New Opportunities in Non-Contact 3D Measurement

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1 Introduction

The availability of non-contact 3D data capture systems capable of acquiring dense geometric data from complex surfaces has increased considerably over the past five years. Systems are now being offered by a growing number of manufacturers for use in a wide range of applications ranging from anthropometry to reverse engineering, the vast majority of which are optically based. It is now possible to obtain commercial off-the-shelf devices based on any one of a wide variety of 3D optical sensing techniques, such as:-

- Laser Scanning Triangulation (3D Scanners, Cyberware, Digibotics, Laser Design, Vitronic)
- Moiré Fringe Contouring (Wicks and Wilson, Breuckmann, InSpeck)
- Phase Measuring Profilometry ($[TC]^2$)
- Digital Stereo Photogrammetry (TCTi)

In order that fitness of purpose may be judged or comparisons made, demand is mounting for an independent measure of the performance of non-contact 3D data capture systems. In many applications, understanding both how accurately the systems can determine 3D surface coordinates and also the kinds of error is important. Even in applications where dimensional accuracy is not critical, such as computer graphics, small discontinuities in surfaces can lead to noticeable problems. As with the application of any measuring instrument, the question of traceability to standard units of length of measurements made using these systems must also be addressed.

In this paper, issues concerning the assessment of the performance of non-contact 3D data capture systems are discussed. This is followed by a brief review of the state-of-the-art in the performance assessment of non-contact 3D data capture systems. Finally, we present an overview of a new project which aims to address many of the performance assessment issues raised in our discussion.

2 Performance Assessment Issues

2.1 Calibration Techniques

To determine the measurement accuracy of a measuring system, it is necessary to calibrate it. Ideally, this should be carried out according to standard procedures, however, such procedures do not yet exist for non-contact 3D data capture systems, though they do exist for the calibration of certain three-dimensional measuring systems. For example, ISO standard 10360-2:1994 describes methods for the assessment of the performance of a Coordinate Measuring Machine (CMM), probably the closest conventional measuring instrument to a non-contact 3D data capture system. However, most CMMs employ a contacting, probe-based measuring technique which is usually combined with a straightforward geometrical design employing three or more independent, orthogonal, measuring axes. Measurement accuracy can be determined by first isolating each element and calibrating by comparison with a known standard of length, such as a laser interferometer, then combining the data obtained with a measure of orthogonality to complete the picture. With 3D optical sensing systems, there is no method for isolating each element and calibrating separately, therefore, the methods given in the ISO standard cannot be applied and an alternative method for assessing measurement accuracy must be used.

Another important difference between CMMs and 3D optical sensing systems is the need for calibration. In general, the simple Euclidian geometry of a CMM helps to ensure that if it is assembled to within manufacturing tolerances, it will produce essentially linear measurement data without calibration. Once obtained, the calibration data is used to correct small, position dependent, non-linearities or 'biases' in the response of the CMM. Unlike CMMs, the complex geometry and non-linear nature of 3D optical sensing systems dictate that some form of calibration is required before they can produce any useable measurement data. A mapping, or perspective transformation, usually obtained through calibration, must be applied to the image coordinate data, output by the image sensor in the form of 2-dimensional pixel data, to produce 3-dimensional measurement data in a World coordinate system. The complexity of 3D calibration techniques is dictated largely by the sensor geometry and can vary enormously. However, of the two basic types of calibration technique that exist, the

Reference Artefact method and the System Geometry method, only the reference artefact method can be used when performing an independent assessment, as the assessor will not have access to the design details necessary to model the system geometry and assumptions cannot be made.

Measurement accuracy can be obtained through the application of one of the calibration techniques given above, however, this yields only the baseline, or theoretical, measuring performance. The actual performance of a measuring system is dictated by the measurement application and the characteristics of the sensing technique employed. Therefore, it will also be necessary to determine the influence of application-specific factors on the baseline measuring performance to produce an indication of the actual measuring performance. The ambient conditions under which the system is operating may also influence performance. Furthermore, there is the issue of whether to treat as part of the measuring system the software supplied for the extraction of measurement data from the dense data sets produced by the data capture system and include it in the performance assessment.

2.2 Object Issues

As the majority of non-contact 3D data capture systems are optical sensors, a major consideration in the assessment of their performance will be the optical characteristics of the target object's surface. For example, moiré fringe contouring systems are known to give poor fringe contrast on certain surfaces, one well-documented example being human skin. Takasaki [1] has experimented with several methods to improve it. Though generally more tolerant than fringe-based systems, laser scanners can be prone to specular reflection and surface microstructure noise [2], and photogrammetric systems can present practical problems with the placement and number of targets or features on the object of interest. Furthermore, all systems that project patterns of light onto human skin will be subject to the edge spread effect caused by the skin's translucency. Therefore, optical properties of the target object's surface, such as reflectance, opacity and colour, should be taken into consideration and geometric properties, such as curvature and surface texture, may also influence the optical characteristics of the surface.

2.3 Sensor Issues

A characteristic of most non-contact 3D data capture systems is that measurements to individual object features cannot be made directly. Range coordinates are obtained on a regular grid and it is generally not possible to ensure that any given object feature coincides with one of the measurement grid points. Point-to-point measurements obtained from a data set, therefore, rely heavily on interpolation. This limitation is largely a result of the finite spatial resolution of the image sensor but in fringe-based optical sensing techniques, such as moiré fringe contouring, the technique itself produces an averaging effect.

The triangulation geometry employed in many 3D optical sensing techniques presents an additional set of problems; those of occlusion and obscuration. In many 3D measurement applications, the provision of a complete data set which is free of areas of missing surface data is a principal requirement. However, a triangulation-based sensor geometry may make this difficult to achieve and the shape and orientation of the object being imaged may add considerably to this difficulty.

In applications involving the measurement of live subjects, data acquisition speed has a significant influence on measuring performance and can be fundamental to the success of the data capture technique. Human beings, particularly young children and the elderly, cannot remain perfectly still for more than a few seconds. This can be a major concern if we wish to make measurements to sub-millimetre resolutions, as in medical imaging or anthropometry. In assessing the performance of an instrument designed specifically for the measurement of the human body, it would seem logical to use physical features of the body as reference dimensions which can be used to perform the calibration. Unfortunately, the nature of living organisms is such that they have no external physical features which are dimensionally stable. Many anthropometric dimensions are influenced by subject pose and, therefore, not stable or repeatable. Some, such as the inter-pupillary distance, may remain stable in the short term but can change over time or with growth and can be impossible to measure by independent, traceable means. Furthermore, the complex geometry of the human body makes it virtually impossible to locate exactly the same dimensions on successive scans without the addition of artificial features applied to the body's surface. Markers applied to the skin are unsuitable as they rely on soft tissue for their dimensional stability and subject pose for repeatability. Mannequins may be used to approximate the geometry of the human body but no data on the influence of body movement will be obtained.

In the determination of actual measuring performance, it may be argued that any computer software used for the extraction of measurement data from the dense data sets produced by the data capture system should be treated as part of the system and included in the performance assessment. However, many systems do not include such software and a commercial 3D data processing package, such as Imageware Surfacer or InnovMetric PolyWorks, or assessor-developed software is sometimes used instead. For human body measurement applications, automatic anthropometric measurement extraction software, such as Cyberware's DigiSize and $[TC]^2$'s BMS software, is becoming more common and may be supplied as part of a 3D whole body imaging system.

3 State of the Art

3.1 Performance Assessment Techniques

Despite an increasing awareness amongst users of non-contact 3D data capture systems of the importance of performance assessment, a recent review of assessment techniques for 3D whole body imaging systems [3] concluded that standard procedures for the calibration and performance assessment of such systems do not exist. This might be expected, given the wide variation in data capture techniques and system designs. However, even amongst systems that use the same data capture technique, there was no evidence of any effort by their developers or manufacturers to collaborate on the development of a standard calibration methodology. A pilot project carried out in 1995 by the National Engineering Laboratory (NEL) on methods for the independent assessment of the performance of commercial 3D imaging systems showed promise but the work was never followed up [3].

3.2 Influence of Occlusion and Obscuration

Some researchers have employed computer simulation to address the problem of missing data caused by occlusion and obscuration. Researchers at Ohio University, working in collaboration with Cyberware, have developed a software package, SimScan, which can be used to model the optical path of a Cyberware 3D whole body imager to determine scan coverage [4]. Other work has concentrated on the determination of the optimum position of sensors during the design of multiple viewpoint 3D imaging systems [5, 6]. Work is currently underway at the University of Glasgow's 3D-MATIC Research Laboratory to develop simulation software, for use in configuring stereo photogrammetry based 3D whole body imaging systems, that can both determine the optimum position of the sensors and provide an indication of scan coverage.

3.3 Influence of Body Movement

NEL also pioneered a novel method of determining the influence of body movement on baseline measurement accuracy. In the NEL method, calibrated reference artefacts of simple geometric shape are affixed to a live subject or placed around the subject's limbs during scanning. Care must be taken to ensure that the reference artefacts are firmly attached to the subject's body to minimise the risk of slippage during the scan. Any errors which exceed the baseline measurement accuracy of the system can then be attributed to body movement. The information from these tests was designed to complement the assessment of the baseline measuring performance for each system, which would have been determined using the same reference artefacts in static tests, to produce an indication of actual performance.

3.4 Influence of Measurement Extraction Software

Several recent studies have attempted to test the performance of automatic anthropometric measurement extraction software by comparison of the output data with measurements obtained using traditional anthropometry [7, 8, 9]. Both live subjects and mannequins have been used in these studies but none appear to have involved independent calibration of the test equipment. For reasons of dimensional stability and repeatability, a mannequin is more suitable than a live subject, however, tailoring dress forms or retail display mannequins are not designed to be dimensionally stable and are far from ideal.

3.5 Traceability

As with the application of any measuring instrument, traceability to standard units of length is necessary in order that the measurements made can be proven to be valid. CMM manufacturers routinely provide a certificate of calibration with traceability to national standards. The CMM user is then able to determine the uncertainty of measurement when using it for inspection or quality control tasks, providing confidence in its use. Though there has been some recognition of the subject, the 3D optical sensing community has so far failed to address this issue and few commercial systems currently possess traceability to national or international standards. However, elsewhere in the optical sensing field, there has been some recent work on traceability. For example, some of the surveying instruments used in industrial metrology, such as Sokkia's NET2100 3-D Station, are calibrated and traceable to NIST (National Institute of Standards Technology) measurement standards. They have highly accurate vertical and horizontal encoders as well as highly accurate laser distance measurement hardware. They require that the points of interest to be measured be defined with retro-reflective targets. The stated accuracy of the measurements is about ± 0.8 mm but, using NIST traceable scale bars (documented to ± 0.0005”), measurements in the order of ± 0.05 mm at 15 metres can be achieved.

Some digital camera based industrial metrology systems, such as Geodetic Services’ VSTARS and INCA photogrammetric measurement products, also yield NIST traceable measurements, for critical measurement applications in the automotive, aerospace and nuclear industries. The camera and optical systems used are calibrated to map out measurement errors induced by the optics and image sensor. However, these systems also require that the objects and features to be measured are targeted appropriately.

4 New Research Programme

A new programme of research to address the issue of assessment of the performance of non-contact 3D data capture systems has been initiated by the Imaging Faraday Partnership. The first project arising from this is the Department of Trade and Industry funded ‘Development and Validation of Testing Methods for Non-Contact 3-Dimensional Data Capture Systems Project’. The project began on 1 October 2001 and will run for 18 months. It involves a consortium of five partners led by Sira Limited, with the University of Glasgow’s 3D-MATIC Research Laboratory as the academic partner and three industrial collaborators, Wicks and Wilson Limited, 3D Scanners Limited and TCT international. The active participation of the industrial collaborators, who are all leading UK developers and manufacturers of 3D imaging equipment, will be fundamental to the success of the project, both in terms of their input to the development of a standard testing methodology and in promoting the acceptance of performance assessment throughout the 3D imaging community.

4.1 Project Objectives

The major objectives of the project are to provide a better understanding of the factors affecting the accuracy of non-contact 3D data capture systems and to develop and assess a methodology for testing such systems. In order that the wider community may benefit from the work, the project will also include a significant dissemination element, with the Imaging Faraday Partnership serving as the main vehicle for dissemination.

4.2 Approach

The discussion in Section 2 above serves to demonstrate the range of factors that can influence the performance of non-contact 3D data capture systems. Within the project we shall be concentrating on those aspects that are of most concern to the 3D imaging community. Through preliminary discussions with manufacturers and users, two key performance features were identified:-

- Overall geometric accuracy throughout the measuring volume
- Sensitivity to surface properties

An additional concern raised was that any methodology developed should be straightforward and cost-effective to apply.

4.3 Programme of Work

The programme of work will begin with a review of the capabilities of current non-contact 3D measurement systems to determine the range of variation in system accuracy and the factors affecting that accuracy. This will be followed by the development of a methodology to determine geometric accuracy by means of a reference artefact of simple geometry which has been designed for use within the normal operating environment of the system under test. A methodology will also be developed to assess the sensitivity of the measuring system to the surface properties of the target object. Both methodologies will then be subject to an extensive testing and evaluation programme through their application to a range of commercially available and research systems.

5 Conclusions

We have highlighted many of the issues surrounding the independent assessment of the performance of non-contact 3D data capture systems. A brief review of the state of the art has shown that, despite the example set by CMM and industrial metrology instrument manufacturers, this subject is not being given the attention that it deserves. This has been recognised by the Imaging Faraday Partnership and a programme of research to address the problem has been initiated. The first project to come out of this initiative includes several of the key UK developers and manufacturers within the project consortium. The performance assessment methodologies developed will provide increased confidence in the use of non-contact 3D data capture systems, leading to new opportunities for their manufacturers and users.

6 References

1. Takasaki H., Moiré Topography, Appl. Opt. 12, 845-850, 1973.

2. Chiarella M. and Pietrzak K. A., An Accurate Calibration Technique for 3-D Laser Stripe Sensors, Proc. SPIE Optics, Illumination and Image Sensing for Machine Vision IV 1194, 176-185, 1989.

3. Marshall S. J., Whiteford D. N. and Rixon R. C., Assessing the performance of 3D whole body imaging systems, Proc. 6th Numérisation 3D/Scanning 2001 Congress, Paris, France, 2001.

4. Nurre J. H. and Addleman S., 3D Scan Systems Integration, DLA-ARN Final Report DDFG-T3/P3, [number of pages?], 1998.

5. Tarbox G. H. and Gottschlich S. N., Planning for complete sensor coverage in inspection, Computer Vision and Image Understanding 61 1, 84-111, 1995.

6. Mason S. O. and Grun A., Automatic sensor placement for accurate dimensional inspection, Computer Vision and Image Understanding 61 3, 454-467, 1995.

7. Cross S. and Lock L., A preliminary evaluation of a commercial 2-D automatic body measurement system, DCTA S&TD Research Report No. 96/08, 1996.

8. Paquette S., Brantley J. D., Corner B. D., Li P. and Oliver T., Automated extraction of anthropometric data from 3D images, Apparel Research Network Working Document, 2000.

9. Centre for 3D Electronic Commerce, 3D Technology Proofing Phase 2 Specification, Version 1.6, 2000.