Extracting the Shape and Roughness of Specular Lobe Objects Using Four Light Photometric Stereo

Fredric Solomon[1] and Katsushi Ikeuchi

The Robotics Institute
Carnegie Mellon University

Abstract

Two important aspects of part inspection are the measurement of surface shape and surface roughness. We propose a noncontact method of measuring surface shape and surface roughness. The method, which we call "four light photometric stereo", uses four lights which sequentially illuminate the object under inspection, and a video camera for taking images of the object. Conceptually, the problem we are solving has three parts: shape extraction, pixel segmentation, and roughness extraction. The shape information is produced directly by three light and four light photometric stereo methods. After we have shape information, we can apply statistical segmentation techniques to determine which pixels are specular and which are nonspecular. Then, we can use the specular pixels and shape information, in conjugation with a simplified Torrance-Sparrow reflectance model to determine the surface roughness. The method has successfully been applied to a number of synthetic and real objects.

1: Introduction

In modern manufacturing environments, part inspection is an important part of quality control. Today, the majority of inspection tasks are performed manually. In an effort to automate part inspection, some companies have turned to computer vision techniques. The ability to measure parts in three dimensions would be an important tool for inspecting manufactured parts. Two basic three dimensional measurements that are made on many manufactured parts are the measurement of the shape and surface roughness.

Computer vision research has produced a number of basic techniques for measuring the surface shape of an object: stereo vision, range finders, and photometric techniques. Photometric techniques [1,2] use image intensity to determine shape.

We seek to develop a method that can extract the surface shape and surface roughness of an object that exhibits a specular lobe. The method, which we call "four light photometric stereo", uses four lights which sequentially illuminate the object under inspection, and a video camera for taking images of the object.

Conceptually, the problem we are solving has three parts: shape extraction, pixel segmentation, and roughness extraction. The shape information is produced directly by the three light and four light photometric stereo methods. After we have shape information, we can apply different techniques to determine which pixels are specular and which are nonspecular. Then, we can use the specular pixels and shape information, in conjugation with a simplified Torrance-Sparrow reflectance model [3] to determine the surface roughness.

1.1: Previous Work

Woodham [4] proposed the photometric stereo method to determine the surface shape of lambertian dominant surfaces. Brelstaff and Blake [5] used lambertian constraints to detect specularities.

A number of methods have been developed to recover the shape of specular spike objects. Ikeuchi [6] used three extended sources to determine the surface orientation of specular surfaces. Nayar, Weiss, Simon, and Sanderson [7] developed a system that used 127 point sources to determine the shape of specular objects. Coleman and Jain [8] proposed using four lights to detect specularities.

Healey and Binford [9] used a simplified version of the Torrance-Sparrow reflectance model to recover object curvature of specular lobe objects. Wolf [10, 11] used light polarization and the Torrance-Sparrow model to measure surface shape. Nayar, Ikeuchi, and Kanade [12] developed a method for surfaces that exhibited a lambertian and specular spike component. Ikeuchi and Sato [13] developed a method to recover the shape and roughness of objects that follow the Torrance-Sparrow reflectance model by using an intensity image and a range image. However, their method is sensitive to noise.

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2: Determining Surface Shape and Pixel Segmentation using Four Light Photometric Stereo

An object illuminated by four light sources will produce three categories of regions based upon illumination: regions illuminated by all four light sources, regions illuminated by three light sources, and regions illuminated by only two light sources. If we illuminate an object with four equally spaced light sources, the region map, represented on the gaussian sphere, will look like this:

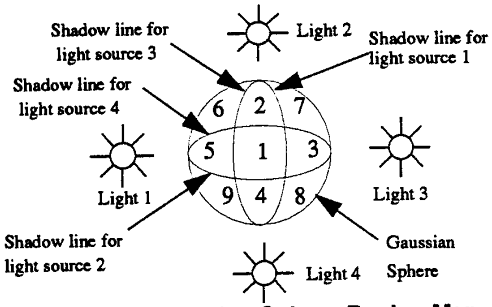


Figure 1. Gaussian Sphere Region Map

Region 1 is illuminated by all four light sources. Regions 2, 3, 4, and 5 are illuminated by three light sources. Regions 6, 7, 8, and 9 are illuminated by two light sources. The region boundaries are formed by the shadow lines of each light source. The size and shape of each region is dependent on the inclination of the light sources.

Different information is available in each of the three categories of regions. Therefore, we use different techniques for determining surface shape and for performing pixel segmentation in each region.

2.1: Determining Surface Shape and Pixel Segmentation in the Four Light Illuminated Region

Coleman and Jain proposed using four lights to determine the shape of surfaces that were nonlambertian. The method is only valid in regions illuminated by all four light sources, the region labeled 1. They proposed to calculate four albedo values based on the four possible combinations of three light sources. For a perfectly lambertian surface, the four albedos would be identical. But, for surfaces that exhibit some specularity, this is not the case. If we assume that the specular lobes of each light source do not intersect, then a specularity in one light source will cause the three albedos that use that light source to be high, while the albedo that does not use the light source will be low. Given four intensity values, (I1, I2, I3, I4), and four light source directions, (**S1, S2, S3, S4**), we can define four albedos, (Ra, Rb, Rc, Rd), as follows:

$$\mathbf{Sa} = \begin{bmatrix} S1x & S1y & S1z \\ S2x & S2y & S2z \\ S3x & S3y & S3z \end{bmatrix} \qquad \mathbf{Sb} = \begin{bmatrix} S2x & S2y & S2z \\ S3x & S3y & S3z \\ S4x & S4y & S4z \end{bmatrix}$$

$$\mathbf{Sc} = \begin{bmatrix} S3x & S3y & S3z \\ S4x & S4y & S4z \\ S1x & S1y & S1z \end{bmatrix} \qquad \mathbf{Sd} = \begin{bmatrix} S4x & S4y & S4z \\ S1x & S1y & S1z \\ S2x & S2y & S2z \end{bmatrix}$$

$$\mathbf{Ia} = \begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix} \quad \mathbf{Ib} = \begin{bmatrix} I2 \\ I3 \\ I4 \end{bmatrix} \quad \mathbf{Ic} = \begin{bmatrix} I3 \\ I4 \\ I1 \end{bmatrix} \quad \mathbf{Id} = \begin{bmatrix} I4 \\ I1 \\ I2 \end{bmatrix}$$

$$Ra = \left|(\mathbf{Sa})^{-1}\mathbf{Ia}\right| \qquad Rb = \left|(\mathbf{Sb})^{-1}\mathbf{Ib}\right|$$

$$Rc = \left|(\mathbf{Sc})^{-1}\mathbf{Ic}\right| \qquad Rd = \left|(\mathbf{Sd})^{-1}\mathbf{Id}\right|$$

(S1x, S1y, and S1z are the x, y, and z components of the unit vector to light source number one.)

If I1 is specular, Ra, Rc, and Rd will be elevated above their lambertian levels. Rb will be the lambertian albedo, since I2, I3, and I4 are not specular.

Therefore, we can identify the nonspecular light sources, by using the four albedos, and we can use these nonspecular light sources to produce a valid surface normal. Since the surface is lambertian, the surface normal is equal to:

$$\begin{bmatrix} S2x & S2y & S2z \\ S3x & S3y & S3z \\ S4x & S4y & S4z \end{bmatrix}^{-1} \begin{bmatrix} I2 \\ I3 \\ I4 \end{bmatrix} = \begin{bmatrix} Nx \\ Ny \\ Nz \end{bmatrix}$$

However, due to image noise, the four albedos will never be exactly equal. We need to establish a threshold to determine when the differences in albedo indicate a specularity, and when they are just due to random events.

We propose a classification scheme which would use the variance of the camera's intensity response to determine a statistically meaningful threshold. If σ_i^2 is the camera's intensity variance measured at a particular pixel, then we can establish a specular threshold based on a +/-3σ distribution. We assume that the light source directions are known without any uncertainty. Then, in the case where R1 is the maximum albedo and R2 is the minimum albedo, we can define Rdev as:

$$Rdev = R1 - R2$$

A pixel is specular if Rdev is greater than the specular threshold:

$$a = \frac{\partial}{\partial I1}R1 + \frac{\partial}{\partial I1}R2 \qquad b = \frac{\partial}{\partial I2}R1 + \frac{\partial}{\partial I2}R2$$

$$c = \frac{\partial}{\partial I3}R1 + \frac{\partial}{\partial I3}R2 \qquad d = \frac{\partial}{\partial I4}R1 + \frac{\partial}{\partial I4}R2$$

$$Rdev > 6\sqrt{a^2\sigma_i^2 + b^2\sigma_i^2 + c^2\sigma_i^2 + d^2\sigma_i^2}$$

This threshold assumes a worst case 6σ separation between R1 and R2. In practice each pixel in the image has its own light intensity variance, due to variations in manufacture of the camera's CCD array. Therefore, the variance needs to be measured for each pixel.

2.2: Determining Surface Shape and Pixel Segmentation in the Three Light Illuminated Region

The region labeled 3 is illuminated by light sources 2, 3, and 4. Its borders are formed by the shadow lines of light sources 1, 4, and 2. If we assume that the specular regions of each light source are nonoverlapping, and if the surface is specular, region 3 may have a specularity from light source 3. Illumination by light sources 2 and 4 will be non-specular in region 3.

Under these assumptions, we can determine an accurate surface normal using light source 2, light source 4, and the shadow line of light source 1. We do not use light source 3 because it may be specular. We can write three equations, in three unknowns:

$$\frac{I_2}{\rho} = S2xNx + S2yNy + S2zNz \qquad \frac{I_4}{\rho} = S4xNx + S4yNy + S4zNz$$

$$(Nx)^2 + (Ny)^2 + (Nz)^2 = 1$$

The albedo, ρ, the light source directions S2 and S4, and the image intensities I2 and I4 are known. The albedo is calculated form the albedos of the lambertian pixels within a 10X10 pixel area within the four light illuminated region.

This set of three equations has two sets of solutions. If we define the following intermediate variables:

$$a = \frac{S2x}{S2z} \quad b = \frac{S2y}{S2z} \quad g = \frac{I2}{\rho S2z} \quad c = \frac{S4x}{S4z}$$

$$d = \frac{S4y}{S4z} \quad h = \frac{I4}{\rho S4z} \quad f = \frac{d-b}{c-a} \quad e = \frac{-g+h}{c-a}$$

$$A = f^2a^2 + f^2 - 2abf + b^2 + 1 \qquad C = -2age + a^2e^2 + e^2 + g^2 - 1$$

$$B = 2agf - 2efa^2 - 2ef + 2abe - 2bg$$

The two sets of surface normal solutions are:

$$\begin{aligned} Ny_1 &= \frac{-B + \sqrt{B^2 - 4AC}}{2A} & Ny_2 &= \frac{-B - \sqrt{B^2 - 4AC}}{2A} \\ Nx_1 &= e - fNy_1 & Nx_2 &= e - fNy_2 \\ Nz_1 &= g - aNx_1 - bNy_1 & Nz_2 &= g - aNx_2 - bNy_2 \end{aligned} \qquad (1)$$

The proper solution can be selected by using the boundary condition of light source one's shadow line. (It is possible that due to degenerate positioning of light sources 1, 2, and 4, that both surface normals are on the same side of light source one's shadow line. We do not consider this case.) In region number 3,

$$S1xNx + S1yNy + S1zNz < 0$$

Selecting the proper solution becomes more complex in the presence of intensity noise, which causes uncertainty in the normals, and uncertainty in the location of the shadow line.For a pixel to confidently be in region number 3, the following relation must hold for its surface normal:

$$S1xNx_1 + S1yNy_1 + S1zNz_1 < 3\sqrt{\sigma^2_{Nx_1}(S1x)^2 + \sigma^2_{Ny_1}(S1y)^2 + \sigma^2_{Nz_1}(S1z)^2} \qquad (2)$$

This expression expresses with a 3σ confidence that the surface normal solution is in the three light illuminated region, region number 3.

In order to classify a pixel as specular, we can determine whether its measured brightness, with respect to a given light source, is larger than its predicted lambertian brightness for the same light source. If the derived normal vector for the pixel under consideration is (Nx, Ny, Nz), and the measured brightness of the pixel due to light source three is I3, then the pixel is specular if:

$$I3 > \rho\,(S3xNx + S3yNy + S3zNz)$$

We need to consider the uncertainty of I3, ρ, Nx, Ny, and Nz. If σ^2_{I3} is the uncertainty of the measured brightness, and the uncertainty of the predicted lambertian brightness, Ilam, is σ^2_{Ilam}, then we can say that a pixel is specular, assuming a 3σ distribution, if:

$$I3 - Ilam > 6\sqrt{\sigma^2_{Ilam} + \sigma^2_{I3}}$$

2.3: Determining Surface Shape and Pixel Segmentation in the Two Light Illuminated Region

It is possible to determine the surface normal in the region illuminated by only two lights. The region labeled 7 is illuminated by light sources 2 and 3. Its borders are formed by the shadow lines of light sources 1 and 4. If we assume that neither light 2 nor light 3 have a specularity in region 7, we can write the a set of equations similar to equation 1. The proper solution can be selected by using the boundary condition for light source one's shadow line, and the boundary condition for light source four's shadow line. The threshold for selecting the proper surface normal can be determined by using an equation similar to Equation 2.

The assumption that light source one and four do not produce a specularity in the two light illuminated region is not strong. However, if one of the lights does produce a specularity, the surface normal solutions may become imaginary. Pixels may not be sufficiently specular to cause the surface normal solutions to become imaginary. In this case, the surface normal solutions will be erroneous, and it will be not be possible to detect the condition.

2.4: Consistent Segmentation

The uncertainty of segmentation in the three light illuminated region has a higher uncertainty than segmentation in the four light illuminated region. The derivation of the surface normals in the three light illuminated region involves a lot of computation; this increases their variance, making σ^2_{Ilam} large. In order to produce consistent segmentations, we increase the uncertainty threshold of the four light illuminated region by 2X, to match the three light illuminated region. The amount of increase was found by observing the segmentation of synthesized images.

3: Extracting Specular Intensity and Surface

Roughness

The Torrance-Sparrow reflectance model allows us to determine the specular intensity and surface roughness of an object that exhibits a specular lobe. In this section, we develop a simplified version of the Torrance-Sparrow model. Then, we develop the specular intensity and surface roughness extraction algorithms.

3.1: Simplified Torrance-Sparrow Model

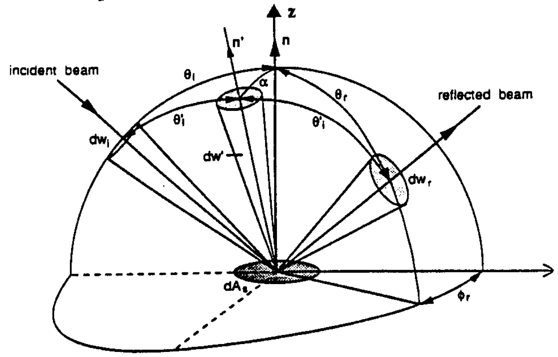


Figure 2. Geometry for Torrance-Sparrow Model

For a fixed incident light angle and for a given material, the surface radiance is:

$$E = F(\theta_i', \mathbf{n}') \left[\frac{G(\theta_i, \theta_r, \phi_r)}{\cos\theta_r}\right] exp(-c^2\alpha^2)$$

$F(\theta_i', \mathbf{n}')$ is the Fresnel reflectance coefficient. For insulators, with incident angles of less than 40 degrees, the Fresnel coefficient can be approximated by a constant.

$G(\theta_i, \theta_r, \phi_p)$ is the geometric attenuation factor. For incident angles between 0 degrees and 60 degrees, and reflected angles between 0 degrees and 80 degrees, the geometric attenuation factor is close to unity.

With these assumptions, and the camera at N=(0,0,1), the total surface radiance will be the sum of the underlying lambertian radiance, A, and the radiance of the specular lobe.

$$E = A + B\left(\frac{exp(-K\alpha^2)}{Nz}\right)$$

3.2: Specular Intensity and Surface Roughness Extraction Algorithm

Once the surface shape is determined and the specular pixels are extracted, the specular intensity and surface roughness can be determined. In the simplified Torrance-Sparrow model, we determine B, the specular intensity, and K, the specular sharpness which is proportional to the surface roughness. We use the following algorithm:

Using the extracted surface normals and lambertian albedo, we can determine the lambertian intensity, A, at each image point. We can define D, the difference between the measured image brightness at each specular pixel and the lambertian intensity.

$$D = I - A = B\left(\frac{exp(-K\alpha^2)}{Nz}\right)$$

Many surfaces have a weighted lambertian albedo. So we modify our definition of D to include an offset term:

$$D = I - A = B\left(\frac{exp(-K\alpha^2)}{Nz}\right) + Offset$$

Where the offset is the difference between the unweighted lambertian albedo and the weighted lambertian albedo. This equation has three unknowns, B, K, and the Offset. The equation can be solved by simultaneously searching for a solution in three dimensional (B,K, Offset) space by using gradient descent. Our metric is CHISQR.

We define CHISQR as:

$$CHISQR = \sum_{i,j} [(I(i,j) - A(i,j)) - D(B,K,Offset)]^2$$

4: Experimental Results

The experimental results consist of images of two objects, a specular painted sphere and a plastic helmet.

A ceiling mounted, Sony XC-57 camera, with an 85 mm Nikkor lens, was used. The camera to object distance was approximately 2.5 meters. Four ECA, 250 watt, light bulbs were mounted on light stands. The bulb to object distance was approximately 2.6 meters.

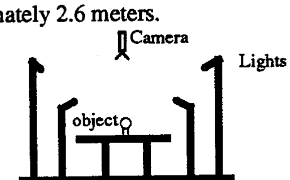


Figure 3. Experimental setup

4.1: Painted Specular Sphere

Four images of a painted, 12.7cm diameter, sphere were taken. The needle map, using a lambertian albedo increased by the Offset, produced from the four intensity images is shown in figure 4.

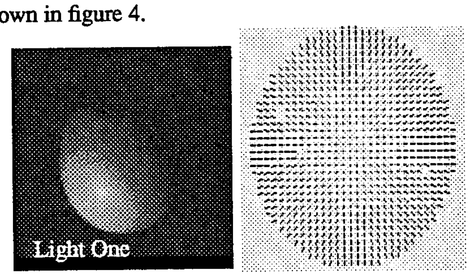


Figure 4. Sphere Needle Map

The pixel segmentation for the images is in figure 5. The

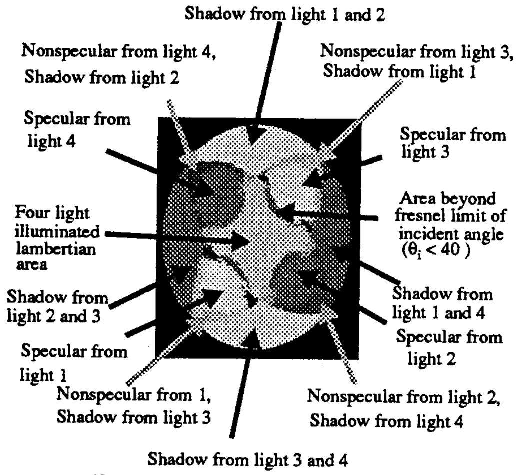


Figure 5. Sphere Segmentation

specular intensity, B, specular sharpness, K, and the offset, Offset, extracted for the four specular spots is (The extracted lambertian albedo, ρ, is 139.8.):

	Offset	B	K
Specular light one	10.1	43.5	16.7
Specular light two	8.2	55.1	17.0
Specular light three	14.6	45.8	21.2
Specular light four	15.1	39.9	22.8
Average values	12.0	46.1	19.4

The plot of measured intensity versus incident angle for light source three is shown in figure 6. The plot of the

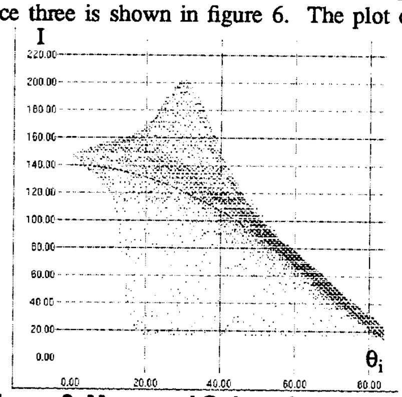


Figure 6. Measured Sphere Intensity

intensity versus incident angle using the extracted values of B, K, and Offset for the specular spot due to light source three is shown in figure 7. (For this plot, since the area of interest is the specular lobe, the lambertian albedo is the sum of Offset and ρ.)

If our data follows the simplified Torrance-Sparrow model, a plot of α^2 versus ln[(D-Offset)*Nz] should be linear. This is shown in figure 8.

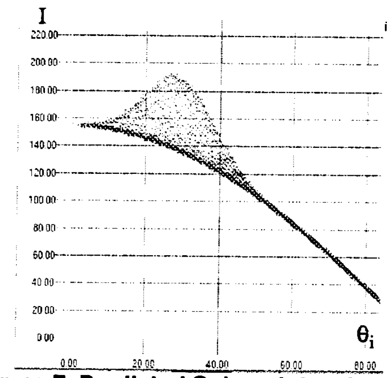


Figure 7. Predicted Sphere Intensity

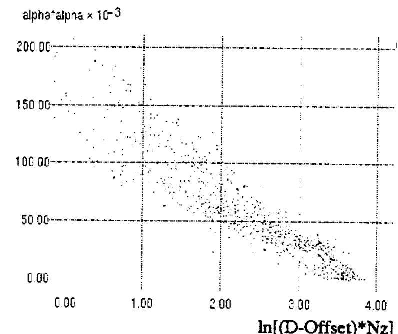


Figure 8. Sphere α^2 versus ln[(D-Offset)*Nz]

4.2: Plastic Helmet

Four images were taken of a plastic helmet. The four images contain interreflections due to concavities in the surface of the helmet. Since our model does not include interreflection, we manually segmented the images to eliminated any areas where interreflection might occur.

In addition to interreflection the plastic exhibited a small specular spike. Due to the averaging nature of the pixels in the CCD array, most of the images did not show the spike. However, the image due to light source number two did show the spike. The spike's presence caused the gradient descent fit to not converge. To compensate for any spike in the other images, we increased the specular threshold in the four light illuminated area by 0.5X.

With these modifications to our algorithm, we were able to extract the specular lobe's characteristic's for light source one, three, and four.

	Offset	B	K
Specular light one	-2.1	36.5	8.4
Specular light three	-6.4	49.9	10.1
Specular light four	-8.1	41.5	8.3
Average values	-4.2	42.6	8.9

The pixel segmentation for the above images is shown in figure 9:

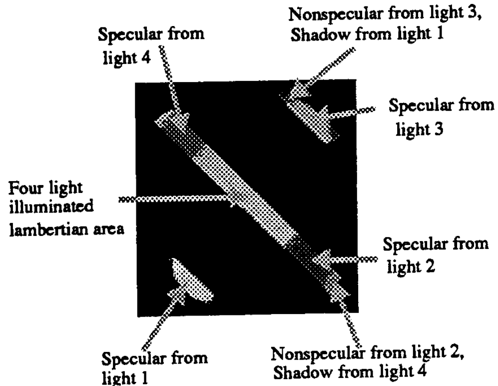
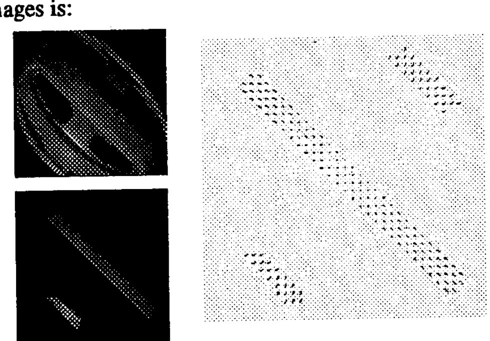


Figure 9. Helmet Segmentation

The needle map produced from the four intensity images is:



Light One **Figure 10. Helmet Needle Map**

5: Conclusions

We have developed a method for extracting the shape and roughness of surfaces that exhibit a specular lobe. The work includes three important parts: determination of shape, segmentation of pixels into specular and nonspecular pixels, and determination of surface roughness. Coleman and Jain's work for performing segmentation in areas illuminated by four lights, was improved by making the segmentation statistically meaningful. We developed methods for recovering shape and for performing statistical segmentation in regions illuminated by three lights. We also developed methods for recovering shape in regions illuminated by two lights. By examining the illumination conditions in the different regions of the gaussian sphere, we were able to extend photometric stereo to the entire gaussian sphere. Finally, by using a simplified version of the Torrance-Sparrow reflectance model, we were able to develop an algorithm for extracting the specular intensity and surface roughness from specular pixels.

Our methods have been shown to produce reasonable results on synthetic and real images. We have recovered the shape and roughness of objects that exhibit imperfect lambertian albedos, and we have also been able to recover the shape of objects that contain moderate to large specular spikes [14].

6: References

[1] W. M. Silver, "Determining Shape and Reflectance Using Multiple Images", S.M. Thesis, Dept. of Electrical Engineering and Computer Science, MIT, Cambridge, Massachusetts, June, 1980.

[2] S. K. Nayar, K. Ikeuchi, T. Kanade, "Surface Reflections: Physical and Geometrical Perspectives", *IEEE Trans. of Pattern Analysis and Machine Intelligence*, Vol. 13, No. 7, pp. 611-634, July, 1991.

[3] K. Torrance and E. Sparrow, "Theory for Off-Specular Reflection from Roughened Surfaces", *Journal of the Optical Society of America*, No. 57, pp. 1105-1114, 1967.

[4] R. J. Woodham, "Reflectance Map Techniques for Analyzing Surface Defects in Metal Castings", PhD Thesis, Artificial Intelligence Laboratory, MIT, Cambridge, Massachusetts, June, 1978.

[5] G. Brelstaff and A. Blake, "Detecting Specular Reflections Using Lambertian Constraints", *1988 IEEE International Conference on Computer Vision*, pp 297-302.

[6] K. Ikeuchi, "Determining The Surface Orientations Of Specular Surfaces By Using The Photometric Stereo Method", *IEEE Trans. of Pattern Analysis and Machine Intelligence*, Vol. 3, No. 6, pp. 661-669, November, 1981.

[7] S. K. Nayar, A. C. Sanderson, L. E. Weiss, D. D. Simon, "Specular Surface Inspection Using Structured Highlight and Gaussian Images", *IEEE Trans. on Robotics and Automation*, Vol. 6, No. 2, pp. 208-218, April, 1990.

[8] E. N. Coleman and R. Jain, "Obtaining 3-dimensional Shape Of Textured And Specular Surfaces Using Four-source Photometry", *Computer Graphics and Image Processing*, Vol. 18, No. 4, pp. 309-328, April, 1982.

[9] G. Healey and T.O. Binford, "Local Shape from Specularity", *Computer Vision Graphics and Image Processing*, Vol. 42, pp. 62-86, 1988.

[10] L. Wolff, "Spectral And Polarization Stereo Methods Using A Single Light Source", *1987 IEEE International Conference on Computer Vision*, pp 708-715.

[11] L. Wolff, "Shape from polarization images", *1987 IEEE Workshop on Computer Vision*, pp. 79-85.

[12] S. K. Nayar, K. Ikeuchi, T. Kanade, "Determining Shape and Reflectance of Hybrid Surfaces by Photometric Sampling", *IEEE Trans. on Robotics and Automation*, Vol. 6, No. 4, pp. 418-431, August, 1990.

[13] K. Ikeuchi and K. Sato, "Determining Reflectance Parameters Using Range and Brightness Images", CMU-CS-90-106, February, 1990.

[14] F. Solomon and K. Ikeuchi, "Extracting the Shape and Roughness of Specular Lobe Objects Using Four Light Photometric Stereo", CMU-RI-TR-91-17, October 1991.