Models of Light Reflection for Facet Stereo Vision

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Abstract
In measuring a surface by means of image processing techniques, the reflectance model applied to the imaged material is crucial for the accuracy and the utilization of the method as well. Simple models cut operating time at the cost of local validity and restrictions for the workable material. Complex reflectance models which are well known in the domain of Computer Graphics and Photometric Stereo are computationally expensive. They require the determination of several parameters for the light reflecting properties of an object. But they allow the treatment of surfaces even with partly mirror-like reflectance components. Facet Stereo Vision aspires to a global solution for the reconstruction of objects made of inhomogeneous material from at least two digital images. Therefore, it must be ensured that the radiometrical model of image formation considers variations of the surface orientation and the directions to light sources and to sensors. At present, three different models of light reflection are in use. They do not need any a priori knowledge about the reflectance properties of the material.

Introduction
Facet Stereo Vision is a method of computing a digital surface model from several recorded images of a scene (WROBEL 1987, 1988). Two interconnected networks of bilinear interpolating functions in object space represent the geometry and the radiometrical properties of the surface. With initial parameters of those functions, an iterative algorithm renders gray level images corresponding to the arrangement of the survey. The parameters are then updated by an adjustment that minimizes the sum of squares of the gray level differences between synthetical and recorded digital images. The precision of the digital surface model resulting from the adjustment depends strongly on the completeness of the radiometric model of image formation applied. In particular, unmodeled effects of illumination on the apparent brightness of the surface cause deformations of the geometrical description. Image forming models considering the dependance of the apparent surface brightness on the light reflecting properties of the material (ambient, diffuse and mirror-like reflectance), several light sources and the line of sight have been developed in Computer Graphics (TORRANCE/SPARROW 1967, BUI TUONG 1975, BLINN 1977, COOK/ TORRANCE 1981). Similar models have been applied by Photometric Stereo in order to determine the orientation of surfaces (HORN 1975, 1987, GRIMSON 1984). Here the properties of the material are predetermined by a calibration with a known object. In Facet Stereo Vision the parameters of reflectance are estimated

from a projection of digital image gray levels onto the surface. The properties of the inverted image forming models which are used to accomplish this task are examined and explained in the following.
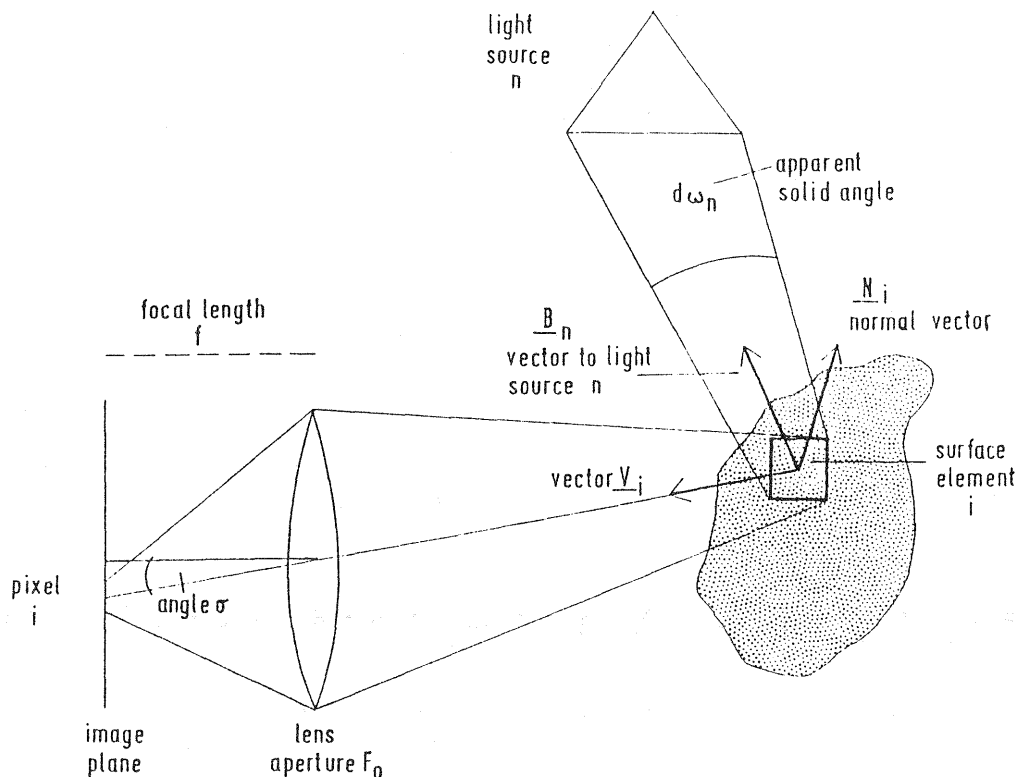

Figure 1:   The Geometry of Image Synthesis

Image Synthesis
The quantized gray level G of the discrete picture element i is a function of the integral irradiation I on the resolution cell of a sensor. Within the dynamic range of the sensor a linear transformation is accepted

$$G_i = a + b \cdot I_i \tag{1}$$

The irradiation is simply the product of irradiance E and exposure time t

$$I = E \cdot t \tag{2}$$

Derivations of the relation between irradiance on the sensor and radiance L_R emitted by non-selfluminous surfaces are given elsewhere (HORN 1987, WEINGÄRTNER 1987).

$$E = \frac{L_R \cdot F_0 \cdot \cos^4 \sigma}{f^2} \tag{3}$$

F_0 is the lens aperture and f is the focal length. The position function of the angle σ between optical axis and incident ray

is generalized by a polynomial of order m to account for corrected lenses, multiple apertures, and vignetting

$$E = L_R \frac{F_0}{f^2} p^m(\sigma) \tag{4}$$

(SIEVERS 1976) gives an overview of models describing environmental influences which are not modeled so far, like extinction and atmospheric haze. (KLASSEN 1987) describes a Computer Graphics model of light scattering by suspended particles. These models may be of interest when working with aerial photographs.
In Computer Graphics a multitude of models for the physical phenomenon of image formation has been developed. They all tend to produce photorealistic images for a human observer, in part without a physical model, but with heuristics. The most interesting part of these models is the relation given for the reflected radiance L_R of a small patch of a surface to a specific direction on one hand and a complex illumination of the scene and the light reflecting properties of the material on the other. A very realistic model has been given by (COOK and TORRANCE 1981).

$$L_R = L_{Ia} \cdot R_a + \sum_n L_{In} \cdot (\underline{N} \cdot \underline{B}_n) \cdot d\omega_{In} \cdot (s \cdot R_s + d \cdot R_d) \tag{5}$$

The first part of the equation describes the reflected radiance L_R caused by incident radiance of illumination from half space L_{Ia} and the semi-spatial reflectance R_a. Ambient light from the unblocked hemisphere is reflected independent from the viewing direction. The sum in equation (5) gives the reflected radiance resulting from n light sources having radiance L_{In}. The scalar product of the unit vectors $\underline{N}$, the surface normal, and $\underline{B}$, the direction to light source n, accounts for the foreshortening of the surface patch. The apparent solid angle $d\omega_{In}$ (in steradiant) of incident radiance from a particular light source allows for the treatment of point sources and extended light sources by the piece. Also, light reflected from every surface patch in the world model can be considered, a computationally tremendous task. In equation (5) the last term in parantheses requires the introduction of the bidirectional reflectance distribution function, the characteristic ratio of radiance to irradiance of a material with given directions. While the diffuse componet R_d does not depend on the location of the observer, the specular component has to be treated differently. A suitable distribution function describes the microstructure of the surface. From this distribution, the specular component R_s is computed by assuming mirror-like microfacets. The fractions of proportionality for specular (s) and diffuse (d) reflectance multiplied with the mirror-like reflectance R_s and the diffuse reflectance R_d respectively, together with the afore-mentioned semi-spatial reflectance R_a closely approximate the reflectance properties of many materials.

Object Reconstruction
Combining equations (1),(2),(4) and (5) a distinct gray level G_i is given by

$$G_i = a + b \cdot t \; \frac{F_0 \cdot p^m(\sigma)}{f^2} \; (L_{Ia} \cdot R_a + \sum_n L_{In} \cdot (\underline{N} \cdot \underline{B})_M \cdot d\omega_{In} \cdot (s \cdot R_s + d \cdot R_d))$$

$$(6)$$

The evaluation of equation (6) requires some simplifications. Without a priori knowledge about the reflectance properties of the material, at least five picture elements are necessary to determine the normal vector

$$\underline{N} = (dZ(x,y)/dX, \; dZ(x,y)/dY, \; 1)^T$$

and ambient, diffuse and specular reflectance of a corresponding surface element (surfel). This is merely a theoretical value which does not consider the ambiguity of the solution, i.e. different combinations of lighting conditions, viewing directions and surface orientations give rise to a constant gray level. However, in estimating the surface of best fit the reflectance properties are only needed to eliminate geometrical deformations caused by illumination. But even for material with a small specular reflectance component such deformations arise, especially if

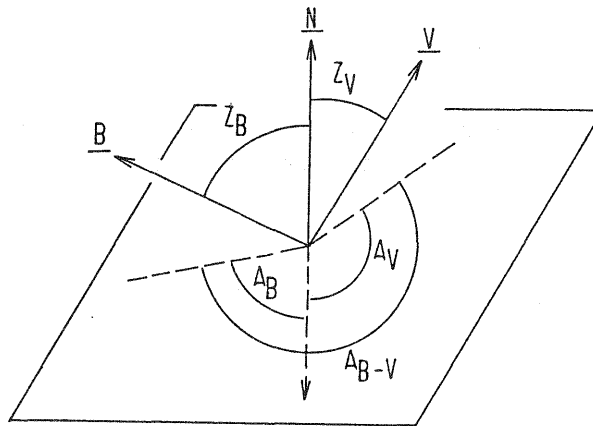$$Z_B \approx Z_V < \frac{\pi}{4} \quad \text{and} \quad A_{B-V} \approx \pi.$$

Figure 2:   The directions to a light source ($\underline{B}$) and to a center of perspectivity ($\underline{V}$) are related to the surface normal ($\underline{N}$).

The reflectance properties of most material are invariant to rotations around the surface normal, see figure 2. R_s is a function of three independent variables.

$$R_s = R_s \; (Z_B, \; Z_V, \; A_{B-V}) \tag{7}$$

For reasons of simplicity only one light source will be considered in the following. The amount of light reflected independently from the viewing direction is summarized by L_{Rd}, the specular component by L_{Rs}.

$$L_{Rd} = L_{Ia} \cdot R_a + L_I \cdot (\underline{N} \cdot \underline{B}) \cdot d\omega_I \cdot d \cdot R_d \qquad (8)$$

$$L_{Rs} = L_I \cdot (\underline{N} \cdot \underline{B}) \cdot d\omega_I \cdot s \cdot R_s \qquad (9)$$

Furthermore, some parameters are constants of an image.

$$\overline{b} = b \cdot t \cdot \frac{F_0}{f^2} \qquad (10)$$

If the sensitivity of the imaging system is calibrated, e.g. by illumination with an Ulbricht sphere-type photometer, the polynomial $p^m(\sigma)$ can be replaced by a lookup-table operation. From equation (6) we yield

$$G_i = a + \overline{b} \cdot (L_{Rd} + L_{Rs}). \qquad (11)$$

Three different models of light reflection have been investigated so far considering their features with respect to the complete model of equations (6) and (11) and to the global solution aimed at by Facet Stereo Vision. The first model uses a linear transformation from optical density D_i, i.e. apparent brightness, of a surfel to the gray level of a pixel. The transformation is valid for an entire window j of a digital image only, if the material has almost perfect diffuse reflectance,

$$G_i = a_j + \overline{b}_j \cdot D_i \qquad (12)$$

The second model assumes perfect Lambertian reflectance. All incident light is reflected according to the cosine law.

$$L_R = L_I \cdot \cos(Z_B) \qquad (13)$$

Thus equation (12) is modified by splitting up the apparent brightness into the direction component and the product of the incident light and the albedo, i.e. the attenuation of the incident light by the surface.

$$G_i = a_j + \overline{b}_j \cdot \cos(Z_B) \cdot D_i \qquad (14)$$

The formulation is of interest especially for homogeneous surfaces. If the surface properties vary at low and the surface normals at high rates, a considerable smoothing of the reflectance function follows. By this the number of reflectance facets is reduced. The third model results from applying the transformation (12) to facets instead of windows.
The relations between scenes, windows and facets have been explained elsewhere (WROBEL/WEISENSEE 1987). While the addition constant $\underline{a}$ is still valid for window j, the multiplicative constant $\overline{b}$ applies to a bilinear height- or reflectance facet k

respectively.

$$G_i = a_j + \bar{b}_k \cdot D_i \tag{15}$$

From equation (11) it is evident that all models apply to
material having $L_{Rs} = 0$. While the Lambertian function which
refers the material to an ideal white surface requires no
further explanations, the difference between equations (14) and
(15) is not obvious. If we consider the special cases of a
hemispherical and a point light source, the local validity of
the multiplicative constant gets a geometrical meaning. For the
hemispherical light source the radiance emitted by a surface
patch decreases as a function of the tilt of the surface normal
to the vertical direction, see (HORN 1987). Similar, the
radiance of a surface patch illuminated with a point light
source is attenuated by $\cos(Z_B) = (\underline{N} \cdot \underline{B})$, see equation (6).
Thus, equation (15) approximates equation (14) by substituting
the 'true' bilinear geometry of a facet by a plane of best fit,
with the assumption the light source and the sensors are
distant from the object. A third geometrical interpretation
finally arises from the fraction of the blocked hemisphere of
ambient illumination which was neglected in equation (6).

The models of light reflection introduced so far lack the abili-
ty to process specular reflecting material. Any application of
a complete shading model requires some knowledge about the bi-
directional reflectance distribution function of the material,
at least about the specular component. In case of known surface
properties, e.g. in industrial applications, the calibration of
an object can provide such information. Another clue to the
reflectance properties of a material can be the gray levels of
the digital images themselves.
Further considerations have to deal with the support of the
precise geometrical reconstruction by the interpretation of a
scene. Two different approaches seem to be feasible. A low-
level preprocessing of the digital images provides a dependence
or cooccurrence matrix. With this matrix highlights are sepa-
rated, either to omit them by a blanked-out area or to adapt
the model by introducing parameters of a specular reflectance
function. Alternatively, a classification or an object recog-
nition algorithm together with a knowledge based system can
provide 'reflection-polynomials' see (SIEVERS 1976), or equi-
valent descriptions of the material.

Conclusion
The effects of illumination and line of sight on a recorded
image depend on the light reflecting properties of the material
under observation. Without any a priori knowledge about the
parameters of the specific reflectance function a simple linear
transformation from surface radiance to image irradiance is
applied. The domain of definition of the multiplicative con-
stant is variable. Thereby, the underlying model of image for-
mation is adaptable to many scenes. If the parameters of a
reflectance function are available they can easily be introduced
into Facet Stereo Vision.

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