

AN APPLICATION OF THE PHOTOMETRIC STEREO METHOD.

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The idea of photometric stereo is to determine the surface orientation of the points of an object in a picture using several views of an object taken with varying illumination, but from the same viewing direction. We can implement this method using reflectance map techniques. In order to calculate the reflectance map, we consider primarily the specular component of surface reflectance, since most industrial materials are very specular. The technique has been demonstrated by experiment.

0 Conclusion

The technique of photometric stereo has been proven by an experiment whose schema is shown in Fig. 1. Orientations of surface patches on a sphere obtained using this technique are shown in Fig. 2.

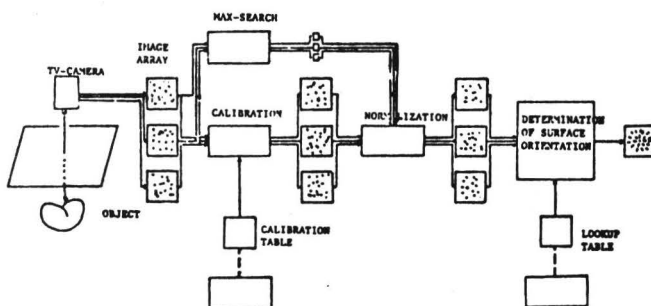


Fig. 1 The total schema of the experiment.

The schema has two parts of jobs, one is an off-line job, represented by broken lines. The other job is one-line. Image brightness is obtained by using a TV camera. We search for maximum values of brightness in each array. Brightness arrays are also calibrated and normalized. A lookup table has been constructed off-line from the reflectance map by using Newton's method. The lookup table is used to obtain surface orientation.

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1 Reflectance Map and Photo-Metric-Stereo

We can express the geometric dependence of the reflectance characteristics of a surface in terms of the slope components p and q , used as axes in gradient space [1].

$$p = \Delta z / \Delta x$$

$$q = \Delta z / \Delta y$$

(1)

If we take the direction from the surface to the viewer as the direction of the z -axis, then the reflectance properties of a surface patch depend on (p, q) , the direction of the surface normal and (p_s, q_s) , the direction to the source [1]. Each point in gradient space, corresponds to a particular surface orientation (based on the direction of the viewer).

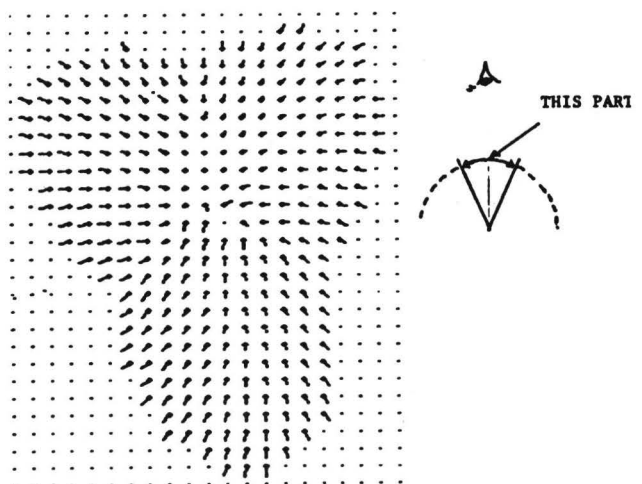


Fig. 2 Orientations of surface patches on a sphere obtained using the technique. Each needle, shown striding up out of a point, represents the orientation of a surface normal.

If we know the reflectance characteristics of an object, we can calculate how bright a surface element with that orientation will appear. This brightness distribution on the gradient space is denoted by $R(p, q)$, and is called as "the Reflectance Map".

Using the reflectance map, the basic imaging equation is

$$E_p(x, y) = R(p, q, p_s, q_s) \quad (2)$$

where $E_p(x, y)$ is the brightness (image irradiance) in the image-forming system at the point (x, y) in the image plane, provided that we can use the orthographic projection; in other word, the object is small compared with the distance to the source and the image-forming system. This equation contains two unknown variables p, q . If we change (p_s, q_s) keeping the other condition as same, we can solve for p and q from the resulting system of (non-linear) equations at the point (x, y) ; namely, if we take more than one image with varying illumination condition, but from the same direction, we can obtain a surface orientation at the point (x, y) . This is the principle of photometric stereo [2].

2 Total Schema of the System

The technique contains two kinds of tasks; one is the off-line(pre computing) job and the other is the on-line(real-time) job which is rather simple compared with the off-line job. The simplicity implies rapid calculation, as desired in any hand-eye system. The off-line job consists of making the reflectance map, constructing a lookup table, and a calibration table of brightness. The on-line job consists of reading the image brightness and determining orientations of a surface patch based on the lookup table. Fig. 1 shows information flow between the on-line job and the off-line job.

3 Calculation of the Reflectance Map

One of the main points of our discussion here is that we consider only specular components of reflectance when we calculate the reflectance map, since most industrial materials are made of metal and have strong specularity with very weak lambertian characteristics. We cannot treat such kind of materials as a usual lambertian model. Meanwhile, ratios of specular components to lambertian components are usually about 50 to 100. This situation allows us to consider only specular components.

For a specular surface and an extended source, we can obtain brightness distribution on the gradient space from the definition of the bi-directional reflectance distribution function (BRDF) and the transformation from the local coordinate system to the viewer coordinate system [1].

$$R(p_n, q_n) = L_s(p_s, q_s) \quad (3)$$

where L_s is the distribution function of the source radiance and

$$p_n = \partial z / \partial x$$

$$q_n = \partial z / \partial y$$

$$p_s = 2 p_n / (1 - p_n^2 - q_n^2)$$

$$q_s = 2 q_n / (1 - p_n^2 - q_n^2)$$

Thus, even though the source distribution may be complicated, only the contribution from a single direction (p_s, q_s) need be considered and one need not be concerned with the effects of other areas of the distributed light source.

4 Consideration of Light Source

We use as a source plane a lambertian surface that is illuminated by a linear lamp shown in Fig. 3. Though a spherical shape source easily can cover directions more than ninety degrees, it is difficult to make an ideal brightness distribution. It is possible to cover angles of more than ninety degrees by making a box-like source. In that case, however, we have to treat each plane separately because the surface normal is not differentiable at the intersection of two planes. Thus, we consider one plane surface which has the lambertian characteristics and is illuminated by a line source as a representative case.

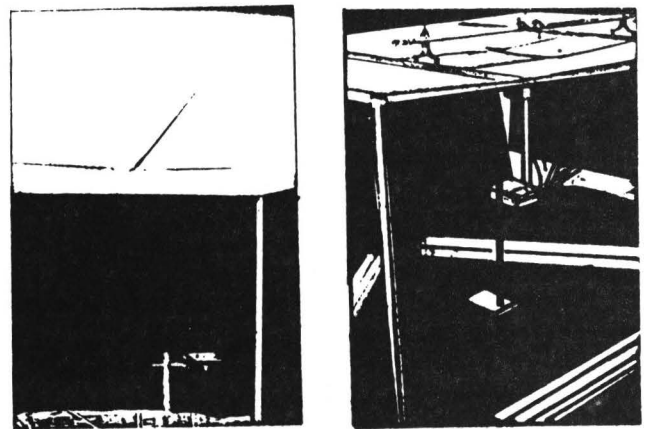
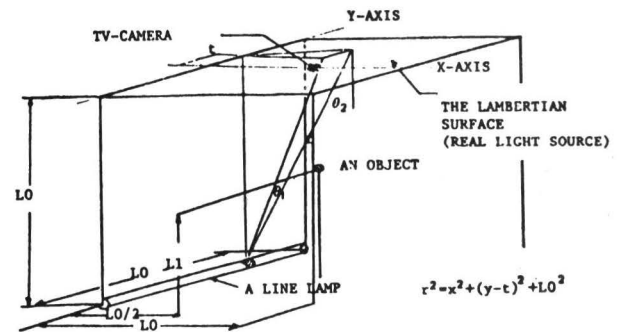


Fig. 3 The light source is a wide lambertian surface. The surface is illuminated by a line lamp.

Brightness distribution on the surface is calculated by Eq. 4. Let f be the flux rate per unit source length [watt/(m sr)], total irradiance E [watt/m²] is

$$E = f \cos \theta_1 \cos \theta_2 / r^2 dt, \quad (4)$$

where $\cos \theta_1 = \sqrt{x^2 + l_0^2} / r$ and $\cos \theta_2 = l_0 / r$ and l_0 is the distance from the lamp and the source plane.

We put an object just under the point $(x, y) = (0.5l_0, 0.0)$. If we denote the distance from the surface to the object as l_1 ,

$$\begin{aligned} x &= l_1 p_s + l_0 / 2 \\ y &= l_1 q_s \end{aligned} \quad (5)$$

Finally, by using Eqs. 3,4 we can get a reflectance map

$$\begin{aligned} R(p_s, q_s) &= [l_0 / 2 \{ (l_1 p_s + l_0 / 2)^2 + l_0^2 \}] [\\ &\tan^{-1} \{ (l_1 q_s + l_0 / 2) / \sqrt{(l_1 p_s + l_0 / 2)^2 + l_0^2} \} \\ &- \tan^{-1} \{ (l_1 q_s - l_0 / 2) / \sqrt{(l_1 p_s + l_0 / 2)^2 + l_0^2} \} \\ &+ \{ \sqrt{(l_1 p_s + l_0 / 2)^2 + l_0^2} (l_1 q_s + l_0 / 2) \} \\ &/ \{ (l_1 p_s + l_0 / 2)^2 + l_0^2 + (l_1 q_s + l_0 / 2)^2 \} \\ &\{ \sqrt{(l_1 p_s + l_0 / 2)^2 + l_0^2} (l_1 q_s - l_0 / 2) \} \\ &/ \{ (l_1 p_s + l_0 / 2)^2 + l_0^2 + (l_1 q_s - l_0 / 2)^2 \}], \end{aligned} \quad (6)$$

where p_s and q_s are as defined above.

5 Construction of the Lookup Table

The most convenient method for converting a triple of brightness to an orientation is first to make a lookup table from the reflectance map. We can lookup the table by using a triple. Each entry of the table contains a particular surface orientation corresponding to a triple.

We construct the lookup table by using the Newton method. In the case of a lambertian reflector and point sources an elegant method exists[2]. In our case, however, we have to calculate it numerically. Namely, we solve three expressions of Eq. 6 with respect to (p, q) . The three expressions are different in their source directions (p_s, q_s) .

From the lookup table we can get the surface orientation. The lookup table is actually two triangular two-dimensional matrixes. Although it is possible to make a three dimensional lookup table in which each dimension corresponds to the brightness of a surface patch under three sources, the weakest brightness likely contains measurement error and we only use it to determine a solution between two alternatives caused by the non-linearity. Thus, the lookup table can be two dimensional.

6 Information Flow in the On-line Job

Image brightness is obtained from the TV camera. Actually, we took more than one picture per light source, and arrays corresponding to the same light source were averaged. The resulting three brightness arrays, one for each light source, were input to the photometric stereo system.

We search each array for its maximum brightness. If objects are compact and the visual angle is wide enough, the image array always contains the brightness corresponding to the maximum source brightness. So, by using these values, we can cancel the effect of varying albedo and can identify the maximum value in an image array with the value 1.0 in the reflectance map.

We look up an entry using the two largest brightness values. To increase the accuracy of computation and economy of memory use, the first dimension represents the largest image brightness. The second dimension represents to the second largest. Since the non-linearity gives rise to two solutions for each brightness pair, each mesh of the matrix contains two alternative solutions. Each alternative solution contains the corresponding surface orientation and the smallest image brightness. In order to decide which one of the two alternatives is the real one, we compare the distance between the actual third image brightness and the element of the matrix, and choose the solution corresponding to smaller distance among the two solutions.

7 Experiment and Discussion

Experimental results are shown in Fig. 2. The algorithm reads the table twice by exchanging second brightness and third brightness and determines the solution by averaging.

A direct application of our technique is an industrial hand-eye system that picks up an object out of a jumble of material. Although this technique cannot detect the surface orientation when there is mutual illumination, the technique recognizes this condition and does not produce an erroneous result. This is not so harmful as the result of mis-determination of the orientation. Because the mis-understood guidance to a hand may cause the hand or materials unrecoverable physical defects.

Another application of our technique is to inspect surface condition of metals. If a surface has a crack, stain, or finger print, the image brightness triple yields insistent values for the surface orientation in the area of the blemish.

REFERENCES

- [1] Horn, B and Sjoberg, R. "Calculating the Reflectance Map." AI-Memo 498, AI Lab, MIT, October, 1978.
- [2] Horn, B, Woodham, R, and Silver, B. "Determining Shape and Reflectance Using Multiple Images." AI-Memo 490, AI Lab, MIT, August, 1978.