and 4 μm to 8 μm for the other (medium accuracy CMM).

Several other papers have been identified which may be of interest regarding the use of CMMs for free-form surface measurement. They are summarised below.

Wolovich and Yalcin [16] have published work addressing the issue of probe motion and probing points on free-form surfaces. They also report with Albakri [17] on the use of implicit polynomials to calculate the radius correction for ball centre data on a free-form surface. The manufacturers Brown and Sharpe supported the work, the goal being to be able to report the errors between a model artefact and corresponding points on an unknown identical part. To overcome the problem of determining which points on the model artefact correspond to the measured points, they illustrate a method where the perpendicular distances are calculated between the modelled and calculated points. The technique is best suited when a model component exists to compare against. In the example in the paper a three bladed propeller is used. Blade one is used as the model to which the other blades are compared. The distance approximation errors are less than 1 μm .

Li and Liu [18] present a novel method for determining the probing points for achieving efficient measurement and reconstruction of free-form surfaces. The method is based on the assumption of the availability of both a vision system, to quickly obtain an approximation of a surface, which is then used to guide the more accurate, but much slower touch probe of a CMM. The authors investigated the use of B-spline models to represent free-form surfaces and proposed the modified Bayesian information criterion method for selecting the optimal model structure from the cloud of data points acquired by a 3D vision system. The authors then state that based on the model structure, the

number of measurement data points required for the high-precision measurement can be determined. In order to obtain a more accurate model, the uncertainty of the model is analysed. Then using statistical analysis, the locations of the measurement data points are optimised to reduce the uncertainty in the model. Based on the results of the optimised measurements, a touch probe can then be used more efficiently to obtain the accurate measurements for the reconstruction of the free-form surface. The experimental results show that the proposed method is effective and promises to be a useful application of integrated multi-sensor measurements such as vision-guided CMMs for reverse engineering. When combined with an adaptive modelling scheme based on the features of a free-form surface, adaptive localization of the measurement data points can also be implemented. The proposed method allows the advantages of the high speed in vision sensing and the high accuracy in touch sensing to be utilized for efficient and accurate reconstruction of free-form surfaces. However, the example free-form surface described is fairly simple and if this paper is correct, the selection of number and distribution of sampling points is not as easy as it at first might seem. The authors' conclusions are very relevant if single point probing on a CMM is used to measure the free-form artefacts produced as part of the current project.

Ainsworth, Ristic and Brujic [19] have also published work in this area and it is mainly concerned with planning a measurement strategy for measuring a free-form component on a CMM. The work reported, whilst novel at the time, was written in 2000. It is possible that it has found its way into mainstream software. In essence, the idea was to use the CAD model to create an offset surface to minimise errors from probe radius compensation and to improve computational efficiency. Automatic collision detection routines, interactive graphic tools and fully rendered computer animations of the measurement process were also developed.

Lin and Sun [20] published work in 2003 relating to probe radius compensation and this deals with the analysis of free-form data. They present an improved multi-cross product method to perform probe radius compensation by weighting the data. The best way to probe-radius-compensate is using NURBS (Non-Uniform Rational B-Splines), but this can have a penalty in terms of computational time. Other solutions are iterative and again have a penalty in terms of computational time, however, this is probably less of an issue in 2006 with the advances in computing speed. A method of compensating a point by using the cross-product of the tangential vectors deduced from the probe centre of the compensated point and its four nearest points has been reported by Xa [21]. This method has the best performance in terms of convergence, computing time and computer memory space. However, its accuracy is lower than is the case for other methods. Lin and Sun [20] propose an improvement to this method by using a systematic weighting factor, which significantly reduces the error of measurement.

2.1.3 Traceability of CMM measurements

True traceability in CMM measurements is virtually impossible to achieve. The structure of the CMM is so complex that the error propagation is too difficult to analyse with sufficient accuracy to provide a reliable enough error budget to fulfil the strict traceability requirements. Only in a very restricted set of circumstances, primarily when the CMM is being used as a simple comparator, can the results be said to be traceable. Typically, reference artefacts such as those developed by NPL (shown in Figure 16) and ring and plug gauges can be used to make comparative measurements. Normally the error associated with CMM measurements is only approximately known, and has generally been determined by tests, such as ISO 10360, of the generic operation of the

machine over a limited portion of its overall measurement volume. However, ISO 10360 is generally accepted as a way of demonstrating traceability.

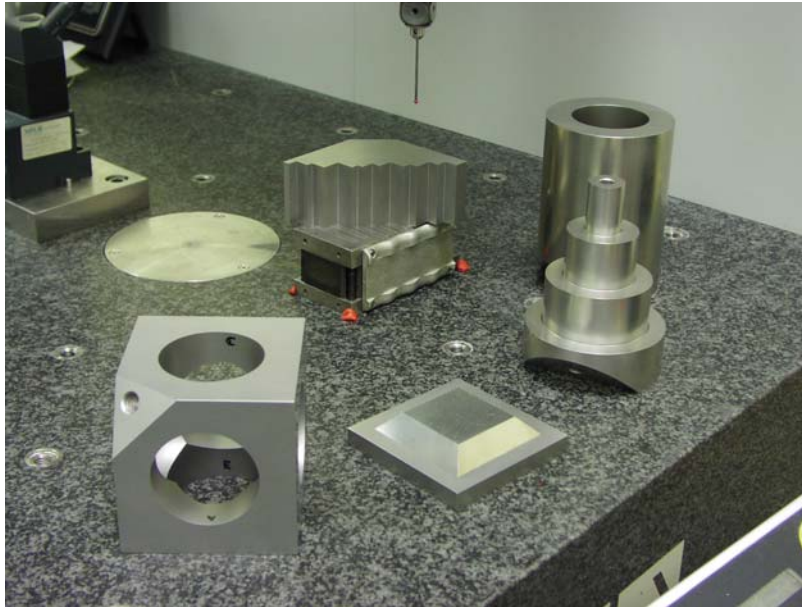


Figure 16: NPL CMM reference artefacts (nominally 100 mm)

Feautrier and Bourdet [22] describe a method for separating the errors in a free-form component from the errors present in the CMM performing the measurements. The method builds on the various repositioning and reversal techniques used in dimensional metrology. In simple terms, for a 2D profile, if n points are collected on the profile, between each measurement, the surface is displaced by a distance equal to the point separation. The technique is similar to those that have been developed at NPL in the past in relation to prismatic components. The technique would be useful to pursue where traceability is required or when form errors need to be measured with uncertainties of a few micrometres. The work probably has less relevance to the current project where instrument uncertainties are tens of micrometres, but the manufactured free-form artefacts are likely to be calibrated to within $\pm 10 \mu\text{m}$.

For the case of measurement of ‘standard’ shapes, it may be possible to use the CMM as a comparator (against such artefacts as plain setting ring gauges and gauge blocks), such that the results can be said to be traceable (ISO/TS 15530-3 *Geometric Product Specifications (GPS) – Coordinate measuring machines (CMM) Techniques for the evaluation of the uncertainty of measurement – Part 3: Use of calibrated workpieces*).

For measurements made with a CMM in scanning mode (see section 2.1.1), there are additional contributions to the uncertainty, which are difficult to quantify, and the overall uncertainty is very likely to be significantly affected by local surface texture and form. When attempting to measure unknown free-form surfaces, the situation is even more complex since the software must attempt to determine the local surface normal in order to radius-correct the measurement, and the method for doing this is likely to be inaccessible and impossible to test.

2.2 CMMS AS CARRIERS FOR NON-CONTACT SENSORS

The inability of CMMs fitted with touch trigger probes to gather large volumes of data quickly, has been a major limiting factor. Nextec [23] commercial literature illustrates this fact well:

Mechanical touch probes are the most common sensors used for CMM inspection. Most CMM applications today are based on a touch trigger probe for point-to-point measurement. The amount of data that can be collected using the touch probe is limited and most of the applications are limited to simple prismatic geometry parts. With the industry trend of moving towards free-form 3D geometry shapes, the traditional solution of touch trigger probes is limited since the geometry definition of complex free-form surface requires thousands of data points.

To address this issue, removing the mechanical link between the probe and the co-ordinate system origin has increased the flexibility of tactile systems further. CCD camera vision, laser point probes and laser scanning heads have been developed to bring a new lease of life to the mechanical CMM. These non-contact probes will be discussed in greater detail in sections 2.3.2 and 2.3.3.

2.3 OPTICAL NON-CONTACT MEASUREMENT SYSTEMS

Optical non-contact measurement systems fall into three main categories:

- photogrammetry and structured light systems;
- laser scanning techniques;
- vision CMMs.

Non-contact measuring systems can be divided into ‘target-type’, where the measurement is of single, discrete, points which are features of the object (edges, lines, *etc.*) and ‘form-type’, where the measurement is of arbitrary points on a continuous surface (such as the measurement of featureless surfaces, body scanners *etc.*). One of the project aims is that, in collaboration with leading industrialists, equipment suppliers and academics, design criteria for specific, industrially orientated, 3D free-form calibration artefacts will be established that are suitable for use with non-contact as well as contact probe systems. The intention is that prototype artefacts will be designed and appropriate measuring techniques will be developed using NPL and industrially based metrology equipment.

There are many 3D imaging and scanning systems available. These range from the whole-body scanners found in health clubs, through scanning devices used in heritage applications, to devices used in the automotive industry for scanning models of prototypes. The techniques used include laser scanning triangulation, Moiré fringe contouring, phase measuring profilometry and digital stereo photogrammetry. Some of these systems were characterised by Stevens [24] in 2001. The following illustrates some of the common types and applications of 3D imaging systems.

2.3.1 Photogrammetry and structured light systems

Photogrammetric and structured light systems offer users significant advantages over conventional contact measurement techniques. The lighting specialist manufacturer, StockerYale [25] describe structured light as:

The projection of a sheet of light (or plane, grid, or more complex shape) at a known angle onto an object. When a light intersects with an object, a bright line of light can be seen on the surface of the object. By viewing this line of light from an angle, the observed distortions in the line can be translated into height variations.

Structured light scanners can capture complete surfaces from a particular point of view. If an object is scanned in different orientations, the data from these multiple points of view can be combined to create a complete 3D model. Two major advantages of these systems over laser-based instruments are that the light source is usually an ordinary halogen white light, so there are no safety concerns related to using lasers and they are very fast, able to digitise up to millions of points per second. These two features make them strongly favoured for digitising human beings. A wide selection of application-specific instruments is available for digitising complete human bodies, for example from [TC]² [26] and Wicks and Wilson [27], and for more specialised areas such as the face and other localised parts of the body, using equipment such as the Ettemeyer3D Medical Digitiser G-Scan [28].

Industrial systems such as Geodetic Systems V-STARS [29], CogniTens Optigo 200 [30] and GOM ATOS [31] (see Figure 18) are used in real time in the aerospace, antenna, automotive, shipbuilding and other industries, making measurements in large volumes. However there are limitations in the use of such optical systems. Broadband source systems in general, are somewhat less accurate than laser systems and, for the most part, limited to smaller scanning volumes, typically a cubic metre or less. This may not be a strong limitation, however, since scans can be merged to completely cover very large objects, although it may take considerable time and computing power to do so.

During industrial visits, it became apparent that a number of companies have acquired non-contact structured light measurement systems. For example BMW (see section 6.2 Swindon Pressings) are beginning to use such systems to monitor the form quality of boot lids and bonnets for the Mini-R56, which is conceptually shown in Figure 17.



Figure 17: Mini-R56 concept car

BMW are also considering scanning new machine tools and analysing tool wear characteristics, with the aim of improving tool designs. Figure 18 shows a Mini-R56 boot lid, which was being measured using a structured light system during a recent visit to BMW Swindon. A typical measurement analysis of a Mini Cooper rear-end is shown graphically in Figure 19, where colour coding is used to indicate departures from design. Note that the colour-coding index scale is not shown in this example for commercial confidentiality reasons.



Figure 18: Mini-R56 boot lid being measured using structured light

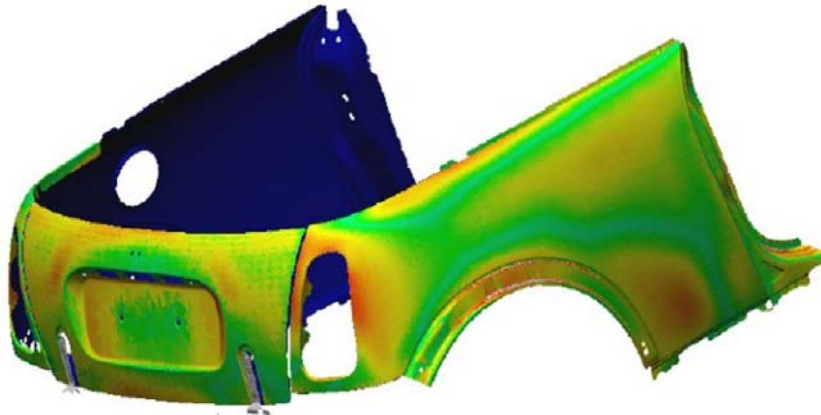


Figure 19: Form of Mini boot (compared with CAD model) using structured light

Other companies and universities employing structured light measuring techniques include:

- Rolls-Royce (see section 6.16), who are using structured light techniques to measure the form of gas-turbine blades.
- Landrover (see section 6.8), who are using structured light to measure clay models and then for reverse engineering purposes.
- McLaren (see section 6.10), who are using structured light for measuring the body form of the Mercedes-Benz SLR sports car.
- Heriot-Watt University (see section 6.5), who are developing a new multi-wavelength structured light technique. During a visit to the university, one of the NPL geometrical artefacts was used to test the performance of their system and an example of the coloured fringes used as part of the measurement process is shown in Figure 20.

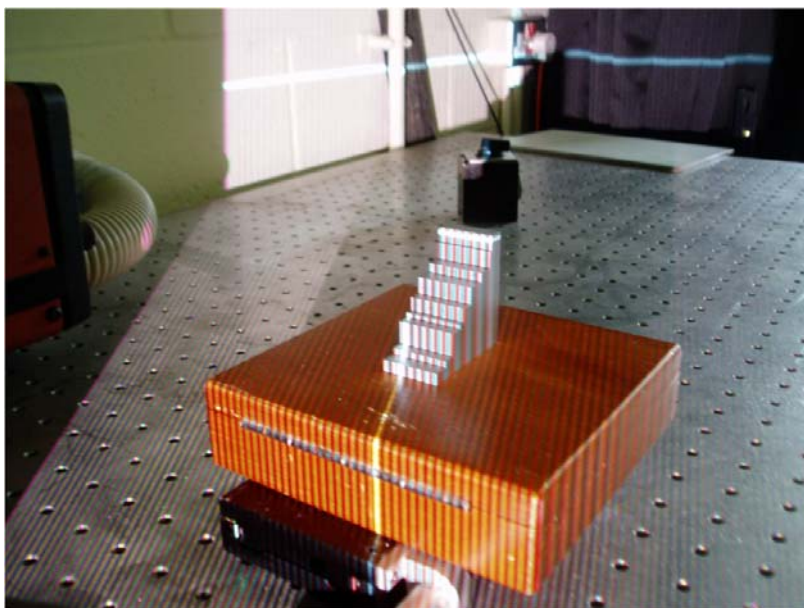


Figure 20: Heriot-Watt's multi-wavelength system being analysed using NPL reference artefact

2.3.1.1 GOM ATOS and TRITOP

The GOM ATOS [31] optical measuring system as shown in Figure 21, is based on the principle of triangulation. Projected fringe patterns are observed with two cameras. The 3D coordinates for each camera pixel are calculated with high precision, producing a polygon mesh of the object's surface. In order to enhance the capabilities of the system, it can be used in conjunction with the TRITOP optical CMM (see Figure 22). The TRITOP system is used to predefine the reference markers on large or complex objects required to support the high accuracy digitising of the ATOS instrument. This system is free of any physical constraints and is designed to define the exact 3D position of markers and visible features.



Figure 21: GOM ATOS



Figure 22: GOM TRITOP

Digitising in 3D with the mobile ATOS system is practical for many object sizes and complexities. Proprietary software means the measurement data can be used to feed back into the CAD/CAM process. Although acquisition times may be up to a few minutes, depending on the area being measured and the data point density, the system can measure entire artefacts relatively quickly. The system is therefore, particularly suited to reverse engineering, rapid prototyping and milling applications.

During late 2005, GOM visited NPL and carried out some measurements on the NPL Phantom Man. An example of the fringes projected as part of their measurement process is shown in Figure 23. Note the significantly curved fringes that are seen around the head and arms.

Another example of the GOM ATOS system in use is shown in Figure 24. In this figure, the measuring unit is mounted on a robotic arm, enabling the system to make measurements from different positions. Although in the example shown, a model car is being measured, such an arrangement could be employed for measuring both sides of objects (for example, car door panels, aero-wing structures, *etc.*).



Figure 23: NPL Phantom man being measured using GOM structured light system



Figure 24: GOM ATOS mounted on a robotic arm at their UK facility

The GOM ATOS system is used extensively in the automotive industry by amongst others, Landrover at Gaydon and Solihull, for the quality control of large objects, verification of jigs and fixtures, shape and position tolerance conformance and static deformation analysis. The TRITOP deformation module allows for capturing multiple load situations from an object. From the displacement of the markers and the features, the movement and the deformation of the corresponding object is defined. A typical scenario for this feature is measuring chassis deformation after impact testing or accidents.

Jao, Gindy and Chen [32] describe a non-contact process and inspection strategy for the measurement parameters required on a given object. The authors have developed an automated approach and have explored some areas likely to be of interest to the current project. For example, the transformation of free-form cloud point data into the co-ordinate system to ensure good alignment. The introduction is thorough and cites several publications that may be of particular interest in relation to non-contact

measurement of free-form surfaces. Subsequent chapters describe the inspection process and system, using a GOM ATOS II, including two practical measurement examples; a turbine blade root and a free-form surface.

2.3.1.2 Photogrammetric body scanners

An example of a 3D body scanner is the TriForm developed by Wicks and Wilson [27]. In operation, a series of fringes are projected on to the subject. Each fringe pattern is captured by a camera and stored in a PC. An additional all white frame is captured and used to produce the colour texture map of the subject. The distortion of the fringes is then analysed and a 3D point cloud of the subject produced. The Tri Form is shown in Figure 25 (with and without the NPL Phantom Man) and typical fringe structures projected by TriForm are shown in Figure 26. Its operation is similar to the 3D body scanner manufactured by [TC]² [26].



Figure 25: Tri Form Body Scanner measuring NPL Phantom Man at Wicks and Wilson, Basingstoke



Figure 26: Tri Form in use

Ri, Fujigaki and Morimoto [33] have published work, which gives useful background into the principles of fringe projection. The actual reported technique is unlikely to be

of practical use to the current project but does illustrate the potential of such a system to perform accurate 3D metrology with uncertainties of the order $\pm 100 \mu\text{m}$. Their paper is principally concerned with grating projection as a method for non-contact shape measurement of an object. The paper describes a 360° shape measurement system using Multi-Reference-Planes Method (MRPM). The technique requires both a measured object and a reference object to be measured simultaneously from different directions. The resulting point clouds may then be merged together using a transformation matrix.

2.3.1.3 Mavis - MavisCal

MAVIS II [82] is a portable, non-contact, photogrammetric wound measurement system for monitoring the progress of chronic wounds such as leg ulcers. Mavis II is shown in Figure 27. It was developed by the Medical Imaging Research Group at the University of Glamorgan and calibrated in-conjunction with NPL reference artefacts also shown in Figure 27. It uses a commercially available camera and stereo-optics to record a pair of images from which the area and volume of the wound is calculated. The system also records colour, which is an indicator of the wound condition. To monitor wound healing effectively, it is essential that these measurements are consistent between instruments.



Figure 27: MavisCal with NPL Dimensional and Colour calibration artifacts

2.3.2 Laser probe and scanning systems

Laser measurement is a non-contact process that involves passing a laser beam over the surface of an object and collecting the reflected light using an optical detector mounted next to the laser head that records the X, Y, and Z ordinates of a point in space. Laser based systems are suitable for measuring flexible or fragile materials, which often present severe challenges for tactile CMMs due to the risk of indentations or surface scratches. When using a CMM mounted laser probe, utilising the *in-situ* probe connections, all the existing functionality of the CMM is still available, as laser scanning is fully compatible with touch probe technology. Scanning can generate a complete 3D point-cloud of a part within minutes and enables complete modelling and inspection of parts with complex free-form surfaces or features such as holes, slots, *etc.* Traditional touch probes can take hours or even days to measure full parts. All the

major CMM manufacturers offer non-contact laser probe/scanner options. Typically they are used in the automotive industry (for example, see Figure 28) for reverse engineering and the incorporation of styling modifications from clay models and part inspection. They can also be used to transfer a physical concept car into a CAD model.



Figure 28: Use of a scanner in the automotive field

During some of the industrial visits it was noted that a number of laser probes were being used or promoted. These include:

- Nissan (see section 6.13), who use the Tokyo Boeki [78] articulating arm fitted with a laser scanner. The scanner shown in Figure 29 is employed at their Sunderland plant for measuring the form of pressings required to build the new (2006) Micra.
- McLaren (see section 6.10), who use a FARO articulating arm (see figure 9) for measuring the body form of the Mercedes-Benz SLR, as in the example shown in Figure 30.



Figure 29: Tokyo Boeki scanner used at Nissan

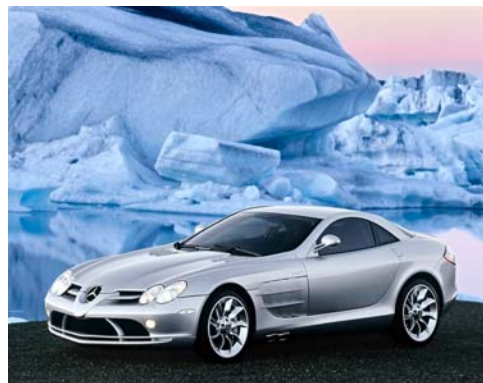


Figure 30: Mercedes-Benz SLR McLaren manufactured in Portsmouth

- Smiths Aerospace (see section 6.17), who also use a FARO articulating arm (see Figure 9) for measuring the body form of complex automotive lightweight structures.

- Ploughman Craven (see section 6.14), who employ a Cimcore articulating arm (as for example shown in Figure 31), fitted with a Perceptron scanning head [41] and [77].
- Metris (see section 6.11) [40] who exhibited at Control-2006, provide laser scanning probes for CMMs, such as the example shown in Figure 32 and also portable (pistol grip type) hand held scanners such as their K-scan [79].



Figure 31: Perceptron scanning head (Europac)



Figure 32: METRIS laser scanner for CMMs

Another important application for laser probes is the 3D scanning and modelling of heritage collections and of sculptures (see Figure 33). An example of this is the European PURE-FORM project [34]. PURE-FORM's main objective is to realise a Museum of Pure Form as a virtual reality system, whereby people can interact through the sight and touch with digital models of 3D art forms and sculptures.



Figure 33: Heritage applications

2.3.2.1 Point probes

A suitable example of a laser point probe is the Nextec WIZprobe [35], shown in Figure 34. It is an advanced non-contact optical laser point scanning sensor for fast, accurate and highly reliable geometric measurements. A point probe operates using a

laser beam focused into a single spot that is projected onto the work surface at a fixed angle. The light is reflected back to the probe that contains a CCD chip. The output from this is processed along with the host machine co-ordinate data to give a measurement of the surface at that point. The speed at which these points are processed is dependent on the machine controller and the characteristics of the optical sensor. Data acquisition can be around a hundred points per second. Probes such as this can be used for surface measurements and, with appropriate processing, edge detection. These point probes are designed to be integrated onto CMM systems, most utilising a standard Renishaw PH-10 interface which can replace or be used in conjunction with conventional mechanical touch probes. NEXTEC state that “the WIZprobe has a single point measurement accuracy of $6\text{ }\mu\text{m}$ (1σ) and has a system accuracy in the order of $12\text{ }\mu\text{m}$ (1σ) when integrated with their largest Hawk CMM” [36].



Figure 34: Nextec WIZprobe

Other point probes include the Renishaw optical trigger probe [37], Laser Design [38] and the Wolf and Beck OTM3M [39] which was demonstrated by Zeiss at Control-2006 and is shown in Figure 35.

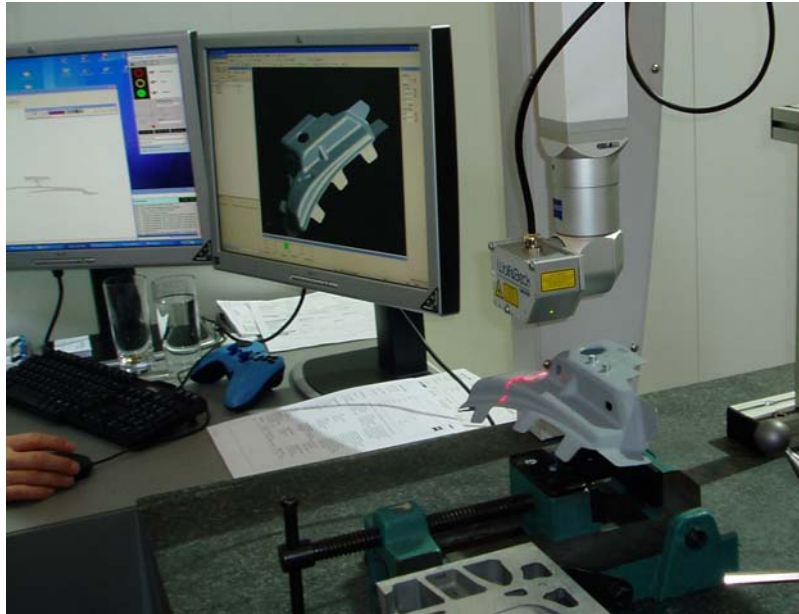


Figure 35: Wolf and Beck probe

2.3.2.2 Laser line scanners

Laser line scanners use a similar process to point probes, except that the laser is projected as a line (stripe) of several hundred points. These points are reflected from the surface to a sensor. Each line is processed as a profile of the surface at that machine position. The data (hundreds of surface points for each scan) is collected at tens of thousands of points per second. This allows some features (such as holes and small slots) to be measured in a single pass where, with tactile probes and spot lasers, multiple measurements are required. Because of the high rate of data, solid models can be created from the surface profiles making these probes ideal in reverse engineering applications. A variety of scanning heads are available from manufactures such as Metris (K-Scan) [40], Perceptron [41] and Steinbichler (T-Scan) [42] (as shown in Figure 36).



Figure 36: NPL Phantom man at The University of Birmingham being scanned using a Steinbichler T-SCAN

Typical measurement uncertainties ($k=2$) for the T-Scan, when incorporated with a Leica Geosystems PCMM tracker [43] are:

Spatial Length: $\pm 60 \mu\text{m}$ for values $< 8.5 \text{ m}$
 Sphere Radius: $\pm 50 \mu\text{m}$ for values $< 8.5 \text{ m}$
 Sphere Surface: $\pm 95 \mu\text{m} + 1.5 \mu\text{m m}^{-1}$
 Plane Surface: $\pm 95 \mu\text{m} + 1.5 \mu\text{m m}^{-1}$



Figure 37: VIVID 9i non-contact 3D digitiser

Other types of laser scanner are available, each using slightly different technology to operate. Camera systems such as the Konica Minolta VIVID 9i (see Figure 37) and 910 non-contact 3D digitisers [44] are simple to use, point and shoot scanners, with

measuring areas up to 1 m² and subject size ranges from 0.5 m to 2.0 m and larger. The manufacturer states that the VIVID 910 system has a precision of $\pm 8 \mu\text{m}$ and an accuracy of $\pm 100 \mu\text{m}$, whilst the 9i has an accuracy of $\pm 50 \mu\text{m}$. In Europe the VIVID brand name is replaced by VI.

Setan *et. al.* [45] have reported the measurement verification tests performed on artefacts with free-form surfaces using several non-contact systems, including Konica Minolta VIVID910 and VSTARS scanners. The instruments were used to measure facial and boat forms to illustrate the suitability of optical non-contact methods to perform metrology in medical and industrial fields. The authors report the measurement method and procedure, but do not disclose any measurement results from the metrology. The paper may have little bearing on the current project, but does demonstrate the ability of cross-software platform processing to produce 3D surface and form data.

Laser scanner systems, such as the FastSCAN Cobra and Scorpion [46], can be used to make anthropometrical measurements. However, the relatively long scanning time of these systems is a disadvantage, as the subject would have to remain still for a considerable length of time. Zhang *et. al.* [47] have published work describing a stereovision laser triangulation system for the measurement of free-form surfaces, which appears similar in operating principle to the FastScan Cobra. Whilst no measurement data is offered for review in the paper, the authors describe the principles of operation and of particular note, the use of a 2D grid plate to calibrate the imaging system.

2.3.2.3 Combined sensor systems

It is also possible to combine touch probes with scanners and align them in the same measurement field. This is demonstrated by the FARO Laser Scanner LS [48], which is claimed to be industry's first ever seven-axis contact/non-contact measurement device incorporating a fully integrated laser scanner. An example is shown below in Figure 38.



Figure 38: FARO Laser Scanner LS

The touch probe and laser scanner are able to digitise seamlessly. Users can collect simple point variations with the touch probe, then laser scan the sections requiring larger volumes of data (more than 19 000 points per second), without the wasted time of adding or removing attachments, untangling cabling, or having to use a separate CMM and then trying to import the data. Technical data states that the laser line probe has an accuracy of $\pm 50 \mu\text{m}$ with a repeatability of $\pm 50 \mu\text{m}$ (2σ). The Faro Platinum model,

with a 2.4 m span, has a system performance of $\pm 80 \mu\text{m}$. This value increases to $\pm 172 \mu\text{m}$ for the Advantage model of the same span.

2.3.3 Vision CMMs

Vision inspection machines, such as the NPL system shown in Figure 39 are used in many diverse industries, with typical users including pharmaceuticals, food production, engineering, electronics and aerospace. They make it possible to measure complex, precisely fabricated items and materials such as automotive and aerospace components, printed circuit boards, microelectronic circuits and features that cannot be accessed by conventional contact type machines and gauges. Measurements can be obtained from thin or soft workpieces and brittle, elastic or moving parts can be measured accurately and quickly, as the measurement technique is neither invasive nor destructive. This is advantageous in a production environment, allowing quality control and real time feedback to be readily integrated into the manufacturing process. Most vision CMMs (or conventional CMMs fitted with optical CCD heads) are limited in their functionality in that they are only suitable for measuring 2D structures. However, to improve measurement capabilities, some manufacturers have integrated rotary tables, enabling genuine 3D metrology capabilities.



Figure 39: NPL Mitutoyo Vision CMM

3 DESIGN AND ANALYSIS SOFTWARE

Many manufacturers produce software suitable for analysing data from free-form surfaces. Capabilities that are likely to be of interest in relation to the current project are those that offer tailored software for turbine blade measurement or, indeed, free-form surface measurement. Some commercial packages with those facilities are summarised in the following sections.

3.1 OEM PACKAGES

Mitutoyo offer a software package called MCOSMOS (Mitutoyo Controlled Open System for Modular Operation Support) [49] which includes components for measuring gears (Gearpak), aerofoils (Mafis) and 3D free-form surfaces (3D Tol). These allow for

the generation of surface measurement points and comparison of actual/nominal data. However, there is no indication of the associated measurement uncertainties.

Calypso [50] is a Zeiss package designed to provide high data density scanning. The similarities to the MCOSMOS components are marked, there are separate routines for gear, aerofoil (Blade) and free-form (Curve) surfaces. The Curve package offers 'accurate results', but does not quantify the statement.

HOLOS [51], also supplied by Zeiss, claims to be a one-stop-shop CMM software package, primarily designed for free-form measurement in the model-making environment. The promotional literature is aimed at the automotive industry and the software can be used to control the measurement and milling of components.

ScanWorks™ [52] is the package supplied with Perceptron scanning systems. The software creates a point cloud representing the surfaces and characteristics of the scanned form of an object quickly and accurately, acquiring data at more than 23 000 points per second. The cloud of points created is compatible with third party software products used for inspection, reverse engineering and other applications.

QUINDOS [53] from Hexagon Metrology Ltd controls not only Brown and Sharpe CMMs but can also be connected to a number of other manufacturers' CMMs, roundness testers and camshaft measuring machines. It is a powerful software package that combines ease of operation with flexibility. Besides the inspection of standard prismatic parts, *i.e.* engine blocks and gear boxes. QUINDOS provides more than thirty optional packages to measure even the most complex geometries such as curves and surfaces that cannot be described with standard geometric elements. The package Curves and Surfaces provides the tools to compute and evaluate 2D and 3D curves as well as free-form surfaces.

The GOM ATOS software [54] is multi-faceted and not only performs measurement, but calibration and fringe projection quality verification for each measurement. It can perform polygon mesh generation and editing for hole filling or thinning, whilst integrating all measurements into one high quality mesh. Primitives such as spheres, cylinders, cones, planes and lines can be generated, intersected and projected from mesh data (this software capability is certified by PTB and NIST). CAD data can be imported and the deviation from measured data to reference data visualised and calculated.

3.2 COMMERCIAL PACKAGES

OEM software tends to be more functional and instrument specific, whereas other platform independent software packages are available that can integrate with commercial systems, such as QUINDOS [53] and PC-DMIS [55] from Hexagon Metrology Ltd, Rapidform [56] from INUS Technology and CAPPS [57] from Applied Automation Technology. PC-DMIS provides measurement routines for all part types, including complex forms such as blades and gears, and will also control any brand of CMM. Rapidform software can directly control and interface to, amongst others, the Mitutoyo 3D-LSI, FARO ScanArm, Konica Minolta VIVID/700, 900, 910, 9i, Perceptron ScanWorks and the Nextec Hawk Series.

In an industrial environment, using software that combines both design and analysis features, allows the use of high-density point clouds and contact-probe datasets of

digitised prototype parts and assemblies to quickly identify deformations and to fix problems in the early stages of the manufacturing process. Tooling may also be monitored within the production cycle by automatically measuring the wear of tools and quickly detecting any abrupt degradation in product quality. In the final production stage, assembled products can be checked for compliance through sample check inspection. Some software packages are able to perform all these tasks. Popular post-measurement software includes Polyworks [58] from InnovMetric, PowerInspect [59] from DELCAM and Geomagic Inc. [60] digital shape sampling and processing products. These are just some of a number of packages with metrology, reverse engineering, high-density point cloud and contact-probe dataset processing capabilities, enabling feedback to control the quality of parts and tools at every phase of a CAD/CAM process. Major automotive and aeronautic companies are using this type of technology for prototype, first-article, manufactured, and assembled part inspection.

3.3 POINT CLOUD PROCESSING RESEARCH

The point clouds produced by non-contact systems are not usually used directly. Most software applications, especially those used for production and CNC interfacing, do not use point clouds, but output measurements as polygonal 3D mesh models. The process of converting a point cloud into a polygonal 3D model, called reconstruction, involves finding and connecting adjacent points in order to create a continuous surface. The ability to convert a point cloud into a polygonal 3D model is important to accurately reflect the form of the measured surface. Numerous algorithms are available for this purpose, including:

- Polygonal – where the model of an object is created by building triangles from the points in a point cloud.
- NURBS - Non-Uniform Rational B-Spline, a mathematical model used for generating and representing curves and surfaces.
- Hybrid - A polygonal model that uses surfacing and traditional solid modelling techniques and is used when basic geometric features merge with complex contours.

Various research papers have been written assessing the relative merits of different methods of surface registration, matching and reconstruction. The following papers should provide useful sources of reference when measurement strategies associated with this current NMS project are planned.

Luo *et. al.* [61] have published work entitled *Surface reconstruction based on laser scan data*. The paper investigates a CMM mounted laser scanning system and describes the measurement and processing of cloud point data from a shoe mould. The use of NURBS to reconstruct the mould surfaces is described and interfaces between initial graphic exchange specification (IGES) and stereo lithography interface specification (STL) with CAD and rapid prototyping manufacturing (RPM) systems are discussed. The authors note that the developed system cannot currently process a model with deep occlusions.

Gruen and Akca [62] have published work entitled *Least-squares 3D surface and curve matching*. This paper is the detailed peer reviewed version of a new algorithm for 3D surface matching [63]. Non-contact measurement rarely gathers all the surface data

from an object in one scan, so data from numerous scans has to be merged. The paper reports on a surface matching process for overlapping scanned surfaces using point clouds of an artefact. The authors present a comprehensive review of previous work on surface matching, discussing methods of point cloud registration, such as ICP (iterative closest point) and its closely related variants and SVD (single value decomposition). The authors then proceed to detail their solution, least squares 3D surface matching in some mathematical detail and give some practical results based on the registration of close-range laser scanner and photogrammetric point clouds.

Varady *et al.* [64] have reported on constructing solid models of 3D objects from measured data for the purposes of reverse engineering. The report, RECCAD, was a deliverable document for the COPERNICUS project, No 1068, *Report on data acquisition, pre-processing and other tasks in 1995/1996*. Chapter 1, which is also identical to the paper *Reverse Engineering of geometric models--an introduction* [65], gives a general non-mathematical introduction to the acquisition, processing and surface fitting of data in order to create a CAD model. Subsequent chapters detail the acquisition of scan data, instrumentation, how data and geometries are classified and how the surfaces are fitted to the acquired data. Given its date of publication and the subsequent advances in techniques and instrumentation, the initial relevance to the current free-form verification project is not immediately apparent, but it does provide useful background information for the reader on the processes of reverse engineering, scanning, data reduction and instrument calibration.

Li and Gu [66] have described a procedure for localising measured data to a design model. Free-form surfaces are often compared to CAD data and a tolerance zone of acceptance is applied to the results. The extent to which the two data sets are aligned will have a direct effect on the position of the surface within the tolerance range. The authors investigate the use of data to provide transformation information that enables the measured surface to be aligned with the design CAD model. The method does not require the two data sets to have corresponding points and is not constrained by the method of measurement, be it contact or non-contact. It is likely that the measurement procedure for the free-form verification project will include an appropriate translation methodology, in order that individual and inter-system performance can be compared. This paper gives a sound introduction to that process.

3.4 CORRECTNESS OF FREE FORM SURFACE FITTING SOFTWARE

Fitting a fixed surface to data has become an important problem in coordinate metrology. For example, in order to check that a manufactured part conforms to its design, the part is measured using a coordinate measuring system to generate a set of coordinate data. This data set is then compared with the part specification, increasingly defined by a CAD system. As part of this comparison two frames of reference, one for the data points and the other for the CAD drawing, have to be aligned using a fitting procedure. If the data is gathered by a CMM using a spherical probe tip, then the measured coordinates do not represent points on the part but instead those on an offset surface. This can introduce further complications into the part assessment task. Metrology system providers have developed software to perform these fits, and developers and users alike require independent verification that such software is achieving its stated purpose within acceptable tolerances.

The Mathematics and Scientific Computing Group at NPL carries out work concerned with the reliable application of mathematics and computing to measurement. A paper

from this group, by Forbes *et. al.* [67] describes an algorithm to determine the best match of a set of points to a fixed, free-form surface. The algorithm has the advantages that it can be implemented using standard optimisation software and it can cope in a simple way with non-zero stylus tip radii. A procedure to generate test data with which to validate surface fitting algorithms is also presented. By comparison with the surface-fitting problem, the data generation procedure is extremely straightforward and requires only a capability to generate points lying exactly on a surface along with their corresponding normal vectors. The procedure also caters for tip radius compensation in a simple way. The main advantage of the data generation scheme is that it allows the behaviour of approximate solution algorithms to be assessed without the need to implement a comprehensive algorithm that addresses the true computational aim. Both the algorithm and data generation procedure apply to practically any fixed surface. Results are presented for the particular case where the surface is aspheric. For example, Figure 40, shows an aspheric surface (shown as blue dots) together with thirty one data points (shown as green asterisks) obtained from the data generation procedure.

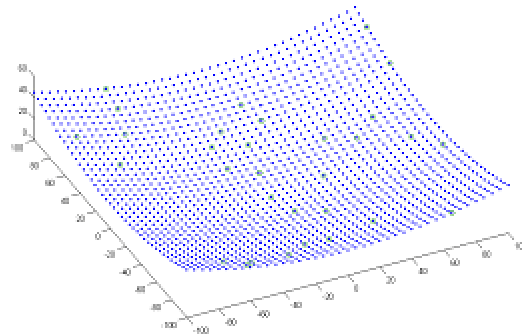


Figure 40: Aspheric surface

The data generation scheme has been used to test an approximate algorithm that introduces simplifications to both the fitting problem and to the tip radius compensation. The test results show that, for data similar to that illustrated, the approximate fit deviates from the true fit by distances that amount to about 10% of the standard deviation of the simulated measurement noise and that the simplified probe radius compensation scheme introduces no significant approximation errors. On this basis, it is established that the simplified algorithm is fit for purpose.

4 WORK AT THE NATIONAL LABORATORY LEVEL

This section reviews some of the work being carried out around the world at the National Measurement Institute level. From a literature search it is apparent that some work is already being carried out at the National laboratory level to address issues with 3D scanning systems although the work seems to be at an early stage and quite fragmented. This section also reports some work being carried out by certain universities and other government run laboratories.

4.1 CANADIAN NATIONAL RESEARCH CENTRE (NRC)

At the Canadian National Research Centre (NRC) the development of 3D digitising and modelling technologies has been underway since 1981. The shape (X, Y, Z) and colour (B and W or RGB) of objects, people and environments is digitised by patented laser-based 3D cameras at a speed from 10000 to 10 million coordinates per second. A variety of prototypes have been built for the demonstration of the technology in the fields of industrial automation, inspection, space robotics and medicine. NRC's work is focused on developing the technology rather than providing traceability. The NRC Institute for Information Technology (NRC-IIT) conducts research in software and systems technologies including algorithms, methodologies and software engineering, as well as some applied research. The Institute has had an active research program called 3D Technologies [68] at least up until 2004. Although not described with the phrase free-form, the following projects have been noted:

4.1.1 Research area: 3D data mining and management

NRC-IIT State [68]:

With the recent diffusion of 3D digitizing techniques and CAD, the number of 3D objects and scenes has increased tremendously. It has become necessary to store them in databases. New paradigms are necessary in order to index and describe them. A new content-based approach, based on three-dimensional shape and chromatic appearance has been designed in order to facilitate their analysis, comparison, clustering and retrieval. Such an approach will have an important impact in numerous applications like: anthropometry, CAD/CAM, industrial design, multimedia production, e-commerce, medical diagnostics, data mining and biotechnology. In the later case, the 3D shape is related to the functionality, which means that the system can be utilized for functionality retrieval of proteins and molecules: an important application in the pharmaceutical industry.

Current projects:

- Alexandria
- Cleopatra
- The Human Shape Variability Study
- The Virtual Boutique

4.1.2 Research area: Automation of image-based modelling

NRC-IIT state [68]:

Automation of Image-Based Modelling researches how new techniques in automating the processing stage of 3D modelling can provide an expanded use of the technology. The project, which started in 2000, is expected to run until 2005.

This ongoing VIT research has already resulted in a successful licensing of a 3D measurement and modelling software (ShapeCapture) to an Ottawa company and project partner, ShapeQuest Inc. Methods generated by this research have proven extremely useful in museum and heritage applications, with collaborative partners such as ITC (Istituto Trentino di Cultura) of Trento, Italy, and University of New Castle, Australia.

Problem Statements

Three-dimensional modelling from images, when carried out entirely by a human, can be time-consuming and impractical for large-scale projects. On the other hand, current fully automated methods may not be achievable or accurate enough for many applications such as heritage documentation. Three-dimensional modelling from images requires the extraction of features, such as corners, and that their appearance in multiple images. However, in practical situations those features are not always available, sometimes not even in a single image, due to occlusions or lack of texture on the surface.

The Objectives

- *To use both interactive and automatic techniques, each where it is best suited, to accurately and completely model complex objects.*
- *To focus on automating the construction of unmarked surfaces such as columns, arches, and blocks from minimum available clues.*
- *To extract the occluded or invisible corners from existing surfaces and lines.*
- *Product resulting from this research*
- *ShapeCapture Software tools for 3D shape modelling from images.*

4.1.3 Paper: *Free-form surface reconstruction from multiple images* [69]

This paper by Shu and Roth [69] describes the reconstruction of 3D surfaces from 2D images, with particular emphasis on free-form surfaces. The process described is related to computer vision and photogrammetric techniques. It is noted that ideally, the calibration of the imaging system is achieved using a calibration chart before taking the images of the object of interest. However, it is possible to derive the 3D structures in detail using a method of auto-calibration, which is presented. The mathematical approach is detailed and the application of the B-spline function explained.

To quote the authors [69]:

It is widely appreciated that 3D structures may be computed from multiple 2D images of the same scene given point correspondences between images. We review the process from a projective geometry perspective. Of greater interest, however, is the generation of surfaces that give a compact representation of the geometric model. Assuming we are dealing with smooth surfaces, we show that B-spline is a good choice for this purpose and we describe how to construct it by approximating the 3D data points. The crucial step is the parameterization of the 3D points in a 2D domain. By studying the geometric constraints of multiple views, we show that the original images can be used for parameterization. The implications of the B-spline surfaces for improving the quality of texture mapping is discussed.

4.2 PHYSIKALISCH-TECHNISCHE BUNDESANSTALT

The Physikalisch-Technische Bundesanstalt (PTB), Braunschweig and Berlin, is the NMI of Germany. PTB have activities of some relevance.

4.2.1 Optical sensors

Working Group 5.34: Optical Sensors [70] led by Dr. Ulrich Neuschaefer-Rube is involved in the development of standards and procedures for optical non-contact measurement systems.

In PTB's words [70]:

Optical sensors are increasingly used in coordinate metrology. They measure fast and contactless and are particularly suited for object with elastic and damageable surfaces and for microparts. Furthermore, area-based optical measurements yield more information about the object than tactile measurement points. The working group develops artefacts and procedures to test optical sensors. It is involved in the preparation of national and international standards and guidelines.

4.2.2 Computed tomography scanners

The Coordinate Metrology Department has a current project to determine the measurement uncertainty and capability of computed tomography scanners in dimensional metrology [71].

The computed tomography (CT) project is looking at 3D scanning systems that make use of X-rays. CT scanners were originally designed for medical applications where qualitative information was required, but are now being used in automotive applications where dimensions are required.

The department reports that [71]:

The PTB helps provide the bases for a highly developed metrological infrastructure, which is a prerequisite for general quality assurance. It is an important objective of PTB activities to support in this way the competitiveness of industry. Against this background, the company Rautenbach-Aluminium-Technologie GmbH in Wernigerode and the Department for Coordinate Measuring Technology and Measuring Instruments Technology of the PTB in Braunschweig have started a joint project aiming to investigate the metrological capabilities of industrial computed tomography for dimensional quality assurance.

By computed tomography using x-rays (see) it is possible to look inside motor components to ascertain dimensions of wall thicknesses or the location of structures without cutting this part open and thus destroying it. While in medicine the information gathered has up to now mostly been evaluated in qualitative terms, here the dimensions of the internal component geometry in accordance with the tolerances have to be determined with sufficient accuracy. The questions to be clarified are the measurement uncertainty of computed tomography and the suitability of using it to solve the new tasks with the accuracy required. Furthermore, procedures will be developed which allow computed tomography systems to be accepted and routinely checked in order to ensure the quality of the measurements also from economic aspects over a long period of time. The PTB will investigate these questions together with Rautenbach. The solutions found in the project which is scheduled to take two years will contribute to helping meet

the requirements of the relevant standards (e.g. DIN EN ISO 9001 or the guidelines of the Association of the Automotive Industry VDA 6.1, VDA 5) which require just this determination of the measurement uncertainty. On the other hand, the project results will build confidence in the use of computed tomography in industrial quality assurance.

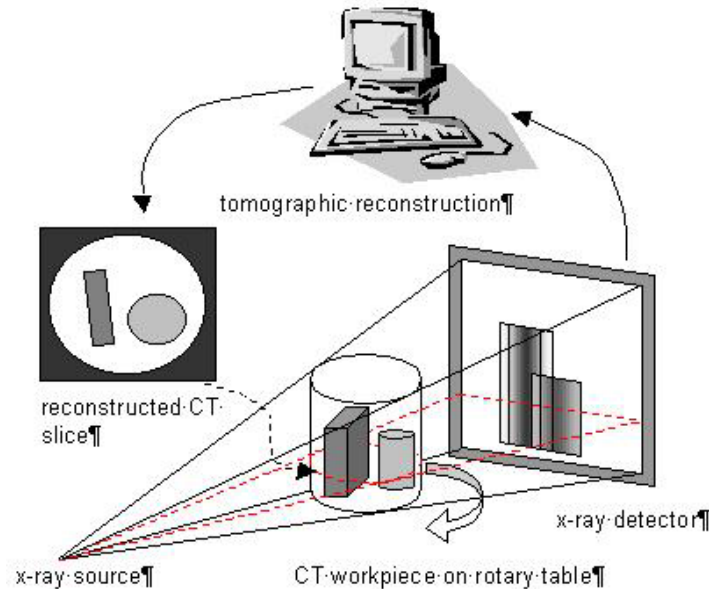


Figure 41: Computed tomography using x-rays [71]

4.2.3 Large area curvature scanning (LACS)

Working Group 4.21, Imaging Optics have developed a Large Area Curvature Scanning instrument [72] for the measurement of aspheres and free-form surfaces of all shapes and dimensions.

The system is described as follows [72]:

The form measuring technique for aspheres and free form surfaces is in wide areas not yet in a position to fulfil the present demands. Therefore at PTB a new measuring system is developed which is based on PTB patents. It scans the surface under test and determines the form from the measurement of the local curvature. The method is called Large Area Curvature Scanning (LACS), see , since for the determination of the curvature a rather expanded local two-dimensional surface element is used.

The curvature is a property of the surface, which is independent of position of the surface in space. With the new concept, measurements without use of an external form reference are possible for optical surfaces of any size. Moreover, it is of high importance that the method can be traced back absolutely and with high accuracy to the base unit length and has only small sensitivity to error influences. The method can be used for various measurement demands from high-accuracy aspheres for photolithography to free form surfaces in the spectacles industry, to list only two applications.

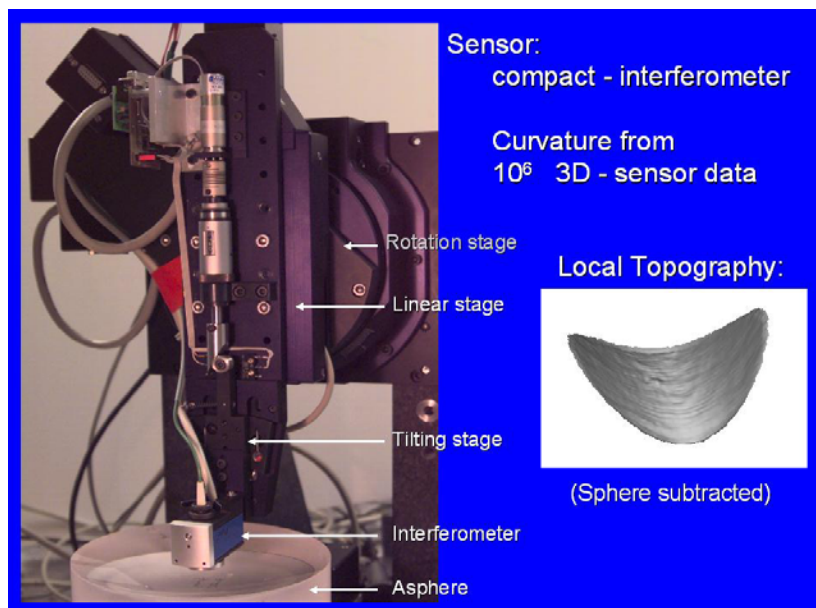


Figure 42: LAC scanner [72]

The measurement principle is also suitable for universal measurement set-ups, which, for example, can guide the curvature sensor at the arm of a robot. This vision is shown in .

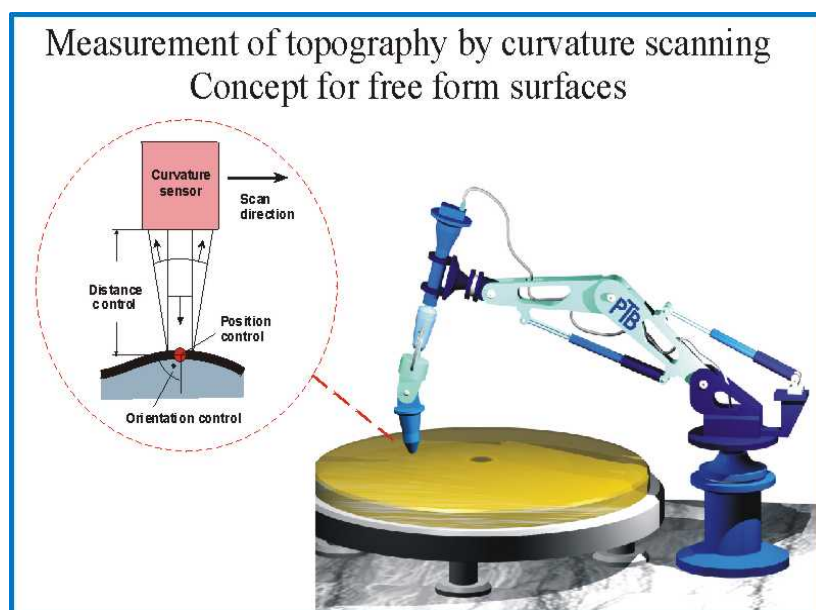


Figure 43: Concept instrument for scanning free-form surfaces [70]

4.3 NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

The National Institute for Science and Technology (NIST) is the NMI of the United States of America. NIST have a project to ‘*Develop and deliver timely dimensional measurements and standards to address identified critical US industry needs for traceable dimensional metrology, particularly for the support of trade and innovation, process control and quality in manufacturing from the micro- to the macro-scale*’.

The work is being carried out by the Large Scale Metrology Team. The team reports that [73]:

4.3.1 Complex surface metrology

Complex surfaces are increasingly employed in manufacturing, especially for large components. Not surprisingly a boom in instruments and methodologies to measure these structures is underway. A wide range of technologies such as multilateration, photogrammetry, LADAR (Laser Detection and Ranging), and structured light are rapidly advancing due to the availability of high-speed electronics and inexpensive computer power. The U.S. is a major supplier of frameless metrology systems used in scanning large structures, however, demonstrating their metrological capability is problematic. In a 2003 workshop chaired by NPL, PTB, and NIST on large-scale measurement systems, one of the summary findings stated “So far, no common procedures for the evaluation of measurement uncertainty or for performing an interim check are in existence for large-scale measurement systems. In the near future, the rigorous implementation of quality systems, not just in the aircraft and automotive industries, but in a wide context will generate a huge need for action in this area”.

The problem is typified by NIST’s Building and Construction Research Division (BCRD) that plans to use a three-dimensional (3D) LADAR measurement system to establish the true value of a construction measurement test course against which other measurement systems are evaluated. Unfortunately, they have no means to evaluate the accuracy of the LADAR system and, hence, its contribution to calibration errors in the test course. BCRD is very interested in having the LADAR system evaluated in a metrologically rigorous manner.

Complex mechanical surfaces often act as the interface with their environments in dynamic structures such as airframes, turbine blades, and ship hulls. Small deviations in manufacturing or assembly prevent optimal function and cause inefficiencies that can consume large quantities of energy. It is often said that aircraft are actually powered corkscrews indicating that small deviations from the designed form create drag that degrades performance. Accurate metrology can minimize these effects. Major manufacturers such as Boeing, Caterpillar, and Pratt and Whitney increasingly rely on measurements of complex surfaces by frameless measurement systems. Traditional methods such as large fixed CMMs represent large fixed capital investments and are not reconfigurable as required in a flexible manufacturing environment.

The program seeks to focus on metrology instruments that are used in advanced manufacturing of complex surfaces. We anticipate providing rigorous calibrations of a wide class of instruments that will facilitate better instrument selection by metrology practitioners, improved designs by instrument manufacturers, and traceability of these measurement systems. The program is also researching conventional CMM probing systems and associated data fitting for complex surfaces.

4.3.2 Complex geometry dimensional metrology

Objective #4: Develop metrological capabilities and facilities to calibrate instruments and probing technology capable of collecting large data sets on complex geometry surfaces.

Complex geometry surfaces are among the most challenging areas of dimensional metrology. Some of the difficulties include the complexity of scanning probes, the optical and mechanical metrology in the measuring instruments, huge data files, and fitting algorithms for these surfaces. Most of these instruments are sufficiently transportable (unlike conventional CMMs), that testing at NIST is a reasonable procedure. The program seeks to develop a calibrated test range traceable to the SI unit of length for frameless coordinate measurement systems. Use of the test range by instrument manufacturers may lead to improved accuracy through the discovery of unknown systematic errors.

Scanning probes for conventional CMMs are gaining widespread use for inspecting complex workpieces. These probes are, in effect, miniature three axis CMMs with a very short thermal time constant. All of the thermally induced errors normally associated with CMM structures can also appear in the probe and are accentuated due to the short time constraint. The program will test CMM scanning probes in the NIST Advanced Measurement Laboratory's (AML) thermally controllable lab to simulate conditions on the shop floor.

Finally, the program seeks to develop an E-metrology effort where coordinate metrology information, and in particular, data sets and their associated algorithm fits can be readily accessed by industry. This is an expansion of the current Algorithm Testing System (ATS) into the domain of complex surfaces and large data sets.

5 UNIVERSITY RESEARCH

Various universities have been identified as having expertise and either past or current research programmes related to free-form metrology. No attempt has been made here to investigate further the activities of the academic institutions, nor has the relevance of the work been assessed in relation to the project. Current research projects are bullet-pointed and free-form related papers are reviewed. Further investigations will be carried out when collaborators are sought at latter stages of the project.

5.1 UK UNIVERSITIES

The following UK universities have been identified as being active in the free-form field.

5.1.1 University of Bath

The Engineering Innovative Manufacturing Research Centre the University of Bath, Design Technologies Group

Website: www.bath.ac.uk/eimrc/index.shtml

- Generating Free-form Surfaces in a Novel Reverse Engineering Application

Website: www.bath.ac.uk/eimrc/projects/DT/DT-Project-Free-formSurfaces.pdf

5.1.2 University of Birmingham

Vehicle Technology Research Centre

Website: www.vtech.bham.ac.uk/

Geometric Modelling Group, School of Engineering, The University of Birmingham

- Geometric Surface Modelling
- Point-based Plug-ins to Enhance the Quality of Geometric Data for Computer Aided Engineering

Website: www.eng.bham.ac.uk/mechanical/geomod/research.htm

5.1.3 Brunel University

Website: www.brunel.ac.uk/about/acad/sed/sedres/dm/cad

- In the field of computer-aided design (CAD) techniques enabling designers to access CAD at the early stages of the design process are being investigated. Current research is concerned with the use of neural network technique in a free-hand 2D sketching and recognition system. This system enables designers to rapidly produce both 2D and 3D geometric models from interpretations of sketches. The work is being extended into free-form surfaces.

5.1.4 Cardiff University

Manufacturing Engineering Centre

Website: www.mec.cf.ac.uk/research/?view=index&style=plain

- Facility based research/services including Reverse Engineering

Website: www.mec.cf.ac.uk/research/?view=reverse_eng&style=plain

5.1.5 The University of Edinburgh

Machine Vision Unit, part of the Institute of Perception, Action and Behaviour,
School of Informatics

Website: www.ipab.informatics.ed.ac.uk/

- Reverse engineering of CAD models from objects, buildings and bodies

Projects Web Link:

Website: www.ipab.inf.ed.ac.uk/mvu/

5.1.6 Heriot Watt University (Edinburgh)

Department of Mechanical Engineering

Website: -www.hw.ac.uk/

- Multi-wavelength fringe projection

Optical shape measurement systems, which employ high-resolution high-density point cloud data sets, are increasingly being used by engineers for quality control and reverse engineering. A related project at Heriot Watt University concerns the development of a multi-wavelength source and associated analysis software. Their system currently requires further development and evaluation to establish the uncertainty in the data across a measurement volume.

5.1.7 Imperial College, London

Faculty of Engineering; Department of Mechanical Engineering

Website: www3.imperial.ac.uk/mechanicalengineering/research

- Geometric Modelling and Manufacturing. The overall aim of the research in the Group is improvement in flexibility and to reduction of lead times during design, process development and manufacture of complex engineering products. A particular focus has been in dealing with free-form engineering parts defined using NURBS, as the main modelling entity in modern CAD/CAM systems.

Website: www3.imperial.ac.uk/geometricmodelling

5.1.8 Trent University, Nottingham

School of Computing and Informatics

Website: www.ntu.ac.uk/research/school_research/cpi/31002gp.html

- Current emphasis is on the development of intelligent information processing techniques for robotic applications. Work includes the Digital representation of (2D and 3D) curves and surfaces; fairing of B-spline curves; measurement of surfaces using laser scanners.

Paper: *The analysis and decomposition of free-form surface models* [74]

This paper, by Bardell *et. al.* [74] addresses the analysis and decomposition of free-form surface models by the use of free-form measurement to reverse engineer free-form surfaces. In particular it discusses the problems that can occur at discontinuities. The measurement system used is a CMM with a touch trigger probe. Normal curve fitting techniques try to smooth out the discontinuity. The example the authors give is the discontinuity at the neck region of a bottle. A technique called curvature-based surface decomposition is suggested to overcome this problem. It is a 3D surface segmentation tool, specifically aimed at surfaces derived from CMM data.

5.2 INTERNATIONAL UNIVERSITIES

The following international universities have been identified as being active in the free - form field.

5.2.1 University of Padova, Italy

Department of Engineering

See section 2.1.2 which describes their involvement in CMM touch probe free-form measurement.

Paper: *Metrological analysis of a procedure for the automatic 3D modelling of dental plaster casts* [75]

Brusco and Andreetto [75] have looked at errors associated with 3D models associated with the single-view acquisition error and the 3D modelling procedure. The work makes use of a range-camera based on pattern projection. The authors highlight the lack of standardised methods for the verification of 3D data acquisition devices and the problems associated with interpreting manufacturers data. To assess the performance of the data acquisition system the authors use a substitution (or comparison) method. A discussion of the various sources of errors in 3D modelling is included in this paper. The errors in the acquisition system are ascertained by comparing measurements made with the optical range-camera with measurements made on a CMM. Probe radius correction is discussed and the point is made that CMMs are not suitable for accurate free-form measurement when no CAD model exists. Because of this limitation a reference object with regular geometry was used. The repeatability of single acquisition measurements is also investigated along with the effect of lighting conditions. The relationship between the number of points and noise under various lighting conditions is also investigated, along with the effect of progressive degradation of the calibration set-up and registration error.

They state:

From the metrological viewpoint, this work gives an example of how to carry a systematic experimental error analysis of a practical 3D modelling method for free-form surfaces, mainly through the comparison with the results of a CMM. It also shows that simple error propagation models can be rather useful for practical simulation purposes.

5.2.2 University of Aachen, Germany

Laboratory for Machine Tools and Production Engineering (WZL)

Paper: *Free-form surface measurement for tool correction* [76]

The paper, by Pfeifer *et. al.* [76] relates to the forming tools that are often used to manufacture free-form surfaces. In free forming, the geometry of the workpiece is fully or partially determined by that of the tool. Therefore, the quality of the finished product largely depends on the geometry of the tools. However, the tool geometry can change in the course of the manufacturing process because of wear caused by friction and optimisations carried out manually during tryout.

The tool is often designed on the same system as the free-form surface. However, once made the tool has to be optimised during the tryout phase (an extensive operation).

Generally no record is kept of these geometrical modifications applied to the tools. Pfeifer *et. al.* present a model in the form of a closed quality control loop to feed back geometrical modifications to CAD and CAM systems. A means of creating the individual components of the quality control loop is described. In order to minimise the required cost and time particular care has been taken to ensure that both the measurement and the feedback are limited to selected areas.

The authors state:

Nowadays, geometric tests conducted using the described measuring methods on the forming tools which have been milled, usually confirm the high quality and efficiency of the manufacturing techniques. Since virtually no measuring is carried out after optimisation or after use, there is a complete lack of information relating to the geometrical modifications which is needed, when the time comes to manufacture a new tool. On the other hand, it is virtually impossible to restrict repair only to the worn areas of forming tools. So there is a lack of feedback of the geometrical modifications carried out which is required in order to optimise and enhance the quality of tool manufacture.

They also state that as a result of technical advances in the techniques used to manufacture free-form surfaces and ever higher customer expectations in terms of product design, such parts will become increasingly important. Requirements relating to the quality of the surfaces, in particular, will become more exacting.

The paper is probably not immediately relevant to the current project, however, tool monitoring is an issue that has arisen during company visits, so it may have industrial relevance to project partners. It should also be noted that the authors used HOLOS for their work and they suggest that CMMs are the best way to measure free-form surfaces (however, note that this paper was written in 2000).

5.2.3 IPT Technical University of Denmark

Website: www.dtu.dk/English.aspx

See 2.1.2 which describes their involvement in CMM touch probe free-form measurement.

6 INDUSTRIAL CONTACTS

To complement the literature survey, a number of companies were visited as detailed in table 2 below. Findings from these visits are included in the summary chapter 7. In the following paragraphs, the names of the companies, web sites, main contact person and phone numbers, together with brief information about the company are provided.

Places Visited
University of Birmingham (Edgbaston)
BMW (Swindon Pressings)
Carl Zeiss (Rugby) Division of Metrology
GOM UK Ltd (Coventry)
Heriot Watt University (Edinburgh)
Hexagon Metrology Ltd (Telford)
Konica / Minolta (Milton Keynes)
Land Rover (Warwickshire)
Leica (Milton Keynes)
McLaren (Portsmouth)
Metris UK Ltd (Derby)
Mitutoyo UK (Andover)
Nissan (Sunderland)
Plowman Craven (Harpenden)
Qinetiq (Malvern)
Rolls Royce (Hucknall)
Smiths Aerospace (Hamble-Le-Rice)
Control (Sinsheim Germany)
TEAM NEC (Birmingham)
Wicks and Wilson (Basingstoke)

Table 2 List of companies/industrialists visited

6.1 UNIVERSITY OF BIRMINGHAM (EDGBASTON)

HP Visual and Spatial Technology Centre

Website: www.vista.bham.ac.uk/contact.htm

Contact: Steve Wilkes (0121 414 5513)

Key related interest: **Laser scanning of archaeological surfaces**

Relevant equipment: Steinbichler T-Scan and Minolta VIVID/VI-910.

HP VISTA has a comprehensive 3D laser scanning facility based around company strategic partnerships with Leica and Steinbichler. The range of scanners situated in the VISTA centre goes from the large landscape level with the latest generation of Leica's HDS3000 along with the HDS2500, down to small manufacturing components with Steinbichler's T-Scan and COMET VarioZoom. For colour applications the Minolta

VI-910 is also in use. These give HP VISTA one of the most complete laser capture suites available. This facility has been based on successful laser scanning work with previous generations of 3D scanners including Wicks and Wilson Triform models for the Chancellors Cup, and artefact-rendering projects.

6.2 BMW (SWINDON PRESSINGS)

Website: www.bmwgroup.com

Contact: *Kevin Titcombe (01793 536 281/551901)*

Key related interest: **Form of car body panels**

Relevant equipment: *CMMs, GOM ATOS*

Swindon Pressings Ltd based in Swindon was founded as a wholly owned subsidiary of the BMW Group in South England on 9 May 2000. Its main production operations with its highly complex press lines are based in Swindon.

With thirty-three dedicated press lines and sub-assembly facilities covering more than 380000 m², Swindon produces high-quality steel and aluminium pressings. Roughly 2000 employees produce, in excess of 100 different parts for the Mini alone. This includes the complete body structure and also high-quality skin parts.

The Swindon plant is supplemented by a second, smaller facility at Saltley, Birmingham, which is used mainly for the production of prototypes.

6.3 CARL ZEISS UK, DIVISION OF METROLOGY (RUGBY)

Website: www.zeiss.co.uk/

Contact: *David Sykes (01788 821770)*

Key related interest: **CMMs with scanning probe.**

Relevant equipment: *CMMs*

Carl-Zeiss are a market and technology leader in the field of Co-ordinate Measurement Machines. Their product line ranges from horizontal-arm and bridge-type measuring machines to form, contour and surface measuring instruments. They are based in a recently constructed purpose-built Technology Centre which covers demonstration, applications and service support requirements for the UK.

On site is a dedicated Contract Measurement facility where specialists are available to provide CMM measuring solutions. They are active in providing CMM retrofits to non-Zeiss users offering leading software products such as Calypso and Holos.

6.4 GOM UK LTD (COVENTRY)

Website: www.gom.com

Contact: *Andy Cuffey (02476 430 230)*

Key related interest: **Structured light for measuring engineering component**

Relevant equipment: *GOM ATOS, GOM TRITOP*

The parent company is GOM mbH - Gesellschaft für Optische Messtechnik and was founded in 1990 as a spin-off of the Technical University of Braunschweig.

GOM develops and distributes optical measuring systems with its main focus on applications like 3D digitising, 3D coordinate measurements, deformation measurements and quality control. GOM systems are used for product development and for quality assurance, material and component testing.

Worldwide, GOM systems are used in the automotive industry, aerospace industry and consumer goods industry as well as by their suppliers. This also includes numerous research centres and universities.

6.5 HERIOT WATT UNIVERSITY (EDINBURGH)

Website: www.hw.ac.uk/

Contact: *Dr Dave Towers (0113 3432159 [Leeds])*

Key related interest: **Multi-wavelength Fringe projection**

Relevant equipment: *Custom*

See section 5.1.6

6.6 HEXAGON METROLOGY LTD (TELFORD)

Website: www.hexmet.co.uk

Contact: *Ian Wilcocks (0870 446 2667)*

Key related interest: **Laser scanners for engineering**

Relevant equipment: *CMMs, Leica Tracker, Romer Arm*

Hexagon Metrology Ltd is the metrology business area of the Hexagon AB global technology group. From hand gauges to CMMs and robots, to advanced metrology software and integrated systems for quality assurance - Hexagon Metrology Ltd is a world leading supplier of precision industrial metrology products. The company formed from the acquisition and management of a group of worldwide leading companies, such as Brown and Sharpe, ROMER CimCore and Sheffield (USA), Hexagon Metrology Qianshao (China), Leitz Messtechnik (Germany), CE Johansson (Sweden), DEA (Italy), Romer (France), TESA (Switzerland) and now Leica. In addition the group includes metrology software developers like Wilcox Associates and Mirai.

6.7 KONICA/MINOLTA (MILTON KEYNES)

Website: www.konicaminolta.co.uk/

Contact: *Peter Smith*

Key related interest: **Laser scanning for industrial applications and archaeology**

Relevant equipment: *Minolta VIVID*

For many years the company has been supplying the VI-series of non-contact 3D digitisers, which enable rapid non-contact measurements of the 3D shape of objects to universities, government facilities and general corporations.

The instrument scans an existing solid object (such as a part or model) and sends the 3D data obtained to a computer for processing, providing improved efficiency for 3D data management in a wide range of fields, including industrial, research and computer graphics.

6.8 LAND ROVER (WARWICKSHIRE)

Website: www.landrover.com

Contact: David Marklow (01926 641111)

Key related interest: **Form of clay prototype model, panel / body shape**

Relevant equipment: CMMs, GOM ATOS, GOM TRITOP

Land Rover together with Jaguar Cars, Aston Martin and Volvo makes up the Ford Motor Company's Premier Automotive Group. The Vehicle Geometry and Surface group at Land Rover's Gaydon plant relies heavily on clay models, which can be measured using non-contact measuring techniques. Such data sets can also be used for reverse engineering purposes.

6.9 LEICA (MILTON KEYNES)

Website: www.leica-geosystems.com/uk/en/lgs_35317.htm

Website: www.leica.co.uk/

Contact: see Hexagon Metrology Ltd above

Key related interest: **Laser trackers with ball probe, 6DOF tactile and laser probe**

Relevant equipment: Tracker, T-Scan, 6DOF probe

Leica Geosystems Ltd (now part of Hexagon Metrology Ltd) is one of the world's foremost providers of solutions in the field of surveying, mapping and monitoring. From simple levels and theodolites to machine guidance and global positioning systems, Leica Geosystems offer a variety of solutions including laser trackers.

6.10 MCLAREN (PORTSMOUTH)

Website: mclarencars.com/company/portsmouth.htm

Contact: Brian Pallottolo (02392-212305)

Key related interest: **Body form of Mercedes-Benz SLR McLaren**

Relevant equipment: CMMs, GOM ATOS

Their Portsmouth facility is the centre of McLaren Automotive's expertise for carbon fibre component production. The facility assembles the Mercedes-Benz SLR McLaren carbon fibre body-shell. The operation was originally formed to produce carbon fibre parts for the McLaren F1 road car but moved to Portsmouth to accommodate a larger facility in order to meet the technical and volume demands for the Mercedes-Benz SLR McLaren. In producing the Mercedes-Benz SLR McLaren, the production engineers have overcome the challenge of tolerance control and, in addition, combine composite materials to their best design and process capability. Much of the monocoque (body) requires tolerances of just ± 0.5 mm or less.

6.11 METRIS UK LTD (DERBY)

Website: www.metrisc.com/

Contact: Alan Instone (01332 811349)

Key related interest: **Laser probes for CMM, laser radar, 6-DOF**

Relevant equipment: CMMs, laser scanners, K-Scan, arms

Metris provides integrated solutions for automotive and aerospace metrology. The portfolio comprises CMMs, optical CMMs, 3D laser scanners, laser radar and iGPS systems completed with focus inspection and reverse engineering software.

Metris designs, develops and markets a unique range of 3D hardware and software inspection systems for the automotive and aerospace sectors. The company offers metrology solutions for both design and manufacturing communities. The product family covers a large range of measurement volumes, in both fixed and portable configurations and with optical and touch sensors.

Metris provides precision equipment and metrology solutions for classical CMM measurements featuring bridge and horizontal arm CMMs. Metris is a leader for CMM based laser inspection, with the Metris LC and XC laser scanners offering full surface and feature measurement.

6.12 MITUTOYO UK (ANDOVER)

Website: www.mitutoyo.co.uk/

Contact: Ken Edmett (01264 353123)

Key related interest: **CMMs fitted with optical (Metris) and tactile (Renishaw) probes**

Relevant equipment: CMMs, Scanning head, Minolta type scanner expected 2007

Mitutoyo is a leading supplier of high precision dimensional measuring equipment in UK. They are a major supplier of state of the art CMMs and vision inspection systems. Mitutoyo offer complete packages; IT support, training, bespoke gauging and UKAS calibrations.

6.13 NISSAN (SUNDERLAND)

Website: www.nissan-global.com/

Contact: David Bambrough (0191 415 2612)

Key related interest: **Body form using articulating arm with laser scanner**

Relevant equipment CMMs, Articulated arm

Based in Sunderland, Nissan Motor Manufacturing (NMUK) builds 60% of Nissan vehicles sold in the European market. Nissan has the largest UK presence of any car manufacturer, accounting for 20% of total UK production.

NMUK is split into three logical areas: body assembly, paint and final assembly sections. Each is further broken down into areas known as 'shops' press shop, body shop, paint casting shop and axle shop. Linked directly to the press shop, the body shop is a highly-automated section of the factory with over 500 robots in operation. Pressed-panels are welded together to create complete body shells. Plastic components such as bumpers are injection-moulded on site. The newest facility at NMUK produces axles on-site.

6.14 PLOWMAN CRAVEN (HARPENDEN)

Website: www.plowmancraven.co.uk/3d.htm

Contact: Duncan Lees (01582 765566)

Key related interest: **Contract metrology, laser scanning and photogrammetry**

Relevant equipment: Tracker, articulated arm large, photogrammetry equipment

Plowman Craven and Associates are a leading supplier of image and point based spatial data collection services. They provide commercial laser scanning and, photogrammetry services to a variety of industries. With their significant investment in CAD they are

able to produce 3D models from accurate data sets. Their team of dedicated 3D modellers produce 3D models and animations for use by a wide client base. Their equipment includes: electronic distance measuring devices, theodolites and a Cimcore portable measuring arm fitted with a Perceptron Laser scanner.

6.15 QINETIQ (MALVERN)

Website: www.qinetiq.com/

Contact: *Maurice Stanley (01684 894000)*

Key related interest: ***Photogrammetric measurements of feet***

Relevant equipment: *Foot scanner*

QinetiQ is a defence technology and security company specialising in leading edge technology devolved from the UK's national defence laboratories. Civil customers have access to solutions that are often beyond those readily available in commercial markets. One such example is the Clarks-shoes foot scanner. The QinetiQ scanner is being installed in Clarks shops, it uses infra-red light to map the size and shape of a child's foot. The technology was originally used to help bomb disposal robots navigate around obstacles and these new systems should make shoe fitting quicker and more accurate.

6.16 ROLLS ROYCE (HUCKNALL)

Website: www.rolls-royce.com/

Contact: *Nick Orchard (0117 979 6925 Bristol)*

Key related interest: ***Form of turbine blades. Scanning /Structured light***

Relevant equipment: *CMMs, laser scanners, GOM ATOS*

Rolls-Royce, is a world-leading provider of power systems for use on land, at sea and in the air, operating civil aerospace, defence aerospace, marine and energy global markets. An operational supersonic Short Take-Off and Vertical Landing (STOVL) fighter has been the goal of several aircraft acquisition and development programs over the past forty years. The Joint Striker Fighter (JSF) program began in 1994, and today JSF is developing a family of next-generation strike fighters for the US/UK. In August 2006, the US Department of Defense awarded the General Electric and Rolls-Royce team a \$2.4 billion contract to develop its F136 engine. Significant metrology capabilities are required to support the production of Rolls-Royce's LiftSystem which incorporates their Liftfan, engine to fan driveshaft and three-bearing swivel module used for thrust vectoring.

6.17 SMITHS AEROSPACE (HAMBLE-LE-RICE)

Smiths Mechanical Systems Aerostructures

Website: www.smiths-aerospace.com/

Contact: *Glen Martin (02380 453371)*

Key related interest: ***Form of complex composite automotive structures***

Relevant equipment: *FARO articulated arm*

Smiths Aerospace are leaders in the design and manufacture of major structures and precision airframe components in metallic, composite and acrylic materials for the global civil and military aerospace market. Through the introduction of new materials and manufacturing techniques, with planned investment in technology improvements,

the aerostructures business provides a competitive, cost effective world-class service. It also produces lightweight composite structures used, for example, in the production of high performance road/racing cars.

6.18 CONTROL (SINSHEIM GERMANY)

Website: www.eventseye.com/fairs/trade_fair_event_517.html

Contact: *co P. E. Schall GmbH (+49 7025 92060)*

Key related interest: ***Metrology exhibition; 2006 was highly non-contact related***

Relevant equipment: *N/A*

Control is a trade fair held annually at the Sinsheim exhibition centre. In 2006, nearly all of the exhibitors were leading suppliers of measuring equipment from both inside and outside of Germany. It is reported by the promoter (P. E. Schall GmbH) that the number of visitors from outside of Germany is climbing, thus increasing its international status. The exhibitor product lines include a significant amount of non-contact form measuring equipment. General length, displacement encoders, measuring machines, special measuring equipment, modules for measuring and test benches, materials testing devices and machines and software for computer-aided quality systems were also on show.

6.19 TEAM NEC (BIRMINGHAM)

Website: www.inspex.co.uk/releases.htm

Ithaca Media Ltd

Contact: *Mark Napier (020 8232 1600)*

Key related interest: ***Metrology exhibition in UK (smaller than Control above)***

Relevant equipment: *N/A*

INSPEX is the main UK event dedicated to metrology, testing, inspection equipment and quality management. INSPEX embraces every quality control technology from dial gauges through to sophisticated form measuring 3D CMMs, to cover every inspection and quality control need. INSPEX runs concurrently with seven other dedicated manufacturing events for UK industry: automation; computers in manufacturing; contract manufacturing; the design engineering show (des); factory services; time compression technologies; and tooling as part of TEAM (Total Engineering And Manufacturing, incorporating Manufacturing Week) and alongside WELDEX.

6.20 WICKS AND WILSON (BASINGSTOKE)

Website: www.wwl.co.uk/3dbodyscanner.htm

Contact: *Stuart Winsborough (01256 842211)*

Key related interest : ***Human body scanning using structured light***

Relevant equipment: *Body scanner*

Wicks and Wilson manufacture 'TriForm', a technology that uses normal white light to quickly and safely capture the 3D geometry and colour of a surface. The TriForm BodyShape Scanner is designed to capture the human body in three dimensions. The whole body is captured in under ten seconds and a 3D point cloud is processed and displayed in under one minute. The curtained booth provides privacy for the person being scanned who will ideally be wearing light, form fitting clothing, or underwear. Stripes of normal white light are used to capture the 3D shape of the person. The light is

harmless, in the visible spectrum only and produced without using lasers. The resulting images are analysed automatically by the TriBody software and processed to produce a 3D point cloud containing approximately 1.5 million coordinate points.

7 SUMMARY

A detailed literature search and an industrially based survey to determine the current industrial capabilities and traceability requirements for free-form measurements has been conducted.

It is clear that there are numerous tactile and non-contact free-form related measuring systems being used by UK industry. Machine suppliers are promoting such systems and there is a considerable worldwide drive to improve the measuring techniques employed, and to understand the relevance of the recorded measurement data.

Putting aside issues relating to the sensor supporting systems (CMM, arm, static box *etc.*), from a sensor point of view, tactile systems commonly suffer from radius of stylus tip corrections, while non-contact systems suffer from surface and light-source related problems. There are thus, often significant, measurement differences experienced between the two types of sensors employed. Even within the tactile sensor systems and to a larger extent between the non-contact probing techniques, there are significant differences in the measurement data recorded and the ways the data is interpreted.

From an industrial perspective, there is a great attraction to make more measurements in a shorter time and to improve quality control by, for example, measuring greater surface areas of more parts on a given production line. The industrial visits highlight the fact that many companies are now using the new generation of rapid-measuring large-area non-contact systems in favour of traditional CMMs fitted with touch probes. However industrialists are generally sceptical about the capabilities and overall performance of these non-contact types of measuring systems. A common discussion point amongst industrialists is the current lack of both physical and specification standards (ISO or other) and who will be responsible for providing them. Some industrialists seek individual 'gold-standards' of their own custom design, however, this is an impractical solution for the current free-form project (as described in section 1.2), since the NPL artefacts need to be of a generic design, enabling them to support a vast range of equipment and end users.

The industrial visits indicate that for the vast majority of medium-sized (500 mm x 500 mm area) free-form measurements made, challenging uncertainties in the order of 50 μm to 100 μm are required on complex surfaces. Outside of this, there are a few specialised applications, where measurement uncertainties need to be much tighter, however these are on much smaller components.

The reference artefacts and the inter-comparisons proposed in the NMS project related to this report (described in section 1.2) will considerably boost industrial confidence when using free-form measuring systems or at least highlight weaknesses that need to be addressed.

The review clarifies that:

- There is no specific ISO standard that address current free-form requirements.
- There are no physical standards currently available to support an industry that is becoming more reliant on free-form measuring systems.
- More and more sophisticated free-form measuring systems are being designed and are entering the market place.
- Verified free-form metrology capabilities are essential if UK industry is to compete globally.
- The proposed development of a free-form verification process and supporting artefacts is demanded by industry. Both are essential if the NMS is to support the rapidly developing wealth-earning UK industries which are becoming increasingly reliant on using free-form measurements.

8 ACKNOWLEDGEMENTS

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