The Virtual Point Light Source Model the Practical Realisation of Photometric Stereo for Dynamic Surface Inspection

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Abstract. The implications of using commercially available non-collimated and distributed illuminates for the application of photometric stereo to dynamic surface inspection tasks are considered. A new form of lighting model, termed the virtual point light source model, is proposed for modelling real distributed illuminates in relative close proximity. The new technique has application for the two- and three-dimensional inspection of moving surfaces using an innovative technique known as dynamic photometric stereo. Such surface inspection tasks have previously been considered difficult or impossible to undertake using conventional imaging techniques. Experimental results are presented in the paper.

1 Introduction

Previous work [1, 2] has shown how photometric stereo (PS) has useful application for the capture and analysis of fine surface texture and specifically a potential for the inspection of complex surfaces possessing concomitant two- and three-dimensional surface features. The technique enables precisely registered pixel based 2D albedo patterns and 3D surface topographic features and textures to be isolated and subsequently separately analysed [3]. It is important to appreciate that such complex surfaces had previously been considered difficult or impossible to reliably inspect using conventional 2D-image capture and processing techniques. Not surprisingly it has been realised that this approach may have potential application across a range of difficult surface inspection and analysis tasks, including the industrial inspection of textiles, leather, ceramics and wood products [1], as well as new applications in forensic science and medicine [4] using portable hand-held devices. In all cases the richer data set afforded by the utilisation of the PS method is recognised to potentially offer significant theoretical advantage over conventional 2D image intensity or scalar based imaging techniques [1-3]. Before considering issues relating to the practical application of PS it is useful to briefly review the basic theory of conventional 'static' PS. A detailed explanation will not be given here; instead the interested reader is

referred to [1]. However, given the importance of achieving practical application, particular consideration will be given to those idealised assumptions commonly made in PS literature.

2 Theory of Conventional Static Photometric Stereo

2.1 Two Light Source Photometric Stereo for Planar Surface Inspection

Figure 1 shows two distant point light sources forming a right-angled triangle with an unknown surface normal. The surface is assumed to be Lambertian and the viewing position is held to be distant. Assuming the image intensity under each illuminate to be I_1 and I_2 respectively, then within the plane of the triangle:

$$\text{Albedo} = (I_1^2 + I_2^2)^{0.5} \quad (1)$$

$$\text{And, Topography (i.e. normal sense within the plane)} = \tan^{-1} (I_1 / I_2) \quad (2)$$

Fig. 1. Two-light photometric stereo schematic

Hence, the method is able to isolate 3D topography and 2D albedo patterns for nominally planar surfaces, commonly encountered in numerous industrial inspection tasks. (Note that in order fully to define non-planar three-dimensional surfaces a third light/image must be introduced.)

3 Dynamic Photometric Stereo

A new form of dynamic photometric stereo (DPS) has recently been proposed [5] in which the conventional static form is extended to allow application to the inspection of fast moving surfaces, typically encountered in industrial quality control tasks. In order to realise a dynamic application it is necessary to either use a single composite image or to acquire multiple images simultaneously. DPS uses different forms of multiplexing in order to allow the simultaneous acquisition of multiple views. Channel isolation (where the term 'channel' is used here to refer to a separate lighting

image combination) may be achieved using methods of spectral, spatial or temporal multiplexing. A detailed description of the DPS technique can be found in [5, 6]. Figure 2 shows a schematic of the lighting and camera configuration used for DPS.

Fig. 2. Web inspection using nearby linear illumination and line scan camera

4 Theoretical Assumptions About Lighting in Photometric Stereo Method

Several factors are fundamental to successful lighting for machine vision. These include angle of illumination, intensity, uniformity, distribution and spectrum of light. Although these factors may be altered and arranged to achieve lighting for highly application specific situations, in all cases the availability of commercial lighting solutions will set a limit on what may be achieved within practical design constraints. As with PS the theory of DPS is based on a number of idealised assumptions. In particular it is assumed that the light sources used are collimated in nature, i.e. take the form of distant point sources. While this may be reasonably well approximated in the laboratory setting, achieving collimated illumination with sufficient uniformity in intensity, over a suitable area for the practical inspection of large fast moving surface, becomes more problematic.

4.1 Real Illuminates

Real illuminates have a finite size and proximity. In order to achieve the necessary intensity distribution required for the imaging of moving surfaces at production rates often exceeding 200m/minute it is often necessary to employ distributed sources in relative close proximity, such as the line lights depicted in Figure 2. Such lights may take the form of florescent tubes, linear arrays of fibre optics or high intensity LED's and would appear to be far from 'point source' in nature.

Modelling real illuminates. First consider the problem associated with the nearby point source, as illustrated by Figure 3. As a result of non-collimation the local position of the source appears to vary between surface locations (i.e. $a \neq b$). Although a calibration may be applied to accommodate this variation, the distributed nature of a real source would seem to suggest that it would be unrealistic to treat it as a point source.

Fig. 3. A near-by point source, where $a > b$

However, in the case of diffuse reflection, we show here that a nearby-distributed illuminate can in practice always usefully be approximated by an equivalent virtual point source.

The virtual point light source

Consider a Lambertian surface illuminated by a continuous linear illuminate source, rather like a long strip light, as shown by Figure 4, for which it is assumed that the length of the source (L) is significantly greater than the length of the surface (S).

Fig. 4. Distributed linear illumination, where angle A is in Radians

This is not an unreasonable assumption in practice. Any two points, say P_1 and P_2 , on the source that are equally spaced either side of a given surface point of interest, P_s , will be at an equal distance and appear with equal intensity, I_1 . For $0 < A < \pi/2$ we may consider the strip source to be composed of a large number of such equally spaced sources as $L \rightarrow \infty$. Now, by analogy, consider two point sources of intensity, I_1 , as shown by Figure 5(a), for which A is known where we wish to find the equivalent single virtual point source P_v , located above P_s and with intensity I_2 , as shown by Figure 5(b).

From Figure 5(a), for a rotation of the surface θ , where to avoid occlusion $\theta < ((\pi/2)-A)$ the intensity (i) at P_s is given by

Fig. 5. Virtual point light source

$$i = I_1 \cos(A+\theta) + I_1 \cos(A-\theta) \quad (3)$$

$$i = I_1 [\cos(A+\theta) + \cos(A-\theta)] \quad (4)$$

$$i = I_1 [2 \cos A \cdot \cos \theta] \quad (5)$$

$$i = I_2 \cos \theta \quad (6)$$

$$\text{Where } I_2 = 2I_1 \cos A \quad (7)$$

This result is interesting in that, ignoring occlusion and inverse square effects, i.e. for distant sources, any group of real point sources may be replaced by an equivalent virtual source, as depicted by Figure 6. Furthermore, in the case of a real distributed source, we may consider the source to be the superposition of a large number of symmetrical point sources and as such modelled by a single virtual distant point source. This assumes that the entire illuminate remains visible and is not occluded by surface features or subject to end effects. The situation remains much the same for an extended source, such as a strip light typically used in web inspection, while in close proximity, as shown by Figure 2. For a long (in relation to the illuminated surface) strip light, and a nominally planar surface, in which the amplitude of topographic features is relatively small, these assumptions hold, even if the source is nearby. This is essentially because end-effects may be ignored and by making assumptions about

Fig. 6. Approximating an extended source

symmetry it is possible to ignore inverse square effects, as there will always exist symmetrically spaced illuminate points of equal intensity. Even for a distributed source for which $L \propto s$, at $L > 5Y$ the variation due to inverse square is found to be less than 2%.

4.2 Experimental Validation of the Virtual Point Light Source

Figure 7 shows a plot of reflected intensity using an extended illuminate in the form of a 122cm long strip light located at a distance of 42cm from a matt surface. Figure 7(a) shows that the intensity function, where θ is the angle between the normal and the light source vector, appears to obey Lambert's law and this is confirmed by Figure 7(b), where a linear regression analysis gives a squared correlation coefficient of better than 99.9% There are important practical implications of these findings in terms of application to dynamic PS. In practice LED line lights are often used in web inspection as they offer good stability and long life. Such illuminates are composed of many small sources, each emitting a cone of light, as depicted by the schematic Figure 8(a).

Fig. 7. Matt surface illuminated by an extended source

(a) Schematic of real linear array of LEDS (motion of surface is out of plane) (b) Equivalent virtual point sources

Fig. 8. Modelling a distributed linear source

At any given surface location although a differing group of LEDs will be visible, the size of the group will be similar and will be dependent upon the LED element size, spacing and radiant cone angle. As has been shown, in each case the symmetrical group of LEDs may be replaced by a single virtual source immediately above the surface point of interest, as depicted by Figure 8(b). Hence, it is possible to simulate the nearby-distributed source in terms of known idealised virtual point sources.

5 Dynamic Application Using Line Scan Imaging

Figure 9 shows the results of applying dynamic PS using IR LED line lights, the virtual point light source model and line scan camera acquisition. The ceramic surface was travelling at 30m/minute.

Fig. 9. Dynamic photometric stereo operating at 30m/minute

As can be seen, the albedo is generally very well removed in Figure 9(b) and the detail of the surface topography is clearly visible.

6 Conclusions

The implications of using real illuminates have been considered in the context of the practical application of photometric stereo (PS) to moving surfaces. A new form of virtual lighting model has been proposed, which is able to model real distributed illuminates in close proximity. Experimental results have validated the theoretical findings. The employment of dynamic photometric stereo for the capture and analysis of two- and three-dimensional surface data represents a useful method of enabling surface quality control for rapidly moving production line situations. The technique also offers new potential for the use of free-roaming hand-held devices for surface texture acquisition in medical, forensic science and other evolving fields.

References

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