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# Shape from 2D Edge Gradients.

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## Shape from 2D Edge Gradients

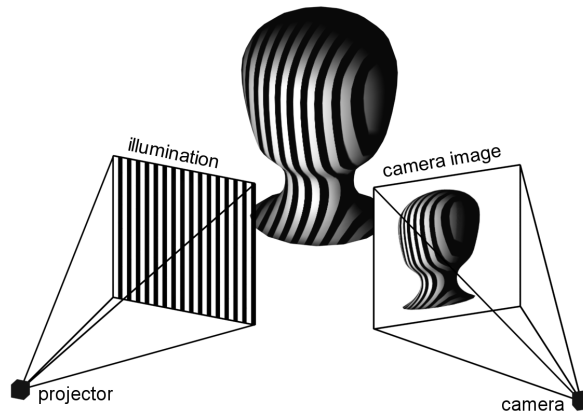
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**Abstract.** This paper presents a novel strategy for rapid reconstruction of 3d surfaces based on 2d gradient directions. I.e., this method does not use triangulation for range data acquisition, but rather computes surface normals. These normals are 2d integrated and thus yield the desired surface coordinates; in addition they can be used to compute robust 3d features of free form surfaces. The reconstruction can be realized with uncalibrated systems by means of very fast and simple table look-up operations with moderate accuracy, or with calibrated systems with superior precision.

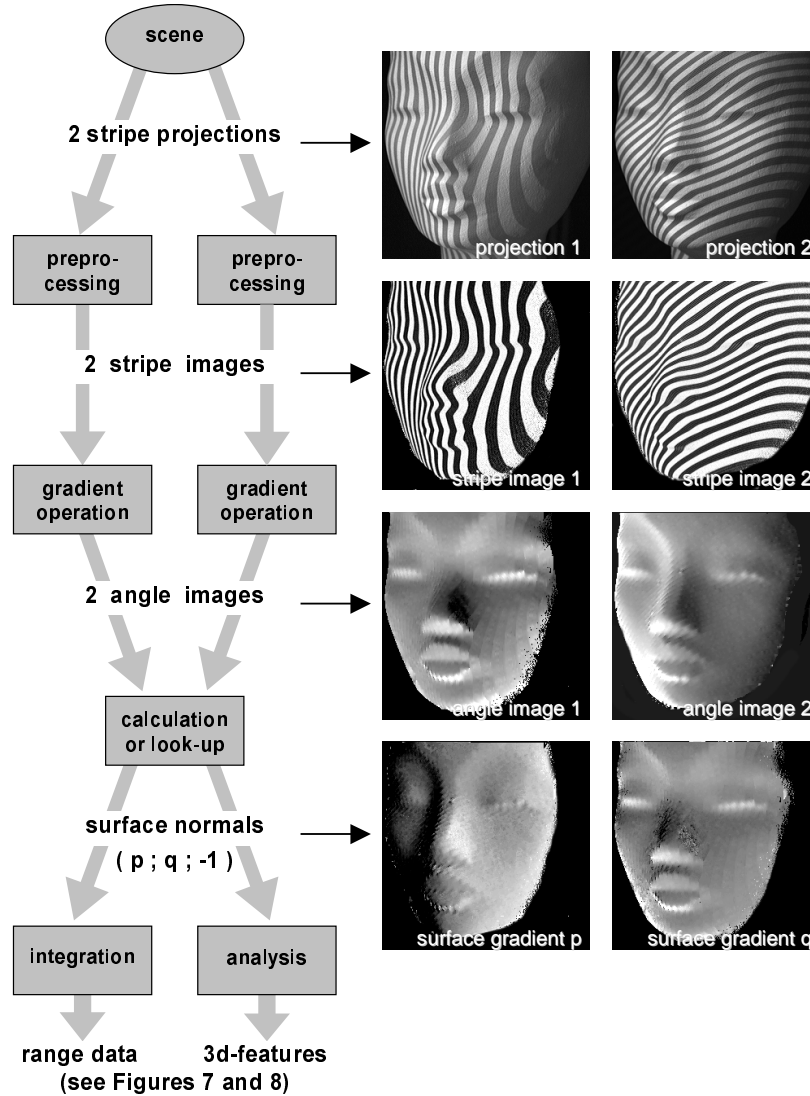
### 1. Introduction

Many range finding techniques have been proposed in the open literature, such as stereo vision [1], structured light [2,3,4,5], coded light [6], shape from texture [7,8], shape from shading [9], etc.. Similar to some structured light methods, our suggested novel approach for 3d surface reconstruction requires one camera and two light stripe projections onto an object to be reconstructed (Fig. 1). However: *Our reconstruction technique is based on the fact, that angles of stripes in the captured 2d image depend on the orientation of the local object surface in 3d. Surface normals and range data are not obtained via triangulation, like in the case of most structured light or coded*



**Fig. 1.** System setup with light projector and camera

light approaches, but rather by computing the stripe angles of the 2d stripe image by means of gradient directions. Each stripe angle determines one degree of freedom of the local surface normal. Therefore, the total reconstruction of all visible surface normals requires at least two projections with rotated stripe patterns relative to each other. At first glance, an almost similar method using a square pattern has been presented in [10]; in contrast to our approach it requires complex computation, e.g. for detection of lines and line crossing and for checking of grid connectivity. Moreover, it utilizes a lower density of measurement points yielding a lower lateral resolution.

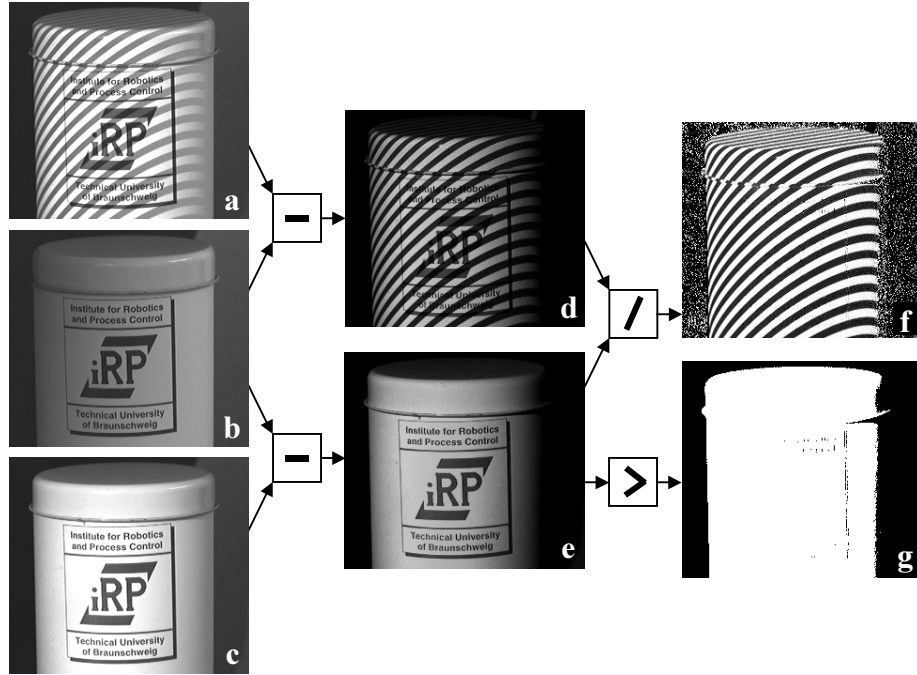


**Fig. 2.** Processing steps of the 'Shape form 2D Edge Gradients' approach

## 2. Measurement Principle

The surface reconstruction can be subdivided into several functional steps (see Fig. 2). First, we take two grey level images of the scene illuminated with two differently rotated stripe patterns. Undesired information, like inhomogeneous object shadings and textures are eliminated by an optional appropriate preprocessing (Section 3). Subsequently, local angles of stripe edges are measured by a gradient operator. This leads to two angle images, which still contain erroneous angles and outliers which have to be extracted and replaced by interpolated values in an additional step (Section 4). On the basis of two stripe angles at one image pixel we calculate the local 3d surface slope or surface normal (Section 5). The surface normals can be used to reconstruct the surface itself, or they can be utilized as basis for 3d feature computation (Section 6).

## 3. Preprocessing

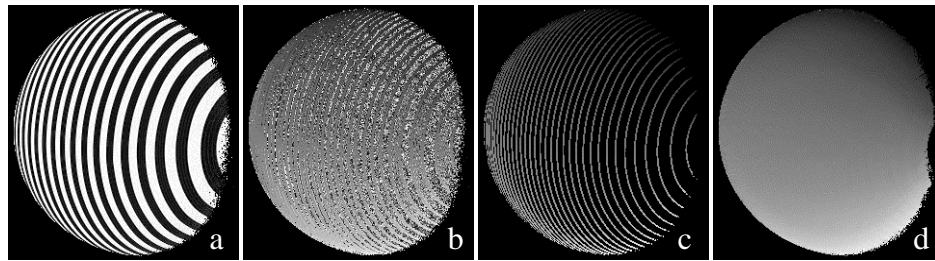


**Fig. 3.** Preprocessing steps of a textured test object. (a) object illuminated with stripe pattern; (b) object with ambient light; (c) object with homogeneous projector illumination; (d) absolute difference between (a) and (b); (e) absolute difference between (b) and (c); (f) normalized stripe image; (g) binary mask

In order to be able to detect and analyse the illumination stripe patterns in grey level images, we apply an adapted optional preprocessing procedure, which separates the stripe pattern from arbitrary surface reflection characteristics of the object (color, texture, etc.). Fig. 3 illustrates this procedure: After capturing the scene with stripe illumination (a) we acquire a second image with ambient light (b) and a third one with homogenous illumination by the projector (c). Using the absolute difference ( $d = |a-b|$ ) we scale the dark stripes to zero value and separate them from object color. However, shadings and varying reflections caused by the projected light still are retained in the bright stripes. For this reason we normalize the stripe signal (d) to a constant magnitude by dividing it by the absolute difference (e) between the illuminated and non-illuminated image ( $f = d / e$ ). As can be seen from Fig. 3f, noise is intensified as well by this division; it gets the same contrast as the stripe patterns. This noise arises in areas, where the projector illuminates the object surface with low intensity. Therefore we eliminate it by using the mask ( $g = 1$  if ( $e > \text{threshold}$ ),  $g = 0$  else ).

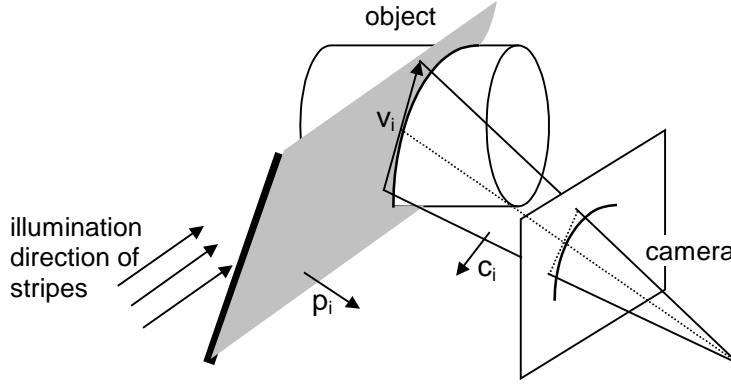
#### 4. Stripe Angle Determination

After preprocessing the stripe images, determination of stripe angles can take place by well-known gradient operators. We evaluated different gradient operators like Sobel, Canny, etc. to investigate their suitability. Fig. 4 shows the preprocessed stripe image of a spherical surface in (a), gradient directions in (b) (angles are represented by different grey levels); in this case the Sobel operator has been applied. Noisy angles arise mainly in homogenous areas where gradient magnitudes are low. Thus low gradient magnitudes can be used to eliminate erroneous angles and to replace them by interpolated data from the neighbourhood. For angle interpolation we propose an efficient data-dependent averaging interpolation scheme: A homogeneous averaging-filter is applied to the masked grey level image and the result is divided by the likewise average-filtered binary mask (0 for invalid and 1 for valid angles). In this way one obtains the average value of *valid* angles within the operator window. Finally, erroneous angles are replaced by the interpolated ones.



**Fig. 4.** Computation of angle images. (a) Stripe image; (b) Sobel gradient angles (angle image); (c) masked angle image by means of gradient magnitude; (d) interpolated angle image

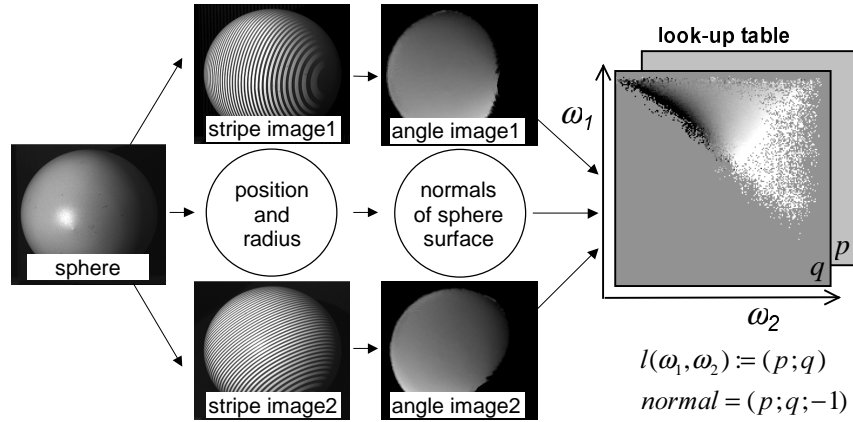
## 5. Surface Normal Computation



**Fig. 5.** Projection of a stripe on an object

We investigated two methods to compute surface slopes (or normals) from stripe angles: A mathematical correct computation with calibrated optical systems (camera and light projectors) on the one hand and on the other hand a simple table look-up method which maps two stripe angles to one surface normal. Due to the limited space of this paper, we only will give a general idea of the mathematical solution: The angle values  $\omega_1, \omega_2$  of both rotated stripe projections and their 2d image coordinates specify two “camera planes”  $p_1, p_2$  and corresponding normals  $c_1, c_2$  (see Fig. 5). The tangential direction vector  $v_i$  of a projected stripe on the object surface is orthogonal to  $c_i$  and orthogonal to the normal  $p$  of the stripe projection plane. So we can use the following simple equation to calculate the surface normal:  $n = (c_1 \times p_1) \times (c_2 \times p_2)$

Generation of the look-up table in the second approach works in a similar way like the look-up table based implementation of photometric stereo [9]:

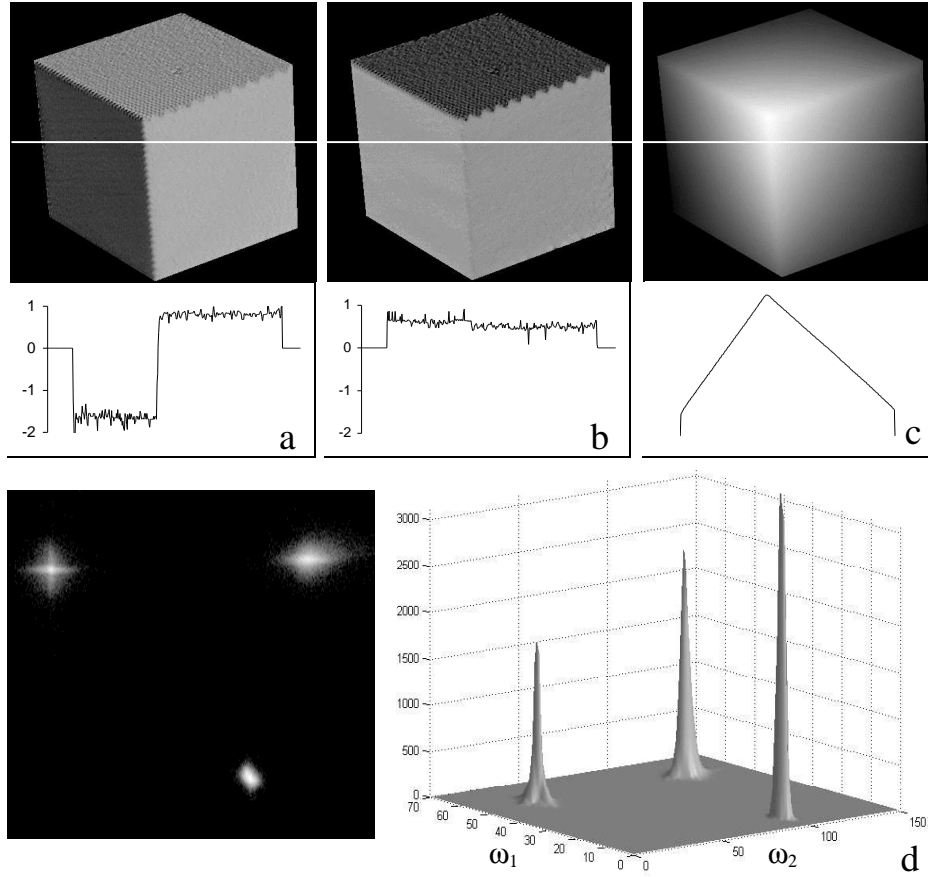


**Fig. 6.** Computation of the look-up table with use of stripe projections onto a spherical surface

By means of the previously described processing steps, we first estimate the stripe angles of two stripe projections rotated relatively to each other onto a spherical surface (see Fig. 6). As the surface normals of a sphere are known, we can use the two angle values  $\omega_1$ ,  $\omega_2$  at each surface point of the sphere to fill the 2d look-up table with  $\omega_1$  and  $\omega_2$  as address. Subsequently, missing values in the table are computed by interpolation. Now the look-up table can be used to map two stripe angles to one surface normal. To compute range data from surface slopes we applied the 2d integration method proposed by Frankot/Chellappa [11].

## 6. Experimental Results and Conclusions

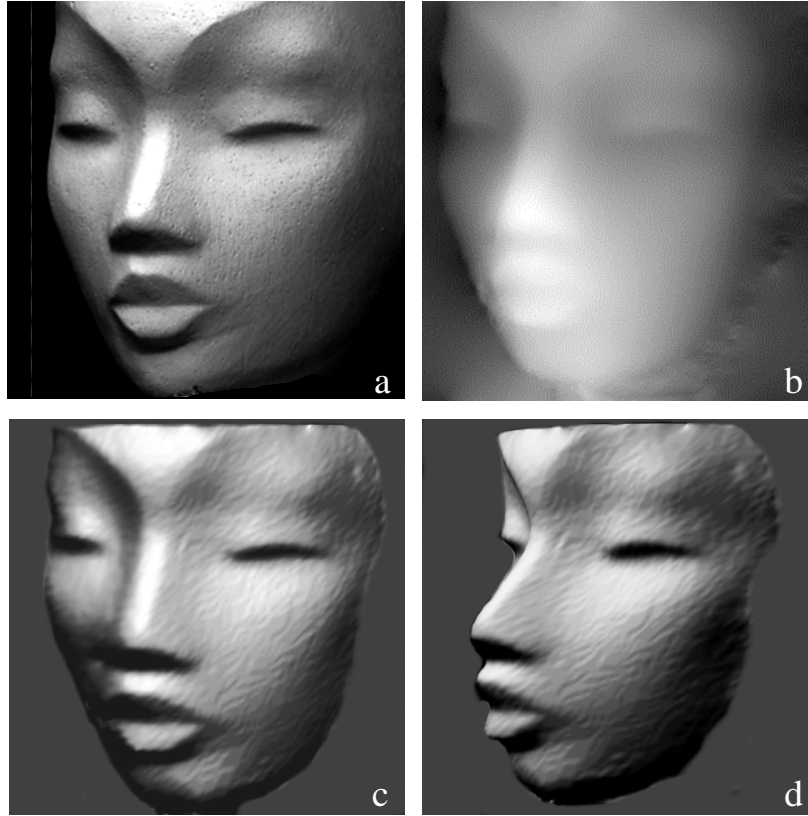
The following images illustrate experimental results of the look-up table approach proposed above.



**Fig. 7.** Depths data and plane features of a test cube: (a) surface x-gradient, (b) surface y-gradient, (c) range map with corresponding line profiles; (d) histograms of  $(\omega_1, \omega_2)$ -tuples

Fig. 7 shows the gradients of a cube and plots of sample lines. The ideal surface gradients are constant within every face of the cube. Thus, accuracy of measurement can be evaluated by the standard deviation within a face, which in our first experiments shown here is approximately 0.4109 degree. Errors are reduced after integration (see Fig.7(c)). Fig.7(d) shows the 2d histogram of the gradient direction tuples  $\omega_1, \omega_2$ , corresponding to the three faces of the cube.

Fig. 8 shows the 2d grey level image of a styrofoam head, its reconstructed range map and its corresponding rendered grey level images from two different viewing directions. Using more than two stripe projections from different illumination directions can improve the reconstruction result.



**Fig. 8.** Reconstruction of a styrofoam head: (a) grey level image; (b) reconstructed range map; (c and d) corresponding rendered grey level images from two different viewing directions obtained by virtual illumination in 3d

In many applications surface normals are an important basis for robust 3d features, as for example surface orientations, relative angles, curvatures, local maxima and saddle points of surface shape. An advantage of our approach is, that it is very efficient and directly generates surface normals without the necessity deriving them subsequently



from noisy range data. In case of textured and inhomogeneously reflecting objects our technique offers a higher robustness in comparison to most other methods.

Due to the limited space of this paper, we only have been able to present a rough outline of our new approach. Discussions about important aspects like a detailed error analysis, applications of our technique, etc. are subject of further publications [12]. Regarding accuracy, we should mention, that in the experiments shown above, we used optical systems with long focal lengths. Although our experiments are very promising, the new technique is open for improvements. E.g., the reconstruction time can be reduced by color-coding the two stripe patterns and projecting them simultaneously. Acquiring several stripe images with phase shifted stripe patterns could increase the number of gradients with high magnitudes, thus reducing the need for replacing erroneous gradient directions by interpolation. An alternative augmented technique uses only one stripe projection for full 3d surface reconstruction [13]. This is possible by determining the stripe angles and the stripe widths as source of information to estimate surface orientations.

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