THE USE OF DIODE LASER COLLIMATORS FOR TARGETING 3-D OBJECTS.

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Commission V

KEYWORDS: diode-laser, collimator, targeting, speckle, 3-D, coherence.

ABSTRACT

The use of high contrast targeted features in digital close range Photogrammetry is desirable for accurate 3-D measurement. Retro-reflective targets are often used because of their unique ability to provide an exceptionally high contrast target, as opposed to simple black on white targets. Hence, any background noise is minimised because of the small lens aperture required to prevent saturation, which also confers the greatest depth of field in the object space. Unfortunately, the requirement to individually place large numbers of targets upon the subject, and possibly repeat the process many times to gain sufficient measurement coverage, means that they are not entirely satisfactory for rapid measurement. A diode laser collimator is able to project a small, highly intense, spot of light onto a surface which may provide an alternative to other forms of target. In this paper the advantages and disadvantages of diode laser collimators are described and an analysis made of their suitability for targeting a surface. The discussion is made within the context of automated 3-D measurement of objects in the range 0.1m³ - 5m³, which includes a wide range of engineering applications. One of the prominent problems with a laser target is speckle. If a target image is affected by speckle, differing views will have differing speckle patterns and any method of locating these target images to subpixel accuracy will be affected. Hence, the theory of speckle is explained, the magnitude of the location error due to speckle is estimated, and methods are demonstrated which can minimise or remove its effect.

1. INTRODUCTION.

Retro-reflective targets provide a common means of targeting or signalising an object. While they have many advantages, the time for their manual application can be a major limitation as hundreds can be required to adequately describe a surface. Hence, target application can be a laborious process as skill is required if a minimum number of targets is to adequately describe the shape of the surface being measured. Furthermore, not all subjects are suitable to be targeted in this way and in many cases it is desirable for measurements to take place at finer increments than can be achieved in one iteration. By contrast with the time taken for the target application process the measuring system will often be able to obtain images in a few seconds with the three dimensional co-ordinates of these measured points being available minutes later. The use of retro-reflective targets, for all their virtues, will often place a practical limitation on the number of observations that are made. Alternative methods, such as the use of natural features, or other projection methods also have disadvantages. Feature based methods fail where there are few distinguishable features (often the case on gently curved or planar surfaces). Projection techniques require a powerful source of light, a high degree of spatial stability of the projected targets, and a small target spot over the measurement range, these characteristics are difficult to obtain.

In this paper the use of collimated beams of laser light is investigated and their advantages and disadvantages discussed. A laser with suitable beam characteristics has been available for many years, however, the Helium Neon (HeNe) laser has rarely been used probably because of its price (often around £500), size (125-450mm long x 50mm diameter), and high voltage (kV) operation. The recent explosive growth in the use and development of the semi-conductor laser means that suitable devices are accessible to the layman. The main advances which have allowed this are: (i) the availability, in quantity, of self contained devices consisting of a diode laser, drive electronics, and collimator at a reasonable price; (ii) during the same period the wavelength of these devices has dropped from 780nm to 635nm, with the 670 nm device being the most widespread; and (iii) the modern diode laser collimator operates with minimal current at around five Volts DC. Although lasers have found many uses in levelling, alignment, and theodolite targeting, few, if any reports of them being used to replace conventional targets have been found. The reason for this may be explained in terms of the cost/functionality arguments, but is equally likely that the phenomena of speckle has been perceived to be a problem. Figures 1 & 2 show target images with and without speckle.

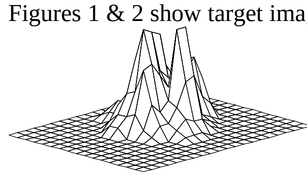


Figure 1. A 3-D intensity profile with speckle.

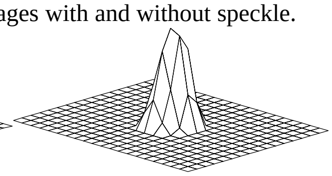


Figure 2. A 3-D intensity profile with speckle minimised.

Speckle is formed because of the coherent properties of the laser allowing rays of light with differing path lengths to interfere with each other due to random phase differences. Unfortunately the speckle pattern is formed on the surface of the sensor and will have a different appearance when viewed from other angles, distances, and with differing setting of the camera lens. This non-uniformity of intensity structure will have serious effects on any subpixel target location algorithm, hence, unless the effect of speckle can be removed or at least quantified, the use of laser beams for the production of target features cannot be recommended for high precision applications. In this paper, the characteristics of laser beams are described and a simplified explanation of the origin of speckle is given. Experimental tests are described to assess the characteristics of speckle and to quantify its effect on the calculation of the location of target images. Other considerations such as the possibility of multiple reflections or the variation in the shape of the laser beam as it impinges on differing surfaces are beyond the scope of this paper and will not be considered further, but are the subject of further investigations.

2. CHARACTERISTICS OF LASER BEAMS.

2.1 Introduction to lasers beam properties.

Laser beams provide a source of high intensity light. Their advantages in the context of the production of target images are: (i) laser beams can be collimated to provide small, diffraction limited parallel beams of light; (ii) the wavelength of many diode lasers is in the range of the maximum spectral sensitivity of silicon (633-780nm); (iii) the intensity profile of a laser beam is approximately Gaussian in shape (this is not true of the images of most large targets) enabling high precision location; (iv) diode laser collimators are becoming cheaper to purchase with better optics, modulation, and focussing capabilities; and (v) simple devices are available which have modest power requirements which can be supplied by a battery (≈100mA @ 5 Volts). Recent developments, because of better manufacturing technology, have meant an explosive growth in the use of diode lasers and a wide diversity of uses. Correct use of the laser diode can result in a MTBF of 50,000 hours.

2.2 Physical characteristics.

The semi-conductor diode laser consists of a small 0.01mm³ chip which is mounted directly on a heat sink and placed inside a metal can. The laser light is emitted from either side of the cleaved face of the silicon chip. Due to the small size of the active region where laseing takes place (approx. 0.1µm x 5µ m), the divergence due to diffraction is of the order of 30° by 10° producing an asymmetric elliptical shaped beam.

2.3 Electrical characteristics.

When a laser is driven by a low current the laser acts like a light emitting diode. As the forward current increases laseing action will take place as illustrated by Figure 3 for operation at three different temperatures. The light produced from the back face of the diode laser is used to provide feedback to the sensitive electronic circuits required to avoid damaging the laser. As the current requirements change with temperature such circuits enable the output power to be maintained at the desired level.

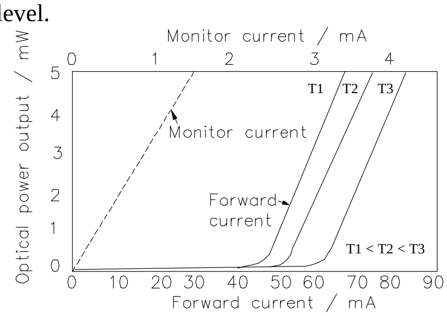


Figure 3. Electrical characteristics of the diode laser.

Diode lasers are highly efficient converting 20% of the input power to light, this compares with approximately 0.02% for a HeNe laser. The theory behind producing laser light can be found in many standard text books (Wilson & Hawkes, 1983; Svelto, 1989).

2.4 Wavelength properties.

Laser light originates in an optical cavity which gives positive feedback to a particular wavelength as the light passes back and forth in the cavity. The bandwidth of lasers is very narrow which allows the use of narrow band-pass filters for rejection of other wavelengths. The relative optical power output plotted against wavelength for a typical laser of 750nm operating at its optimum power output is illustrated in Figure 4.

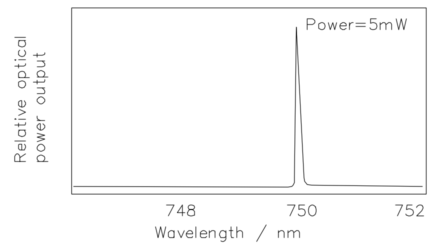


Figure 4. Diode laser relative output power vs. wavelength.

The common 670nm wavelength diode laser is a good choice when used in conjunction with a CCD sensor as its output coincides with the maximum spectral sensitivity of the sensor.

2.5 The physical size of a typical diode laser collimator.

The configuration and dimensions of the laser diode collimator used in this investigation are shown in Figure 5. The small dimensions of the complete device means that it is feasible to place the collimators close together ensuring a high density of targets on the object.

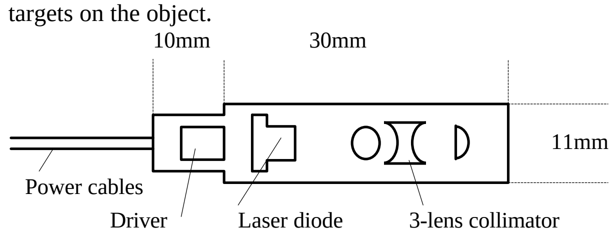


Figure 5. Physical dimensions of the LDA 1011 Laser diode collimator.

2.6 Beam characteristics.

The suitability of a focussed laser beam to act as a target is dependent on the shape of the laser beam. For accurate target location the requirements are: (i) a target shape which will not bias a centroid calculation of position when viewed from a variety of angles; and (ii) a high contrast with the background. The laser beam emission characteristics are shown in Figure 6. The large divergence of the beam means that conditioning optics have a short focal length of a few millimetres depending on the beam size required.

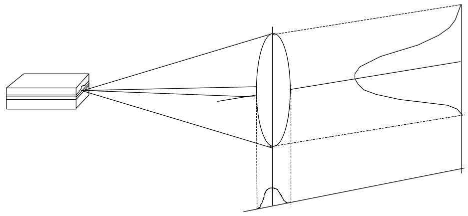


Figure 6. Typical diode laser emission pattern.

The angle of divergence of a typical laser beam will be about 10° in one direction, to 30° in the other. Vertical cavity lasers hold a promise of better beam conditioning with 7-10° divergence of a circular beam (Hecht, 1993) but it is not certain whether they will be suitable as a replacement for the usual diode laser configuration.

2.7 Coherence properties.

Lasers have a high degree of spatial and temporal coherence. The temporal coherence of a HeNe laser can extend for hundreds of metres, while a typical diode laser will have a coherence length of around 8 metres. By contrast an incandescent source has a coherence length of a few tens of millimetres, and a tungsten lamp of the order of a millimetre. Spatial coherence is described by two points which have no path difference which are on the same part of a wave-front. While coherence is essential for interference systems it can be a significant disadvantage in other applications. It is the coherence property of laser light that causes speckle. The phenomena of speckle was noticed by workers with laser devices soon after its invention. However, its formation by other sources such as the Sun, stars and incandescent sources was noted much earlier. Speckle, initially an unwanted phenomena, has been used to perform many tasks such as lens focussing, displacement measurement, and deformation measurement. In other areas such as Holography, it is a significant problem and measures are taken to reduce its effect. Speckle is caused by constructive and destructive interference between wavelets formed by different scatterers on an object surface on: the retina of the eye; film; a sensor surface of an imaging system; or in free space. A thorough statistical description of the properties of speckle can be found in a number of texts (Svelto, 1989; Jones & Wykes, 1983; Dainty, 1984).

2.8 Gaussian beam properties.

Because laser beams are highly spatially and temporally coherent all parts of the wave act as if they originated from the same point. Therefore, the emerging wave-front can be defined and can be more precisely focussed and controlled than would be possible with an incoherent source. The shape of a Gaussian beam is illustrated in Figure 7. Because there is no easy method of determining the size of the beam, the $1/e^2$ (13.5%) of the peak value points are often used to define the beam size.

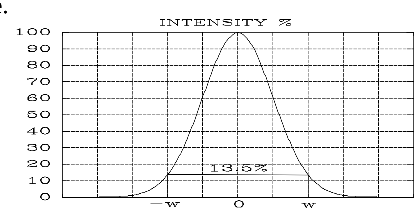


Figure 7. The Gaussian intensity distribution.

If a Gaussian laser beam wave-front is perfectly flat with all of its elements moving in precisely parallel directions, it would quickly acquire curvature and begin spreading in accordance with

$$R(z) = z[1+(pw_0{}^2/lz)^2] \qquad (1)$$

and

$$w(z) = w_0[1+(lz/pw_0{}^2)^2]^{1/2} \qquad (2)$$

where the terms are defined and illustrated in Figure 8.

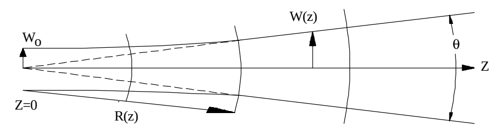


Figure 8. Far field beam distribution.

2.9 Astigmatism.

For gain guided lasers the beam of the laser appears to diverge from a point 5-50μm behind the surface of the chip surface in the plane of the active layer, whereas from the perpendicular direction the beam appears to diverge from the surface itself. For index guided lasers there is less astigmatism.

2.10 Directionality.

One of the most useful properties of lasers is their high degree of directionality which distinguishes them from conventional sources. The benefit of this directionality is that most of the output generated by the laser can be concentrated in a small area ensuring a high signal to background noise level. This intensity can be in excess of what is possible with retro-reflective targets because of the problem of illuminating the background as well as the surface under inspection. The high directionality, and therefore brightness, of a laser beam is connected to the coherence of the light and the fact that the resonant cavity generating the laser light has parallel faces. Beam divergence is governed by diffraction which is unavoidable by better optic design. For the case of perfect spatial coherence of the laser beam divergence is given by

$$q = K\frac{l}{D} \qquad (3)$$

where D is the diameter of the aperture through which the laser beam passes, and K is a factor of the order of unity which for the case of a single mode Gaussian beam is ≈ 2/π (Figure 9) For a wave with partial spatial coherence the divergence will be larger. The importance of the diameter of the emerging beam can be seen in Table 1, where D' = D + 2.L.Tan(**θ**) is used to calculate the final beam size.

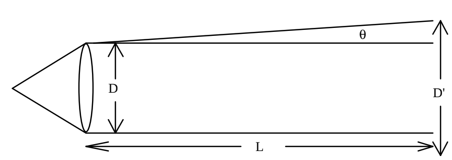


Figure 9. Divergence of a laser beam.

D/mm	0.5	1.0	2.0	4.0	8.0

θ/mrad	0.85	0.42	0.21	0.1	0.05
D' @ 2m	3.3	2.6	2.83	4.4	8.2
Factor increase	6..6	2.6	1.4	1.1	1.025
D' @ 10m	14.6	9.0	6.1	6.0	9.0
Factor increase	29.2	9	3.05	1.5	1.125

Table 1. Size of laser beam at two distances.

By inspection of Table 1 it can be seen that a large initial beam size, given diffraction limited optics, diverges less than a small beam. This fact must be balanced against the spot size required on the measured surface and the loss of signal to noise with a larger beam size. In practice, rather than use a small highly divergent beam, or a larger less intense beam, a weakly focussed beam can be used to obtain the best results over a range of measurement. To investigate this a small 25µm pin hole and electro-optic detector were positioned so as to transverse the beam at a number of discrete distances. The results of these experiments are shown in Figure 10 and 11 where the size of the laser beam has been focussed to a size which would be used in practice.

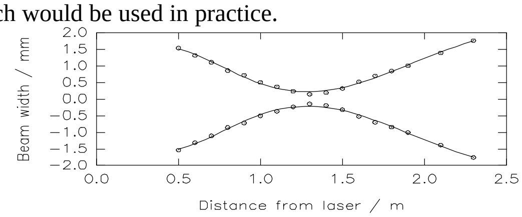


Figure 10. Laser beam $1/e^2$ dimensions measured at discrete points, x axis.

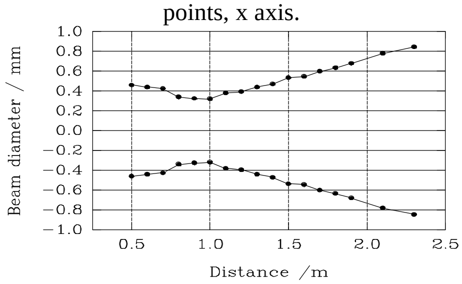


Figure 11. Laser beam $1/e^2$ dimensions measured at discrete points, y axis.

From these graphs it can be seen that a spot size of approximately 1mm was achieved over the range 1.0 to 1.5 metres. The laser beam intensity profile was measured at a distance of 1.5m and is show in Figure 12.

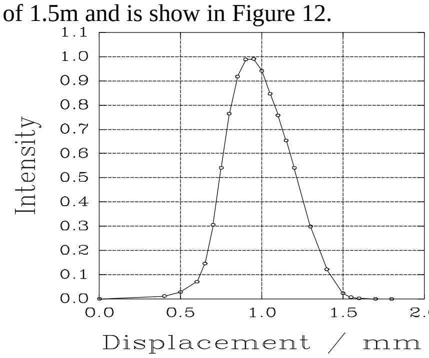


Figure 12. Laser beam intensity profile at 1.5 metres.

2.11 Pointing stability.

The pointing stability of a laser beam is dependent on temperature, for the laser collimators used was quoted as 0.03mrad/°C which is typical giving a mrad change in direction over a 30 degree temperature range. However, this is of no consequence when the laser is being used to provide target images.

3. THE REDUCTION OF SPECKLE IN TARGET IMAGES.

3.1 Speckle Theory.

When a surface is illuminated by a coherent, monochromatic beam of laser light it will have a granular appearance the intensity structure of which will vary as the viewing angle is changed. There will be no obvious correlation between the macroscopic properties of the illuminated surface and the speckle pattern. The condition for the appearance of speckle is a rough surface where surface height variations are of the order of, or greater than, the wavelength of light (approx. 1µm). The phenomena of speckle can be detected both in observed intensity changes with varying position in reflected or projected laser light, called *objective speckle*, and also in intensity variations in the image formed with a lens, called *subjective speckle*. The statistical properties of speckle are complex and derivations under a variety of conditions can be found in the many texts on the subject as discussed in section 2.7. However, for the purposes of this paper, a simple explanation is given which is necessary for an understanding of how speckle is formed and how, under certain circumstances, it may be reduced.

3.2 Objective speckle.

Consider a rough surface which is located in the x,y plane and illuminated by a laser beam as shown in Figure 13.

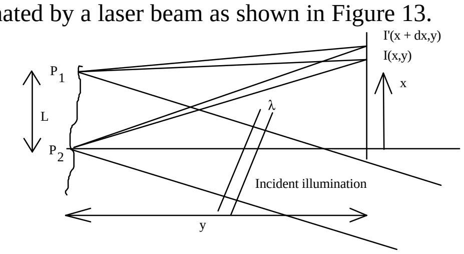


Figure 13. The formation of objective speckle.

The surface height at point x,y is given by H(x,y), the complex amplitude of the reflected light at point I(r) is the sum of the components scattered from the whole surface and may be written

$$I(r) = k \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u(x,y)\exp[(2pi/l)GH(x,y)]dxdy \quad (4)$$

where k is a constant, **u(x,y)** is the complex amplitude of incident light at **(x,y)**, **G** is a form factor associated with the illumination and viewing direction and constant where **I** is far from the surface. The viewing height will vary randomly by several wavelengths, hence, the resultant amplitude at **I** will be the sum of a set of random vectors often known as a drunkards walk in the complex plane (Figure 14).

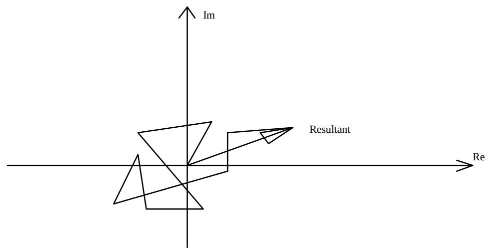


Figure 14. Random walk in the complex plane.

The random total amplitude, which will vary form zero to a maximum, is known as speckle. For the situation shown in Figure 13 the path length difference between point I and I' and P_1 and P_2 are

$$(P_1 I - P_2 I) \cong \frac{L^2}{2y} - \frac{Lx}{y} \qquad (5)$$

$$(P_1 I' - P_2 I') \cong \frac{L^2}{2y} - \frac{Lx}{y} - \frac{L\Delta x}{y} \qquad (6)$$

hence the relative change in path, Δs, from I to I' is given by

$$\Delta s \cong \frac{\Delta x L}{y} \qquad (7)$$

The path length required to go from constructive to destructive interference is equal to λ/2, hence the size of objective speckle is given by

$$(d_s)_{obj} = \frac{l y}{L} \qquad (8)$$

where it can be seen that the size of objective speckle is dependent on the size of the illuminated area, the distance from the illumination and the wavelength of the illumination.

3.3 Subjective speckle.

For the formation of speckle to occur on a sensor surface it is necessary that there is overlap of individual contributions from speckle scattering sites for interference to be possible. Such overlap will occur due to diffraction and imperfections in the lens. However, it must be noted that for speckle to be observed on the sensor it is also necessary for the sensor to be able to resolve the incident speckle. A simple analysis of Figure 15 is sufficient to derive an approximation to the speckle size.

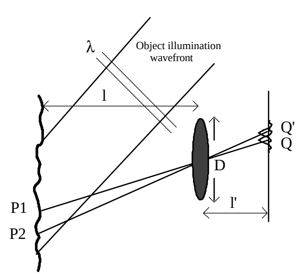


Figure 15. Subjective speckle formation.

By consideration of Figure 15, light scattered from a point P_1 will produce an Airy disk diffraction pattern on the sensor surface. Light scattered from a point P_2 will form a similar pattern close to that resulting from light at P_1. If the two points are close together then the resultant image will be formed from the sum of the phases from the two contributions and it will be possible for speckle to be formed. However, if the two points are too far apart then they will not interfere and no speckle can be formed. By using the first minima of the Airy diffraction pattern it can be shown that the largest distance QQ' for the formation of speckle is given by

$$QQ' = \frac{1.22\, l\, l'}{D} \qquad (9)$$

and the largest speckle size will be

$$(d_s)_{subj} \cong \frac{2.4\, l\, l'}{D} \qquad (10)$$

From this equation some simple calculations reveal the expected average size of speckle which will form upon the sensor surface.

Aperture/mm	1	2	4	8	16
Speckle size / μm, l' = 25mm	40	20	10	5	2.5
Speckle size / μm l' = 12.5mm	20	10	5	2.5	1.25

Table 2. The influence of aperture on speckle size.

The distance P_1P_2 which is the radius of the illuminated area on the object which scatters light to cause interference at point Q is given by

$$(r_s)_{obj} = \frac{1.22\, l\, l}{D} \qquad (11)$$

where the terms are defined in Figure 15. $(r_s)_{obj}$ can be considered the maximum radius of the laser spot required to produce speckle. This is illustrated in Figures 16(a-c) which show that when the scatterers are close together no speckle can be formed.

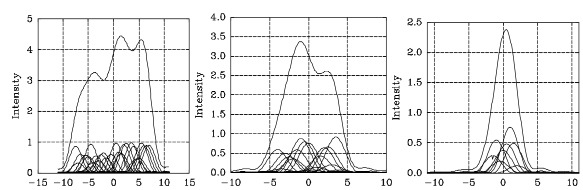


Figure 16. (a) (b) (c)
The addition of varying numbers of displaced Sinc functions.

This configuration would appear to offer the possibility of reducing the effect of speckle.

Analysis of the equations which predict the behaviour of speckle formation show that there are several parameters which can be adjusted to minimise the effect of speckle. However, it is not practical to adjust all of the parameters but, there would appear to be two practical solutions: the first is to minimise the size of the speckle formed on the sensor surface; and the second is to reduce the size of the scattering site so speckle cannot be formed. A number of experiments were designed to test this hypothesis which are described in the next section.

4. THE USE OF LASERS FOR TARGET FORMATION.

4.1 Introduction.

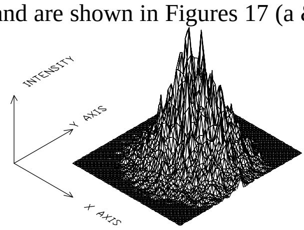
Although lasers have been routinely used, for example, in providing a single target for automated, or manually operated theodolite systems (W.F. Teskey, 1993; S. Kyle, 1989), they have not generally been applied to high density targeting. There are three possible reasons for this: (i) each diode laser collimator currently costs in the region of £100, and as an array of up to one hundred lasers can be desirable, this means they are too expensive for most applications; (ii) most lasers which are suitable for the requirements of laser targeting (a small intense spot) are not safe for direct viewing; and (iii) the phenomena of laser speckle can be a significant problem as it causes targets viewed from disparate positions to have a different intensity profile, thereby giving poor precision of target location.

To investigate the suitability of collimated diode laser beams to act as targets a number of experiments were devised based on the theoretical behaviour of speckle to: (i) illustrate the speckle phenomena; (ii) analyse the parameters affecting its formation; and (iii) investigate the predicted methods for reducing the effect of speckle.

4.2 Speckle property experiments.

4.2.1 Aperture variations.

To show the effect of speckle on the surface of a CCD sensor, a Pulnix TM6CN with a 25mm Fujinon lens and a HeNe laser were placed about two metres from a screen. The beam was expanded to approximately 30mm in diameter. By using the camera's electronic shutter a series of images were collected at each lens aperture setting (f/1.4 - f/16). A section of these images was converted to a format suitable for display in 3-D and are shown in Figures 17 (a & b).



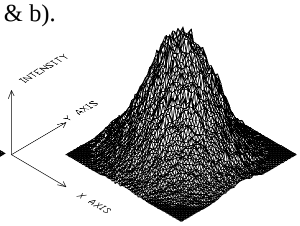
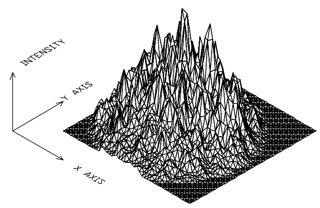


Fig. 17(a) Aperture of 1.5mm Fig. 17(b) Aperture of 17.8mm

The image with the aperture of diameter 17.8 mm shows the least speckle. The implication is that for minimum speckle a wide aperture should be used as the speckle becomes small enough to form many speckles over a area of a pixel hence averaging their effect. This method has been used to minimise the effect of speckle (Rioux, 1993). However, variations in intensity can still be observed which would imply a detrimental effect on the accuracy of location. Furthermore, the consequent narrow depth of field would be unacceptable in many close range photogrammetric measurement situations where a variation in object distance of the order of 10 to 20% of the object to camera distance are common.

4.2.2 Illumination area variations.

The situation illustrated in the previous section is the case where a large number of scattering sites contribute to the speckle on the sensor surface. In this section the situation where there are few scattering sites is considered as illustrated in Figure 16. Under these circumstances it is not possible for speckle to be formed. Instead the difference in phase of the light from the small number of scattering sites produce changes in the overall intensity of the image. This is analogous to the twinkling of stars when viewed by eye whereas using a large aperture telescope, and short time exposure, individual speckles can be resolved. To illustrate this case an aperture was placed in front of the expanded laser beam as used in the previous experiment. The partial images collected from these experiments are shown in Figures 18(a-d).



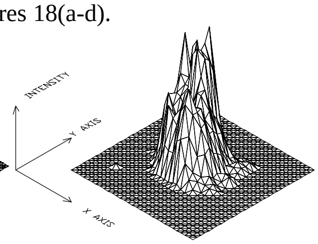
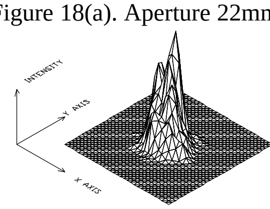


Figure 18(a). Aperture 22mm. Figure 18(b). Aperture 5mm.



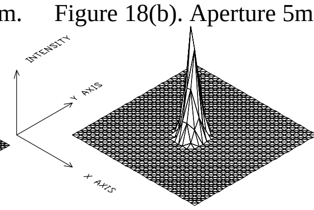


Figure 18(c). Aperture 4mm. Figure 18(d). Aperture 2mm.

From these images the effect of reducing the number of scatterers can clearly be seen so that the image illustrated in Figure 18(d) shows no perceptible speckle.

4.3 Target location performance of laser targets.

Two methods have been illustrated for the removal of speckle from a target image to the extent that it is not easy to see the effect of speckle in the image. However, the subpixel location algorithms available are highly sensitive and extensive testing was considered necessary to isolate the degrading effect of speckle on the location of the target image.

4.3.1 Experiments with a moving background.

Speckle formation is affected by changes in surface structure, changes in camera location, or object movement. To isolate these effects from target image calculations the following items were assembled as shown in Figure 19: two cameras; a laser; and a linear movement mechanism with a optically rough surface.

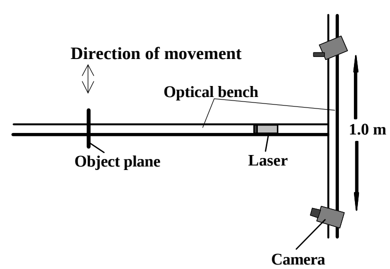
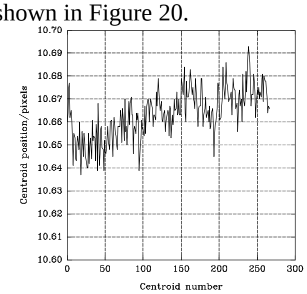


Figure 19. The configuration of the testing apparatus.

Under these conditions any small change in the position of the screen will not affect the angle between the target and the cameras but will cause changes in the projected speckle pattern and possibly influence the subpixel location of the laser target image. One of the cameras was mounted with the laser target on the axis of the lens and the other with the target aligned at the edge of the image to detect any effects caused by differences in the optical path lengths of rays from varying points across the aperture. The screen could be left stationary or moved in the direction indicated in Figure 19.

The results of computing the location of the target image a large number of times with the background stationary are shown in Figure 20.



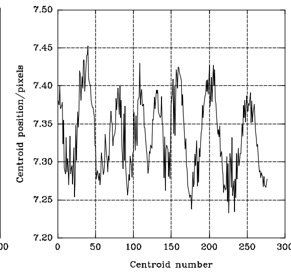


Fig. 20. Stationary background. Fig. 21. Moving background.

For the case of the stationary background the magnitude of the variations in location of the centroid appear to be within 0.03 of a pixel but there is a systematic drift. When the background was moved the magnitude of the error increased dramatically to 0.2 of a pixel. A further test was conduced to illustrate the two conditions and is shown in Figure 22.

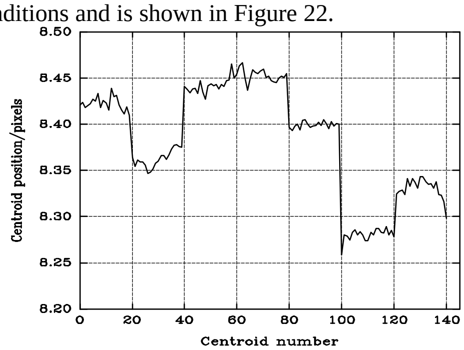


Figure 22. Combination of a moving and stationary target.

A number of similar tests were carried out and no significant difference was found to exist between the two viewpoints. The camera aperture was altered, as was the size of the laser image and the distance of the cameras to the target surface, in each case similar results were obtained. An explanation of the large location error experienced in this test may be made with reference to the discussion of target image formation with no apparent speckle in section 3.2 and 4.2.2. While it is the case that no speckle pattern can be visually distinguished, the finite size of the target image means that the distribution of contributions from each scattering site will not necessarily be even across the whole target image. If there is a bias of destructive interference on one side of the image then this will clearly affect the image location.

4.3.2 Target location with a small camera aperture.

Further experiments were carried out to see whether using an aperture which was smaller than the f/16 Fujinon lens would result in a reduction in the target location error. A lens with an aperture which could be completely closed was obtained. The results obtained by using this lens with an aperture as small as possible are shown in Figure 23.

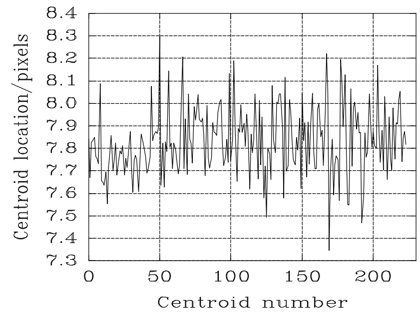


Figure 23. Location of target image using small aperture.

Large intensity fluctuations were experienced, as predicted by theory. However, while not exhibiting the same characteristics as the previous tests the maximum location variations are significantly worse than for the Fujinon lens at f/16.

4.3.3 Experiments with a multi-mode laser.

The fundamental cause for the formation of speckle is the coherence of the illumination. There are a number of ways of overcoming the effect of the coherence such as temporal averaging with a moving object but such methods are likely to be impractical in the 3-D measurement environment. Another technique is to decrease the coherence of the laser. One method for achieving a less coherent laser beam is the use of a multi-mode laser. The experimental set up used earlier was again used to analyse the performance under these conditions. This time instead of the long coherence mono-mode laser, a multi-mode laser was used operated just above the laseing threshold. Figure 24 shows the results.

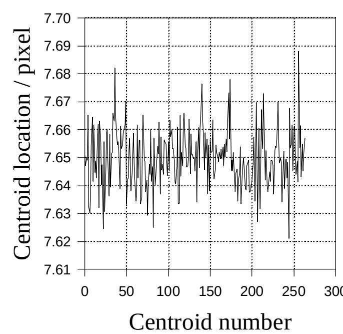


Figure 24. Results of using a multi-mode laser near threshold.

By analysis of Figure 24 it can be seen that the magnitude of the location error is of the same magnitude as that obtained with the laser in a stationary position. Further tests were conducted at threshold levels nearer to the maximum for the laser used (Figure 25). In this case the central modes are more dominant and so the possibility of coherent contributions to the image is increased.

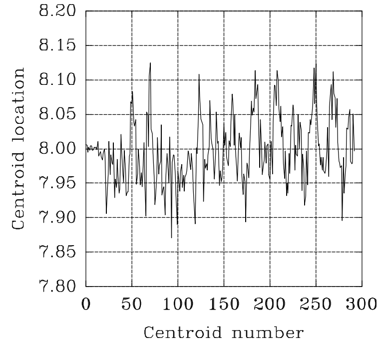


Figure 25. Results of using multi-mode laser at peak power.

By analysis of this graph it can be seen that the location error has deteriorated significantly.

4.4. Conclusion.

The measurement accuracy from of all of the speckle experiments conducted in this series of tests has to be compared with that occurring because of other error sources such as quantization or electronic noise. Figure 26 shows the results of conducting the same tests for a retro-reflective target as for the laser targets.

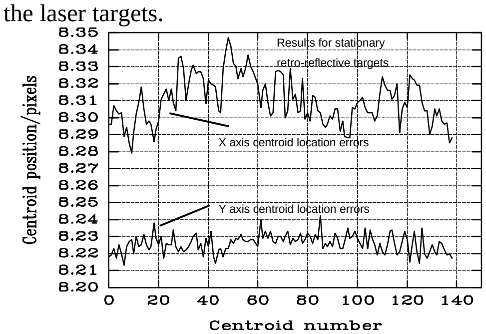


Figure 26. Results of centroid location of a retro-target.

This series of test has shown conclusively that laser targets cause significant errors in target location. These errors are particularly difficult to overcome as they are not systematic, but different for each viewpoint. The use of multi-mode lasers does offer the possibility of overcoming the problem caused by the coherence of the laser. By comparing Figure 24 with Figure 26 it can be seen that the errors are of a similar order of magnitude. Further work is required to assess whether laser targets can reach the same levels of location precision as obtained with retro-reflective targets.

5. CONCLUSIONS.

In this paper the properties of lasers have been described, where appropriate the advantages and disadvantages of their use in providing target images has been discussed. The phenomena of speckle has been also been covered in the same context. Two arrangements of the available parameters were investigated to minimise the effect of speckle using either large or small lens apertures. The former works by creating fine speckle which has a modest effect, and the latter by not allowing individual speckles to form. However, it has been shown in this paper that even when it is not possible to visually see the speckle in the intensity profile of a target image, a severe degradation of location performance was still present. In the light of these investigations and conclusions, a further practical method of reducing the effect of speckle was analysed, that of using a multi-mode diode laser. A further series of experiments was performed which was able to show the potential of this solution. The work carried out for this paper has shown that it is possible to use laser diode lasers to produce target images. Whether diode laser collimators can compete with retro-reflective targets in terms of the highest precision still needs to be proven, but at lower levels they are certainly usable. Other methods can be used to reduce, or eliminate speckle from images, but they are beyond the scope of this paper, but may be covered by future work.

6. ACKNOWLEDGEMENTS.

Dr. T.A. Clarke is currently supported by the Science and Engineering Research Council of the U.K.

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