Available online at www.sciencedirect.com
SCIENCE DIRECT®
Image and Vision Computing 23 (2005) 177–189
image AND vision COMPUTING
www.elsevier.com/locate/imavis

Reconstruction of Lambertian surfaces by discrete equal height contours and regions propagation

Achille Braquelaire, Bertrand Kerautret*

LaBRI-UMR 5800 of the CNRS, 351 cours de la Libération, F33405 Talence, France

Received 16 January 2004; received in revised form 19 May 2004; accepted 29 June 2004

Abstract

This paper describes two new methods for the reconstruction of discrete surfaces from shading images. Both approaches are based on the reconstruction of a discrete surface by mixing photometric and geometric techniques. The processing of photometric information is based on reflectance maps, which are classic tools of Shape from Shading. The geometric features are extracted from the discrete surface and propagated along the surface. The propagation is based in one case on equal height discrete contour propagation and in the other case on region propagation. Both methods allow photometric stereo. Results of reconstruction from synthetic and real images are presented.

Keywords: Computer vision; Shape from shading; Photometric stereo; Discrete geometry

1. Introduction

Shape recovery is an important domain of computer vision the problematic of which is to reconstruct a surface from 2D images of this surface In general we consider only topographic surfaces S defined by $z=Z(x, y)$. The human system of vision may combine different information in order to perform such a reconstruction, like shadings, focus, or stereo information. But the combination of these information is not trivial and the methods developed in computer vision are generally based on the processing of one kind of data: shading, shadows, motion, stereo-vision, defocus. In this paper, winch is an extended version of Ref. [1], we address the problematic of *shape from shading* which consists in using shading information to retrieve the normal to the surface and thus its shape. This approach was introduced in 1970 by Horn [4] and many different methods have their been proposed (see Zhang et al. [20] for a comprehensive survey).

The main difficulty of shape from shading is that, for a given light source direction, a gray level may correspond to many different orientations of surface normal. The possible surface orientations for each intensity are usually represented by a map called *reflectance map*. Four approaches have been proposed:

- The global minimization approaches, the principle of which is to minimize a global energy function. Usually this energy measures a difference between the image intensity and the intensity calculated from the reconstructed surface. Additional constraints like smoothness or integrability of the surface are often used (see, e.g. Ikeuchi and Horn [6], and Frankot and Chellappa [3]).
- The local derivative approaches, the principle of which is to try to recover the shape information from the intensity image and its derivatives. For example Lee and Rosenfeld [10] compute the normal vector to the surface by using the first derivative of the intensity.
- The linear approaches used the linear approximation of the reflectance function (see Pentland [11] or Tsai and Shah [17]).
- The propagation approaches, which consist in propagating shape information from singular points. The first shape from shading technique introduced by Horn was a propagation approach with a reconstruction based on the extension of characteristic strips [4].

* Corresponding author. Tel.: +33 5 40 00 6091; fax: +33 5 40 00 38 95.
E-mail addresses: keraute@labri.fr (B. Kerautret), achille@labri.fr (A. Braquelaire).

0262-8856/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.imavis.2004.06.006

In some areas of the image, the reconstruction of the surface may be altered by self shadows or inter-reflections. Self-shadows depend both on the orientation of the surface and on the position of the light source. Thus the reconstruction may be improved by considering more than one image of the surface, for instance with several different light source directions. This technique, called photometric stereo, was introduced by Woodam [19] for the reconstruction of the surface gradient from several images and is suited to minimization methods (e.g. Saito proposed a method based on this principle for recovering the skin surface [12,18]).

In this work we develop methods based on the processing of geometric features extracted from the explicit reconstruction of the discrete surface. The reconstruction of the surface is based on the propagation of geometrical features related to equal height contours or regions. The propagation of equal height information called level sets has been introduced by Kimmel and Bruckstein in 1995 [8,9]. A closed curve was initialized in the areas of singular points and propagated according to the light source direction. The evolution of the parametric curve was solved *via* a Eulerian formulation. The propagation direction in the direction of the light source makes possible to solve the ambiguities and to choose between multiple solutions. But this restriction is not compatible with the use of several light sources.

In the following, we propose two methods of shape from shading based on the local estimation of the discrete surface normal and the propagation of height information. Both methods can be used with several images in order to improve the reconstruction. We have tested these methods both on computer-generated images and on real images provided by archaeologists. The real images we use are photos of carved stone and of resin casts of small archaeological objects. In both cases, it is possible to make the hypothesis that the surface to reconstruct is a Lambertian surface. A Lambertian surface is a surface with only diffuse reflectance. The intensity only depends on the normal vector and on the light source direction and thus does not depend on the position of the observer.

In Section 2 we briefly recall the definition of reflectance map introduced by Horn in 1977 [5] to describe the luminance of a Lambertian surface in function of the orientation of the surface normal. In Section 3 we present a shape from shading method based on the propagation of equal height contours and in Section 4 a method based on the propagation of regions.

2. Reflectance map

It is convenient to choose a coordinate system (O, x, y, z) where the z-axis is in the direction of the observer. In this viewer-oriented coordinate system a direction can be measured with polar and azimuth angles θ and ϕ (Fig. 1). The directions of light sources or of surface normals are defined by both these angles. Moreover, a surface of an object may be specified as an elevation function $Z(x, y)$. Then the normal direction can be given with the partial derivatives of height of the surface $Z(x, y)$:

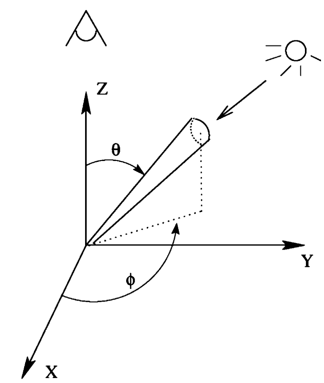

Fig. 1. Viewer-oriented coordinate system, with polar and azimuth angles θ and ϕ.

$$p = \frac{\partial Z(x,y)}{\partial x} \text{ and } q = \frac{\partial Z(x,y)}{\partial y}$$

We can thus derive the value of p and q from the polar and azimuth value:

$$p = -\cos\phi \tan\theta \text{ and } q = -\sin\phi \tan\theta \quad (1)$$

where (ϕ, θ) is the direction of the normal at the point (x, y).

Given a light source of direction (p_s, q_s) and a surface $Z(x, y)$ it is convenient to describe the intensity of the surface by a function $R(p, q)$ of the orientation of the normal. This function is called a *reflectance map*. For a Lambertian surface the reflectance map is given by:

$$R(p,q) = B\rho \frac{1 + pp_s + qq_s}{\sqrt{1 + p^2 + q^2}\sqrt{1 + p_s^2 + q_s^2}} \quad (2)$$

where ρ represents the surface albedo, i.e. the ratio of the amount of reflected light over the amount of incoming light, B is the strength of the light and p_s and q_s are associated with the light source direction.

The reflectance map is usually depicted as a series of iso-intensity contours. Fig. 2 shows an example of reflectance map for a Lambertian surface. Given an image intensity L_i the possible orientations of the surface at this point are given by the *reflectance equation*:

$$R(p,q) = L_i \quad (3)$$

By substituting p and q by ϕ and θ in Eq. (3) we get:

$$\sqrt{1 + \tan^2\theta} = \frac{1 - \omega \tan\theta}{K} \quad (4)$$

with

$$K = \frac{L_i}{B_\rho}\sqrt{1 + p_s^2 + q_s^2}$$

and $\omega = p_s \cos\phi + q_s \sin\phi$.