Non-Contact Surface Geometry Measurement Techniques

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Abstract

It is often necessary to be able to create computer models from physical objects. This is often done for the purposes of reverse engineering, or archival. Many of the contact methods, such as callipers or Co-ordinate Measuring Machines, are unsuitable for use in areas where the material is delicate. There are numerous techniques that are capable of performing quick accurate measurements of surface geometry, a number of which are reviewed.

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I INTRODUCTION

There are numerous instances where it is necessary to be able to accurately measure the geometry of an object. Today, much of the manufacturing industry uses CAD packages to design parts, these computer models are then used to control milling machines, which fashion the part. However it is often the case that there is no CAD model available, usually because the part pre-dates the use of CAD.

Thus it is necessary to construct (or reverse engineer) a model from a sample part (or parts). The construction of a CAD model can often be a painstaking process, especially when the part has to fit into existing equipment. Thus it is advantageous to be able to automatically construct a model from the physical object [14]. This essentially comes down to measuring a set of points across the surface of the object, from which a surface representation (such as a triangulated mesh or surface patches) can be constructed.

It is often the case where the use of contact measuring techniques, such as callipers, micrometers or Co-ordinate Measuring Machines (CMMs) is not applicable, usually due to the fragile nature of the subject [11], or the inherent limitation on the speed of such measuring techniques [13]. One such area is that of Archaeology, where artefacts are often delicate and must be handled with care so as to minimise the risk of irreparable damage. Other areas include quality control for delicate machine parts, such as components for disk drives or printer circuit boards.

This document is a review of some of the techniques, which have either been employed in industry or proposed in research, for non-contact measurement of small/medium sized features. It gives an overview of the operation of various methodologies, and tries to look at their suitability for use, and their accuracy. The second section takes a more detailed look at Laser Triangulation, providing a mathematical basis for the operation of the technique, and details some of the circumstances under which the technique will suffer from reduced accuracy, or fail completely.

II EXISTING TECHNIQUES

This section is concerned with reviewing the many techniques, both utilised in industry and proposed in research, which are suitable for the measurement of surface geometry. The techniques have been categorised according to the fundamental way in which they group their data, single points, lines of points or grids or points.

II.1 MODE OF OPERATION

The mode of operation of a *Surface Measurement System* (SMS) classifies a system by the fundamental way in which it obtains its data. There are 3 basic groups in which a system can be placed *Point, Line and Grid*. A particular system may lie somewhere between two groups, a hybrid approach which extends a technique partially into the next category.

II.1.1 POINT BASED TECHNIQUES

Techniques are said to be *Point-Based* if they make their measurements on a *point-by-point* basis. That is to say that the only obtain a single measurement for each cycle. These operate in a similar fashion to CMMs, i.e. they perform measurements in a sequential fashion, which require lots of movement of the device [13]. *Point-Based* techniques are often extended to provide more complete sets of data (such as lines or grids). The use of (*auto-synchronising*) optics can make the scanning head sweep over the surface, without having to move the entire system [2, 19]. As the data is acquired in a sequential manner, the surface must be stable for the duration of the measurement. Also the mechanics/optics required to perform the scan, can increase size, complexity and weight, and can make the system sensitive to vibration.

II.1.2 LINE BASED TECHNIQUES

Lines-Based techniques are those that perform a number of measurements, in a line across the surface, in a single pass. As all the points are measured in parallel, these techniques are generally faster than *Point-Based* ones. As with *Point-Based*, optics can be used to perform a sweep across the surface, providing a grid of readings (*Range Image*). As before, this requires that the surface be stable for the duration. This also allows the object to move in a linear fashion past the sensor, such as on a conveyer belt.

II.1.3 AREA BASED TECHNIQUES

Area-Based techniques provide the most flexible form of data, measurements are organised in a grid across the surface (*Range Image*). These techniques are usually much more involved, and they usually require multiple images of the subject, which means that they are usually not truly simultaneous.

II.2 POINT BASED TECHNIQUES

II.2.1 TIME-OF-FLIGHT (LASER RANGE FINDING)

Time-of-Flight utilises time as a surrogate measure for distance. In the case of *Laser Range Finding*, shown in Figure II-1, this is the time taken for a light pulse to travel back, having reflected off the surface [2, 23].

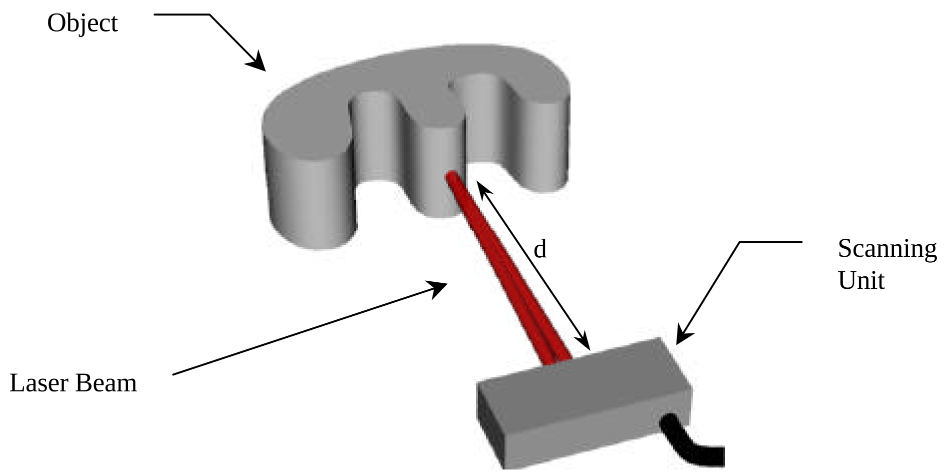

Figure II-1 - Time of Flight

The calculation of distance from time relies on the well-known formula:

$$\underset{m/s}{\text{speed}} = \frac{\underset{m}{\text{distance}}}{\underset{s}{\text{time}}} \qquad \text{[Eqn II.1]}$$

The distance to the object surface is ½ the distance travelled by the light pulse, therefore this equation can be rearranged to:

$$\underset{m}{\text{distance}} = \underset{m/s}{1.5*10^8} * \underset{s}{\text{time}} \qquad \text{[Eqn II.2]}$$

As light travels at extremely high speeds, very sophisticated circuitry is required to measure the return time of the laser beam. This also has an impact on the accuracy obtainable from such systems [23], e.g. the Polhemus LMS has an accuracy of 10mm @ 1m for a single sample, which can be improved to 5mm @ 1m by averaging 100 samples.

As the measurement employs a laser, a rotating mirror can be used to scan a line across the surface. Thus allowing a number of (radial) measurements to be made in quick succession. This increases the usefulness of the system, but also increases weight, e.g. The Polhemus LMS weighs 3KG, and is about 6inches in all dimensions.

II.2.2 LASER RADAR (LIDAR)

Laser Radar also uses a surrogate measure for distance. The phase shift experienced by an amplitude modulated laser beam, as it reflects of the surface, can be related to the distance by a calibration step [5, 19].

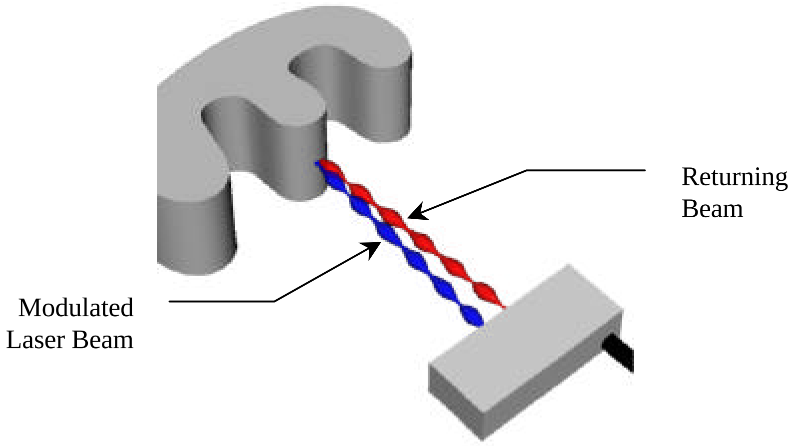

Figure II-2 - Laser Radar (LIDAR)

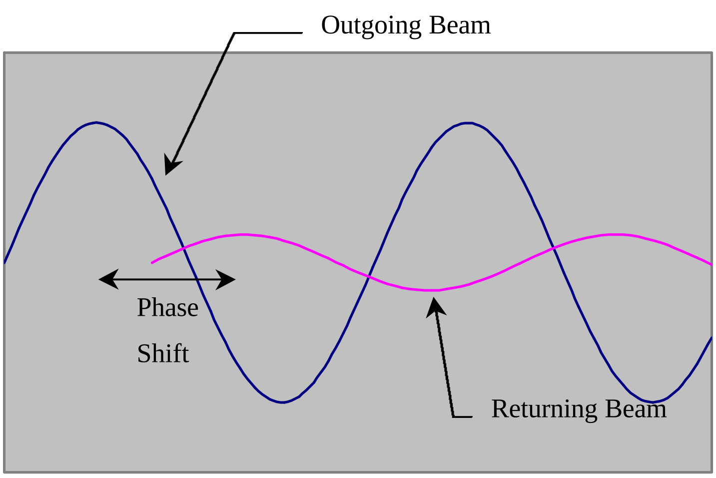

Figure II-3 - LIDAR (Phase Shift)

The structure of the system, allows high data rates, i.e. it is capable of performing continuous measurements. However the data is often quite noisy, and contains an appreciable number of erroneous readings [5].

The main feature of the LIDAR is that it is incapable of giving an unambiguous measurement. This results from the periodic nature of the modulation, which results in measurements of the form:

$$d = k * n + f(phase) \qquad \text{[Eqn II.3]}$$

Where n is the length of the periodic function (modulation wavelength) and k is a positive integer, the value of which is elusive. However the frequency of the modulation can be used to define an envelope, within which the readings will lie [5], which allows it to provide readings over a long range [19]. As with *Time-of-Flight* optics are required to perform line or surface scans which can increase the systems weight and size.

II.2.3 LASER TRIANGULATION

Triangulation is a commonly used technique for determining spatial relations. It has been utilised in areas as cartography and the Global Positioning System (GPS). *Laser Triangulation* is an *Active*[1] *Structured Light (ASL)* technique, in which a laser dot is observed (through a lens) by a sensor.

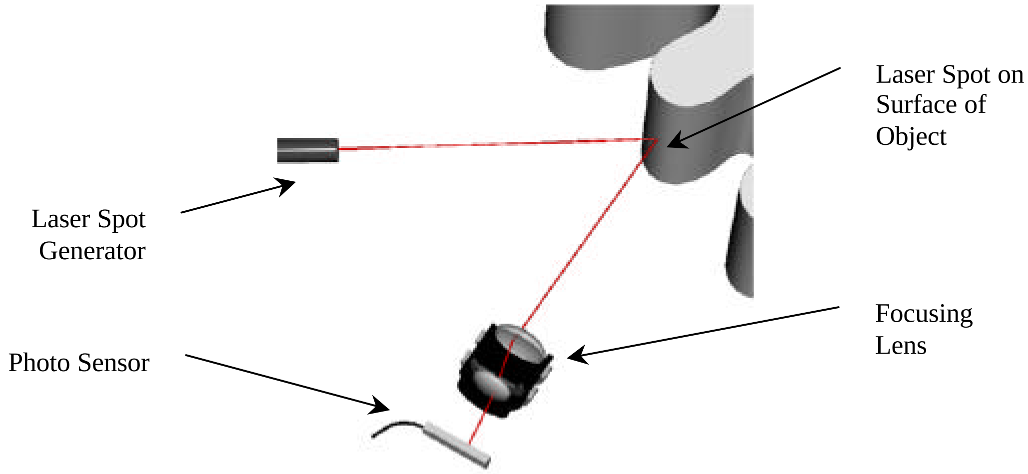

Figure II-4 - Laser Triangulation

The position of the laser spot on the sensor is related to the position of the surface (along the beam) by using triangulation [10, 11].

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[1] The system is said to be *active* as the geometry of the laser beam is used in the measurement and so need to be known [9].

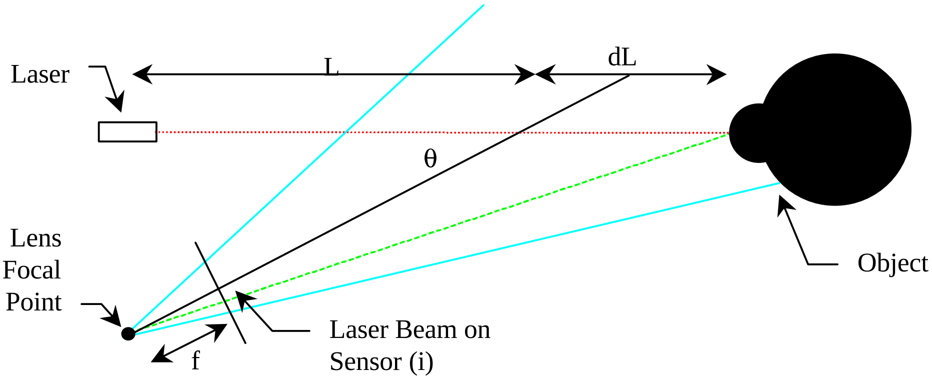

Figure II-5 - Laser Triangulation

$$dL = g(f, i, L, q)$$ [Eqn II.4]

The triangulation angle (and the lens) can be used to achieve the required balance of range and accuracy [11]. In [6] precisely controlled mirrors are used to control the base line for the triangulation. As the laser is positioned at a non-zero angle, relative to the sensor, it is possible for part of the surface to obscure the camera's view of the line (generated by the laser). This is less prevalent at lower angles [6], however the accuracy is also reduced, which limits the distance over which triangulation can be used [20]. Triangulation is capable of providing high (sub-micron) accuracy over short ranges [11, 20].

As the triangulation can be implemented with an analogue photo-sensor extremely high data (and hence measurement) rates are possible, 200K measurements/sec [10, 11]. The use of pixelised (array) sensors allow errors, such as multiple reflections, to be detected [10, 11], however this does reduce speed.

II.3 LINE BASED TECHNIQUES

II.3.1 LASER LINE TRIANGULATION

Laser Triangulation, presented previously, can be easily extended to take a line of measurements in parallel. This is achieved by replacing the laser point generator with a laser line generator, which produces a line on the surface [13]. Multiple sensors, stacked upon each other, are then required to take readings along the length of the line. It is often simpler, and cheaper, to use a standard *off-the-shelf* CCD camera, the rows of which represent the different sensors in the stack. The CCD array also acts as a pixelised sensor, which allows multiple bright spots to be detected and the erroneous data to be discarded.

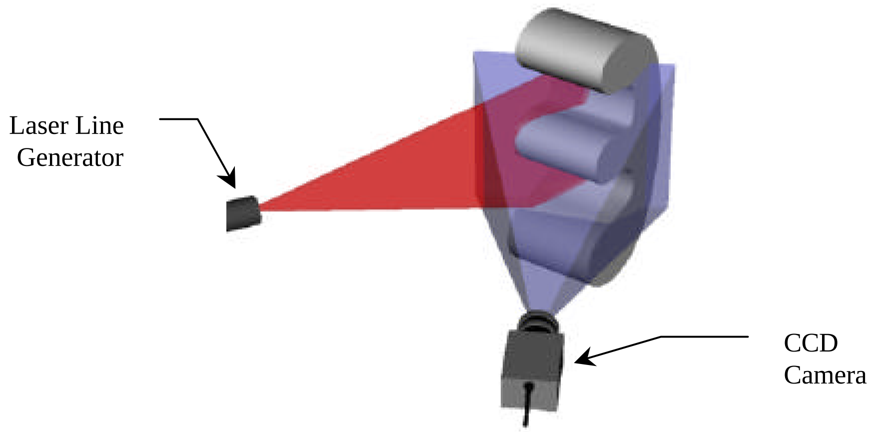

Figure II-6 - Laser Line Triangulation

As with the *Point-Based* version, this also suffers from the problems of occlusion. [6] reduces the angle (or applies the light from the opposite side of the camera) to overcome this, [4] uses a pair of light sources (both of which are visible in the image), to minimise it's effect. Others [24] use multiple cameras to minimise the problem, and allow noisy readings to be removed [25], however this has added problems as the relative positions of each of the cameras must be determined [6]. As the triangulation angle is never zero, it is always possible for occlusion to occur. Using *off-the-shelf* components it is possible to achieve sub-millimetre (0.15mm) accuracy [24].

The structured light pattern used for the triangulation can be generated in a number of ways, [4, 17] uses a while light strip to allow eye safe operation. [2, 6, 24] uses commercially available laser line generators.

Some researchers have extended this idea to use the edge of a shadow for triangulation, as it can be easier to detect the transition, from light to dark, than to detect the centre of a narrow strip [17, 21].

Cyberware (www.cyberware.com), BIRIS (National Research Council of Canada) and PRIME (California Polytechnic) are examples of commercially available systems that utilise this technique.

II.4 AREA BASED TECHNIQUES

II.4.1 SHAPE FROM SHADING

Shape-from-Shading or *Photometric-Stereo* determines the structure of the object surface from images observed through a camera, under differing illumination conditions [12, 13, 22]. By analysing the reflectance properties of the surface illuminated by a carefully calibrated light source, a set of surface normals are generated, from which a height field can be generated [12, 13]. More detailed analysis of the actions of the lighting, such as shadows [22], inter-reflections and highlights can be used to improve the overall accuracy of the result [13].

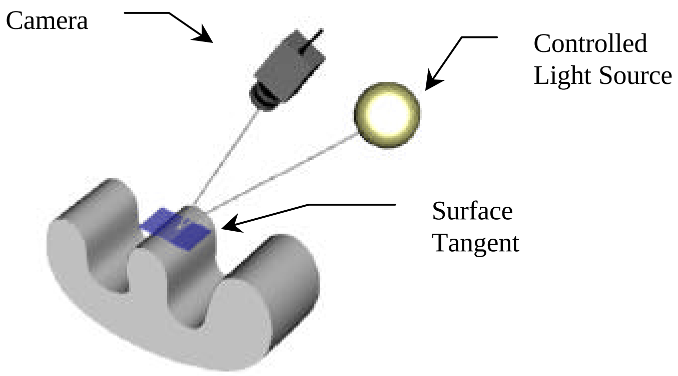

Figure II-7 - Shape From Shading

In [21] a similar technique is presented for determining surface geometry. Highly parallel light rays are projected onto the surface, which are observed by a camera. From this a three dimensional binary level shadow diagram (a 3D ShadowGram) is built up as the light is moved. This *3D ShadowGram* is then used to determine the height field for the surface. However the perspective projection of the image acquisition equipment is ignored, which can result in systematic distortions of the results.

The main advantage of *Shape-from-Shading*, is the simplicity of the equipment (a CCD camera and a few light sources), which provides an inexpensive set-up. Also, the equipment is readily available of providing surface textures, which are in perfect alignment (registration) with the geometry [13]. However, as such techniques rely on highly controlled lighting conditions [21], they are limited to use in controlled environments, such as a box unit into which objects can be placed.

II.4.2 Depth from Focus/Defocus

Depth-from-Focus is a technique where the geometry of a surface, is determined by analysing the focal properties of the surface images. If the surface has a high enough level of detectable texture a focus filter, such as a *Laplacian-of-Gaussian*, can be used to quantify the level of focus at each point in the image [18, 28].

By moving the object through varying positions along the optical axis of the imaging system [18], or by varying the focal properties of the camera [15], the focus of the image will increase, reach a peak, and then fall off again. The position (or focal length) at which this peak is achieved (for each pixel) is used determine the geometry of the surface.

As with many techniques this one relies on the surface exhibiting a high level of detectable texture [2, 18]. In [18] a *Passive Structured Light*[2] (PSL) system is developed, whereby a checkerboard pattern is projected onto the surface so as to apply an artificial (and optimal) texture. The researchers also show how this can be used to accurately make measurements on the surface of silicon wafers, and printed circuit boards.

As this technique requires a number of images of the same scene, at different distances or focal lengths, the technique cannot be considered a truly parallel one. It also requires that the surface be fixed (in shape and position) for the duration of the scan, which typically contains 10-15 images [18].

Depth-from-Defocus uses a similar set-up, but only requires two images. It relies on an analysis the images, in the frequency domain, by applying a number of convolution filter kernels [28], which is computationally expensive.

II.4.3 PHOTOGRAMMETRY

Photogrammetry (or *Stereo Vision*) is a *triangulation-based* method. Due to the perspective projection, which occurs in a camera, a point in an image corresponds to a line of points (vector) in 3D space [27]. By taking the same point in a number of images, taken from known positions and intersecting their vectors, the point in 3D is found [13].

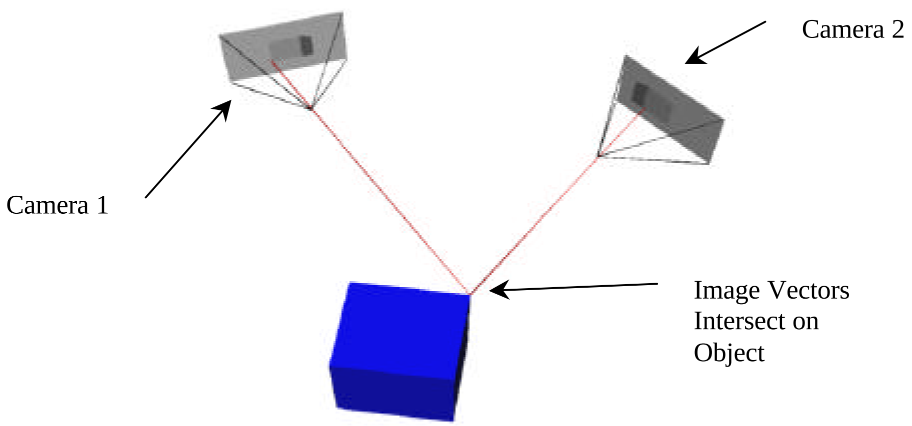

Figure II-8 - Photogrammetery

This obviously requires multiple images of the same scene, taken from different positions [13]. This can be done using multiple cameras, for a truly simultaneous system, or by moving a camera to different positions, as done when performing site surveys. It is also possible to use a single static

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[2] . The system is said to be *passive* as the geometry of the pattern is not used in the process, and so doesn't need to be known [9, 16].

camera, equipped with a variable focal length (zoom) lens. The change in focal length is equivalent to a translation of the camera along the optical axis, which allows the triangulation to occur [15].

One of the long-standing problems with *photogrammetry* is finding the correspondences between the different images, i.e. which points in this image correspond to points in the other images. Traditional *photogrammetric techniques* require the user to supply these correspondences by hand, which obviously require that the surfaces/scenes contain sufficient texture for these to be found [2, 13]. Although this topic has been the focus of much research, there is still no general-purpose solution for determining these correspondences [13], and those that do exist are computationally expensive [28].

To try to overcome the problems encountered by lack of surface texture, and to automate the determination of correspondences, Maas [16] uses *Passive Structured Light* (PSL). This involved the application of an artificial texture by the projection of a structured light pattern on the surface. The use of 3 (or more) cameras allows the correspondence between the dots (in the pattern) to be computed using *epipolar* lines.

II.4.4 PHASE MEASUREMENT PROFILEOMETRY

Laser Triangulation can be used to perform *Area-Based* scans of surfaces, using either a scanning line or by using multiple lines. One of the major problems with the former is that the surface must be still for the duration of the scan (4.7 sec for BIRIS), while the latter presents the problem of determining which of the multiple strips appear in the image. In [23] the use of a sinusoidal pattern of light overcomes this, a pseudo-interfermetric approach.

The pattern, generated using a laser and a grating, is projected onto the surface. This is observed, from an angle, by a camera. Using a reference image [23], or a number of images with the pattern shifted slightly [3], the phase of each pixel can be determined, using phase sensing techniques [23].

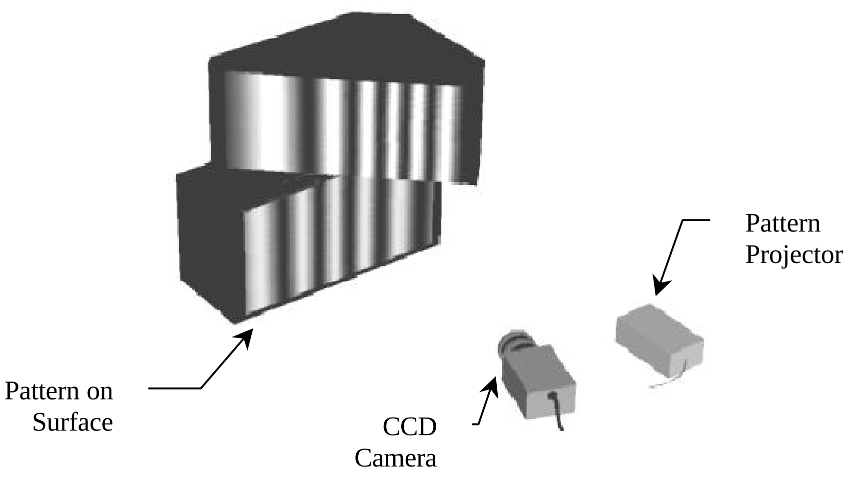

Figure II-9 - Sinusoidal Intensity Pattern

The use of such a pattern is equivalent to using a very large number of laser strips. The problem of which section of the pattern corresponds to the pixel is reduced, as it is possible to count the peaks in the image. This is possible as the pattern is much more tolerant of sharp discontinuities in the surface, which would cause lines to be lost [23].

As with laser triangulation, the accuracy of the system can be controlled, by changing the *base-line* and *stand-off distance* for the triangulation, and by changing the field of view (through the focal length). [23] reports an accuracy of 0.2mm, for $25mm^2$ area 1m from the camera. A similar technique is used in the $[TC]^2$ full body scanning, in the clothing industry [3].

III LASER TRIANGULATION IN DETAIL

Laser Triangulation [2, 4, 6, 10, 11, 13, 17, 20, 24, 25, 25], as mentioned in the previous section, is a simple technique for recovering information about the surface shape of objects. Using the *Line-Based* version offers increased speed, configurability and can be implemented using *off-the-shelf* components. In this section a more detailed description of the technique is presented. Two mathematical models, for such systems are also presented, one allowing an exploration of issues regarding configuration, the second being more practical. Lastly some of the limitations of the system are exposed, some of the limitations reduce the accuracy of the system, and others cause it to fail entirely. Wherever possible a solution is given.

III.1 STACK MODEL

Line-Based Laser Triangulation can be modelled as a stack of laser beams and sensors. This model allows equations, for the operation of the system, to be derived. As the system is capable of supporting multiple cameras, the model uses the laser beam as its primary axis, although the camera's co-ordinate space could be used.

Below is a schematic of a slice through the system, the laser and camera/sensor are positioned so that they form a triangle. When the laser beam illuminates the surface of the object, the point of illumination is projected, towards the focal point of the camera, onto the image sensor.

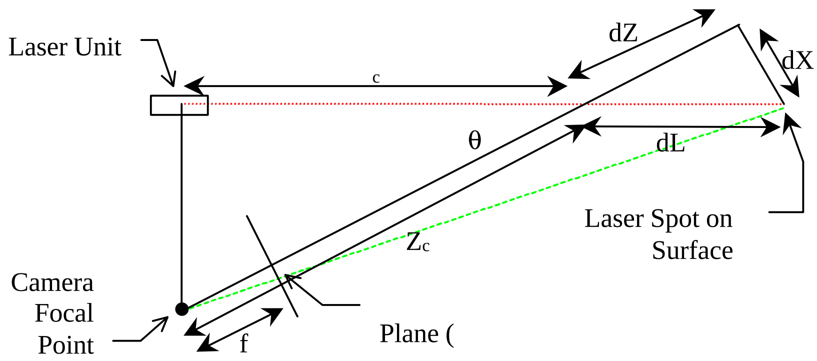

Figure III-1 - System Schematic

This perspective projection can be modelled by the pinhole camera model [27], and so the position on the image plane is related to the position of the object by:

$$dX_{mm} = \frac{i_{mm}\,(Z_{c_{mm}} + dZ_{mm})}{f_{mm}} \qquad \text{[Eqn III.1]}$$

The dimensions of the small triangle, are related by the Sin Rule:

$$\frac{dX_{mm}}{\sin(q_{\deg})} = \frac{dZ_{mm}}{\sin(90 - q_{\deg})} \qquad \text{[Eqn III.2]}$$

$$dL_{mm} = \frac{dX_{mm}}{\sin(q_{\deg})} \qquad \text{[Eqn III.3]}$$

By rearranging [Eqn III.2] for dZ, and substituting into [Eqn III.1], we get:

$$dX_{mm} = \frac{i_{mm}}{f_{mm}}\left(Z_{c_{mm}} + dX_{mm}\,\frac{\sin(90 - q_{\deg})}{\sin(q_{\deg})}\right) \qquad \text{[Eqn III.4]}$$

which can be rearranged to get an equation for dX:

$$dX_{mm} = \frac{Z_{c_{mm}} * i_{mm} * \sin(q_{\deg})}{\left(\sin(q_{\deg}) * f_{mm} - i_{mm} * \sin(90 - q_{\deg})\right)} \qquad \text{[Eqn III.5]}$$

this is then substituted for dX in [Eqn III.3], and rearranged to give :

$$L_{mm} = L_{c_{mm}} + \frac{Z_{c_{mm}} * i_{mm}}{\sin(q_{\deg}) * f_{mm} - i_{mm} * \sin(90 - q_{\deg})} \qquad \text{[Eqn III.6]}$$

By similar methods an equation for the position along the laser line, can be derived in terms of the *j* (row) position on the image plane, where dZ can be derived from [Eqn III.2]:

$$Y_{mm} = \frac{j_{mm}\,(Z_{c_{mm}} + dZ_{mm})}{f_{mm}} \qquad \text{[Eqn III.7]}$$

III.2 PLANE MODEL

The above model makes the assumption that the system is acting as a stack of sensors, with perspective projection. On a more practical level this assumption translates into a requirement that the laser beam be perfectly aligned, perpendicular to the rows of the CCD array. This is an extremely difficult thing to ensure, and therefore an alternative model can be used.

This model comes from *ray casting*. The perspective projection, which occurs in the camera, is modelled as a ray. The ray originates at the origin of the camera (focal point), and passed through the pixel. This forms a vector:

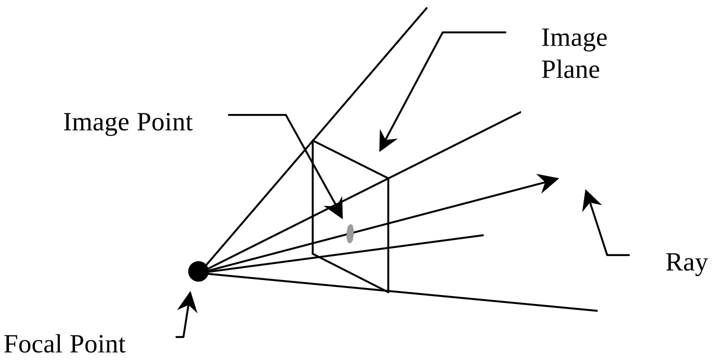

Figure III-2 - Ray Casting

The set of points which lie along the ray, can be expresses by the *Ray Equation*:

$$P = O + t\vec{V}, t \geq 0 \qquad \text{[Eqn III.8]}$$

The laser strip exists as a plane in the camera space, which has the form:

$$ax + by + cz + d = 0 \qquad \text{[Eqn III.9]}$$

Thus by substituting the ray equation [Eqn III.8] into the plane equation [Eqn III.9], we can solve for *t*:

$$a(O_x + tV_x) + b(O_y + tV_y) + c(O_z + tV_z) + d = 0$$

$$t = -\frac{aO_x + bO_y + cO_z + d}{aV_x + bV_y + cV_z} \qquad \text{[Eqn III.10]}$$

Thus the point in 3D space can be found by projecting a ray, through an image pixel, and onto the plane, using [Eqn III.10] & [Eqn III.8].

III.3 CONFIGURABILITY

The theoretical configurability of a laser triangulation system can be seen from the *Stack Model* (Section III.1). The accuracy of the system depends on the triangulation angle and the focal length, which can be altered to provide the required balance between range and accuracy.

III.3.1 LASER CAMERA ANGLE

The triangulation angle effects the relationship between *dL* & *dX*, as defined in [Eqn III.3], the wider the angle the more prevalent the displacement in the image plane:

$$\lim_{q \to 90} \frac{1}{\sin(q_{deg})} \Rightarrow 1 \qquad \text{[Eqn III.11]}$$

[6] uses precisely controlled mirrors to alter this angle, and hence configure the system's range/accuracy. However it should be noted that as the angle increases the system becomes more susceptible to the effects of occlusion, see below.

III.3.2 FOCAL LENGTH

The focal length (of the sensor lens) effectively controls the field of view of the camera/sensor, as this field of view is narrowed, the area visible to the camera is smaller and so the resolution of the sensor is increased, which increases the resolution of the system. Thus the size of the area visible to a pixel of the sensor [Eqn III.1], at a given distance, decreases:

$$\lim_{f \to \infty} \frac{Z_{mm}}{f_{mm}} \Rightarrow 0 \qquad \text{[Eqn III.12]}$$

III.4 LIMITATIONS

There are a number of conditions under which *Laser Triangulation* suffers from reduced accuracy, or even fails completely. These are explained and their effects on accuracy mentioned. Also, wherever possible, a solution is presented.

III.4.1 ADVERSE ILLUMINATION

When the surface is illuminated strongly, particularly when it is bright in colour, the contrast of the image is greatly reduced. This results in a bad separation between the laser line, and the background colour of the surface, hence making detection difficult. The images below show the difference between a laser strip shining on a dark surface, and an illuminated light coloured one. In the illuminated one, it is clear that the laser beam becomes hard to distinguish (due to lighting) and scattered (due to light coloured surface).

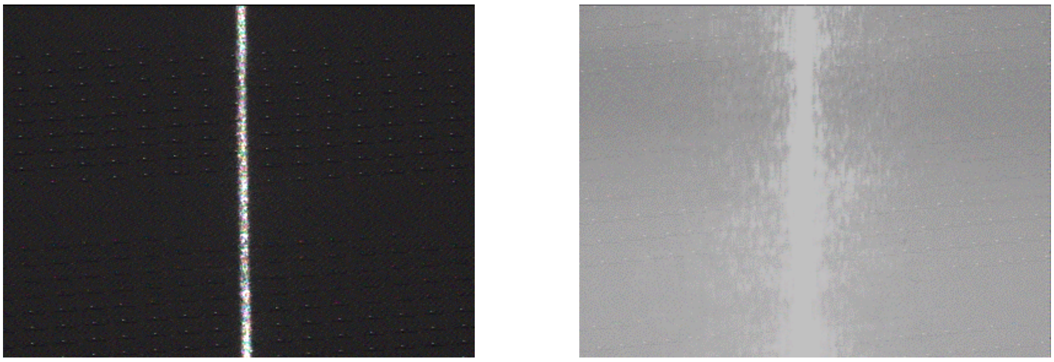

Figure III-3 - Adverse Illumination

This situation can present itself when working in strongly illuminated areas or with very lightly coloured materials. The problems incurred by the light coloured surface can usually be remedied by narrowing the aperture of the lens, hence reducing the scatter. If incident light a factor, then a filter may alleviate the problem. The filter only allows a narrow band of wavelengths (i.e. those produced by the laser) to pass into the camera sensor, hence reducing the ambient lighting effects. However it should be noted that many forms of light, sunlight for instance, contains a full range of wavelengths. Which could reduce the effectiveness of the filter, or even render it ineffective.

III.4.2 Occlusion

As *Laser Triangulation* is light based, it is necessary that the camera/sensor have a clear view of the laser strip as it falls across the surface of the object. If the shape of the object is such that it gets in the way of the camera's view, then it is impossible for the laser strip to be detected, as seen below.

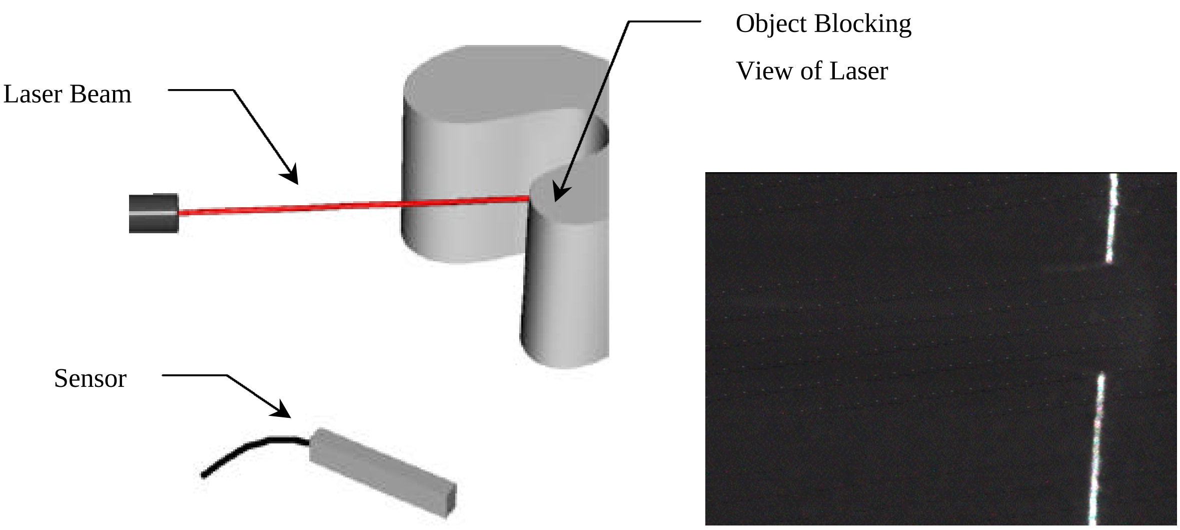

Figure III-4 - Occlusion

A second view [6, 25, 25], a second strip [4], or a narrower triangulation angle [6] is usually sufficient to reduce the problem of occlusion, and can even be used to improve accuracy [25].

III.4.3 EDGE CURL

At the corner of objects, it is often the case that only part of the laser is seen striking the surface, as illustrated below.

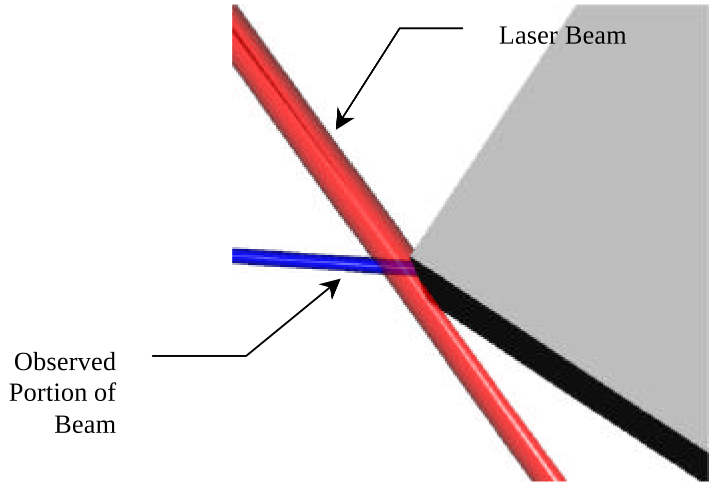

Figure III-5 - Edge Curl

As triangulation works by intersecting a vector, through the observed beam, with the vector/plane of the laser, the intersection point is computed incorrectly [7, 8, 9]. This results in the corner of the object being lifted away from its real position, by a distance proportional to the width of the beam. Some researchers detect the edges, from an intensity image, and use this to reduce the effects of edge curl [8, 9].

III.4.4 TEXTURE

Sharply contrasting textures on the surface of the object can have an effect similar to edge curl. At the boundary between light and dark areas, the laser beam is reflected at different intensities. Different quantities of the incident light are reflected into the sensor, at different positions. This results in the laser beam losing its symmetry [7, 8], the most extreme case being where part of the beam is lost completely.

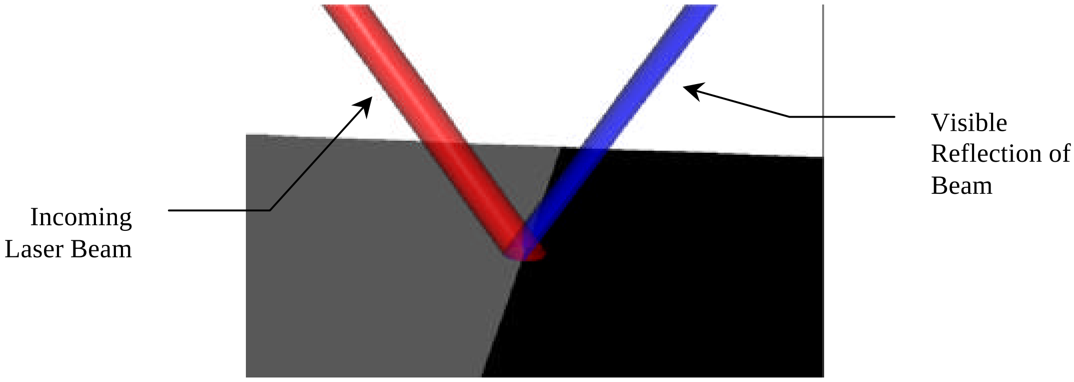

Figure III-6 - Texture

III.4.5 LASER SPREAD

If the laser strikes the surface of the object at a nearly parallel angle, the beam gets spread across the surface (as shown below), this has the effect of blurring (and dimming) the beam, which makes it hard to detect. This is usually not a big concern, as the sensor can be repositioned to fill in any holes.

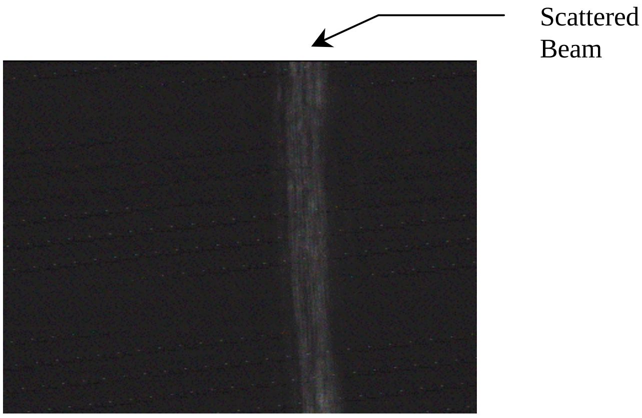

Figure III-7 - Laser Spread

III.4.6 REFLECTION

When working with surfaces, which are highly reflective or which contain pieces of highly reflective material, it is possible for the beam to bounce off one part of the object and illuminate another part. This causes real problems, as the secondary illumination doesn't lie on the laser plane, which results in major errors in the readings. In some cases it may be possible to remove the problems of reflection, by coating the object with a temporary paint [25, 26].

Reflection

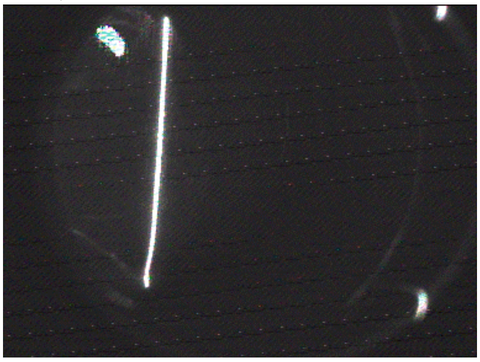

Figure III-8 - Reflection

III.4.7 Motion

Because of the nature of CCD cameras, the images it produces are sampled over a finite period of time. If the camera's motion is such that the beam moves through a number of positions during the frame integration period, then the image becomes blurred. The effects of this can range from misleading images, in which the beam is incorrectly detected, to images in which the beam is undetectable. Faster shutter speeds can be used to alleviate this problem, to a certain extent.

Beam Widened Due to Sideways Motion

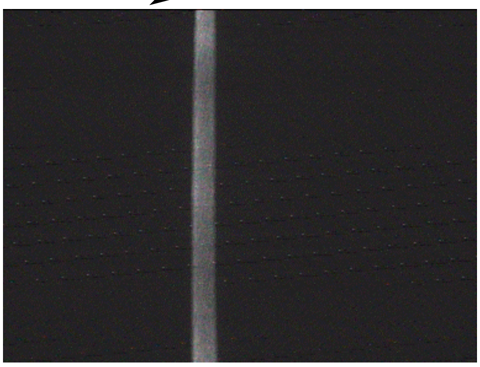

Figure III-9 - Motion

References

1. J.-A. Beraldin , S. F. El-Hakim & F. Blais, *Performance Evaluation of Three Active Vision Systems Build At The National Research Council of Canada.* Optical 3-D Measurement Techniques III, Vienna, October 1995.

2. J.-A. Beraldin, F. Blais, L. Cournoyer, M. Rious, F. Bernier and N. Harrison, *Portable Digital 3-D Imaging Systems for Remote Sites.* Institute for Information Technology, National Research Council, Ottawa, Ontario, Canada K1A 0R6.

3. David Brunner, *An Introduction to the Body Measurement System for Mass Customised Clothing*. [TC]^2, 211 Gregson Dr. Cary, NC 27511-7909 (www.tc2.com).

4. Padraig Butler, David Vernon and Eoin O'Broin, *A Hand-Activated White Light Profileometry Ssytem to Effect the Automatic Recovery of Facial Shape*. Irish Machine Vision and Image Processing Joint Conference, September 1998.

5. Y. D. Chen and J. Ni, *Dynamic Calibration and Compensation of a 3-D Laser Scanning System*. IEEE Transactions on Robotics and Automation, Vol. 9, No. 3, June 1993.

6. Jim Clark, Andrew M. Wallace and Gianni L. Pronzato, *Measuring Range using a Triangulation Sensor with Variable Geometry*. IEEE Transactions on Robotics and Automation, Vol. 14, No. 1, February 1998.

7. Brian Curless and Marc Levoy, *Better Opticla Triangulation through Spacetime Analysis.* Stanford University, 1996.

8. S. F. El-Hakim & J.-A. Beraldin, *Configuration Design for Sensor Integration.* Institute for Information Technology, National Research Council, Ottawa, Ontario, Canada K1A 0R6.

9. S. F. El-Hakim, J.-A. Beraldin and F.Blais, *A Comparative Evaluation of the Performance of Passive and Active 3-D Vision Systems.* Institute for Information Technology, National Research Council, Ottawwa, Ontario, Canada K1A 0R6, June 1995.

10. William P. Kennedy, *The Basics of Triangulation Sensors.* Sensor Magazine (www.sesnormag.com). May 1996.

11. William P. Kennedy, *Can Laser Triangulation Help You ?* QUALITY (www.qualitymag.com). September 1998.

12. Júlio Kiyoshi Hasegawa and Clésio Luis Tozzi , *Shape From Shading with Perspective Projection and Camera Calibration.* Computing & Graphics, Vol. 20, No. 3. 1996.

13. Reinhard Klette, *Image Analysis & Object Surfaces*. CS-TR-152/CITR-TR-9, The University of Auckland, Tamaki Campus, Computing & Information Technology Research, Computer Vision Unit, Aickland, New Zealand. August 1997.

14. Melissa Larson, *Laser Measurement on the Plant Floor.* QUALITY (www.qualitymag.com). December 1996.

15. Jean-Marc Lavest, Gérard Rives and Michel Dhome, *Three-Dimensional Reconstruction By Zooming.* IEEE Transactions on Robotics and Automation, V ol. 5, No. 2, April 1993.

16. Hans-Gerd Mass, *Robust Automatic Surface Reconstruction with Structured Light.* International Archives of Photogrammetry and Remote Sensing. Vol. XXIX (1992).

17. Dr. Alan M^c^Ivor, *An Alternative Interpretation of Structured Light System Data*. Industrial Research Limited, PO Box 2225, Auckland, New Zealand.

18. Minori Noguchi and Shree K. Nayar, *Microscoic Shape from Focus Using Active Illumination.* Department of Computer Science, Columbia University, New York, NY 10027.

19. N. E. Pears, *An Intelligent Active Range Sensor for Vehicle Guidance : System Overview*. Department of Engineering, Cambridge University, Cambridge, CB1 1PZ, UK.

20. N.E. Pears, *Range Feature Extraction during Active Sensor Motion*. Department of Engineering, Cambridge University, Cambridge, CB1 1PZ, UK

21. Daniel Ravaiv, Yoh-Han Pao and Kenneth A. Loparo, *Reconstruction of Three-Dimensional Surfaces from Two-Dimension Binary Images.* IEEE Transactions on Robotics and Automation, Vol. 5, No. 5, October 1989.

22. Karsten Schlüns, *Shading Based 3D Shape Recovery in the Presence of Shadows.* Computing and Information Technology Research, Conputer Science Dapartment, Tamaki Campus, University of Auckland, New Zealand.

23. Venugopal Srinivasan and Ronald Lumia, *A Pseudo-Interferometric Laser Range Finder for Robotic Applications*. February 1989.

24. Emanule Trucco, Robert B. Fiser, *Acquisition of Consistent Range Data Using Local Calibration.* Machine Vision Unit, Department of Artificial Intelligence, University of Edinburgh, Edinburgh, Scotland, EH1 2QL.

25. E. Trucco, R. B. Fiser, A.W. Fitzgibbon and D. K. Naidu, *Calibration, Data Consistency and Model Acquisition with a 3-D Laser Striper.* Machine Vision Unit, Department of Artificial Intelligence (University of Edinburgh) & Heriot-Watt University & City Hospital, Edinburgh, Scotland, EH1 2QL.

26. E. Trucco, R. B. Fiser, and A.W. Fitzgibbon, Data *Calibration and Data Consistencyin 3-D Laser Scanning.* Department of Artificial Intelligence (University of Edinburgh) & Dept. Computing and Electrical Engineering (Heriot-Watt University), Edinburgh, Scotland, EH1 2QL.

27. Roger Y. Tsai, *A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology Using Off-The-Shelf Cameras and Lenses.* IEEE Journal of Robotics and Automation, Vol. RA-3, No. 4, august 1997.

28. Masahiro Watanabe and Shree K. Nayar, *Rational Filters for Passive Depth from Defocus.* International Journal of Computer Vision, 27(3), 1998.