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Comments

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Alok Gupta

MS-CIS-88-32
GRASP LAB 141

Department of Computer and Information Science
School of Engineering and Applied Science
University of Pennsylvania
Philadelphia, PA 19104

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UNIVERSITY OF PENNSYLVANIA
THE MOORE SCHOOL OF ELECTRICAL ENGINEERING
SCHOOL OF ENGINEERING AND APPLIED SCIENCE

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Alok Gupta

Philadelphia, Pennsylvania
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A thesis presented to the Faculty of Engineering and Applied Science of the University of Pennsylvania in partial fulfillment of the requirements for the degree of Master of Science in Engineering for graduate work in Computer and Information Science.

[illegible]

Ruzena Bajcsy
(Advisor)

[illegible]

Richard Paul
(Graduate Group Chair)

Abstract

Three dimensional scene analysis in an unconstrained and uncontrolled environment is the ultimate goal of computer vision. Explicit depth information about the scene is of tremendous help in segmentation and recognition of objects. Range image interpretation with a view of obtaining low-level features to guide mid-level and high-level segmentation and recognition processes is described. No assumptions about the scene are made and algorithms are applicable to any general single viewpoint range image. Low-level features like step edges and surface characteristics are extracted from the images and segmentation is performed based on individual features as well as combination of features. A high level recognition process based on superquadric fitting is described to demonstrate the usefulness of initial segmentation based on edges. A classification algorithm based on surface curvatures is used to obtain initial segmentation of the scene. Objects segmented using edge information are then classified using surface curvatures. Various applications of surface curvatures in mid and high level recognition processes are discussed. These include surface reconstruction, segmentation into convex patches and detection of smooth edges. Algorithms are run on real range images and results are discussed in detail.

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Contents

Chapter 1

Introduction

Three dimensional scene analysis in an unconstrained and uncontrolled environment is the ultimate goal of computer vision. Most of the effort in this regard has gone in extracting three dimensional information from intensity images and arriving at a meaningful and sufficiently unambiguous interpretation of the scene. However, the problem with monocular vision is the loss of 3-D information thereby making the interpretation process underconstrained. Shape from X methods have been widely studied in last two decades to extract depth of the scene using texture,shading,color,contour and motion. Depth extraction from stereo images is computationally expensive and results in sparse depth maps requiring reconstruction techniques for further interpretation. Range images on the other hand are obtained by realtime depth sensors and provide dense 3-D information of the visible surfaces.

Range images are dense depth maps measuring the distance of the physical surface from a known reference plane. Different types of ranging methods are available to obtain range information according to the application. Magnetic resonance imaging systems give true 3-D images, i.e, all the points in 3-D space are specified. Visible surfaces can be scanned by time of flight laser range finders and amplitude-modulated laser range finders. The most common and cheapest are the triangulatiòn-based scanners. Structured lighting systems scan the scene with a laser stripe to obtain depth information of the visible surface in a calibrated workspace. Research interest in range image processing has grown tremendously in recent years due to increasing availability of structured lighting range sensors. While these sensors can be employed in closed environment only and suffer from other drawbacks (like shadows, inability to sense highly reflective surfaces and some colors) they are useful for real-time scanning of good quality at low cost.

The range images dealt with in this work are of $z(x, y)$ type, (i.e., monge-patch surfaces) where each pixel gives the Z-depth at the coordinate x and y. Since range images (or depth maps) contain explicit 3-D information about the scene it is expected that surface description and object recognition should be easier to handle with range images. However if the scene is quite complicated, then the problem cannot be solved that easily by using range images as one might think. Intensity information can be used to complement range information where ambiguity arises in interpretation, but this involves registration and correspondence problems and may even complicate the analysis.

Representation of range images is just like that of reflectance images. A two dimensional array of depth values specifying (x,y,z) coordinates with respect to a known coordinate frame is enough for most applications. This allows many low level intensity image processing techniques to be directly used to process range images by interpreting the pixel value as 'depth' instead of 'reflectance value'. Contrast and brightness however have to be interpreted as surfaces of varying depths.

We have addressed the problem of object and surface segmentation in this report. Segmentation is essentially goal oriented. It can be conveniently divided into two processes : initial segmentation and final segmentation. Initial segmentation process is a result of local computations done in a known neighborhood of every pixel in the image. The final segmentation process does refinement of the initial segmentation using global constraints to arrive at a global interpretation of the scene. We have not assumed any domain knowledge or limited the objects to be of certain type. Our goal is to study boundary based segmentation, surface based segmentation and integration of the two methods. It is possible to segment the scene in flat, convex and concave subparts with detailed description of individual parts using boundary and surface based techniques.

An important aspect of the object recognition problem is the robustness of the recognition approach. It is essential that algorithm be size-invariant, position invariant, orientation invariant and be able to recognize partially occluded objects. As observed by Besl and Jain [9] it is known from the results in differential geometry that Gaussian and mean curvature are visible-invariant features of a surface region in the sense that they do not change under viewpoint transformations that do not affect the visibility of that region. When a surface region is visible, its curvature measurements are invariant to changes in surface parametrization and to translations and rotations. The invariant property is important for 3-D object recognition. Since our final segmentation process will be dependent on the local computations it is necessary that the low-level features be invariant.

While these two approaches are domain independent, any high level recognition approach like model based interpretation makes use of domain specific knowledge. We use a high level volumetric approach using superquadrics described in [23] to illustrate the usefulness of initial segmentation in high level vision. Figure 1 presents the paradigm explored in this work.

It is clear that processing of range images can be divided into three major stages : low level, intermediate level and high level. After range image is acquired from the sensor, it needs to be smoothed before any useful operations can be performed on it. Though it creates localization problems, it reduces the effect of quantization which is important for surface fitting. Low level processing is data-driven with the objective of obtaining useful local features that can be used by higher processing stages. Three dimensional edges constitute important features. We have used the Laplacian of Gaussian operator of [24] to detect step edges. *Smooth* edges have a different significance in case of range images and are more difficult to detect. This will be discussed in chapter 3 in detail.

Computation of curvature involves computing first and second order derivatives at every pixel in the image. Based on curvature signs, initial segmentation of the scene is performed. This is further improved by region growing done with global constraints. Haralick *et al* [6] have described a mathematical treatment for describing the topographic primal sketch of the

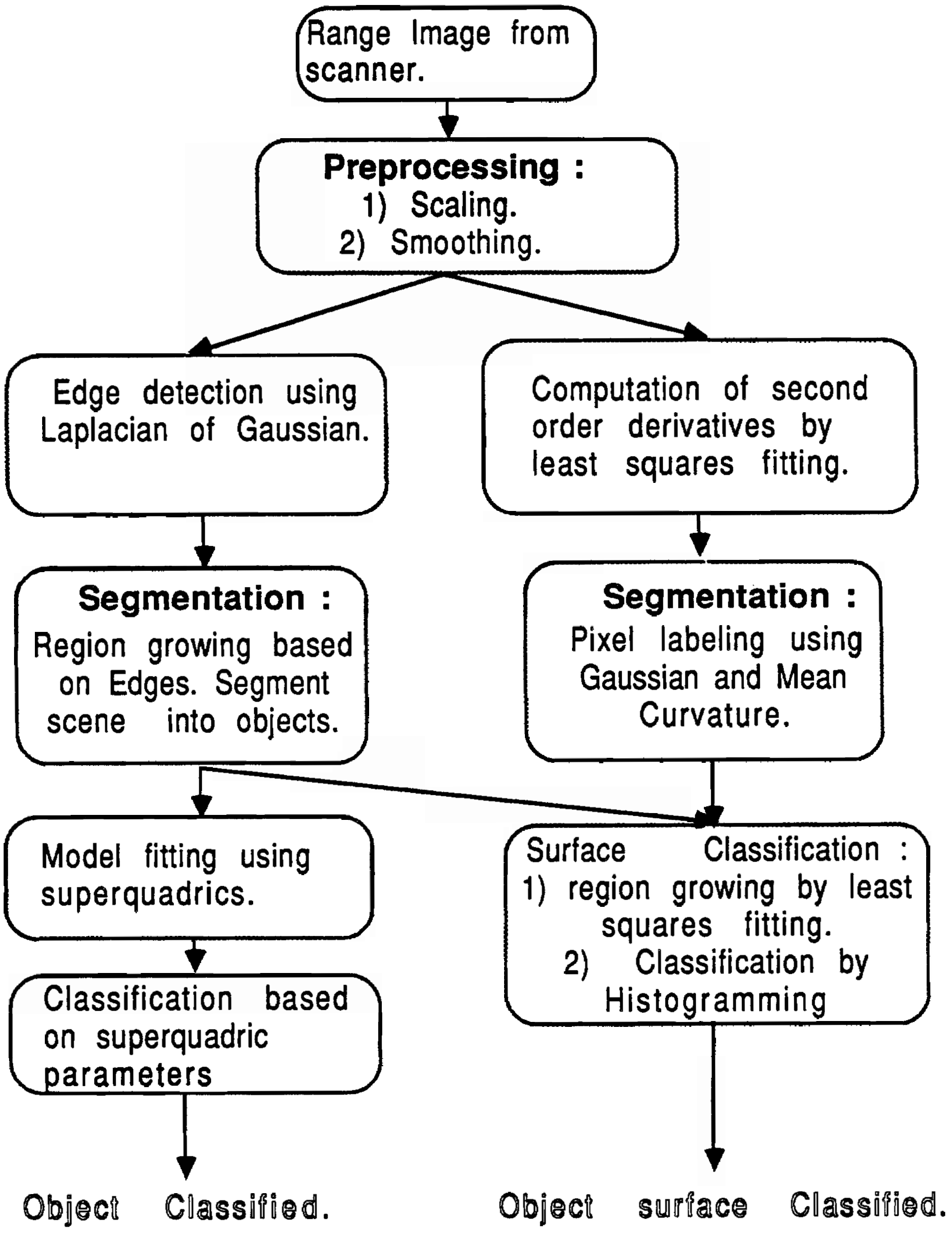

Range Image from scanner.
Preprocessing : 1) Scaling. 2) Smoothing.
Edge detection using Laplacian of Gaussian.
Computation of second order derivatives by least squares fitting.
Segmentation : Region growing based on Edges. Segment scene into objects.
Segmentation : Pixel labeling using Gaussian and Mean Curvature.
Model fitting using superquadrics.
Surface Classification : 1) region growing by least squares fitting. 2) Classification by Histogramming
Classification based on superquadric parameters
Object Classified.
Object surface Classified.

Figure 1: A paradigm for Range Image Segmentation and 3-D object recognition

underlying gray tone intensity surface of a digital image. They use first and second directional derivatives to classify each picture element as one of peak,pit,ridge,ravine,saddle,flat, and hillside. Michael Brady *etal* [4, 5, 7] describe a study of classes of curves as a source of constraint on the surface on which they lie, and as a basis for describing it. Their approach gives a curvature primal sketch of the surface. Tracing lines of curvature in real range images is very unreliable due to the low x-y resolution of the scanner and quantization and other sensing errors. Besides it is noise sensitive and computationally expensive. Besl and Jain [25, 9, 13] have done a comprehensive study of invariant surface characteristics and presented an algorithm for variable order surface fitting for image segmentation. They have summarized the field of 3-D object recognition in their excellent survey [3]

A scale-space based algorithm for extraction and representation of physical properties of a surface, using curvature properties of the surface is discussed in Fan,Medioni and Nevatia [14]. Nackman [19] has described the two dimensional critical point configuration graphs for describing the behavior of smooth functions of two variables by extracting peaks (local maxima), pits(local minima) and passes (saddle points) of a surface. Our approach is to not to go into too much detail of the surface but to label the surface as flat,convex and concave accurately. Thus local variations are ignored in favour of a more global interpretation. Yang and Kak [33] describe an algorithm to analyze the topmost object in a pile. They compute derivatives by fitting B-splines and use local curvature information to label the object as flat and curved. Their method can only handle one type of surface for the topmost object in the scene and has other problems in assuming that step edges form a closed contour, which is not true in a general range image as described in chapter 3. A new approach for surface classification using characteristic contours is proposed by Sethi and Jayaramamurthy [20]. Characteristic contours are defined as the loci of the points where the surface normals are at a constant inclination to a selected reference vector. However it requires segmented surface and normal vector at every point, which limit its usefulness to surface classification in final stage of recognition process.

Their are specific methods available to process images acquired using a light-stripe rangefinder. Smith and Kanade [34] have done contour classification of light-stripes to produce object centered 3-dimensional descriptions. Another method by Martin Herman [35] extracts detailed, complete descriptions of polyhedral objects from light-stripe rangefinder data.

Segmentation of scene into surface primitives is useful in many applications. Most of the techniques discussed above involve curvature determination. Hebert and Ponce [8] have used surface normals (the Extended Gaussian Images) to classify surfaces into three simple primitive surfaces: planar,cylindrical, and conic regions. Duda, Nitzan and Barrett [36] have presented an algorithm for detecting planar regions using registered range and reflectance data.

Most of the high level recognition approaches include model matching. Kuan and Drazovich [37] have represented the objects as viewpoint-independent volumetric model based on generalized cylinders. They perform feature-to-model matching based on low-level features derived from range imagery. Constructing the 3-D model of an object involves integrating data or descriptions of an object obtained from multiple views and representing this intergrated data in a coherent manner. Vemuri and Aggarwal [38] have presented an algorithm for automatic construction of models by determining the orientation of the object in the calibrated workspace and representing the object in cylindrical coordinates. Their method does not require correspondence to be established but requires registered intensity and range data of the scene while building the model. We have used superquadric models to recognize segmented objects. The classification procedure matches superquadric parameters with the parameters of the identifiable models. Since models are well defined by eleven superquadric parameters, there is no need to build models of the objects in advance.

Chapter 2

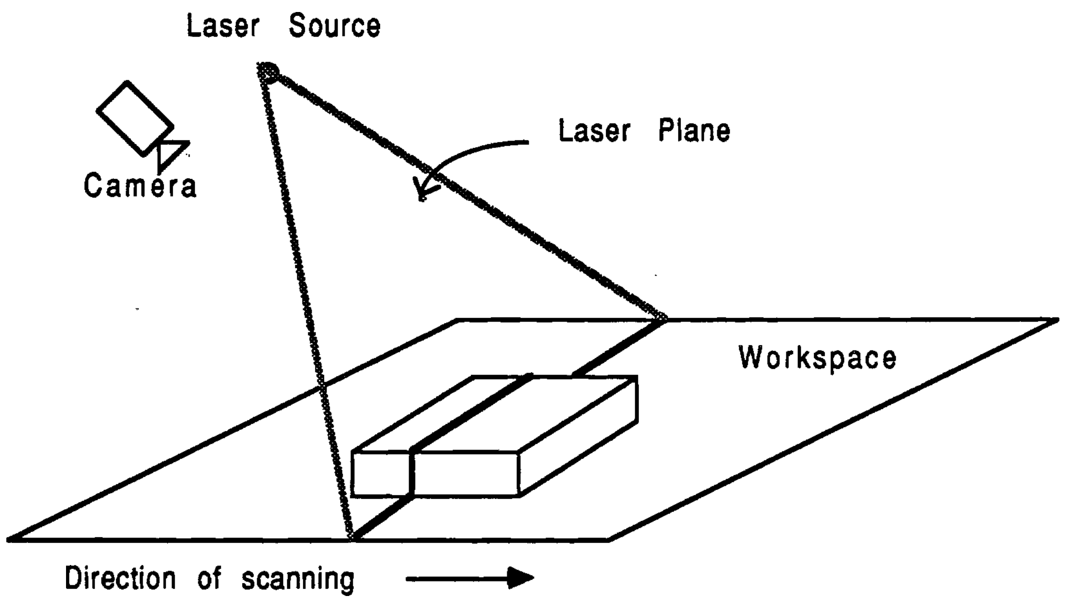
Acquisition and Preprocessing of Range Images

Range images obtained by different scanners differ in the format of the output. In order to apply low level techniques to the image it is necessary that the image points be quantized in Z-depth format with equal resolution factor in X and Y direction. Once converted into Z-depth format the image is smoothed.This chapter discusses some practical aspects of real range image processing which are important if any useful results are desired.

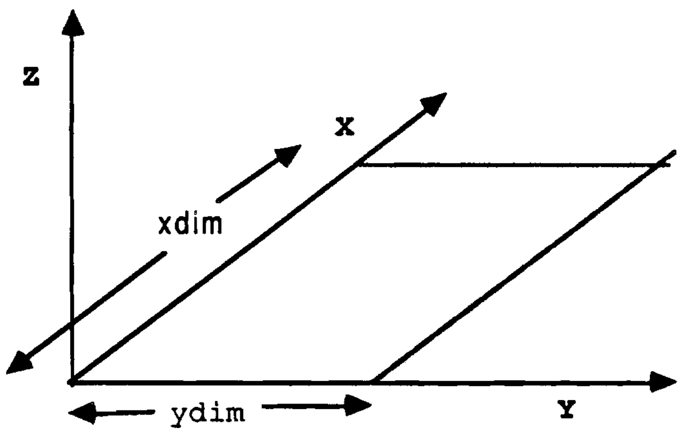
2.1 Range Image Acquisition

The test images used in this work were acquired by structured lighting triangulation based scanners. Figure 2 shows the ranging geometry of a typical range sensor. The trigonometry of a sensor will not be described here.

Either the laser stripe moves and scans the scene or the workspace moves under a vertical laser stripe. If the viewpoint of the sensing camera is not the same as the laser then *shadows* (regions with missing data) are obtained. In order to discriminate between shadows and background, (region of known depth on which object is sitting) background is assigned a nonzero depth.



(a) Ranging using structured lighting.



(b) Z-depth format of range images

Figure 2: Ranging geometry of a structured lighting scanner and Z-depth format

Contrary to the popular assumption made by researchers, it may not always be possible to represent the visible surface in Z-depth format, viewing perpendicular to the background. To be able to represent all the scanned points in Z-depth format, it is necessary to digitize the scene watching parallel to camera's line of sight. This may require rotating the scene to align the Z axis along the line of sight of camera thereby rotating the background which is no longer of constant depth. The segmentation procedure should take this into account. Also, this makes the processing viewpoint dependent. To avoid the trouble arising due to this, it is often convenient to fix the viewpoint at the cost of losing some scanned points. This problem is acute with images obtained from white scanner where $f(x, y)$ is not unique. The solution is to segment the scene from background and then rotate the scene to obtain the Z-depth image.

2.2 Scaling of Range Images

Sampling interval of the scanners depends on the thickness of the laser stripe, value of laser stripe increment and resolution of the camera. More often than not vertical resolution (along Y axis) is different from horizontal resolution (along X axis). Thus the sampled points are not spaced uniformly in X and Y direction. Since we apply neighborhood operators during low level processing of images, it is necessary to rescale the images uniformly in both directions. We have rescaled the Z-depth image by fitting a plane on three neighborhood points. Figure 3 illustrates the difference between unscaled and uniformly scaled images.

2.3 Smoothing of Range Images

Depth resolution of a range image is an important parameter in low level processing. Range scanners usually have depth resolution good enough for most applications. In fact a resolution of 0.01 inch/pixel is too fine and noise sensitive for surface fitting purposes. The problem comes in quantization of z values. If entire scan depth is quantized within 8 bits (most convenient representation), effective depth resolution is drastically reduced thereby

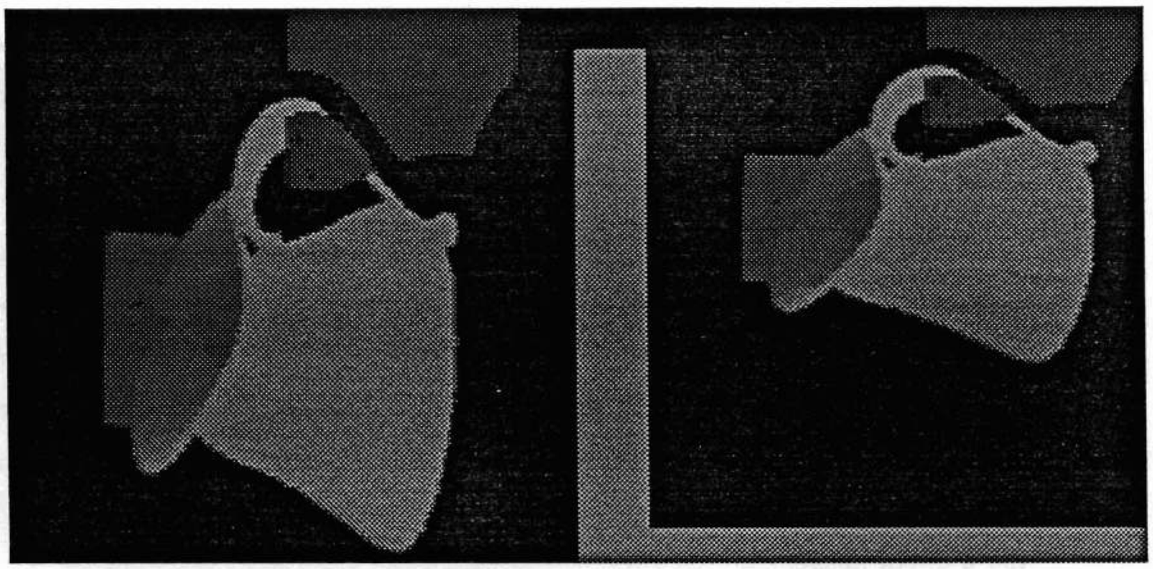


Figure 3: **Z-depth format images.** left :original resolution. right : uniformly scaled

increasing the quantization error. Since surface fitting is very sensitive to quantization error, we have minimized it by following two step procedure :

1. Original depth resolution is preserved by storing the depth value unscaled in 2 bytes. This allows 64k possible quantization levels. Scaling along Z axis is done only when needed.

2. Image is smoothed using a Gaussian operator and smoothed values are stored in floating point buffers so as not to lose any precision.

One way to reduce noise is to perform median filtering of the image. It ensures that isolated noise is reduced and *edges* are not smoothed.

Our approach is to study the scale-space behavior of range images. We have used Gaussian operator to smooth images. The Gaussian function in two dimensions is given by :

$$\mathbf{G}(x, y) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x^2+y^2)}{2\sigma^2}}$$

Since it is separable in X and Y directions, one dimensional Gaussian operator is applied separably on the image. Smoothing is controlled by the size of the operator, which is determined by σ. Gaussian operator has some nice properties that make it a unique operator for our purposes.

Yuille and Poggio [39] have proved that the Gaussian low-pass filter is the only filter with a nice-scaling behavior for linear derivative operators like the laplacian operator. It also satisfies the following conditions :

1. Filtering is shift-invariant and therefore, a convolution.

$$F \times I(x) = \int F(x-\alpha)I(\alpha)dx)$$

2. The filter has no preferred scale. The filter is properly normalized at all the scales.

3. The filter recovers the whole image at sufficiently small scales.

$$\lim_{\sigma \to 0} F(x,\sigma) = \delta(x)$$

   where δ(x) is the Dirac delta function.

4. The position of the center of the filter is independent of scale of the filter. Otherwise zero crossings of a step edge would change their position with change of scale.

5. The filter goes to zero as $|x| \to \infty$ and as $\sigma \to \infty$.

We have studied the behavior of increasing sigma value on edge detection, surface characterization and segmentation. As σ value increases, window size of the Gaussian operator increases and details are lost. Figure 4 and figure 5 show the perspective plots of a range image before and after smoothing respectively.

Minor surface perturbations are smoothed easily. But the undesirable effect of uniform application of Gaussian operator is smoothing of all types of edges. Step edges (chapter 3) are smoothed to form roughly convex and concave subparts (chapter 4).This complicates edge detection, specially detection of smooth edges (concave and convex edges) that are

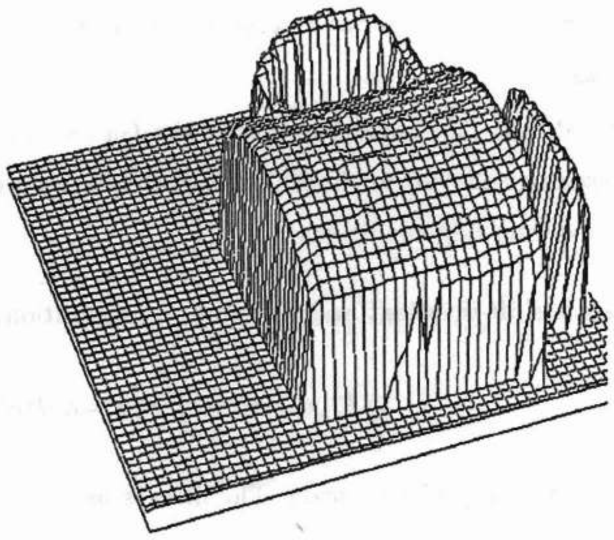


Figure 4: 3-D perspective plot of original image

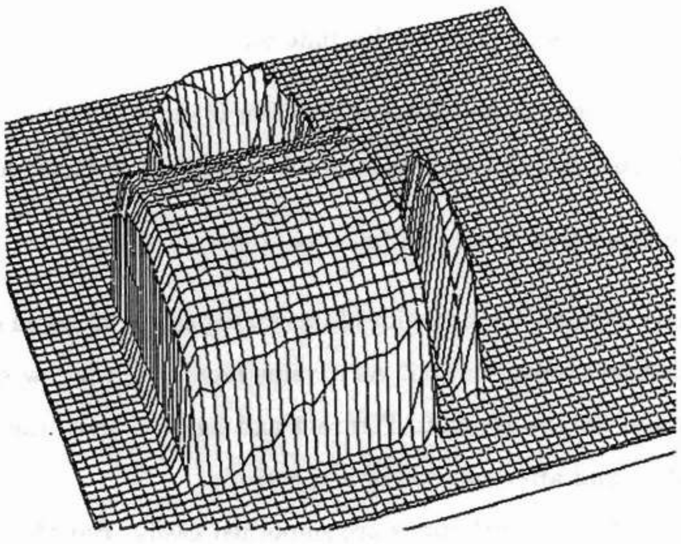


Figure 5: 3-D perspective plot of smoothed image ($\sigma = 1$)

further smoothed. Thin objects tend to merge into the underlying objects, making segmentation difficult. As will be discussed in chapter 3, as we go up the scale objects start merging. We have found sigma value of 1 (window size 5×5) to be best suited for our experiments. In surface based segmentation technique, smoothing alters the local behavior of the surface, but makes the result more reliable, specially away from the edges. Step edges are shown as adjacent convex and concave regions. Segmentation using these effects of smoothing is discussed in chapter 4 in detail.

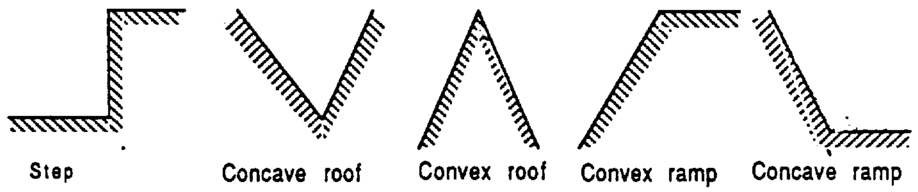


Figure 6: Edges in range images

allows boundaries to be read off as zero crossings of the LOG operated image. We'll discuss the significance of the LOG operator in view of range images. While step edges pose no particular problem, smooth edges are difficult to detect by local operations. In range image segmentation it is of particular interest that the a pile of objects be segmented into convex subparts. This requires detection of concave edges that will delimit the convex subparts. Mitiche and Aggarwal [28] have presented a probabilistic approach of detecting the convex and concave edges by using domain specific constraints.

Though 3-D edges are quite useful for object recognition, there are some inherent limitations in edge information that make their use limited to aiding the higher level recognition processes along with a host of invariant features. Edge classification depends on the orientation of object in 3-D space and is therefore *not* an invariant feature. Thus edge information cannot be the *only* feature used by the recognizer and it has to be used in conjunction with other features. However, as will be seen later, edge information is good enough for early segmentation of range images because the requirement of invariant features does not apply to the initial-segmentation process.

In case intensity information is available range data can be complemented by reflectance data to pick up weak 3-D edges like the step edges created by overlapping thin objects. Wong and Hayrapetian [32] used range information to segment intensity images. Gil, Mitiche and Aggarwal [27] have described experiments in combining intensity and range edges. While intensity images are certainly useful in detecting edges in the scene, they need to be registered in the same way as range images to avoid correspondence problem. This may

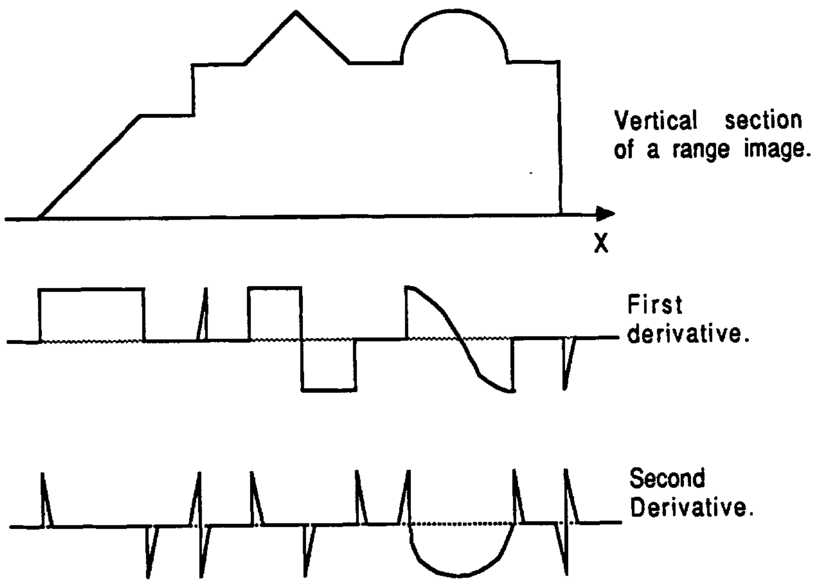


Figure 7: Derivatives of a cross-section of a range image

possibility of extracting smooth edges using the ∇^2G operator.

The Gaussian distribution in one dimension is defined as :

$$\mathbf{G}(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-x^2}{2\sigma^2}}$$

The first and second derivatives are :

$$\mathbf{G}'(x) = \frac{-x}{\sqrt{2\pi}\sigma^3} e^{\frac{-x^2}{2\sigma^2}}$$

$$\mathbf{G}''(x) = \frac{-1}{\sqrt{2\pi}\sigma^3} \left(1 - \frac{x^2}{\sigma^2}\right) e^{\frac{-x^2}{2\sigma^2}}$$

The cross-section of a range image and the profiles of first and second order derivative are shown in figure 7.

In two dimensions the LOG operator becomes :

$$\mathbf{G}''(x,y) = \frac{-1}{\sqrt{2\pi}\sigma^4} \left(2 - \frac{x^2+y^2}{\sigma^2}\right) e^{\frac{-(x^2+y^2)}{2\sigma^2}}$$

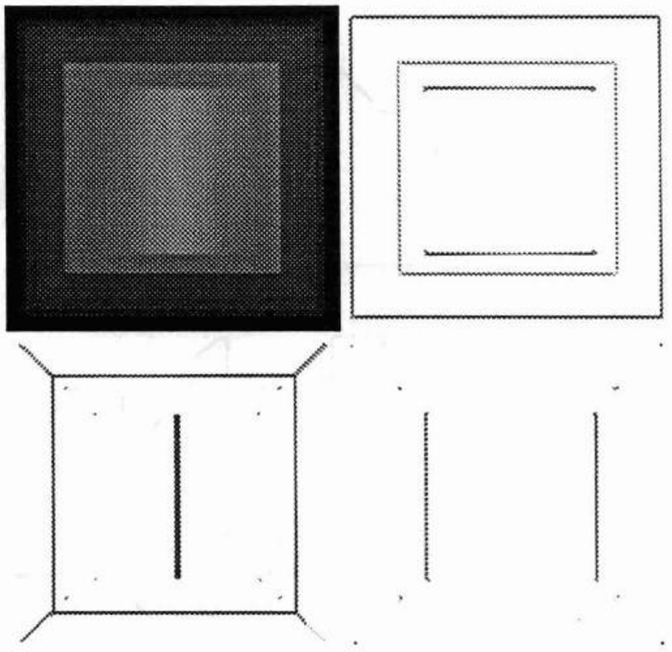


Figure 8: **3-D edges detected in a synthetic range image.** : *upperleft* original image. *upperright* thresholded step edges. *lowerleft* thresholded convex edges. *lowerright* thresholded concave edges.

It is clear that behavior of second order derivatives is unique at every type of change in surface. There are positive spikes at concave ramp edge, negative spikes at convex roof and ramp edges and zero crossings at jump edges. However there are serious practical limitations in using this response to detect concave and convex edges. The response at these edges is dependent on the convexity or concavity of the edge which is roughly the measure of angle at which the two surfaces meet. If the angle is too small and change in depth is gradual as in most situations, the response would be below or same as that due to local surface changes. See figure 8 for the step, convex and concave responses obtained in a synthetic range image having planar regions. Even in synthetic range image the responses deteriorate as image was smoothed and smooth concave and convex edges virtually disappeared.

Thresholding of zero crossings is necessary in case of range images to avoid local surface perturbations. Responses due to weak concave and convex edges would then be filtered. Zero-crossings generated by weak step edges may also lie below the thresholding value. In range images, Value of zero-crossing has direct relationship with the magnitude of *depth* discontinuity. Thus selection of a *threshold* effectively restricts the minimum detectable depth. An object with less than acceptable height would be *invisible* in the edge image.

As observed in the previous chapter, it is absolutely necessary to smooth an image before attempting any local operation it. LOG operator gives following image :

$$\mathbf{f}(x,y) = (\nabla^2\mathbf{G}) * \mathbf{I}(x,y)$$

which can be written as :

$$\mathbf{f}(x,y) = \nabla^2(\mathbf{G} * \mathbf{I}(x,y))$$

Degree of smoothing depends on the value of sigma, which controls the size of the window. Larger the sigma, greater is smoothing. While this effect is interpreted in intensity images as *blurring* and hence reduction of details, In range images it is seen in terms of smoothing the surface at the boundaries in addition to reduction of details. This results in all types of boundaries to become smoothed and can have undesirable effects on boundary detection and surface based segmentation. We have observed that with increasing scale value, range images loose vital boundary information presenting difficulties in edge based segmentation. Empirically determined window size of 5 (sigma value = 1) is chosen for processing all the images.

The **algorithm** for edge detection is given below.

1. Read in the range image.

2. Convolve the image with Gaussian operator separably in X and Y direction.

3. Convolve the **G**(x,y) * **I**(x,y) image with Laplacian operator:

$$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$

4. Label the Zero-crossing (with maximum value) at every pixel in the $\nabla^2 G(x,y) * I(x,y)$ image. Also mark the direction along which maximum crossing value is found.

5. Threshold the image at a predetermined value to label pixels as belonging to step edges.

Figures 11(b),12(b) and other figures show the magnitude of zero-crossings detected in range images.

It is observed that threshold selection is important in defining the acceptable depth, which in turn is determined by the amount of detail seen in the filtered image. Also the thresholding value is different at different scales. Threshold value varies inversely with smoothing parameter (σ).As we go up the scale-space the need for thresholding decreases.

Next we discuss a segmentation technique based on the step edges detected by the LOG operator.

3.2 Segmentation of Range Images using edge information

Segmentation of objects in a range image depends on actual requirements. One should therefore define the problem of segmentation clearly in the relevant context. In order to recognize an object it is necessary to isolate the object, which is not a trivial task. In a practical environment where objects can be of any size and shape, segmentation of individual objects can be a difficult task. Objects in a range image will always be partially occluded making the problem of segmentation and recognition difficult. If the scene consists of a heap of objects and we have to recognize one object then our problem can be simplified by considering the object of immediate importance, the one on the top of the heap. But this method has only specific applications like picking parts out of a bin etc. and is not useful as a general segmentation strategy.

Another approach to a complete segmentation is to segment the picture according to the requirement. Sometimes image segmentation into different surface types may be useful and at other times convex objects need to be segmented. Whatever the method, a segmentation process working on local information cannot always give requisite results. In fact, segmentation at lower-level of processing can at best give locally valid results which may be conflicting from global point of view. Thus a robust segmentation process has to work with higher stages of processing to yield *globally* valid results. This introduces the concept of feedback from higher stages so as to work in a closed loop with the goal of object recognition. Then segmentation can be considered as a part of object recognition stage.

As discussed before, 2nd order derivatives give enough information to delineate objects at the step boundaries. We will develop an algorithm for segmenting the topmost object in a heap of arbitrary objects.

First stage of segmentation process involving isolation of objects from background can be easily accomplished by thresholding the image at known background depth. The difficult part is to identify an individual object from the heap of objects. At this point it is essential to define what is meant by an 'individual object'. An object can be a complex combination of various 'primitive objects' like cube, sphere, cylinder etc.Some important questions need answering here before any further progress can be made : What are the end boundaries(edges) of the object and what are the internal boundaries of the object and how to distinguish between them ?

Different types of 3-D edges are jump edges, concave roof edges, concave ramp edges, convex roof edges and convex ramp edges. Considering any of these edges as the internal or external boundary of the object is going to put restrictions on the object types that can be segmented. For example, a jump edge (Unless it is an occluding edge against the background) need not be the end boundary of the actual object. Since the segmentation process is essentially a local operation and no other knowledge is used this problem cannot be solved at this segmentation level. There are following solutions to this problem :

1. Make assumptions about the type of the objects. For example, assume the topmost object to be convex. This is a very strong assumption and requires convex *internal* boundary information. As noted before, this information is difficult to derive using

second order derivatives. We will see in next chapter, how surface characterization techniques can be used to approximate the presence of smooth internal boundaries of an object.

2. a priori knowledge about the scene. But this is against our approach towards a general and robust segmentation algorithm.

3. Feedback from higher stages of object recognition to eliminate need for a priori knowledge and to relax the strong assumptions made at low-level segmentation stage. Since higher levels of object recognition are global processes and may have knowledge about the domain, a closed loop segmentation procedure is bound to perform better than one having no feedback.

Thus to achieve a reliable segmentation of the initial scene, we will assume that the topmost object is delineated by jump boundaries. This may not always be true as two objects can join at convex or concave edges or one object may merge into next one due to negligible thickness of the object at the point of contact. This means that local information cannot give perfect segmentation in all the cases. In such cases we need higher level processing to figure out the right segmentation of the scene. The segmentation based on external boundary information will give only an initial estimate of segmentation. This estimate is reliable to the point that it can distinguish between objects of predetermined depth.

In the context of invariant object recognition it is important to note that step boundaries may vary with orientation of the object. Thus they are used only to segment the object and not to *recognize* the object. We will discuss the results of recognition and classification of the segmented object using the superquadric technique developed by Franc [23].

The block diagram of segmentation and classification process is shown in figure 9

A practical problem with using zero-crossing as step boundaries is that they do *not* form closed contours. The boundaries delineating the object may not be completely enclosing the object, resulting in region growing process to *overflow* from the object and include the neighboring object as part of the object. This drawback renders the final segmentation result very unreliable. Yang and Kak [33] use a priori knowledge about the width of the

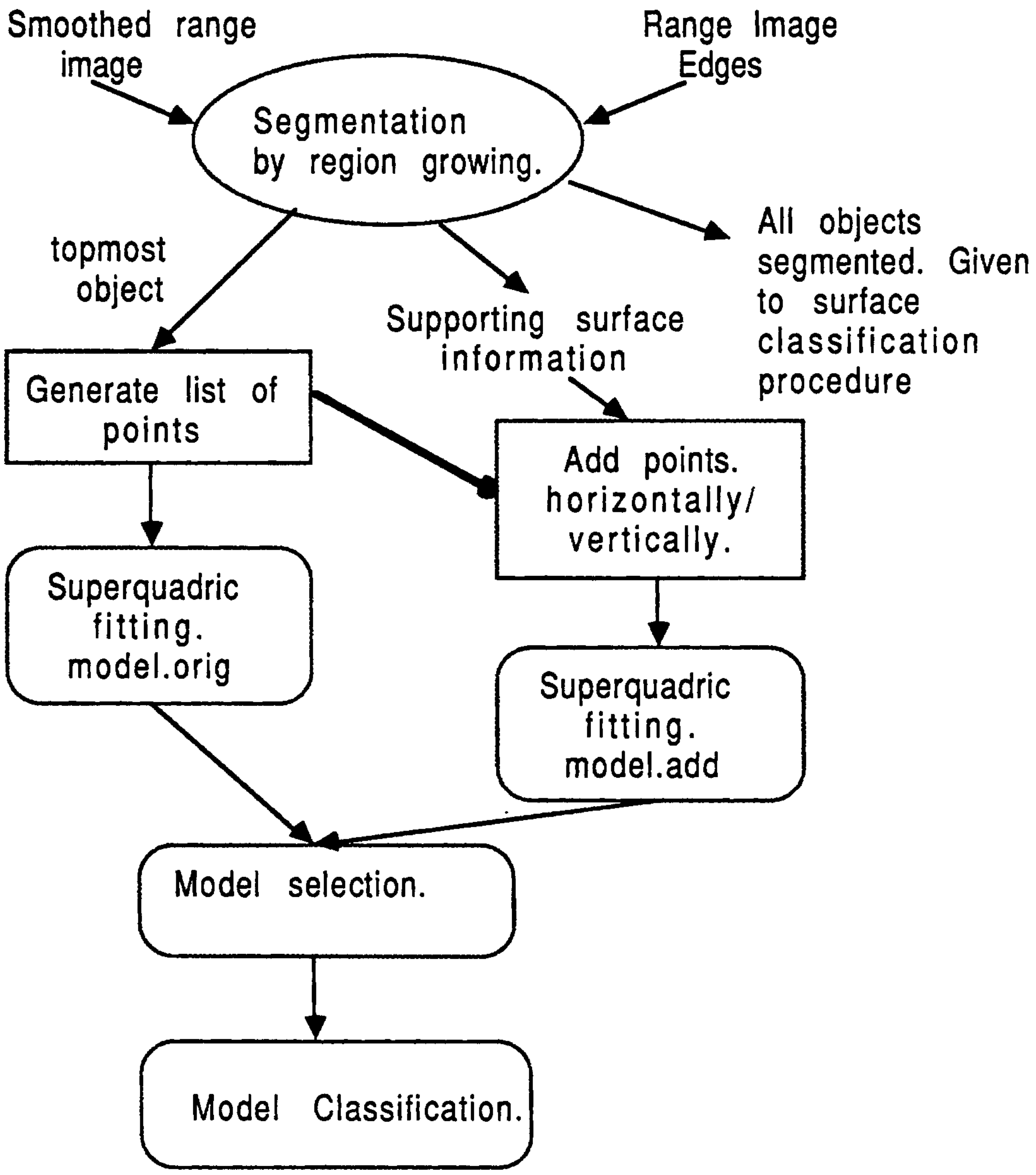

Smoothed range image
Range Image Edges
Segmentation by region growing.
topmost object
Supporting surface information
All objects segmented. Given to surface classification procedure
Generate list of points
Add points. horizontally/ vertically.
Superquadric fitting. model.orig
Superquadric fitting. model.add
Model selection.
Model Classification.

Figure 9: Flow chart of segmentation and recognition process

object and contour tracking to extract the closed contour surrounding the object. Their method does not guarantee success in all the cases. David Heeger [26] has proposed a computational approach to gap filling. It is computationally expensive and not suited for our purpose since we want to avoid explicit contour tracing in the entire image and want the region growing method to take care of it. Peter Allen [29] has used gap filling method based on contour growing proposed by Nevatia and Babu [30]. They perform gap filling on the entire scene using the predecessor-successor graph of all connected contours.See Peter Allen's Ph.D. thesis for details. Contours are then merged based on the requirement of merging N pixel gaps. This approach is again computationally expensive. Peter Allen observes that filling of at most two pixel gaps is acceptable because of the ambiguities resulting with three or more pixel gap-filling requirement. We have implemented two pixel gap filling by constraining the region growing process near the boundaries, thus avoiding the explicit gap filling stage.

One and two pixel gap filling is accomplished by simply requiring that a pixel having a boundary pixel in its 8-neighborhood be *not* grown recursively. Instead, the pixel and the boundary pixel are marked as *grown*. Figure 10 illustrates gap filling in one instance.

Thus we are able to avoid the contour tracing explicitly to fill gaps. Three or more pixel gaps cannot be adequately handled by gap-fillers. Some sort of post processing is necessary to further segment the segmented object in this case. One way is to trace all the boundary pixels of the segmented object and use concavity information to segment the object into parts. This approach is being implemented and will not be discussed here.

The algorithm for segmentation is given below :

1. Read in the original range image I(x,y) and $\nabla^2 G$ * I(x,y) image.

   label_val = 0

2. Segment the objects from background by thresholding at background depth (supplied by the user). In case background is not of uniform depth, a plane can be fitted to represent the background and threshold the objects from the scene.

3. Locate the 3x3 window with maximum height by averaging the pixel values in 3x3

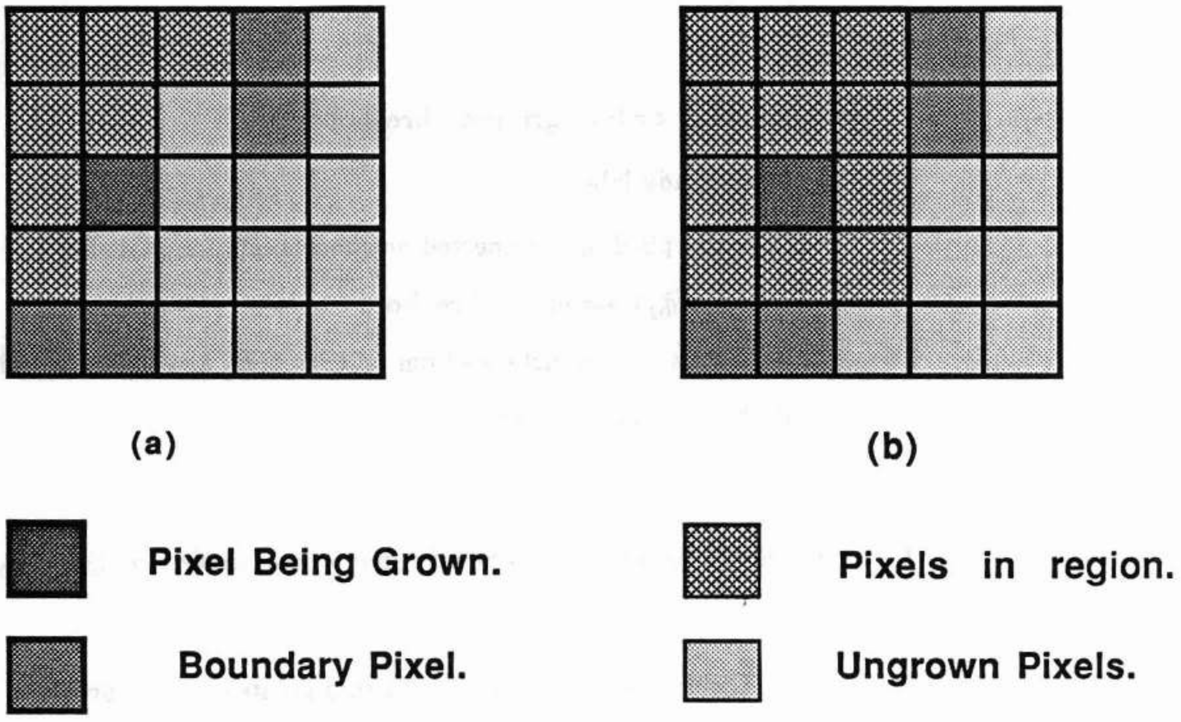


Figure 10: An example of gap filling

window at every pixel in the range image.This gives the seed region for region growing. Clearly the window lies on the topmost object. If there are more than one heap, then also only one seed region is obtained.

4. *label_val* = *label_val* + 1

5. Grow the seed region recursively in all 8 directions. For gap filling procedure to work it is necessary to grow pixels in 8-neighborhood. Let p_{ij} be the pixel being grown . A pixel $\hat{p}_{ij}$ in 8-connected neighborhood of p_{ij} is *not* grown under one of the following conditions :

   (a) $depth(\hat{p}_{ij})$ <=**background_threshold**

   (b) $\hat{p}_{ij}$ is already labeled.

   (c) If $\hat{q}_{ij}$, any pixel in 8-connected neighborhood of $\hat{p}_{ij}$ satisfies :
   $laplacian(\hat{q}_{ij})$ >= **edge_threshold**
   Then p_{ij} is 1-pixel distance from an edge pixel and likely to be in a *gap*. Make :
   $label(\hat{p}_{ij}) = label(p_{ij})$ and
   $label(\hat{q}_{ij}) = label(p_{ij})$.

6. If number of pixels in the extracted region < *acceptable size* then region is invalid else it is valid.

7. If region is valid then determine supporting points of the region.

8. The region extracted in the first pass is topmost region. Subsequent regions are grown from top to bottom, left to right. If any more pixels are left to be processed then pick up any unprocessed pixel and go back to step 5 to grow region.

9. Output topmost region, all valid regions and supporting points in separate image files.

3.3 Segmentation Results

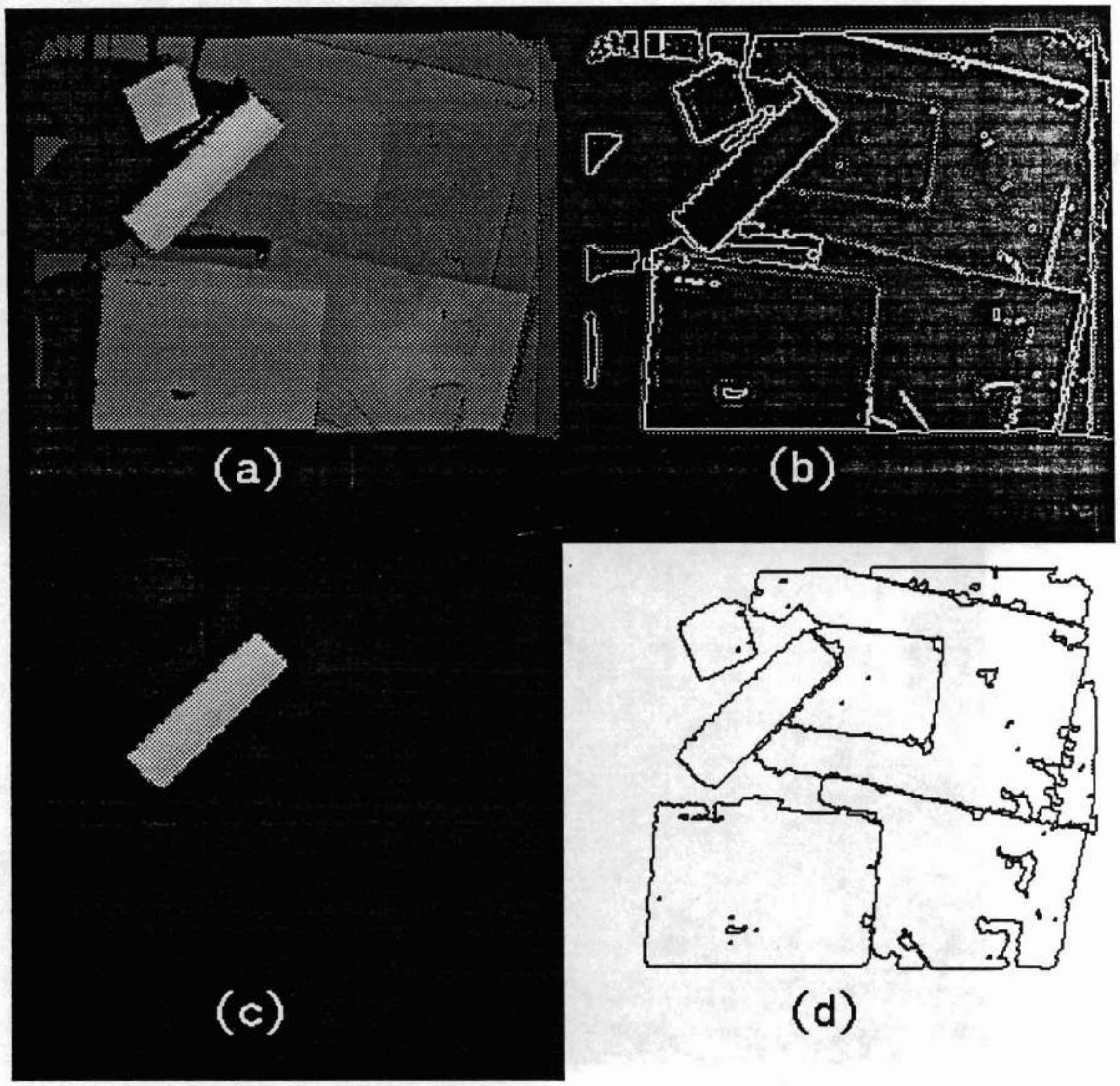


Figure 11: **Segmentation:** (a) original image from RCA. (b) Edges detected. (c) topmost object. (d) all segmented objects

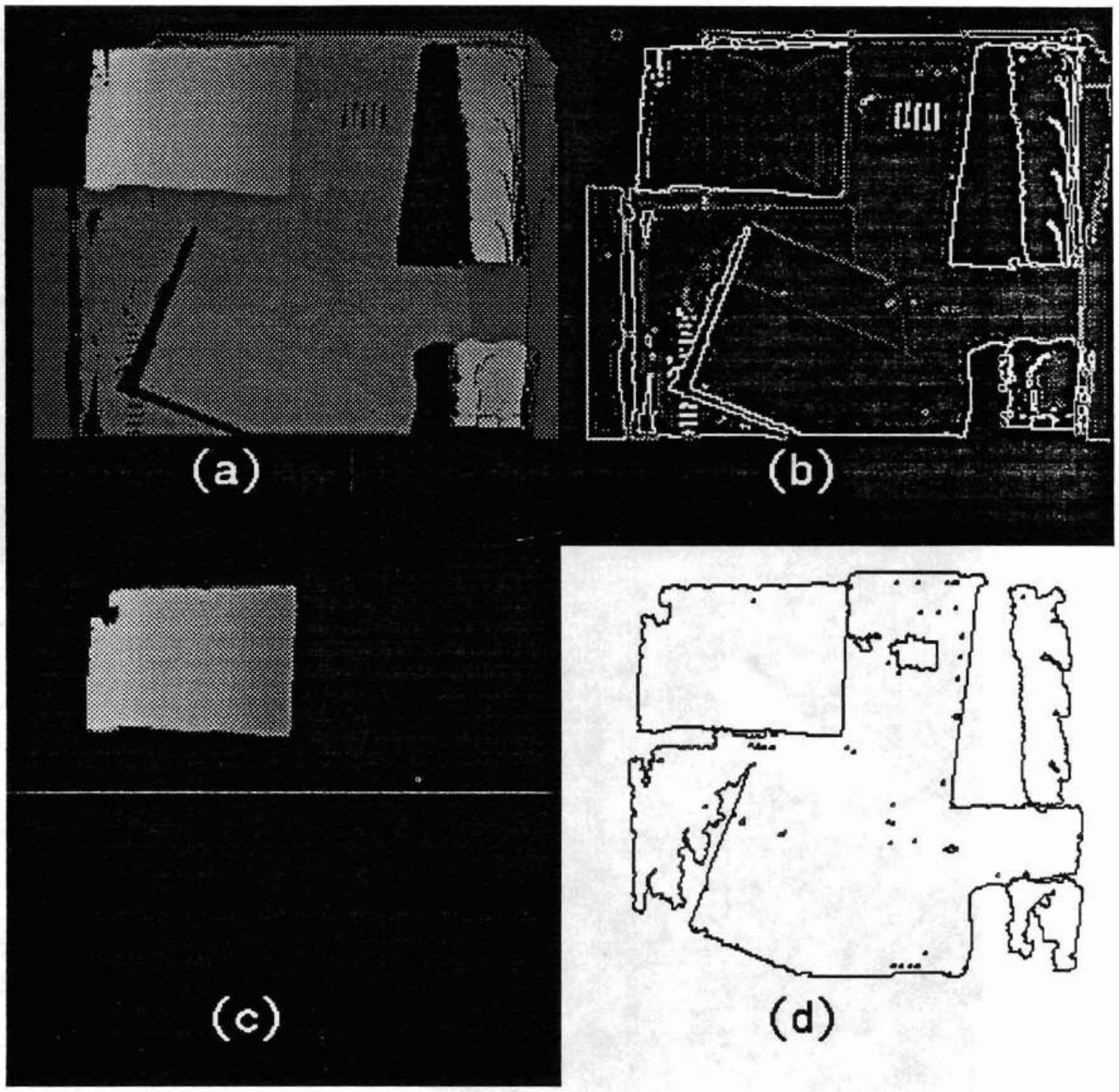


Figure 12: **Segmentation:**(a) original image from RCA. (b) Edges detected. (c) topmost object. (d) all segmented object

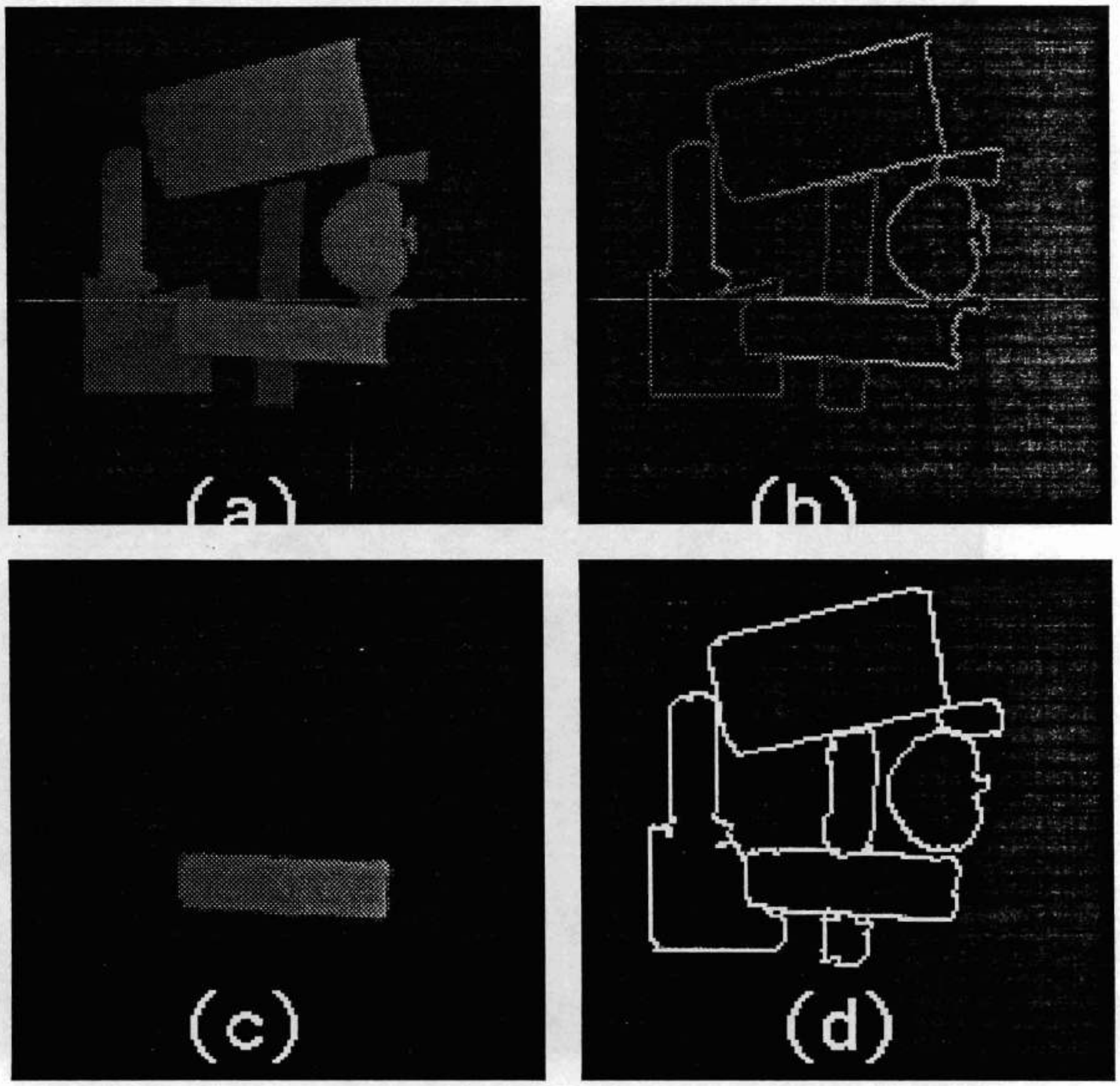


Figure 13: **Segmentation:** (a) original image from grasp lab scanner. (b) Edges detected. (c) topmost object. (d) all segmented objects

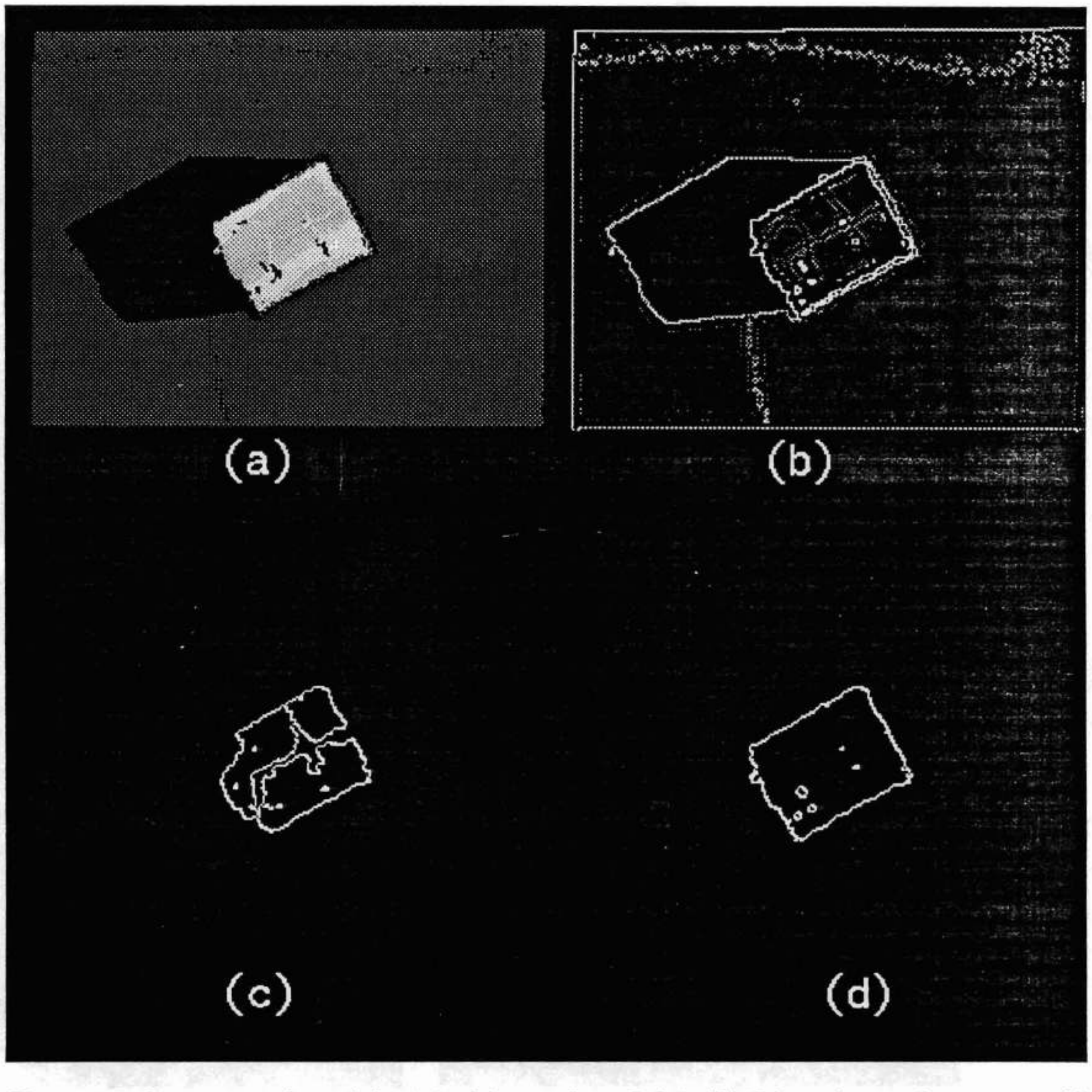


Figure 14: **Segmentation:** (a) original image from RCA. (b) Edges detected at $\sigma = 1$. (c) segmented parts of one object at $\sigma = 1$. (d) Segmentation at $\sigma = 2$, for the same threshold value.

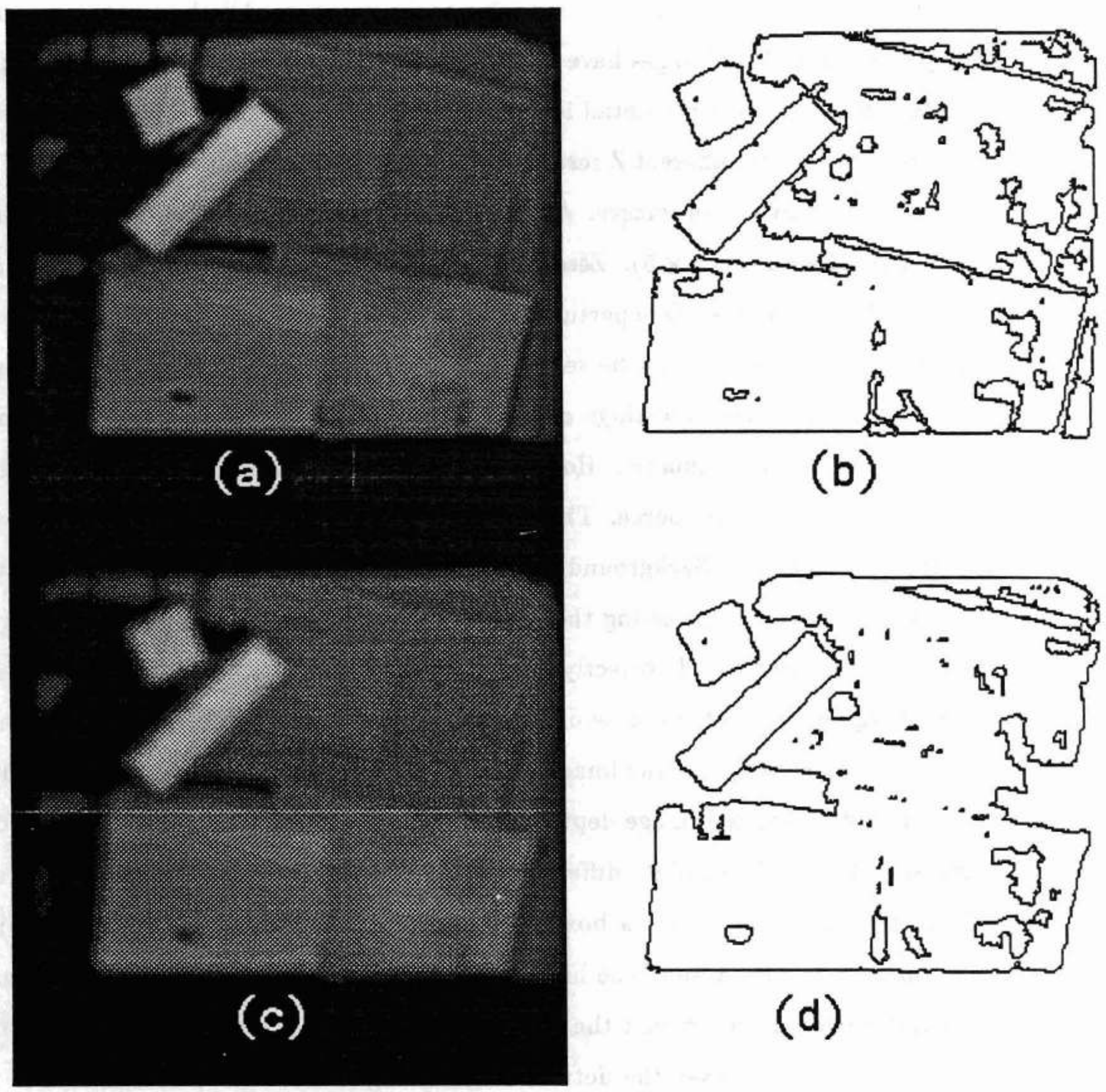


Figure 15: **Segmentation at different scales:** (a) image smoothed at $\sigma = 2.0$. (b) objects segmented. (c) : image smoothed at $\sigma = 3.0$. (d) objects segmented

The programs are written in C and implemented on a VAX-785 running UNIX . Ikonas graphics and PM format for images are used in all programs. Images are acquired from two sources. Most of the images used as examples are from RCA range image database and remaining are scanned by Grasp lab's range scanner. All the images are digitized in Z-depth format. RCA images have better (12 bits/pixel) resolution than Grasplab images (8 bits/pixel). Hence more detail is seen in the former. It makes difference in detection of thin objects. Due to different Z resolution of two scanners, we have used different threshold values for the two sets of images. All the images are smoothed uniformly with Gaussian of $\sigma = 1$ (window size $= 5 \times 5$). Zero-crossings of LOG operator are thresholded to remove response due to minor surface perturbations. The threshold at a given σ value also limits the thickness of objects that can be segmented. Threshold values are determined empirically, since histogram of zero-crossings cannot be used in determining threshold automatically as is done in intensity images. However threshold value remains same for all the images acquired from the same source. This is true for all the empirically determined parameters reported in this thesis. Background value is also known to the program and is constant given a scanner. Results of processing the images are in figures 11, 12,13 and 14. In figure 11 all the objects are segmented correctly. The topmost object is a Cylindrical object. Figure 12 shows merging of objects because of very weak step boundary information. Figure 13 shows results of segmentation on the image obtained from grasp lab scanner. A constant offset of 100 is added to original image depth values and zero-crossings are enhanced for displaying purposes. Figure 14 exhibits different results at two scales for the same edge threshold. The scene has single object, a box with string tied around it, so that the box is divided into 4 partitions. Because of the high depth resolution of the image, edge information due to string is enough to segment the box into three parts at $\sigma = 1$ (figure 14(c)). Increasing the σ value to 2, removes the details of the string and whole visible surface is recovered (figure 14(d)).

To study the effect of increasing sigma value on zero-crossing, one of the multiple object images is processed for $\sigma = 1, 2, 3$. Note that objects start to merge as sigma increases, with thin objects undetectable at $\sigma = 2$.(Figures 11, 15)

3.4 Recognition of segmented objects using Superquadrics

The surfaces extracted by the previous algorithm can be classified as one of the eight basic surface types. We will discuss this classification approach in detail in next chapter. In this section we will describe a high level recognition and classification method that classifies the segmented object into four broad categories.

We have used superquadric model recovery method implemented by Franc [23] to recognize the segmented object in a range image. Details of the procedure for superquadric fitting are discussed in Franc's Ph.D. thesis. Superquadrics are a family of parametric shapes that can be used as primitives for shape representation in computer vision [31]. Superquadrics are like lumps of clay that can be deformed and glued together into realistic looking models. However, we will consider only non-deformed superquadric models for classification of the object into one of the categories :

1. **flat** : Object with negligible height compared to length and width;
2. **roll** : A Cylindrical object.
3. **box** : An object with comparable height,length and width.
4. **Irregular** : Any object not falling in any of the above three categories.

Superquadric implicit equation is given by :

$$\left[\left(\frac{x}{a_1}\right)^{\frac{2}{\varepsilon_2}} + \left(\frac{y}{a_2}\right)^{\frac{2}{\varepsilon_2}}\right]^{\frac{\varepsilon_2}{\varepsilon_1}} + \left[\frac{z}{a_3}\right]^{\frac{2}{\varepsilon_1}} = 1.$$

Parameters a_1, a_2, and a_3 define the superquadric size in x,y and z direction respectively. ε_1 is the squareness parameter in the latitude plane and ε_2 is the squareness parameter in the longitude plane. Based on these parameter values superquadrics can model a large set of standard building blocks, like spheres, cylinders, parallelopipeds and shapes in between. Figure 16 illustrates the various types of shapes obtainable by changing two shape parameters. If both ε_1 and ε_2 are 1, the surface defines an ellipsoid. Cylindrical shapes are obtained for $\varepsilon_1 < 1$ and $\varepsilon_2 = 1$. Parallelopipeds are obtained for both ε_1 and ε_2 are < 1.

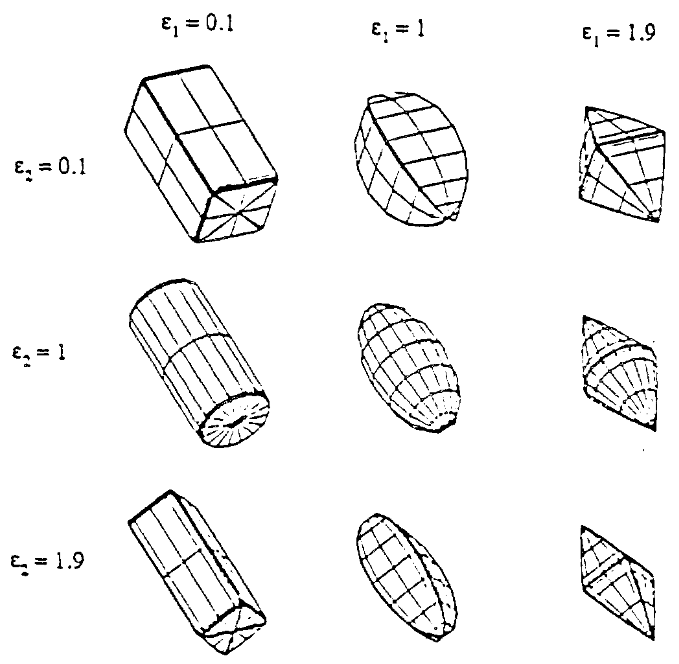


Figure 16: Superquadric models as function of shape parameters $(\varepsilon_1, \varepsilon_2)$ for given size paremeters (a_1, a_2, a_3)

We have restricted the model recovery procedure to fit the models with $0 \leq \varepsilon_1, \varepsilon_2 \leq 1$. We will not discuss the details of model recovery here.

The Criteria used for classification are three size parameters, two shape parameters and the goodness of fit (*GOF*) measure. The superquadric procedure returns a *GOF* measure using the following equation :

$$GOF = \frac{1}{N} \sum_{i=1}^{N} [a_1 a_2 a_3 (F(x, y, z; a_1, a_2, a_3, \varepsilon_1, \varepsilon_2, \phi, \theta, \psi, p_x, p_y, p_z) - 1)]^2$$

Where F is the superquadric inside-outside fuction described in Franc [23]. ϕ, θ, ψ define the orientation and p_x, p_y, p_z define position of superquadric in space.

The object given by the segmentation procedure has only the points visible to the scanner. Much of the volumetric information is lost in the Z-depth format of representation. While this is not a serious problem in case of curved objects like cylinder or segmented surfaces having volumetric information (like a tilted box viewed from above), model fitting becomes ambiguous if the visible surface is flat. If it is known that the original scene had only one object, then the supporting surface can be assumed to be the plane parallel to the known background. The problem complicates in the multiple object scenes, where it becomes impossible to assign correct depth to the segmented object. Given no prior knowledge about the surface type, we need to add points in every case to give volumetric information to the superquadric procedure. Points can be added in two ways :

1. Background is assumed to be the supporting surface of the object. Points are added on the background by backprojecting the visible surface on the background (figure 17(c). While this is desirable in case of flat surfaces, it is *not* right for surfaces with volumetric information.

2. Supporting points of the segmented object are used to determine the immediate supporting surface(s) of the object. Points are added vertically (figure 17(e)) to the object. This technique is more flexible since it can handle objects not lying on the background. But it results in more points to be added in addition to assuming that

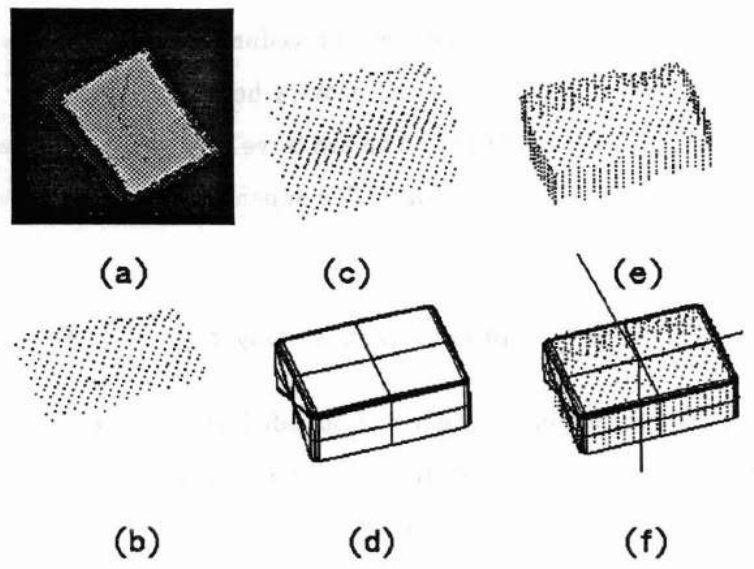


Figure 17: **Horizontal and vertical addition of points.**(a) object. (b) original points. (c) horizontal addition of points. (d) fit with horizontal addition. (e) vertical addition of poins. (f) fit with vertical addition.

the object is actually *touching* the neighboring objects, which may not be true in general.

In general it is not possible to extract correct supporting surface information from a single viewpoint. We have used horizontal addition of points in our experiments as it is faster than vertical addition and recovers the desired model.

The algorithm for model fitting,selection and classification is following :

1. Read the segmented object in Z-depth format.
2. **Format conversion and point addition** : Generate a list of points in 3-D space representing the object. Call it *points.orig.* For every point on the visible surface add

a point at the same (x, y) coordinates on the background. Output the list of original and added points in *points.add.*

3. **Superquadric fitting :** Run Superquadric model fitting procedure on *points.orig.* Model obtained is *model.orig.* Run Superquadric model fitting procedure on *points.add.* Model obtained is *model.add.* Iterative superquadric fitting is stopped if one of the following conditions is met :

   (a) Number of iterations $\geq$ 15.

   (b) Goodness of fit of *i*th iteration ($i \leq 15$) is $\leq$ *Acceptable measure.* This measure is empirically determined.

   (c) If for the *j*th ($j \geq 5$) iteration :

   $$\sqrt{\frac{1}{5}\left[\sum_{i=j}^{j-4}\left(GOF(i) - \sum_{k=j}^{j-4} GOF(k)\right)^2\right]} \leq \textbf{Acceptable\_deviation.}$$

   Condition (a) assumes that model recovery is complete by 15th iteration. Condition (b) stops the procedure if an acceptable model is obtained early in the process. Condition (c) monitors the rate convergence of fitting procedure. It terminates the fitting procedure if the GOF measures of last five iterations do not vary much. All the values used in the above three conditions are empirically determined.

4. **Model selection :**

```
IF ($GOF$(model.add) AND $GOF$(model.orig) $\leq$ Acceptable_fit)
THEN GOTO volume_criterion
ELSE IF ($GOF$(model.add) $\leq$ Acceptable_fit)
THEN model = model.add GOTO classify.
ELSE IF ($GOF$(model.orig) $\leq$ Acceptable_fit)
THEN model = model.orig GOTO classify.
```

```
   ELSE
   OBJECT = Irregular. GOTO Done.
5. Volume_criterion : Volume can be approximated as $a_1 \times a_2 \times a_3$.
   IF($volume.add < volume.orig$)
   THEN $model = model.orig$
   ELSE $model = model.add$.
6. classify : Classify model using $a_1, a_2, a_3$ and $\varepsilon_1, \varepsilon_2$:
   (a) IF (($a_3 \ll a_1$) AND ($a_3 \ll a_2$)AND
       ($\varepsilon_1 < 0.5$) AND ($\varepsilon_2 < 0.5$))
       THEN OBJECT = FLAT.
   (b) ELSE IF (($a_1 \ll a_3$) AND ($a_2 \ll a_3$) AND
       ($\varepsilon_1 < 0.5$) AND ($\varepsilon_2 < 0.5$))
       THEN OBJECT = FLAT.
   (c) ELSE IF (($a_1 > THRESH\_BOX$) AND ($a_2 > THRESH\_BOX$) AND
       ($a_3 > THRESH\_BOX$) AND ($\varepsilon_1 < 0.5$) AND ($\varepsilon_2 < 0.5$))
       THEN OBJECT = BOX.
   (d) ELSE IF (($a_1 > THRESH\_1\_ROLL$) AND ($a_2 > THRESH\_1\_ROLL$) AND
       ($a_3 > THRESH\_2\_ROLL$) AND
       ($\varepsilon_1 < 0.5$) AND ($\varepsilon_2 > 0.5$))
       THEN OBJECT = ROLL.
   (e) ELSE OBJECT = Irregular
```

THRESH_BOX is the minimum acceptable dimension of the box.

THRESH_1_ROLL is the minimum acceptable width and height of the roll.

THRESH_2_ROLL is the minimum acceptable length of roll.

OBJECT	Model	a1	a2	a3	e1	e2	Error
Cylinder	Orig	16.30	8.65	75.70	0.24	0.95	56.21
	Add	16.07	35.29	72.16	0.10	0.14	393.28
Box	Orig	3.47	33.6	45.29	0.10	0.81	1274.40
	Add	38.11	51.14	39.47	0.10	0.10	441.16
Flat	Orig	7.46	46.76	57.72	0.10	0.52	319.32
	Add	8.86	45.75	57.52	0.10	0.17	245.34
Others	Orig	4.928	50.41	76.79	0.10	0.43	4083.61
	Add	9.38	53.00	82.44	0.10	0.10	4178.83

Figure 18: Parameter values of the recovered models

7. **Done :** Output classified model with parameters. Determine Orientation and position of the model in world coordinate system.

3.5 Results of Superquadric Fitting and Classification

The superquadric fitting procedure and classifier were run on the objects segmented previously. The superquadric parameters for the four types of recovered objects are shown in figure 18.

Figure 19 shows model recovery on topmost object segmented in figure 14. The model selection process rejected *model.orig* due to large fit-error and accepted *model.add.* Even if *model.orig* had an acceptable error measure, *model.add* would have been selected due

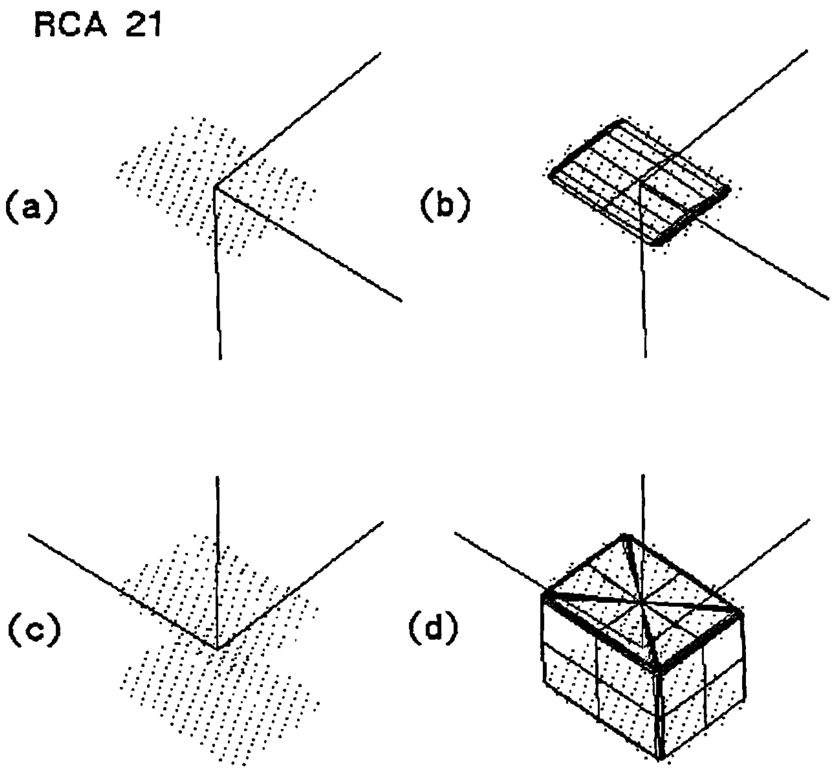


Figure 19: **Superquadric fitting and Model selection** (a box) : (a) original points. (b) fitted model on original points. (c) original and added points. (d) fitted model on original and added points.

to larger volume. The acceptable error magnitude was empirically determined to be 500. In figure 20 *model.orig* is selected and classified as *roll* because of the tremendous error difference between the two acceptable models. *model.add* is accepted and classified as *flat* in figure 22 because of volume consideration, although both the models have acceptable error measures. Finally, the film mailer in figure 23 is classified as *irregular* as the fit-errors of both the models is more than acceptable error measure.

The results are shown for the four classes of objects. Tapered , bent or concave objects cannot be represented by these models and hence will be classified as irregular. Franc Solina's superquadric method also allows for tapering and bending along with segmentation

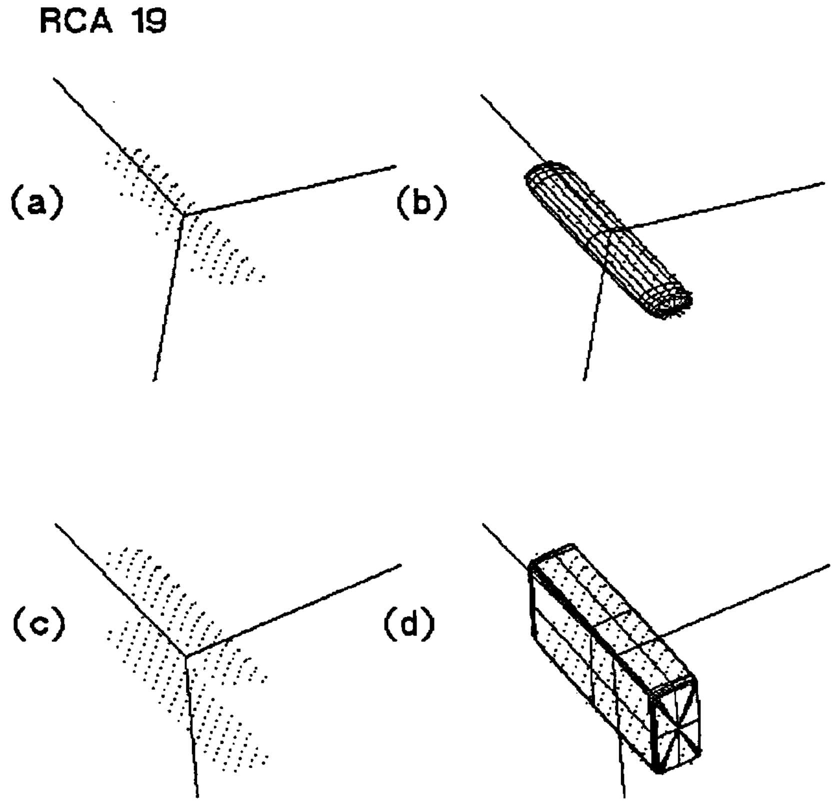


Figure 20: **Superquadric fitting and Model selection** (a Cylindrical object) : (a) original points. (b) fitted model on original points. (c) original and added points. (d) fitted model on original and added points.

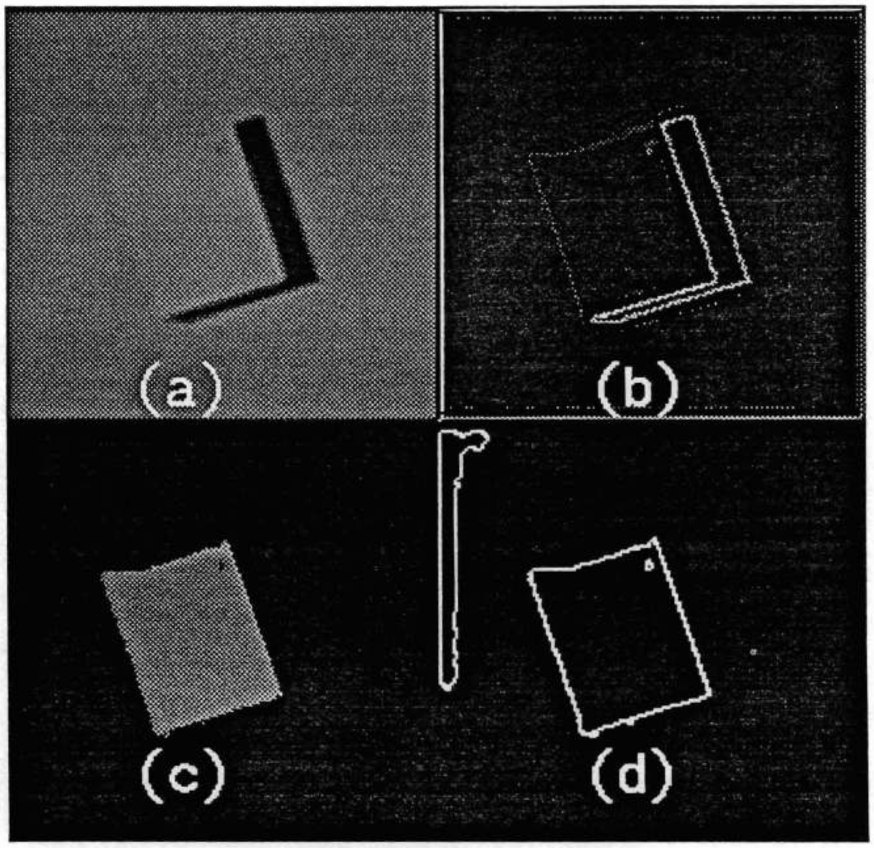


Figure 21: **.Segmentation:** upperleft : original image from grasp lab scanner (aletter) upperright:Edges detected. lowerleft : topmost object. lowerright : all segmented objects

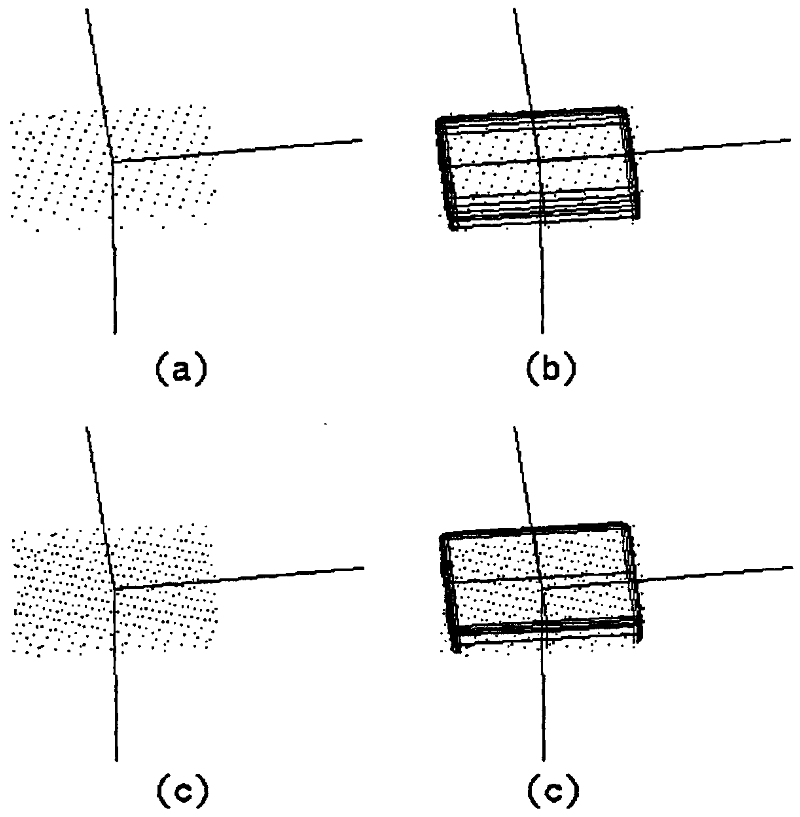


Figure 22: **Superquadric fitting and Model selection** (a letter) (a) original points. (b) fitted model on original points. (c) original and added points. (d) fitted model on original and added points.

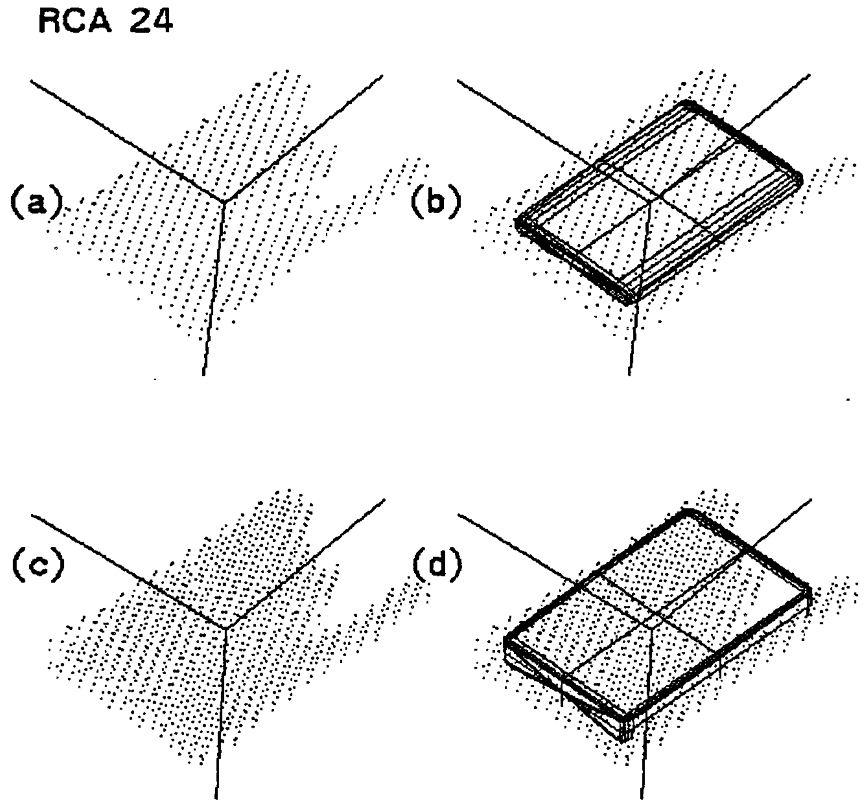


Figure 23: **Superquadric fitting and Model selection** (a film-mailer) : (a) original points. (b) fitted model on original points. (c) original and added points. (d) fitted model on original and added points.

of the complex objects into parts. In the next chapter we will describe a surface classification scheme that uses the output of segmentation routines described in this chapter.

Chapter 4

Surface Characterization and Segmentation

Surface characterization refers to the computational process of partitioning the surfaces into regions with equal characteristics. Since our ultimate goal is object recognition, classification of the surfaces by the characteristics of the surface functions is very useful. Classical differential geometry provides a complete surface description of analytic surfaces so as to obtain a complete set of surface characteristics. Surface characterization can be successfully used in intermediate and high level processing of the object recognition problem.

Important surface characteristics, that are visible-invariant are *Gaussian curvature* and the *mean curvature*. They are invariant to changes in surface parametrization and to translations and rorations of object surfaces. Guassian curvature is an intrinsic property of the surface while mean curvature is an extrinsic property of the curvature.

From differential geometry it is well known that curvature, speed, and torsion uniquely determine the shape of 3-D surfaces. The surface characteristics of our interest are the ones with one-to-one relationship with curve shapes. The mathematics of a general surface representation scheme and calculation of Guassian and mean curvatures is described in following section.

4.1 Differential Geometry of Surfaces

Parametric form of equation for a *regular surface* S with respect to a known coordinate system is :

$$S = (x, y, z) : x = x_1(u, v), y = x_2(u, v), z = x_3(u, v), (u, v) \in D \subseteq \mathbf{R}^2$$

The surface is a locus of points in Euclidean three-space defined by the end points of the vector $\mathbf{X}(u, v)$ with $x_i(u, v)$ the components of the vector. These real functions are assumed to be defined over an open connected domain of a Cartesian u, v plane and to have continuous second partial derivatives there. In our analysis of range images we are assuming that this condition is satisfied.

The second condition for a regular surface is automatically satisfied by Z-depth format images. It requires that the coordinate vectors $\mathbf{X}_u = \mathbf{X}_1 = \frac{\partial \mathbf{X}}{\partial u}, \mathbf{X}_v = \mathbf{X}_2 = \frac{\partial \mathbf{X}}{\partial v}$ are linearly independent :

$$\frac{\partial \mathbf{X}}{\partial u} \times \frac{\partial \mathbf{X}}{\partial v} = \mathbf{X}_1 \times \mathbf{X}_2 \neq 0.$$

The surface in range images is given by :

$$\mathbf{X} = (x_1, x_2, f(x_1, x_2))$$

and coordinate vectors become :

$$\mathbf{X}_1 = \left(1, 0, \frac{\partial f}{\partial x_1}\right),$$

$$\mathbf{X}_2 = \left(0, 1, \frac{\partial f}{\partial x_2}\right),$$

These vectors are linearly independent given the first condition.

It can be shown using differential geometry techniques that first and second fundamental forms(which exist only if the surface is analytic) uniquely characterize a general *smooth* surface. The first fundamental form I of a surface is defined as :

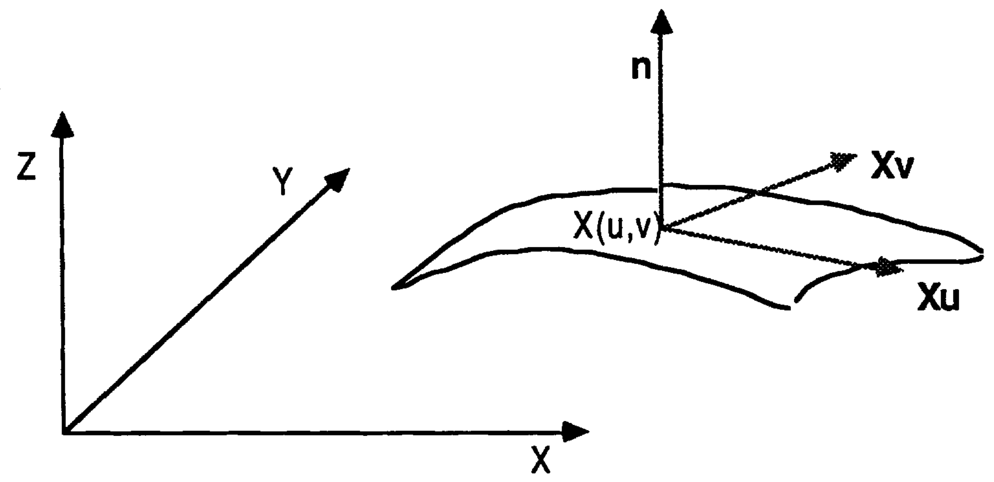


Figure 24: Coordinate frame at the Neighborhood of a point

$$I(u,v,du,dv) = d\mathbf{X}.d\mathbf{X} = \begin{bmatrix} du & dv \end{bmatrix} \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} du \\ dv \end{bmatrix} = d\mathbf{u}^T[g]d\mathbf{u}$$

where $[g]$ matrix elements are given by :

$$g_{11} = E = \mathbf{X}_u.\mathbf{X}_u \quad g_{22} = G = \mathbf{X}_v.\mathbf{X}_v \quad g_{12} = g_{21} = F = \mathbf{X}_u.\mathbf{X}_v$$

The two tangent vectors $\mathbf{x}_u$ and $\mathbf{x}_v$ lie in the *tangent plane T(u,v)* of the surface at the point (u, v). $[g]$ matrix is symmetric for an analytic surface.

figure 24 shows the coordinate frame at the Neighborhood of a point.

The first fundamental form $I(u, v, du, dv)$ measures the small amount of movement in the parameter space (du, sv). The first fundamental form is invariant to surface parametrization changes and to translations and rotations in the surface. Therefore it depends on the surface itself and not on how it is embedded in the 3-D space. The metric functions E, F, G determine all the intrinsic properties of the surface. In addition they define the area of a surface :

$$A = \int\int_R \sqrt{EG - F_2} du\, dv$$

The second fundamental form of the surface is given by :

$$II(u, v, du, dv) = -\, d\mathbf{x}.d\mathbf{n} = \begin{bmatrix} du & dv \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} du \\ dv \end{bmatrix} = d\mathbf{u}^T [b] d\mathbf{u}$$

Where $[b]$ matrix elements are defined as :

$$b_{11} = L = \mathbf{X}_{uu}.\mathbf{n} \quad b_{22} = N = \mathbf{X}_{vv}.\mathbf{n} \quad b_{12} = b_{21} = M = \mathbf{X}_{uv}.\mathbf{n}$$

$$\mathbf{n}(u, v) = \frac{\mathbf{x}_u\ X\ \mathbf{x}_v}{\mid \mathbf{x}_u\ X\ \mathbf{x}_v \mid} = unit\_normal\_vector$$

Where the double subscript denotes second partial derivatives

$$\mathbf{x}_{uu}(u, v) = \frac{\partial^2 \mathbf{x}}{\partial u^2} \quad \mathbf{x}_{vv}(u, v) = \frac{\partial^2 \mathbf{x}}{\partial v^2} \quad \mathbf{x}_{uv}(u, v) = \mathbf{x}_{vu}(u, v) = \frac{\partial^2 \mathbf{x}}{\partial u \partial v}$$

The second fundamental form measures the correlation between the change in the normal vector dn and the change in the surface position at a point (u, v) as a function of small movement (du, dv) in the parametric space. Besl and Jain [9] have discussed the properties of first and second fundamental forms in detail. We will consider some of the important properties of Gaussian and Mean curvature in the following paragraphs.

It can be shown that the [g] matrix and the [b] matrix elements are the continuous functions with continuous second and first partial derivatives respectively and that they uniquely determine the surface type. From the [g] and [b] matrices calculated above surface shape and intrinsic surface geometry can be uniquely determined.

The Gaussian curvature function K of a surface can be defined in terms of the two matrices as :

$$K = det\left(\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}^{-1} \right) det\left(\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & g_{22} \end{bmatrix} \right)$$

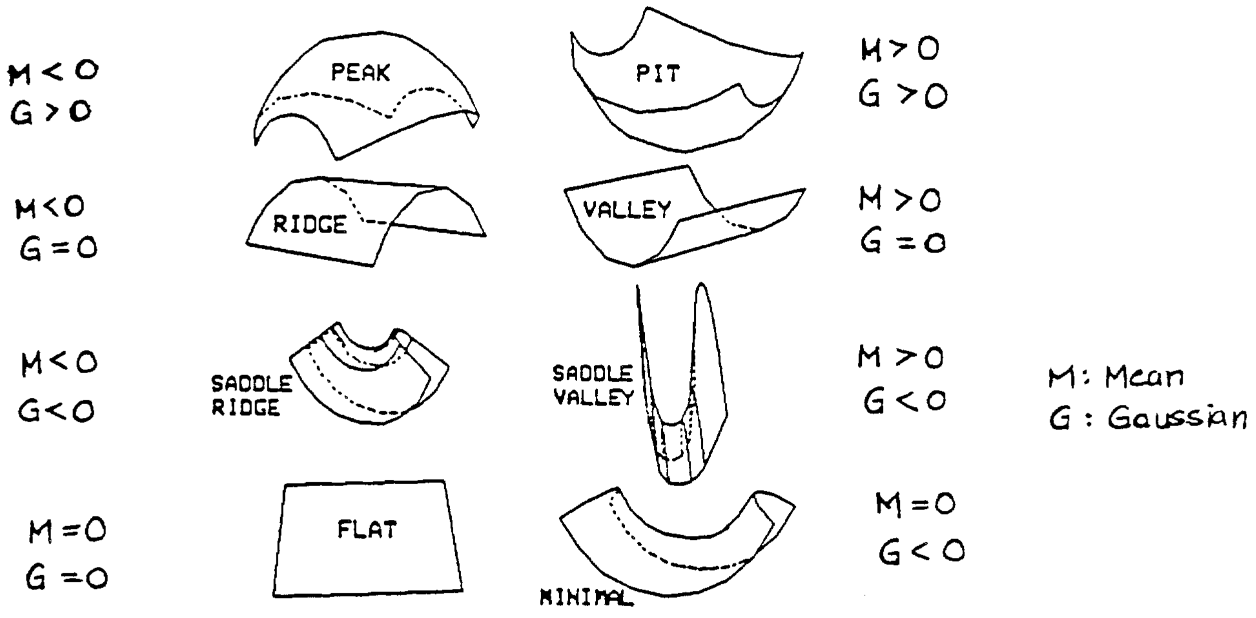


Figure 25: Basic surface types in range images (a) surface types (b) table of surface types.

and the mean curvature of a surface is defined as :

$$H = \frac{1}{2} tr \left(\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}^{-1} \right) det \left(\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & g_{22} \end{bmatrix} \right)$$

The two types of curvatures are together referred to as surface curvature functions. They exhibit very important properties that enable them to be used as features for higher level of processing. For detailed discussion on the properties of surface curvature functions see Besl and Jain [9]. Some of the relevant properties are summarized below :

1. Surface types can be determined by the sign of surface curvatures. They are shown in figure 25
2. Gaussian curvature exhibits isometric invariance properties.
3. Mean curvature is slightly less sensitive to noise than Gaussian curvature.
4. Gaussian curvature function of a convex surface uniquely determines the surface.
5. Mean curvature function of a graph surface taken together with the boundary curve of a graph surface uniquely determines the graph surface from which it was computed.

6. Gaussian and mean curvature are invariant to arbitrary transformations of the (u, v) parameters of a surface as long as the Jacobian of the transformation is always non-zero.

7. Gaussian and mean curvatures are invariant to rotations and translations of a surface. This property enables us to obtain view-independent characteristics.

8. Gaussian curvature is an isometric invariant of a surface. Therefore it is an intrinsic surface quantity. It is independent of the the way the surface is embedded in the 3-D space.

9. Gaussian and mean curvature are local surface properties.

10. Another important property of surface curvatures is that Gaussian curvature indicates the surface shape at individual surface points.When surface is shaped like an ellipsoid in the Neighborhood of(u, v), $K(u, v) > 0$. It is < 0 for locally saddle-shaped surface and is $= 0$ if the surface is flat,rdge-shaped or valley-shaped locally. Mean curvature also indicates surface shapes at individual points when considered together with the Gaussian curvature.

The above observations are very important for surface classification and have been widely studied and used in range image processing.In fact surface characteristics constitute an important part in the realization of the ultimate goal of three dimensional object recognition.

4.2 Computing Surface Characteristics of Range Images

Given a range image, our objective is to calculate the Gaussian and mean curvature. To compute surface curvature we need to know the estimates of the first and second partial derivatives of the depth map. Equations to get the partial derivatives can be simplified in the case of the Z-depth format range image. Parameterization takes a very simple form: $\mathbf{x}_u = \begin{bmatrix} u & v & f(u,v) \end{bmatrix}^T$. The T superscript indicates the transpose. This gives following formulas for the surface partial derivative and the surface normal.

$$\mathbf{x}_u = \begin{bmatrix} 1 & 0 & f_u \end{bmatrix}^T \quad \mathbf{x}_v = \begin{bmatrix} 0 & 1 & f_v \end{bmatrix}^T \quad \mathbf{x}_{uu} = \begin{bmatrix} 0 & 0 & f_{uu} \end{bmatrix}^T$$

$$\mathbf{x}_{vv} = \begin{bmatrix} 0 & 0 & f_{vv} \end{bmatrix}^T \quad \mathbf{x}_{uv} = \begin{bmatrix} 0 & 0 & f_{uv} \end{bmatrix}^T$$

$$\mathbf{n} = \frac{1}{\sqrt{1 + f_u^2 + f_v^2}} \begin{bmatrix} -f_u & -f_v & 1 \end{bmatrix}^T .$$

and the six fundamental form coefficients :

$$g_{11} = 1 + f_u^2 \quad g_{22} = 1 + f_v^2 \quad g_{12} = f_u f_v$$

$$b_{11} = \frac{f_{uu}}{\sqrt{1 + f_u^2 + f_v^2}} \quad b_{12} = \frac{f_{uv}}{\sqrt{1 + f_u^2 + f_v^2}} \quad b_{22} = \frac{f_{vv}}{\sqrt{1 + f_u^2 + f_v^2}}$$

The expression for *Gaussian* curvature is given by :

$$K = \frac{f_{uu} f_{vv} - f_{uv}^2}{(1 + f_u^2 + f_v^2)^2}$$

And the expression for *mean* curvature is given by:

$$H = \frac{f_{uu} + f_{vv} + f_{uu} f_v^2 + f_{vv} f_u^2 - 2 f_u f_v f_{uv}}{2(1 + f_u^2 + f_v^2)^{3/2}}$$

Thus if we are given a depth map function $f(u, v)$ that possesses first and second partial derivatives, Gaussian and mean curvature can be computed directly.

4.2.1 Estimation of partial derivatives of Depth Maps

Partial derivatives of the range image can be obtained by fitting a continuous differentiable function that best fits the data. There are various techniques available in mathematics that have been used by computer vision researchers to determine partial derivatives of depth maps.

Using Discrete Orthogonal Polynomials

Besl and Jain [9] used discrete quadratic orthogonal polynomial fitting at each pixel to estimate derivatives. It is possible to control Neighborhood size for making local estimates which is important in case of actual range images.

A quadratic surface is fit at each pixel in the image, using a window convolution operator of size desired by the user.

Each point in the given window is associated with a position (u, v) from the set UXU where N is odd :

$$U = \left[\frac{-(N-1)}{2}, \ldots, -1, 0, 1, \ldots, \frac{(N-1)}{2}\right].$$

The following discrete orthogonal polynomials provide the quadratic surface fit :

$$\phi_0(u) = 1 \quad \phi_1(u) = u \quad \phi_2(u) = \left(u^2 - \frac{M(M+1)}{3}\right)$$

Where $M = (n-1)/2$. The $b_i(u)$ functions are normalized orthogonal polynomials :

$$b_0(u) = 1/N \quad b_1(u) = \frac{3u}{M(M+1)(2M+1)}$$

$$b_2(u) = \frac{1}{P(M)}\left(u^2 - \frac{M(M+1)}{3}\right)$$

Where $P(M)$ is a fifth - order polynomial in M :

$$P(M) = \frac{8}{45}M^5 + \frac{4}{9}M^4 + \frac{2}{9}M^3 - \frac{1}{9}M^2 - \frac{1}{15}M.$$

$b_i(u)$ vectors are computed according to the window size. First the surface estimate function $\hat{f}(u, v)$ is calculated :

$$\hat{f}(u, v) = \sum_{i,j=0}^{2} a_{ij}\phi_i(u)\phi_j(v)$$

that minimizes the mean square term :

$$\epsilon = \sum_{(u,v)\in U^2} \left(f(u, v) - \hat{f}(u, v)\right)^2$$

Coefficients are given by :

$$a_{ij} = \sum_{u,v \in U^2} f(u,v) b_i(u) b_j(v)$$

The first and second partial derivatives can then be directly read from the a_{ij} coefficients :

$$f_u = a_{10} \quad f_v = a_{01} \quad f_{uv} = a_{11} \quad f_{uu} = 2a_{20} \quad f_{vv} = 2a_{02}$$

After the first and second partial derivatives are determined, surface characteristics at each pixel are calculated.

Using Difference Operators

Brady etal [4] have used 3 × 3 difference operators to locally compute first and second derivatives of the Gaussian smoothed surface. Neighborhood size cannot be increased in this method. The operators are :

$$\begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix} \quad \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} \quad \begin{bmatrix} -1 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & -1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & -2 & 1 \\ 1 & -2 & 1 \\ 1 & -2 & 1 \end{bmatrix} \quad \begin{bmatrix} 1 & 1 & 1 \\ -2 & -2 & -2 \\ 1 & 1 & 1 \end{bmatrix}$$

Using B-Spline fitting

Yang and Kak [33] have derived 3 × 3 operators using B-splines for computing partial derivatives of a range map. These can be combined with Gaussian operator to increase the window size and reduce sensitivity to noise. The operators give partial derivatives at the center pixel of each operator.

$$\mathbf{x}_u : \frac{1}{12}\begin{bmatrix} -1 & -4 & -1 \\ 0 & 0 & 0 \\ 1 & 4 & 1 \end{bmatrix} \quad \mathbf{x}_v : \frac{1}{12}\begin{bmatrix} -1 & 0 & 1 \\ -4 & 0 & 4 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{x}_{uu} : \frac{1}{6}\begin{bmatrix} 1 & 4 & 1 \\ -2 & -8 & -2 \\ 1 & 4 & 1 \end{bmatrix} \quad \mathbf{x}_{vv} : \frac{1}{6}\begin{bmatrix} 1 & -2 & 1 \\ 4 & -8 & 4 \\ 1 & -2 & 1 \end{bmatrix} \quad \mathbf{x}_{uv} : \frac{1}{4}\begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Least Squares Polynomial Fitting

We have used a fast least squares fitting method to derive partial derivatives in the *symmetric* Neighborhood of a pixel. This method allows the Neighborhood size to be controlled.

A surface fit of order n can be written as :

$$f(x,y) = \sum_{i,j=0}^{i+j\leq n} a_{ij}x^i y^j$$

We have used second ($n = 2$) order fitting in the Neighborhood of every pixel to compute first and second order derivatives. Clearly, since the pixel at which derivatives are computed is at the origin, we get :

$$x = 0 \; and \; y = 0$$

$$\frac{\partial f(x,y)}{\partial x} = a_{10} \quad \frac{\partial f(x,y)}{\partial y} = a_{01}$$

$$\frac{\partial^2 f(x,y)}{\partial x^2} = 2a_{20} \quad \frac{\partial^2 f(x,y)}{\partial y^2} = 2a_{02}$$

$$\frac{\partial^2 f(x,y)}{\partial x \partial y} = \frac{\partial^2 f(x,y)}{\partial y \partial x} = a_{11}$$

Thus derivatives are read off directly from the coefficients. We have also used the general least squares fitting procedure for fitting polynomial on surface patches. For the purpose of

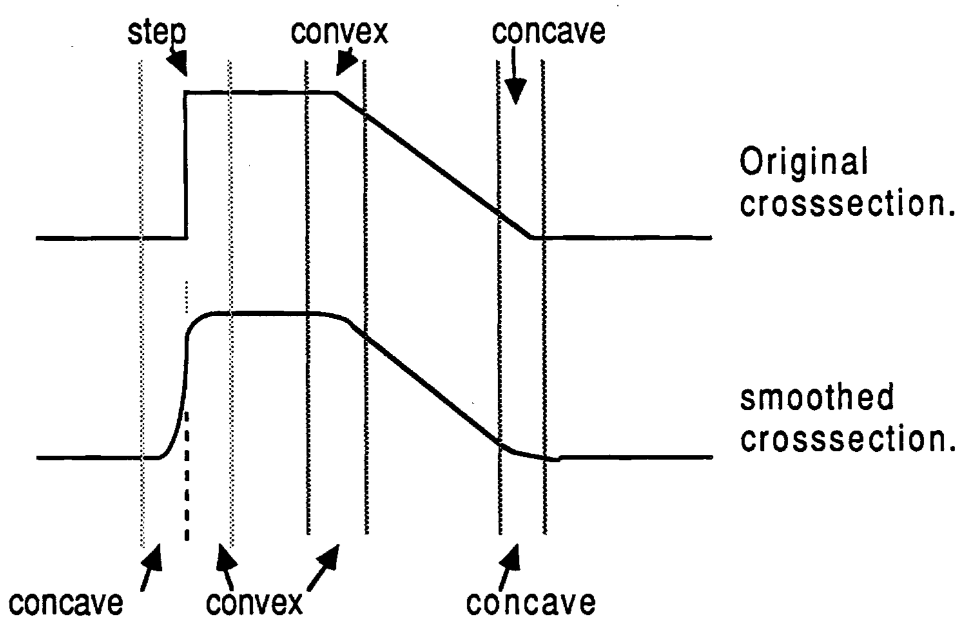


Figure 26: Effect of uniform Gaussian Smoothing

computing derivatives it is observed that we always have symmetric Neighborhood around the pixel. This fact simplifies the least squares equations. See appendix B for the simplified least square fitting equations for second order bivariate approximation in a symmetric Neighborhood.

4.2.2 Results of Initial Segmentation

The above mentioned process is applied to actual range images and results are shown in figures 27,28,29, 30,31,32,33.

The smoothing behavior of Gaussian operator was briefly discussed in chapter 2. It is observed that step edges in range images are actually adjacent convex and concave edges. This is further amplified after smoothing the image with any size of Gaussian operator. Brady etal. [4] have restricted the Gaussian application to inside of the region. We have used Gaussian uniformly in the range image with the intention of uniformly smoothing the image for the purpose of obtaining reliable curvature estimates (see figure 26)

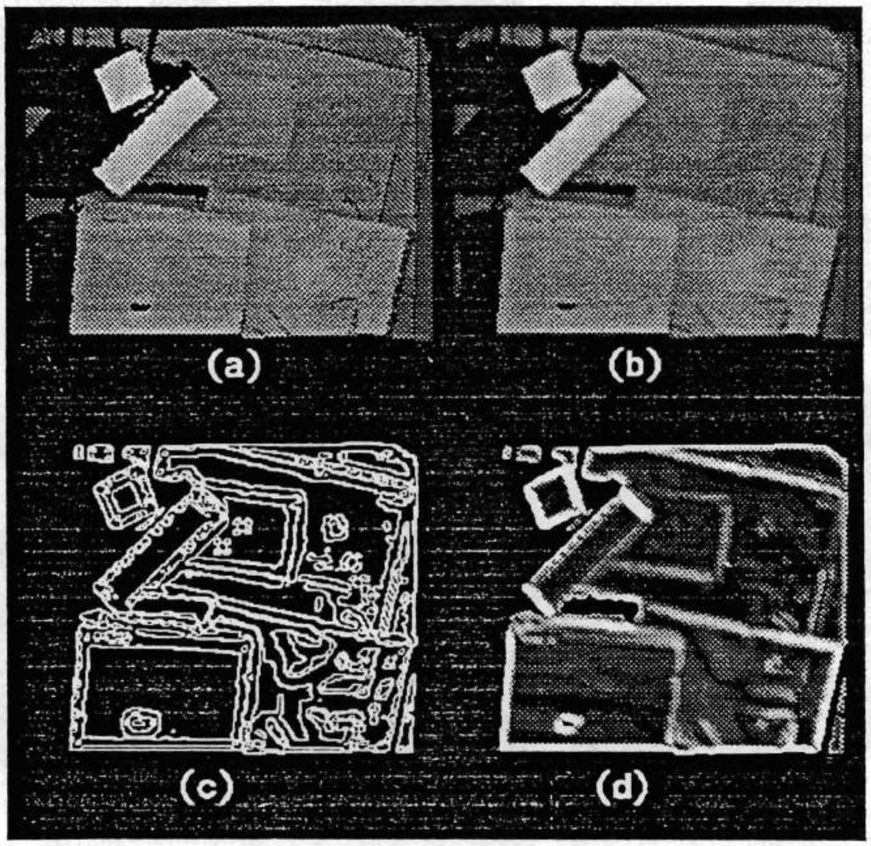


Figure 27: **curvature estimation** (a) original image. 192 × 256 12 bits/pixel image (b) smoothed image. (c) regions. (d) error in fitting

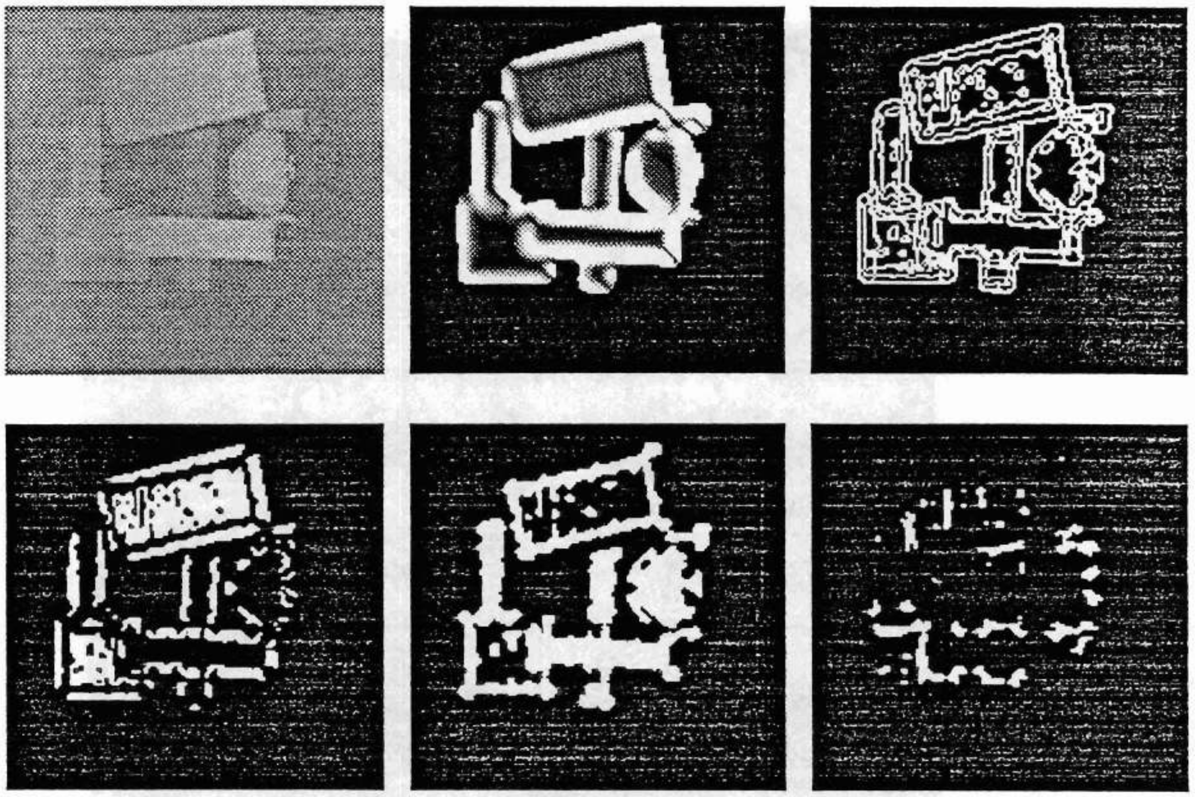


Figure 28: **curvature estimation** left to right,from top; original image.150 × 150 8 bits/pixel image; error in fitting; segmented regions; flat regions; convex regions; concave regions.

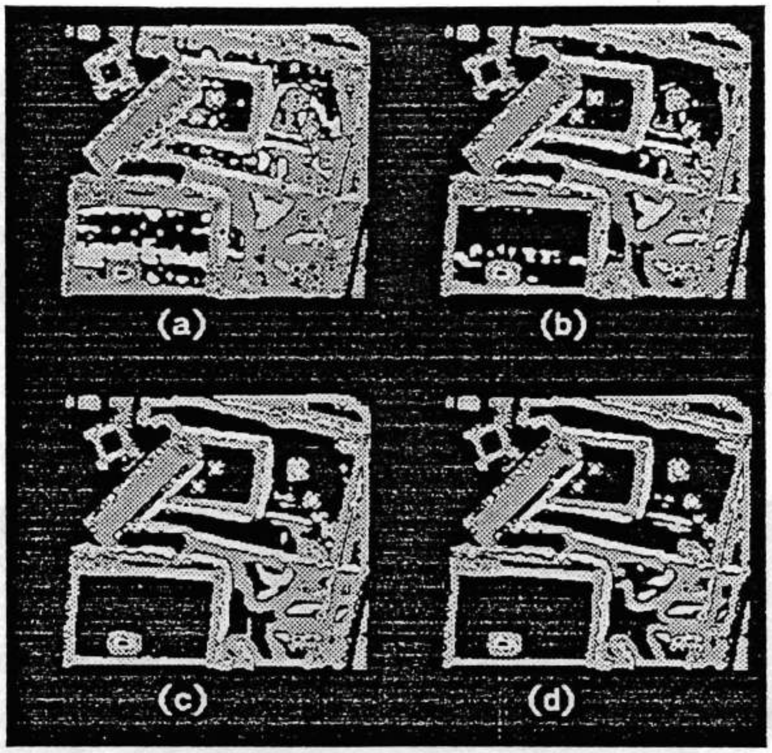


Figure 29: **Initial labeling of scene with different threshold values** (a) 0.01 (b) 0.02 (c) 0.03 (d) 0.04 .

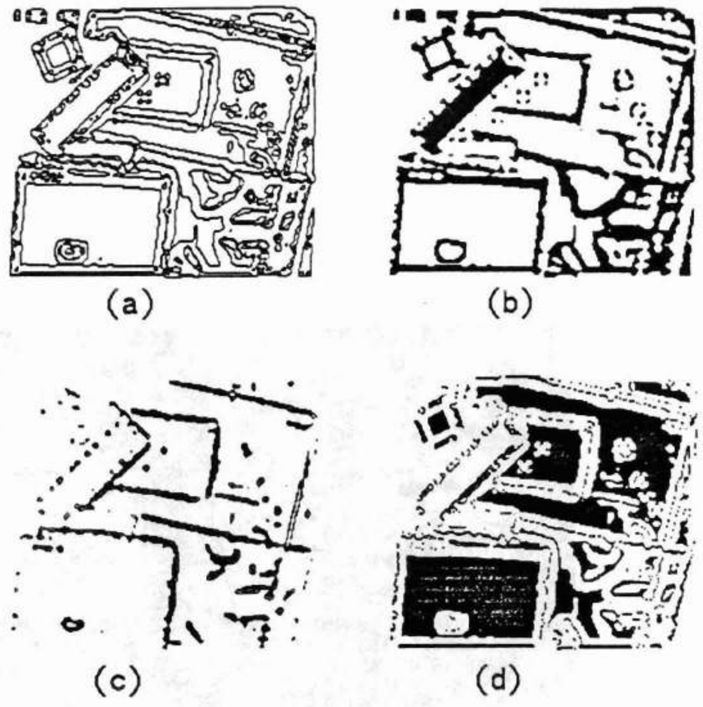


Figure 30: **Labeling** of scene :(a) all regions (b) convex (c) concave (d) flat.

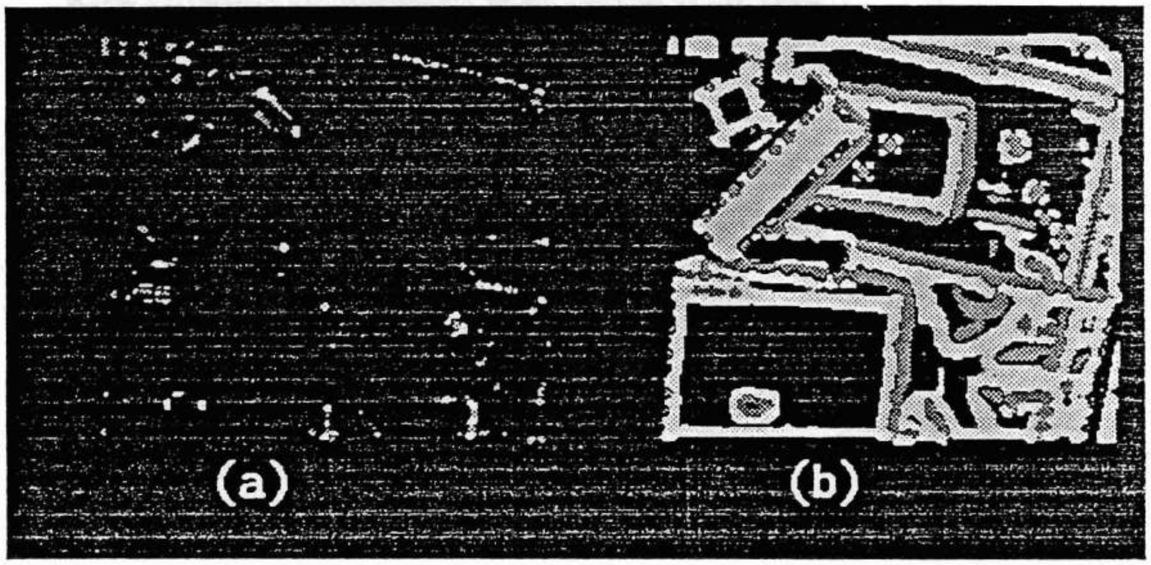


Figure 31: **Thresholded** left : gauss. right : mean. black indicates zero, gray is positive and white is negative value

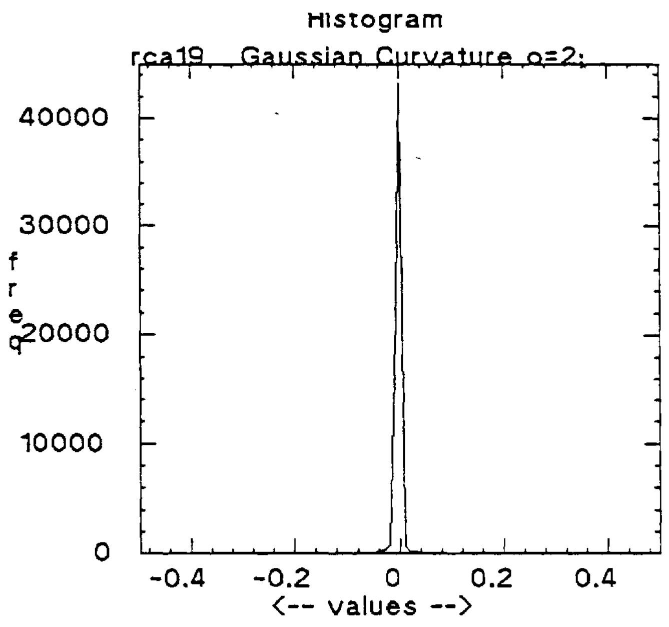


Figure 32: Histogram of Gaussian Curvature

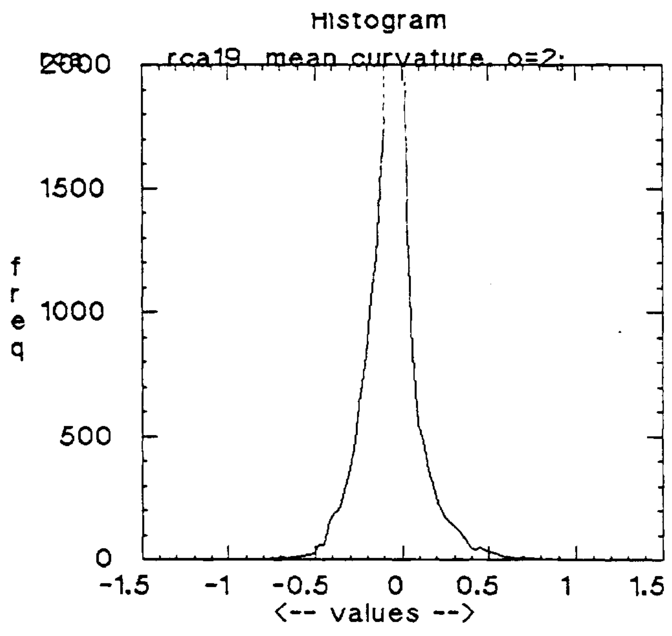


Figure 33: Histogram of Mean curvature

For surface characterization purpose we use higher sigma value (= 1.5) and for post segmentation processing we work at lower level in scale. Step Edges detected at sigma = 1.0 are used to detect region boundaries in higher level processing stage discussed in next section.

Although the response of Gaussian and Mean curvature is reliable it is necessary to threshold the values around zero. 1% of maximum was used as threshold in all examples. Figures 27 and 28 show the labeled regions and error in fitting second order polynomial at the Neighborhood of each pixel, in images with 12 bits/pixel and 8 bits/pixel respectively. The fit-error is appreciable at boundaries including smooth edges. This means that curvature estimates at the edges are not reliable. At such points curvature magnitude may not be reliable though sign of curvatures is reliable. Further results are shown only for image in figure 27.

Figure 29 shows the effect of threshold values on curvature signs. As threshold values for Gaussian and mean curvature is changed, pixel labeling may change if the curvature magnitude is not appreciable. image thresholded at 1% of maximum curvature magnitude (see figure 29(c)) has correct labelings. Further results are shown only for this threshold value. Pixels are classified as one of the eight basic types. We can classify the entire image into concave, convex, and flat regions by simply merging all neighboring pixels having similar type of surface, i.e, flat,concave or convex (see figure 30. Thresholded values of Gaussian and mean curvature are shown in figure 31. White patches indicate zero magnitude, gray indicate positive magnitude and black indicates negative curvature magnitude. It is observed that Gaussian curvature is mostly zero except for isolated patches, since the image has no spherical object. Non-zero mean curvature values are obtained at step edges and on a cylindrical object. Histogram of the magnitude of Gaussian and mean curvature (figure 32 and 33) for the entire image show appreciable mean curvature magnitude in the image and no significant Gaussian curvature. It can therefore be inferred that the scene has flat and possibly cylindrical objects.

4.3 Post processing of Labeled scenes

The segmentation done by labeling the individual pixels using sign of Gaussian and mean curvature is local in nature and threshold dependent. In order to interpret these labelings globally, we need to process the the labeled image with globl constraints. Besl and Jain [25] have proposed a variable order surface fitting algorithm. Surface patches are described as linear,quadric or cubic.

Our approach depends on the actual requirements. We describe two methods, (both are preliminary) to obtain useful segmentation given labeled image. The first method simply groups convex patches to form connected convex subparts of the scene. Second method uses the segmented objects obtained from algorithm described in chapter 3.

4.3.1 Obtaining Convex patches

As noted in third chapter, detection of smooth edges is difficult to extract using only local information. Curvature information at the all types of edges is easy to record. From figure 26 it is clear that edges in smoothed images can be recorded as thin convex and concave regions. In particular, convex edges are of convex cylinder type, with zero Gaussian curvature but appreciable negative mean curvature. Similarly, concave edges are of concave cylinder type, with zero Gaussian curvature but appreciable positive mean curvature. Thus all types of edges give either convex or concave cylindrical response. But the edge response is obtained over wider region due to smoothing and large window size during derivative computation. It is therefore not possible to have exact localization of patches obtained by merging convex regions.

A simple algorithm for obtaining convex patches is given below :

1. Read the labeled image.
2. Label each patch as a region.
3. Initialize the region data structure to record surface type, number of pixels, topmost pixel in the region,neighbours of the region,extremities of the region and the label

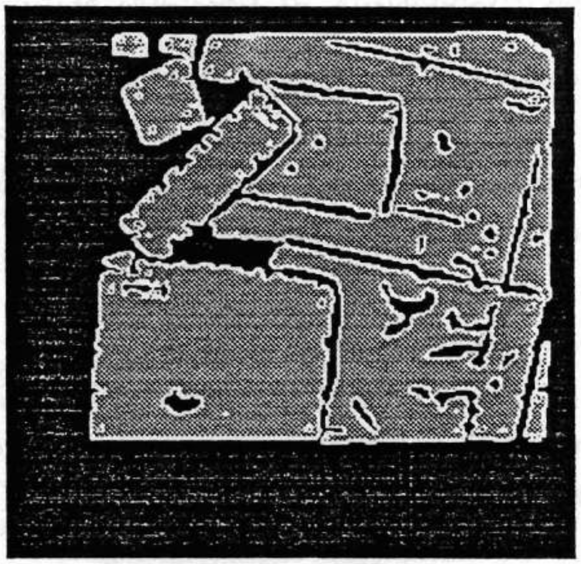


Figure 34: Convex patches

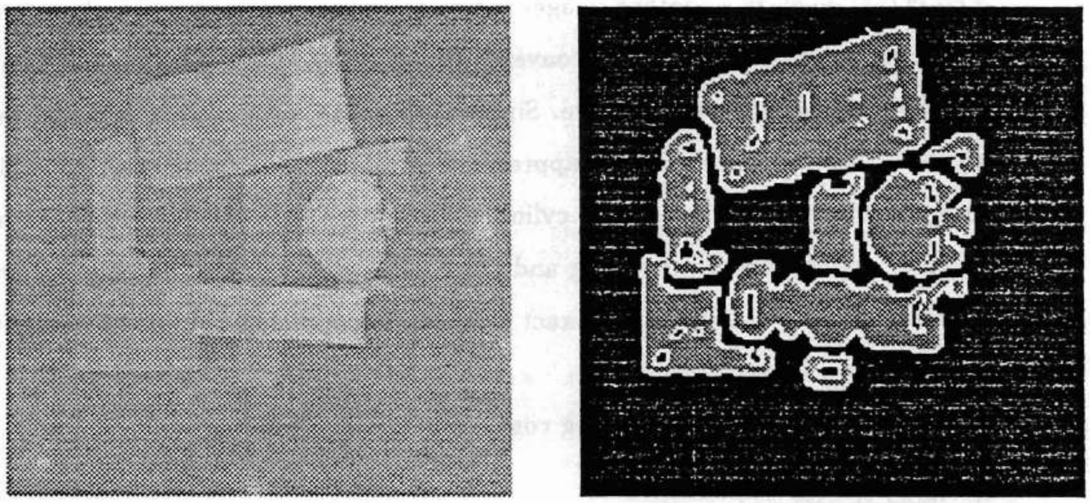


Figure 35: Convex patches

assigned to the region.

4. For the next unprocessed topmost region of the type **flat** or **peak**(convex sphere) or ridge (convex cylinder) with acceptable number of pixels **do**:
   (a) Extend the original region to include all neighboring regions of type **flat** or **ridge**. Other types of regions are considered concave or part of other convex subpart. **peak** patches are not included because they will be selected as seed region.
   (b) Repeat the above step to extend the region, till it is not possible to grow any more.
5. Output the convex subparts. **End.**

Figures 34 and 35 show convex patches obtained from labeled image obtained in figure27 and in figure 28(a) respectively. Majority of objects in figure 34 are merged into one convex patch while they are separated in figure 35

4.3.2 Object Surface Classification

Surfaces on the segmented objects can be classified as one of basic surface type using the initial labeling based on sign of curvatures. Yang and Kak [33] have used extended Gaussian images to identify surface type on isolated surfaces. Histogram of labels in an isolated object can give some idea about the surface and guide the surface fitting process.

The classification algorithm is as follows :

1. Read in the segmented objects image and labeled surface image.
2. For each object in the image do :
   (a) Erode the object in labeled image so as to remove points within 5 pixel distance of the object boundary. This reduces the effect of smoothing and window size during curvature estimation which is mainly contributed by pixels near the boundary, and does not reflect the nature of region.

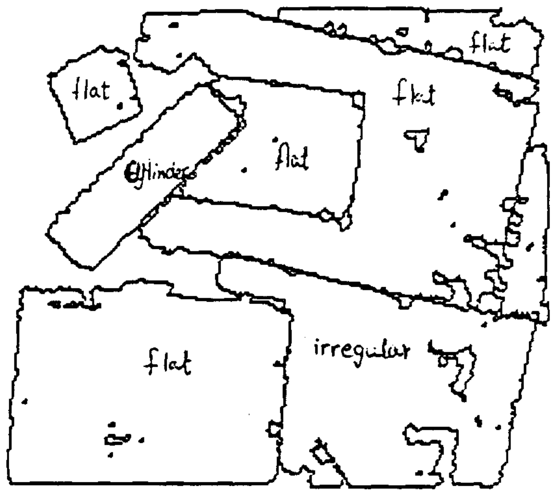


Figure 36: **Classified surfaces**

(b) Histogram the remaining pixel-label values.

(c) If more than 90 % pixels are of one type,either **flat** or **cylinder** or **sphere** then the surface can be classified as such. If there are two or more peaks in the histogram, object has more than one surface type.

(d) In single surface cases fit the best fitting surface on the points. Output the description of surface.

(e) Further processing by region growing by surface fitting is necessary to smoothen the surface patches. Fit surfaces on individual patches and merge them by region growing.

This algorithm is being implemented. Initial classification process will classify the surfaces in figure 11 as 5 plane surfaces, 1 cylindrical and 1 irregular surface (the film mailer). See figure 36.

First and second order polynomials were fitted on *flat* and *non-flat* surface patches respectively in image of figure 11. The reconstructed image is shown in figure 37. Besl

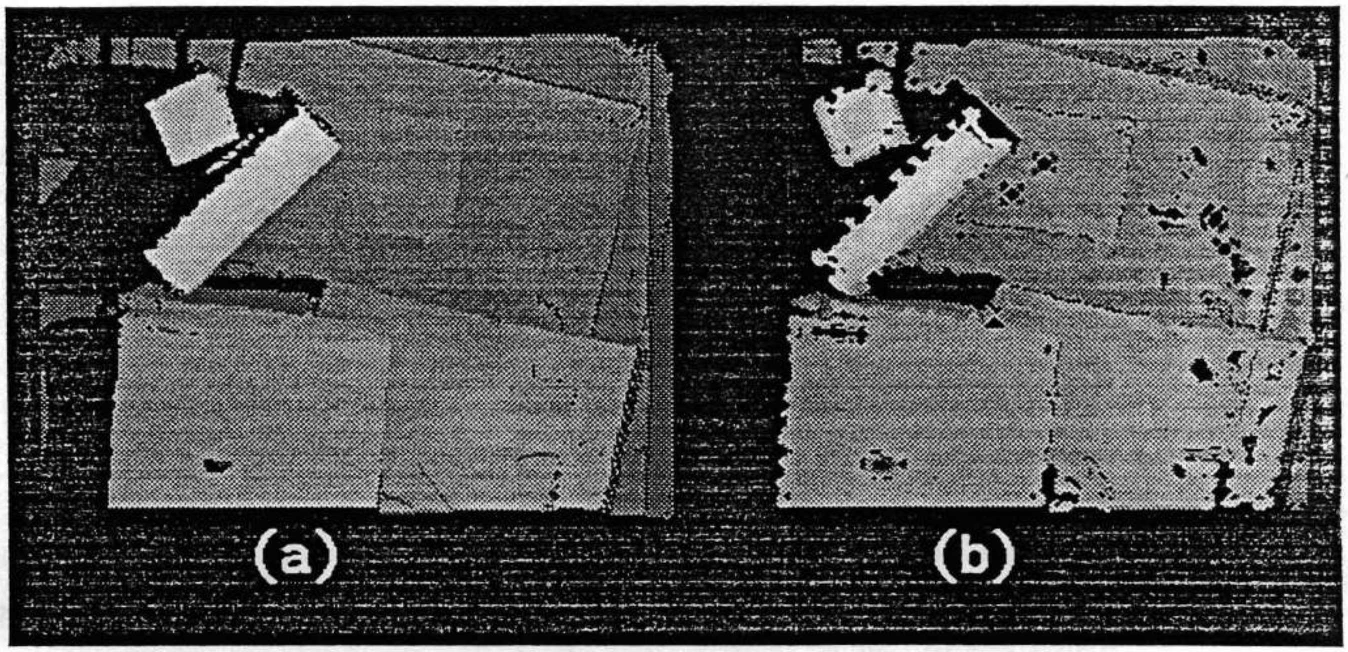


Figure 37: **Original and reconstructed Images.** left: original images right: reconstructed images obtained by fitting 1st and 2nd order surfaces on patches labeled by segmentation process.

and Jain [13, 25] have used initial labeling to obtain seed regions in the final region growing process. They perform variable order surface fitting to approximate the scene as a collection of piece-wise continuous functions.

Chapter 5

Discussion

Though results of running the various algorithms described in previous chapters on images acquired from different scanners are consistent, there is scope for refinement of all the approaches. We will discuss the merits and demerits of each method and suggest improvements.

We need to study the scale-space behavior of range images in detail. This would lead to a better understanding of the scale at which range images should be handled. We have noticed that thresholding of zero-crossings makes the entire segmentation procedure dependent on the threshold value. Though we have obtained consistent results with a fixed empirically determined value for all the images obtained from a particular scanner, threshold selection is not automatic. Secondly, even with *right* threshold value the region may not be completely bounded by the zero-crossings (in case of overlaps by thin objects or sensor noise) To make the whole process less sensitive to threshold, following post-processing steps (region splitting) are suggested :

1. Read in the segmented object.
2. Trace the contours around the object as it is defined now and also any other boundaries that are now lying inside the object. Except for the bounding contours, other contours may not be closed. They may simply lie within the region and actually are boundary of the real object. In such a case mark the beginning and end of the contour. If the

contour touches the closed contour then mark the point of contact as end of *inner* contour.

3. In all the contours mark the concavities.

4. Now split the region by connecting two contours (gap filling) or connecting two points of concavity (gap filling or region splitting) or connecting an end point of contour with a concavity, based on predetermined gap filling *distance.*

5. The output is the segmented object.

The above method should be indifferent to threshold values on higher side as it splits the region consisting of more than one regions. To reduce the sensitivity to low threshold values (which will result too many small regions) some sort of merging is required. Merging is a much difficult task, so it is better to keep the threshold high and have the post-segmentation process perform the splitting, rather than initial segmentation performing splitting due to low threshold value.

Another solution to splitting is to let higher level recognition process make globally valid observations to split the region. The higher level procedure may use a priori information or may make some assumptions or apply global constraints to split the region. Franc Solina's (see [23]) superquadric procedure can split the regions into identifiable parts by performing model fitting on individual part of the object.

In chapter 4 we noticed that labeling of the scene based on curvature sign is threshold sensitive. While thresholding around zero is necessary to obtain meaningful results, it is not clear how that value can be automatically determined. Curvature determination being local, the labeling is sensitive to noise and surface *texture*. It is not well understood how to generate a global interpretation of such surfaces.

Bibliography

[1] R.M.Bolle and D.B. Cooper,*Bayesian recognition of local 3-D shape by approximating image intensity functions with quadric polynomials*, IEEE Trans. Pattern Analysis and Machine Intelligence. PAMI-6,No.4,1984,418-429.

[2] R.Bajcsy;*Three dimensional scene analysis;*Proc. Pattern Recognition Conf. ; Miami,Florida,pp. 1064-1074,1980.

[3] P.J.Besl and R.C.Jain,*Three dimensional object recognition*, ACM Computing surveys 17,No.(1),1985,pp. 75-145.

[4] Brady,M.,Ponce,J.,Yuille,A.,and Asada,H.,*Describing surfaces*, MIT AI lab memo 822,January 1985.

[5] Haruo Asada and Michael Brady ;*The curvature Curvature Primal Sketch*, IEEE Pattern Analysis and Machine Intelligence, PAMI-8,No.1, January 1986.

[6] Robert Haralick,Layne Watson and Thomas Laffey ;*The Topographic Primal Sketch*, International Journal of Robotics Research, vol 2,No 1,Spring 1983,pp 50-72.

[7] Jean Ponce and Michael Brady ;*Toward a Surface Primal Sketch*, IEEE Conference on Robotics and Automation, March 1984, pp 420-425.

[8] M.Hebert and J. Ponce*A new method for segmenting 3-D scenes into primitives* Proc. of the 6th int conf. on pattern recognition. 1982

[9] P.J.Besl and R.C.Jain,*Invariant surface characteristics for 3d Object Recognition in Range Images*,Computer vision,Graphics, Image Processing No.(1),1986,pp 33-80.

[10] R.M.Haralick *Digital step edges from zero crossings of second directonal derivatives*,PAMI-6,No. 1,1984,58-68.

[11] Ballard and Brown *Computer Vision*,1982, Prentice Hall,New Jersey.

[12] B.K.P. Horn *Machine Vision*

[13] P.J.Besl and R.C. Jain *Segmentation through symbolic surface descriptions*,Proc on Computer Vision and Pattern Recognition,1986.

[14] T.J.Fan,G.Medioni and R.Nevatia*Descriptions of surfaces from Range data using curvature properties*, Proc. on Computer Vision and Pattern Recognition,1986.

[15] T.C.Henderson *efficient segmentation method for range data.* Proc. of the society for photo-optical Instrumentation Engineers conference on Robot Vision. 1982.

[16] A. Heurtas and R. Nevatia ;*Edge detection in Aerial Images Using* $\nabla^2 G(x, y)$, in Semi-annual Technical Report on Image Understanding Research, University of Southern California,1981,pp 16-26.

[17] S.Inokuchi *etal* ,*A three dimensional edge region operator for range pictures.* Proc. of 6th international Conference on pattern recognition. 1982.

[18] D.L. Milgrim and C.M. Bjorklund *Range image processing : Planar surface extraction.* Proc of the 5th International Conference on Pattern Recognition. 1980.

[19] L.R.Nackman *Two-dimensional critical point configuration graphs.* IEEE PAMI-6,July 1984

[20] I.K.Sethi and Jayaramamurthy *Surface classification using characteristic contours.* Proc. of the 7th International Conference on Pattern Recognition.IEEE,1984

[21] O.D.Faugeras and M.Hebert;*The Representation,Recognition and Positioning of 3-D Shapes from range data;*in Techniques for 3-D Machine Perception Edited by A. Rosenfeld;Published by North-Holand,1986, pp. 13-51.

[22] B.K.P. Horn;*Extended Gaussian Images;*Proc. of the IEEE,vol. 72,No. 12, pp. 1671-1686,December 1984.

[23] Franc Solina; *Shape Recovery and Segmentation with Deformable Part Models*; Ph.D. thesis, Grasp laboratory, University of Pennsylvania. MS-CIS-87-111.

[24] D. Marr and E. Hildreth; *Theory of Edge Detection*; Proc. of Royal Society of London,B-207,pp 187-217,1980.

[25] P.J. Besl and Ramesh Jain; *Segmentation Through Variable-Order Surface fitting*, IEEE Transactions on Pattern Analysis and Machine Intelligence, 1988.

[26] David J. Heeger; *Filling in the Gaps: A Computational Theory of Contour Generation*, University of Pennsylvania, Grasp Lab, Technical report MS-CIS-84-64

[27] B. Gil, A. Mitiche and J.K. Aggarwal ;*Experiments in combining intensity and range edge maps*,Computer Vision, Graphics and Image Processing 21, 1983, pp 395-411.

[28] A. Mitiche and J.K Aggarwal *Detection of Edges Using Range Information*, IEEE Trans. Pattern Analysis and Machine Intelligence,PAMI-5,No. 2,pp 174-178.

[29] Peter Allen; *Object Recognition Using Vision and Touch*; Ph.D. Thesis, Grasp Lab.,University of Pennsylvania. 1985.

[30] R. Nevatia and K.R. Babu; *Linear feature extractor and Description*, Computer Graphics and Image Processing,vol13,pp. 257-269,1980.

[31] A. P. Pentland; *Perceptual Organization and the Representation of Natural Form*,Artificial Intelligence 28(3),pp 293-331.

[32] R.Y. Wong and Hayrepetian ;*Image Processing with Intensity and Range Data*, Proceedings of the IEEE Pattern Recognition and Image Processing Conference, Las Vegas,June 1982,pp 518-520.

[33] H. S. Yang and A. C. Kak; *Determination of the Identity, Position and Orientation of the Topmost Object in a Pile*, Computer Vision, Graphics and Image Processing 36,1986,pp 229-255.

[34] David Smith and Takeo Kanade; *Autonomous Scene Description with Range Imagery*, Computer Vision, Graphics and Image Processing, Vol 31,No. 3,Sept 1985,pp 322-334.

[35] Martin Herman; *Generating Detailed Scene Descriptions from Range Images*, IEEE conference on Robotics and Automation, March 1984, pp 426-431.

[36] Richard Duda, David Nitzan and Phyllis Barrett ;*Use of Range and Reflectance Data to Find Planar Surface Regions*, IEEE Pattern Analysis and Machine Intelligence, PAMI-1, No 3, July 1979.

[37] Darwin Kuan and Robert Drazovich ;*Model-based Interpretationof Range Imagery*,Proc. of the National Conference on Artificial Intelligence, Austin, August 6-10, AAAI,pp 210-215.

[38] B.C. Vemuri and J.K.Aggarwal;*3-D Model Construction from Multiple Views Using Range and Intensity Data*, IEEE conference on Computer Vision and Pattern Recognition,1986,pp 435-437.

[39] Alan Yuille and Tomaso Poggio ;*Scaling Theorems for Zero Crossings*, IEEE Pattern Analysis and Machine Intelligence, PAMI-8,No 1, January 1986.

Appendix A

2nd order Least squares fitting in symmetric neighborhood

The approximating polynomial is written as :

$$I(x,y) = a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

The square error term is :

$$\Sigma^2 = \sum_{i=1}^{N}(Z_i - I_i)^2$$

$$\Sigma^2 = \sum_{i=1}^{N}(Z_i^2 - 2Z_iI_i + I_i^2)$$

To minimize the least squares term, let $\frac{\partial\Sigma^2}{\partial X_i} = 0$.

which is :

$$\frac{\partial\Sigma^2}{\partial a_{20}} = -2Z_ix_i^2 + 2x_i^2I_i = 0$$

$$\frac{\partial\Sigma^2}{\partial a_{11}} = -2Z_ix_iy_i + 2x_iy_iI_i = 0$$

$$\frac{\partial\Sigma^2}{\partial a_{02}} = -2Z_iy_i^2 + 2y_i^2I_i = 0$$

$$\frac{\partial \Sigma^2}{\partial a_{10}} = -2Z_i x_i + 2x_i I_i = 0$$

$$\frac{\partial \Sigma^2}{\partial a_{01}} = -2Z_i y_i + 2y_i I_i = 0$$

$$\frac{\partial \Sigma^2}{\partial a_{00}} = -2Z_i + 2I_i = 0$$

Writing :

$$S_{jlk} = x_i^j y_i^l z_i^k$$

we get :

$$\begin{bmatrix} S_{400} & S_{310} & S_{220} & S_{300} & S_{210} & S_{200} \\ S_{310} & S_{220} & S_{130} & S_{210} & S_{120} & S_{110} \\ S_{220} & S_{130} & S_{040} & S_{120} & S_{030} & S_{020} \\ S_{300} & S_{210} & S_{120} & S_{200} & S_{110} & S_{100} \\ S_{210} & S_{120} & S_{030} & S_{110} & S_{020} & S_{010} \\ S_{200} & S_{110} & S_{020} & S_{100} & S_{010} & S_{000} \end{bmatrix} \begin{bmatrix} a_{20} \\ a_{11} \\ a_{02} \\ a_{10} \\ a_{01} \\ a_{00} \end{bmatrix} = \begin{bmatrix} S_{201} \\ S_{111} \\ S_{021} \\ S_{101} \\ S_{011} \\ S_{001} \end{bmatrix}$$

In a symmetric neighborhood :

$$S_{pq0} = 0 \ \ for\ odd\ p\ or\ q\ and$$

$$S_{pq0} = S_{qp0}$$

The above system of equations reduces to :

$$\begin{bmatrix} S_{400} & 0 & S_{220} & 0 & 0 & S_{200} \\ 0 & S_{220} & 0 & 0 & 0 & 0 \\ S_{220} & 0 & S_{040} & 0 & 0 & S_{020} \\ 0 & 0 & 0 & S_{200} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{020} & 0 \\ S_{200} & 0 & S_{020} & 0 & 0 & S_{000} \end{bmatrix} \begin{bmatrix} a_{20} \\ a_{11} \\ a_{02} \\ a_{10} \\ a_{01} \\ a_{00} \end{bmatrix} = \begin{bmatrix} S_{201} \\ S_{111} \\ S_{021} \\ S_{101} \\ S_{011} \\ S_{001} \end{bmatrix}$$

Which can be written as :

$$a_{10} = \frac{S_{101}}{S_{200}} \quad a_{01} = \frac{S_{011}}{S_{200}} \quad a_{11} = \frac{S_{111}}{S_{220}}$$

and

$$\begin{bmatrix} S_{400} & S_{220} & S_{200} \\ S_{220} & S_{040} & S_{020} \\ S_{200} & S_{020} & S_{000} \end{bmatrix} \begin{bmatrix} a_{20} \\ a_{02} \\ a_{00} \end{bmatrix} = \begin{bmatrix} S_{201} \\ S_{021} \\ S_{001} \end{bmatrix}$$

Appendix B

Source Code Listing

Listings of source programs is included in following pages.

1. **space.c** : Performs smoothing,median filtering,Gaussian filtering, Laplacian, marking zero-crossings and graphics display of histogram etc. in interactive manner.

2. **segment.c** : Segments all objects and topmost object in the scene, given original image and zero-crossings of LOG image. Also outputs supporting points of topmost object.

3. **rca_calib.c** : Generates a list of points for Z-depth format image. Originally written by Franc, modified to read PM files and add points horizontally and vertically.

4. **classify.c** : Procedure used to select and classify the superquadric models.

5. **spline.c** : Computes various surface characteristics of the image. Interactively displays results and histograms using *quickdraw* routines. Outputs labeled image and other characteristic as desired by the user.

6. **grad.c** : Has code for fast least squares fitting. Polynomial is fitted in the *symmetric* neighborhood of the pixel.

7. **merge.c** : Performs processing on the image labeled according to signs of Gaussian and mean curvature. It computes convex parts of the image, fits polynomials on patches using general least squares routines in **solver.c**.

8. **solver.c** : Has code for a general least squares fitting procedure.

There are other supporting programs that are vital to the algorithms. Superquadric fitting programs are developed by Franc Solina and are not listed here.

```
/*********************************************************************

    Program for computing scale - space description of the input imag
   and lots of other things in interactive manner. Later  will overri
   scale.c.

   Modifications for display of histogram done on Feb 18, 1988.

   March 24 1988 : To read/write in both PM_C and PM_S formats.
   April 1 1988  : All buffers made floating pt. Computation of lapla
                   and zerocrossing made floating pt.
*********************************************************************


#include <stdio.h>
#include <math.h>
#include <local/pm.h>
#include <ik.h>
/* #include <local/qkopt.h> */

#define BUFSIZE 256  /* Image buffer size */
#define BUF_NUM 4    /* # of buffers available for manipulation */

float result[BUFSIZE][BUFSIZE];
float buffer[BUF_NUM][BUFSIZE][BUFSIZE]; /* 0 stores original image *
int temp_buf[BUFSIZE];                   /* temporarily store a buffer

float x[BUFSIZE], y[BUFSIZE]; /* to store points */


int threshold;          /* Threshold for detecting zero-xings */
int bool1,bool2,bool3;
char *cmt;
char input_filename[50];
int sizex,sizey;         /* size of the image */
pmpic *pm1;
u_int image_format;      /* stores the format of the last image read

float min();
float get_median();
float abszz();
float squarezz();

/*************************************MAIN**************************

main(argc,argv)
int argc;
char **argv;
{
```

```
  FILE *infile,*out;  /* pointers to input image and output image fil
  FILE *out2;
  FILE  *infs,*out_pmsmooth,*output_pm;
  char *smooth_cmt;
  char ikonas_disp[10];
  char *out_cmt;
  int count;
  unsigned char c;
  static int nhb_x[8] = {0,1,1,1,0,-1,-1,-1};
  static int nhb_y[8] = {1,1,0,-1,-1,-1,0,1};
  float nbd[8],temp;
  int i,j,k,l,m,n,b;
  float nbr[10];
  int gsize;
  float sigma;    /* size and sigma of the gaussian operator */
  float sum;
  float gauss[60];
  float gsum;
  int offset;
  char input[20];
  int offx = 0,offy = 0;          /* offset coordinates , intialized
  char outfile[30];               /* name of the output file */
  int b1,b2,b3;
  unsigned char *pm_point;
  int disp_row;
  short int *pms_point;           /* pointer to short integer to hand
                                     PM_S format */
  int factor;                     /* # by which PM_S image pixel to b
                                     for display on IKONAS */

  printf("argc : %d\n",argc);

  if (argc != 2)
    {
      printf("usage : scale <input-image-file-pmpic>\n");
      exit(0);
    }

  printf("want to display on ikonas ? ");
  scanf("%s",&ikonas_disp[0]);

  printf("read\n");
  /* open the ikonas display. value of env. variable is taken */
  if(strcmp("y",ikonas_disp) == 0)
    if(ikopen(NULL) == -1)
      {
        printf("can't open ikonas. exiting\n");
        exit(0);
      }

   /* get comment line */

   cmt = pm_cmt(argc,argv);

   /* open input pm file */

   read_picture(argv[1],0);
   read_picture(argv[1],1);

   printf("Rows : %d Columns : %d\n",sizex,sizey);


/*  procesing of the commands starts now :
    various available commands are :
      1. gauss : convolves the image with gaussian filter.
      2. cross : computes zero and other types of crossings in the gi
                 buffer.
      3. save  : saves indicated buffer in a file.
      4. disp  : displays indicated buffer on the ikonas.
      5. add   : adds the two buffers.result is put in buffer 1
      6. sub   : subtracts two buffers. result is put in buffer 1
      7. buffer: selects the current buffer.
      8. offset: offset the picture on ikonas.
      9. original : indicated buffer gets original picture.
      10.read : Reads a file in the designated buffer.
      11.hist : Computes and displays the historam using quickdraw.
      12.ikpm : saves the image displayed on ikonas in the a file in

    five active buffers are maintained to manipulate the original ima
*/
printf(">");

  while(scanf("%s",input) != EOF)
    {
      if((strcmp(input,"median") == 0) || (strcmp(input,"m") == 0))
        {
          /* do median filtering of the image */
          b = readbuffer();

          for(i=1;i<(sizex-1);i++)
            for(j=1;j<(sizey-1);j++)
              {
                count = 0;
                for(m=i-1;m<=i+1;m++)
                  for(n=j-1;n<=j+1;n++)
                    {
                      nbr[count] = buffer[b][m][n];
```

```
                      count++;
                    }
                result[i][j] = get_median(nbr);
              }

          for(i=1;i<(sizex-1);i++)
            for(j=1;j<(sizey-1);j++)
              buffer[b][i][j] = result[i][j];

        } /* end of median filtering */

      else if((strcmp(input,"gauss") == 0) || (strcmp(input,"g") == 0
        {

          b = readbuffer();


          printf("sigma :");
          scanf("%f",&sigma);

          printf("size of window :");
          scanf("%d",&gsize);

          /* compute the gaussian array  */

          gsum = 0;
          for(i= -gsize/2,j=0;i<= gsize/2;i++,j++)
            {
              gauss[j] = (1.0/(sqrt((double)(2.0*3.1415926))*sigma))*
              gsum += gauss[j];
              printf("gauss[%d] = %f",i,gauss[j]);
            }

          if (gsum == 0) gsum = 1;
          printf("\n gsum = %f \n",gsum);

          /* seperably convolve x-axis */

          for(j=0;j<sizey;j++)
            for(i=gsize/2;i<=(sizex-gsize/2);i++)
              {
                sum = 0;
                for(k= -gsize/2;k<= gsize/2;k++)
                  {
                    sum += buffer[b][i+k][j]*gauss[k+gsize/2];
                  }
                result[i][j] = sum/gsum;
              }
          /* seperably convolve y-axis */

          for(i=0;i<sizex;i++)
            for(j=gsize/2;j<=(sizey-gsize/2);j++)
              {
                sum = 0;
                for(k= -gsize/2;k<= gsize/2;k++)
                  {
                    sum += result[i][j+k]*gauss[k+gsize/2];
                  }
                buffer[b][i][j] = sum/gsum;
              }

        }
      else if((strcmp("lap",input) == 0) || (strcmp("l",input) == 0))
        {
          b = readbuffer();

          /* apply laplacian operator */

          for(i=1;i<(sizex-1);i++)
            for(j=1;j<(sizey-1);j++)
              result[i][j] = -4*buffer[b][i][j]+buffer[b][i-1][j]
                +buffer[b][i+1][j]
                  +buffer[b][i][j-1]+buffer[b][i][j+1];

          for(i=1;i<(sizex-1);i++)
            for(j=1;j<(sizey-1);j++)
              buffer[b][i][j] = result[i][j];

        }
      else if((strcmp("cross",input) == 0) || (strcmp("c",input) == 0
        {
          b = readbuffer();

          printf("step edge magnitude desired ? enter 1 if yes >");
          scanf("%d",&bool1);

          printf("concave edge magnitude desired ? enter 1 if yes >")
          scanf("%d",&bool2);

          printf("convex edge magnitude desired ? enter 1 if yes >");
          scanf("%d",&bool3);

          /*  trace zeros  */

          for(i=1;i<(sizex-1);i++)
            for(j=1;j<(sizey-1);j++)
              {
```

```
              for(n= 0;n<8;n++)
                {
                  nbd[n] = buffer[b][i+nhb_x[n]][j+nhb_y[n]];
                }
              edge_p(buffer[b][i][j],nbd,&temp);
              result[i][j] = temp;
            }
        for(i=0;i<(sizex);i++)
          for(j=0;j<(sizey);j++)
            buffer[b][i][j] = result[i][j];

      }

    else if((strcmp("offset",input) == 0) || (strcmp("off",input) =
      {
        printf("coordinates :");
        scanf("%d",&offx);
        scanf("%d",&offy);
      }

    else if(strcmp("robert",input) == 0)
      {
        b1 = readbuffer();

        for(i=0;i<(sizex-1);i++)
          for(j=0;j<(sizey -1);j++)
              result[i][j] = (float) sqrt((double)
                            (squarezz(buffer[b1][i][j] - buffer[b1][i
                             squarezz(buffer[b1][i][j+1]-buffer[b1][i

        for(i=0;i<(sizex-1);i++)
          for(j=0;j<(sizey -1);j++)
            buffer[b1][i][j] = result[i][j];
      } /* robert */

    else if((strcmp("subtract",input) == 0) || (strcmp("sub",input)
      {
        /* subtract two images */

        printf("b3 = b1 - b2\n");
        b1 = readbuffer();
        b2 = readbuffer();
        b3 = readbuffer();

        for(i=0;i<sizex;i++)
          for(j=0;j<sizey;j++)
            {
              buffer[b3][i][j] = abszz(buffer[b1][i][j] - buffer[b
            }
        }


      else if((strcmp("disp",input) == 0) || (strcmp("d",input) == 0)
        {
          /* display the indicated buffer on ikonas */

          b = readbuffer();
          printf("offx : %d ; offy : %d \n",offx,offy);

          if(image_format == PM_S)
            {
              printf("factor to divide each pixel by : ");
              scanf("%d",&factor);
            }

          for(i=0;i<sizex;i++)
              {
                if(image_format == PM_S)
                  {
                    for(j=0;j<sizey;j++)
                      temp_buf[j] = buffer[b][i][j]/factor;
                    lwr_n(offx,i+offy,&temp_buf[0],sizey);
                  }
                else
                  {
                    for(j=0;j<sizey;j++)
                      temp_buf[j] = buffer[b][i][j];
                    lwr_n(offx,i+offy,&temp_buf[0],sizey);
                  }
              }

        } /* end of disp; display on IKONAS */

      else if(strcmp("ikclose",input) == 0)
        ikclose();

      else if(strcmp("ikopen",input) == 0)
        ikopen(NULL);

      else if((strcmp("save",input) == 0) || (strcmp("s",input) == 0)
        {
          /* save the indicated buffer in a file in ikonas format */

          b = readbuffer();

          printf("enter outputfilename :");
          scanf("%s",outfile);
```

```
          /* open output file */

          if((out = fopen(outfile,"w")) == NULL)
            {
              printf("file open error :%s \n",outfile);
              exit(0);
            }
          printf("row : %d col : %d \n",sizex,sizey);

          pm_addcmt(pm1,cmt);

          if(image_format == PM_C)
            {
              pm_point = (unsigned char *) pm1->pm_image;
              for(i=0;i<sizex;i++)
                for(j=0;j<sizey;j++)
                  {
                    *(pm_point) = buffer[b][i][j];
                    pm_point++;
                  }
            }
          else /* format is PM_S */
            {
              pms_point = (short int *) pm1->pm_image;
              for(i=0;i<sizex;i++)
                for(j=0;j<sizey;j++)
                  {
                    *(pms_point) = buffer[b][i][j];
                    pms_point++;
                  }
            }
          pm_write(out,pm1);

          fclose(out);
        } /* end of save */
      else if((strcmp("orig",input) == 0) || (strcmp("o",input) == 0)
        {
          b = readbuffer();

          /* load the input file in buffer b */


          for(i=0;i<sizex;i++)
            for(j=0;j<sizey;j++)
              buffer[b][i][j] = buffer[0][i][j];

        }
      else if((strcmp("read",input) == 0) || (strcmp("r",input) == 0)
        {
          b = readbuffer();

          printf("enter inputfilename :");
          scanf("%s",input_filename);
          read_picture(input_filename,b);
        }

      else if((strcmp("ikpm",input) == 0) || (strcmp("ikpm",input) ==
        {
          printf("Nothing happened\n");
        }

      else if((strcmp("hist",input) == 0) || (strcmp("h",input) == 0)
        {
          b = readbuffer();

          display_histogram(b);

        }

      else if((strcmp("row",input) == 0) || (strcmp("rowscan",input)
        {
          b= readbuffer();
          printf("row : ");
          scanf("%d",&disp_row);
          while(( disp_row < sizey) && ( disp_row >= 0))
            {
              display_row_histogram(disp_row,b);
              printf("row : ");
              scanf("%d",&disp_row);
            }
        }


      printf(">");
    }
}

/* compute edge strength and direction */
/*   mask is like this :

           -------------
           | 5 | 6 | 7 |
           -------------
           | 4 | X | 0 |
           -------------
           | 3 | 2 | 1 |
```

```
           -------------
*/

edge_p(intensity,nbd,p_es)
float intensity,nbd[8],
                *p_es;
  {
        static double delta[8] = {1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0};

        static unsigned char tbl[9] = {0,1,8,7,6,5,4,3,2};
        float *p_ed;
        int i,j,ed,halfgray,maxgray;

        float res,slope;

        res = 0.0;
        ed = -1;
        halfgray = 0;
        maxgray =255;

        if(bool1 ==1)
          {
            if(intensity > halfgray)
              {
                for (i=0;i<8;i++)
                  {
                    if(nbd[i]<halfgray)
                      {
                        slope = (float)(intensity - nbd[i])/delta[i];
                        if(slope >res)
                          {
                            res =slope;
                            ed = opposite(i);
                          }
                      }
                  }
              }
            else if(intensity == halfgray)
              {
                for (i=0;i<8;i++)
                  {
                    j=opposite(i);
                    if((nbd[i]<halfgray) && (nbd[j]>halfgray))
                      {
                        slope = (float)(nbd[j]-nbd[i])/(delta[i]);
                        if(slope > res)
                          {
                            res =slope;
                            ed =j;
                        }
                    }
                }
            }
        }

      if(bool2 == 1)
        {
          if(intensity > halfgray)
            {
              /* if required check for 0+0
                 type of crossings because they are generated by
                 concave surfaces
                 */
              for(i=0;i<8;i++)
                {
                  j=opposite(i);
                  if((nbd[i] == halfgray) && (nbd[j] >= halfgray))
                    {
                      slope = (float)(intensity - nbd[i])/delta[i];
                      if(slope > res)
                        {
                          res = slope;
                          ed = j;
                        }

                    }
                }
            }
        }

      if(bool3 == 1)
        {
          if(intensity < halfgray)
            {
              /* if required check for 0-- or 0-0
                 types of crossings because they are generated by
                 concave surfaces
                 */
              for(i=0;i<8;i++)
                {
                  j=opposite(i);
                  if((nbd[i] == halfgray) && (nbd[j] <= halfgray))
                    {
                      slope = (float)(nbd[i] - intensity)/delta[i];
                      if(slope > res)
                        {
                          res = slope;
                          ed = j;
```

```
                        }

                    }
                }
            }
        }

        if(image_format == PM_C) res = res * 5;
        *p_es = min(res,(float)(maxgray));
        *p_ed = tbl[ed+1];
  }

opposite(i)
int i;
  {
        int opp;

        if (i<4)
          opp = i+4;
        else
          opp = i-4;

        return(opp);
  }

float min(i,j)
float i,j;
{
  if (i<j) return(i);
          else return(j);

}

readbuffer()
{
  int  b;

  printf("buffer :");
  scanf("%d",&b);
  if((b < 0) || (b > 5)) {b=readbuffer();return(b);}
  else return(b);
}

float abszz(num)
float num;
{
  float i;

  if(num < 0) i = -num; else i = num;
  return(i);

}

float get_median(nbr)
float nbr[10];
{
  float nbr1[5];

  sort(nbr,nbr1);
  return(nbr1[4]);
}

sort(nbr,nbr1)
float nbr[10],nbr1[5];
{
  int i,m;
  float large;
  int index;

  for(m=0;m<5;m++)
    {
      large = -100;
      for(i=0;i<9;i++)
        {
          if(large < nbr[i])
            {
              large = nbr[i];
              index = i;
            }
        }
      nbr1[m] = large;
      nbr[index] = 0;
    }
}


read_picture(filename,b)
char filename[];
int b;
{
  int i,j;
  FILE *infs;
  unsigned char *pm_point;
  short int *pms_point;
  int offset;

  /* open input pm file */
```

```
  if ((infs = fopen(filename,"r")) == NULL)
    {
      printf("file open error :%s \n",filename);
      exit(0);
    }

/* read inputfile into the pmpic buffer */

  if((pm1 = pm_read(infs,0)) == NULL)
    {
      printf("error in reading the pmfile %s",filename);
      exit(0);
    }

  sizex = (pm1->pm_nrow);   /* # of rows */
  sizey = (pm1->pm_ncol);   /* # of columns */


  image_format = pm1->pm_form;

  if(pm1->pm_form == PM_C)
    {
      pm_point = (unsigned char *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[b][i][j] = *pm_point;
            pm_point++;
          }
    }
  else if(pm1->pm_form == PM_S)
    {
      pms_point = (short int *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[b][i][j] = *pms_point;
            pms_point++;
          }
    }
  else fprintf(stderr,"Image in unrecognized format. Buffer not initi

}   /* end of read_picture */

display_histogram(buff)
int buff;
{
  int i,j;
  float xmin,xmax,ymin,ymax;
  int iopt;
  int npts;
  int max;
  int value;

  for(i=0;i<256;i++)
    {
      x[i] = i;
      y[i] = 0;
    }

  qterm(4);

  max = -1000;
  for(i=0;i<sizex;i++)
    for(j=0;j<sizey;j++)
      {
        value = absyy((int)(buffer[buff][i][j]));
        y[value] = y[value] + 1;
        if (max < y[value]) max = y[value];
      }

 printf(" max : %d",max);

  iopt = 0;
  npts = 256;

  xmin = 0.0;
  xmax = 255.0;
  ymin = 0.0;
  printf("ymax : ");
  scanf("%f",&ymax);

  qkdraw(npts,x,y,iopt,&xmin,&xmax,&ymin,&ymax);

  qdtitl(" R H ");
  qxlabl("Range");
  qylabl("Values");

  qdone();
}

absyy(value)
int value;
{
  if(value < 0) value = -value;

  if(value > 255) return(255);
```

```
  else return(value);
}

display_row_histogram(row,buff)
int row;
int buff;
{
  int i,j;

  float xmin,xmax,ymin,ymax;
  int iopt;
  int npts;
  int max;
  int value;
  int row_num;

  for(i=0;i<sizey;i++)
    {
      x[i] = i;
    }

  for(i=0;i<sizey;i++)
      y[i] = 0;


  qterm(4);

  max = -1000;

  for(j=0;j<sizey;j++)
    {
      value = absyy((int)buffer[buff][row][j]);
      y[j] = value;
    }

  iopt = 0;
  npts = sizey;

  xmin = 0.0;
  xmax = sizey;
  ymin = 0.0;
  ymax = 255;

  qkdraw(npts,x,y,iopt,&xmin,&xmax,&ymin,&ymax);

  qdtitl(" R H ");
  qxlabl("Range");
  qylabl("Values");
  qdone();

}

float squarezz(number)
float number;
{
  return(number*number);
}
```

```
/**********************************************************************

       This program performs segmentation on the laplacian edge oper
 image and marks the topmost object in the range image.
   Modified on Aug12,1987 .
   Modified on Jan28,1988 to extract supporting surface information
  for the segmented object.
   Feb 1,1988 : Recursive call to grow regin modified to incorporate
  control over the #of pending recursive calls at  given time. This
  requires maintaining a FIFO queue of open nodes.
   March 24,1988 : Modified to accept PM_C and PM_S format images. Ou
                   images in respective format.

                   region label 1 is reserved for unaccpted regions.
                   max regions allowed is determined by MAX_REGION
                      = MAX_REGION-1 to 2.

**********************************************************************

#include <stdio.h>
#include <math.h>
#include <ik.h>
#include <local/pm.h>

#define MIN_VALUE 0  /* =0 if background > shadows  (non-zero backgro
                        else if background = 0 = shadows then = -1 */
#define MIN_ACCEPTABLE 300   /* Minimum # of pixels in a valid region
#define BUF 256             /* Buffer size in one dimension */
#define MAX_NUM_CALL 500    /* Maximum # of pending recursive calls
                               at a given time.To avoid segmentation
#define MAX_REGION 2550     /* Maximum# of regions allowed */
#define UNACCEPT_REGION 1   /* Label of rejected regions */
#define PIXEL_STACK_SIZE 10000 /* size of the pixel stack used for
                                recursive-iterative region growing */

int range_image_buffer[BUF][BUF];       /* input image buffer */
int lap_image_buffer[BUF][BUF]; /* laplacian image buffer */
int third_image_buffer[BUF][BUF];     /* temporary buffer for marking
                                        visited points */
int output_buffer[BUF][BUF];            /* segmented image buffer wit
                                        labeled object */
int support_image_buffer[2][BUF][BUF];   /* supported surface */

int average_image[BUF][BUF];           /* average 2x2 stored */
int vector[65000];

int edge_threshold;                     /* threshold for edge strengt
int nrow,ncol;                          /* global variables to store
                                           and column values */
```

```
long int count;
int distance;                           /* maximum allowable distance
                                           the seed region */
int seedrow,seedcol;                    /* seed region coordinates */
int back_threshold;                     /* threshold for background *
int a_depth;                            /* average depth */

float squarezz();
char accept_region();
ikword value = 255;
char ikonas_disp[10];                   /* Run time display on Ikonas
pmpic *pm1,*pm2,*pm3;                    /* Pointers to PM-picture st
int label;                              /* label value to identify re
int pixels;                             /* # of pixels in the current
int region_count;                       /* # of valid regions found *
int invalid_region_count;               /* counts only invalid region

struct region_type {
  int number;                           /* Label of the region */
  int  valid;                           /* =0 if not valid. =1 if val
  int size;                             /* # of pixels in the region
  int max;                              /* maximum pixel of the regio
  int min;                              /* minumum pixel of the regio
} region[MAX_REGION];


int row_max;                    /* row number of max depth pixel */
int column_max;                 /* column number of max depth pixel *
int max;                        /* depth value of the max depth pixel


struct p_stack {                /* stores the open pixels in circular
  int row;
  int col;
} pixel_stack[PIXEL_STACK_SIZE];

int rownum;                    /*(rownum,colnum)  is the next pixel *
int colnum;                    /*    popped from the stack */

int num_call;                  /* number of calls pending at a given
int stack_length;              /* =current_element if queue is empty
                                  points to the tail of the queue */
int current_element;           /* points to head of the queue */

int nextrow,nextcol;           /* nextcol and nextcol for the seed re
int top_region_label;          /* label of the topmost region */
int max_pixel_region;          /* maximum pixel of the region */
int min_pixel_region;          /* minimum pixel of the region */
int gaprow,gapcol;             /* the nbd edge pixel found, returned
```

```
                                        gapfiller(), if point lies one dist
                                        from the edge */
pmpic *read_pmpic_int();

/******************************MAIN******************************

main(argc,argv)
int argc;
char *argv[];
{

        FILE *range,*laplacian,*outfile,*outfile2,*outfile3;
        int i,j,k,l,m,n;
        char output[50];                /* generated output file name
        int row,column;                 /* # of row and columns in in
        int offset;
        char *cmt;
        int done,found;                 /* used as booleans */
        unsigned char *pm_point,*pm_point2,*pm_point3;
        short int *pms_point,*pms_point2,*pms_point3;
        u_int image_format;             /* stores image format PM_C o


        if(argc != 3)
           {
            printf("segment : usage : segment <range_file> <lap_edge_
            exit(1);
           }

        cmt = pm_cmt(argc,argv);

        printf("Want to display on IKONAS ? ");
        scanf("%s",&ikonas_disp[0]);

        /* open the IKONAS display. value of env. variable is taken *
        if(strcmp("y",ikonas_disp) == 0)
          if(ikopen(NULL) == -1)
            {
              printf("Can't open IKONAS. Exiting\n");
              exit(0);
            }


        if((range = fopen(argv[1],"r")) == NULL)
         {
                printf("segment : Cannot open %s\n",argv[1]);
                exit(0);
         }
```

```
        if((laplacian = fopen(argv[2],"r")) == NULL)
         {
                printf("segment : Cannot open %s\n",argv[2]);
                exit(0);
         }

        if((pm1 = pm_read(range,0)) == NULL)
          {
            printf("Error in reading PM file : %s\n",argv[1]);
            exit(0);
          }

        if((pm2 = pm_read(laplacian,0)) == NULL)
          {
            printf("Error in reading PM file : %s\n",argv[2]);
            exit(0);
          }

        /* open output files */

        strcpy(output,argv[1]);
        strcat(output,".label");
        if((outfile = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        strcpy(output,argv[1]);
        strcat(output,".top");
        if((outfile3 = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        strcpy(output,argv[1]);
        strcat(output,".support");
        if((outfile2 = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        row = pm1->pm_nrow;
        column = pm1->pm_ncol;
        image_format = pm1->pm_form;
        if((row != pm2->pm_nrow) || (column != pm2->pm_ncol))
          {
            printf("Input images are not of same size. Exiting \n");
            exit(0);
          }

        nrow = row;     /* initialize global variables nrow and ncol *
        ncol = column;

        printf("Edge threshold :");
        scanf("%d",&edge_threshold);

        printf("Background threshold :");
        scanf("%d",&back_threshold);

        printf("Max. distance from seed region :");
        scanf("%d",&distance);


        /* read the input image and laplacian edge operated image */

        /* first read the range image */
        if(pm1->pm_form == PM_C)
          {
            pm_point = (unsigned char *) pm1->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 range_image_buffer[i][j] = *(pm_point);
                 pm_point++;
                }
          }
        else if(pm1->pm_form == PM_S)
          {
            pms_point = (short int *) pm1->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 range_image_buffer[i][j] = *(pms_point);
                 pms_point++;
                }
          }
        /* Now read laplacian operated image */

        if(pm2->pm_form == PM_C)
          {
            pm_point = (unsigned char *) pm2->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
```

```
                {
                 lap_image_buffer[i][j] = *(pm_point);
                 pm_point++;
                }
          }
        else if(pm2->pm_form == PM_S)
          {
            pms_point = (short int *) pm2->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 lap_image_buffer[i][j] = *(pms_point);
                 pms_point++;
                }
          }

        /* Initialize output and temporary buffers */
/*      for(i=0;i<row;i++)
           for(j=0;j<column;j++)
             {
               third_image_buffer[i][j] =0;
               output_buffer[i][j] = 0;
               support_image_buffer[0][i][j] =0;
               support_image_buffer[1][i][j] =0;
             }
*/
        bzero((char *) &third_image_buffer[0][0],sizeof(int)*row*colu
        bzero((char *) &output_buffer[0][0],sizeof(int)*row*column);
        bzero((char *) &support_image_buffer[0][0][0],sizeof(int)*row
        bzero((char *) &support_image_buffer[1][0][0],sizeof(int)*row

        /* Open files for output and initialize buffers */
        pm_addcmt(pm1,cmt);

        pm2 = pm_alloc();    /* supporting points image */
        pm2->pm_nrow = row;
        pm2->pm_ncol = column;
        pm2->pm_form = image_format;
        pm2->pm_image = (char *) malloc(pm_psize(pm2));

        pm3= pm_alloc();    /* top most segmented object */
        pm3->pm_nrow = row;
        pm3->pm_ncol = column;
        pm3->pm_form = image_format;
        pm3->pm_image = (char *) malloc(pm_psize(pm3));


        pm1 = pm_alloc();       /* labeled image */
        pm1->pm_nrow = row;
        pm1->pm_ncol = column;
        pm1->pm_form = image_format;
        pm1->pm_image = (char *) malloc(pm_psize(pm1));

        if(image_format == PM_S)
          {
            pms_point = (short int *) pm1->pm_image;
            pms_point2 = (short int *) pm2->pm_image;
            pms_point3 = (short int *) pm3->pm_image;
          }
        else /* image format is PM_C */
          {
            pm_point = (unsigned char *) pm1->pm_image;
            pm_point2 = (unsigned char *) pm2->pm_image;
            pm_point3 = (unsigned char *) pm3->pm_image;
          }
        /* initialize the buffers */

        bzero(pm1->pm_image,pm_isize(pm1));
        bzero(pm2->pm_image,pm_isize(pm2));
        bzero(pm3->pm_image,pm_isize(pm3));


        /***   Segmentation of the picture starts    ***/

        max = -1000;
        if(image_format == PM_S)
          label = MAX_REGION;      /* starting label+1; for unlabeled
        else
          label = MAX_REGION;
        region_count = 0;          /* counts only valid regions */
        invalid_region_count = 0;  /* Counts only invalid regions */
        nextrow = nextcol = 1;     /* initialize the seed region star


        /**********  Loop for segmenting all the objects  in the rang
        do
          {
            region_count++;
            label--;

            if(region_count == 1) find_seed_region();
            else
                seed_region();

            if(max > 0)
              {
                /* call grow_region for recursive region growing */
```

```
                seedrow = row_max;/* seed region coordinates in globa
                seedcol = column_max;
                third_image_buffer[seedrow][seedcol] = 1;
                pixels=0;
                num_call = 1;
                stack_length = 0;
                current_element = 0;
                max_pixel_region = -1000;
                min_pixel_region = 1000;

                grow_region(row_max,column_max);

                while(stack_length != current_element)
                  {
                    get_pixel();         /* returns the pixel */
                    num_call = 1;
                    /*printf("AAAAA");*/
                    if(output_buffer[rownum][colnum] != label)
                      {
                        /*printf(" BBBBB "); */
                        grow_region(rownum,colnum);
                      }
                  }
                smooth_region(label);
                if(accept_region(label) == 'n')
                  {
                    region_count--;
                    invalid_region_count++;
                    region[label].number = label;
                    region[label].valid = 0;
                    region[region_count].size   = pixels;
                  }
                else
                  {
                    printf("label = %d ",label);
                    printf("Top :(%d,%d) = %d ",row_max,column_max,ma
                    printf("pixels : %d ACCEPT ",pixels);
                    printf("Max : %d Min %d \n",max_pixel_region,min_
                    region[label].number = label;
                    region[label].valid  = 1;
                    region[label].size   = pixels;
                    region[label].max = max_pixel_region;
                    region[label].min = min_pixel_region;
                    determine_support(label);
                  }

              }
            else printf("\n No more valid regions \n");
```

```
      } while((max > 0));

    /* Label all the unwanted regions as UNACCEPT_REGION */
    label++;    /* label of the last region */

    for(i=0;i<row;i++)
      for(j=0;j<column;j++)
        if(third_image_buffer[i][j] == 0)
          output_buffer[i][j] = UNACCEPT_REGION;
region[UNACCEPT_REGION].valid = 0;  /* unaccept region is inv

    max = -1000;
    for(i= ( MAX_REGION -1 );i >= label;i--)
      if(region[i].valid == 1)
        if(region[i].max > max)
          {
            max = region[i].max;
            top_region_label = region[i].number;
            max_pixel_region = region[i].max;
            min_pixel_region = region[i].min;
          }

    printf("\nTotal # of Valid regions : %d\n",region_count-1);
    printf("Total # of Invalid regions : %d\n",invalid_region_cou
    printf("Topmost region : Label = %d Max = %d Min %d \n",top_r

    /* output the segmented edge image */

    for(i=0;i<row;i++)
      {
        output_buffer[i][0] = 0;
        output_buffer[i][column-1] = 0;
      }

    for(i=0;i<column;i++)
      {
        output_buffer[0][i] = 0;
        output_buffer[row-1][i] = 0;
      }

    if(image_format == PM_C)
      for(i=0;i<row;i++)
        for(j=0;j<column;j++)
          {
            label = output_buffer[i][j];
            if(j<(column-1))
              if(output_buffer[i][j] != output_buffer[i][j+1])
                if((region[output_buffer[i][j]].valid == 1) ||
```

```
                  (region[output_buffer[i][j+1]].valid == 1))
                 *pm_point = 255;
            if(i<(row-1))
              if(output_buffer[i][j] != output_buffer[i+1][j])
                if((region[output_buffer[i][j]].valid == 1) ||
                  (region[output_buffer[i+1][j]].valid == 1))
                 *pm_point = 255;

            if(output_buffer[i][j] == top_region_label)
              *pm_point3 = range_image_buffer[i][j]; /*top */
/*          if(region[support_image_buffer[1][i][j]].valid == 1)*
            if(support_image_buffer[1][i][j] == top_region_label)
              *pm_point2 = support_image_buffer[0][i][j]; /*sup*/
            pm_point++;
            pm_point2++;
            pm_point3++;
          }
    else  /* image_format == PM_S */
      for(i=0;i<row;i++)
        for(j=0;j<column;j++)
          {
            label = output_buffer[i][j];
            if(j<(column-1))
              if(output_buffer[i][j] != output_buffer[i][j+1])
                if((region[output_buffer[i][j]].valid == 1) ||
                  (region[output_buffer[i][j+1]].valid == 1))
                 *pms_point = 255;
            if(i<(row-1))
              if(output_buffer[i][j] != output_buffer[i+1][j])
                if((region[output_buffer[i][j]].valid == 1) ||
                  (region[output_buffer[i+1][j]].valid == 1))
                 *pms_point = 255;

            if(output_buffer[i][j] == top_region_label)
              *pms_point3 = range_image_buffer[i][j]; /*top */
            if(support_image_buffer[1][i][j] == top_region_label)
/*          if(region[support_image_buffer[1][i][j]].valid == 1)*
              *pms_point2 = support_image_buffer[0][i][j]; /*sup*
            pms_point++;
            pms_point2++;
            pms_point3++;
          }

    pm_write(outfile,pm1);
    pm_write(outfile2,pm2);
    pm_write(outfile3,pm3);

}  /*  end of main program */
```

```
                                          gapfiller(), if point lies one dist
                                          from the edge */
pmpic *read_pmpic_int();

/********************************MAIN********************************

main(argc,argv)
int argc;
char *argv[];
{

        FILE *range,*laplacian,*outfile,*outfile2,*outfile3;
        int i,j,k,l,m,n;
        char output[50];                /* generated output file name
        int row,column;                 /* # of row and columns in in
        int offset;
        char *cmt;
        int done,found;                 /* used as booleans */
        unsigned char *pm_point,*pm_point2,*pm_point3;
        short int *pms_point,*pms_point2,*pms_point3;
        u_int image_format;             /* stores image format PM_C o


        if(argc != 3)
           {
            printf("segment : usage : segment <range_file> <lap_edge_
            exit(1);
           }

        cmt = pm_cmt(argc,argv);

        printf("Want to display on IKONAS ? ");
        scanf("%s",&ikonas_disp[0]);

        /* open the IKONAS display. value of env. variable is taken *
        if(strcmp("y",ikonas_disp) == 0)
          if(ikopen(NULL) == -1)
            {
              printf("Can't open IKONAS. Exiting\n");
              exit(0);
            }


        if((range = fopen(argv[1],"r")) == NULL)
         {
                printf("segment : Cannot open %s\n",argv[1]);
                exit(0);
         }
```

```
        if((laplacian = fopen(argv[2],"r")) == NULL)
         {
                printf("segment : Cannot open %s\n",argv[2]);
                exit(0);
         }

        if((pm1 = pm_read(range,0)) == NULL)
          {
            printf("Error in reading PM file : %s\n",argv[1]);
            exit(0);
          }

        if((pm2 = pm_read(laplacian,0)) == NULL)
          {
            printf("Error in reading PM file : %s\n",argv[2]);
            exit(0);
          }

        /* open output files */

        strcpy(output,argv[1]);
        strcat(output,".label");
        if((outfile = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        strcpy(output,argv[1]);
        strcat(output,".top");
        if((outfile3 = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        strcpy(output,argv[1]);
        strcat(output,".support");
        if((outfile2 = fopen(output,"w")) == NULL)
          {
                printf("segment : Cannot open output file : %s\n",out
                exit(0);
          }

        row = pm1->pm_nrow;
        column = pm1->pm_ncol;
        image_format = pm1->pm_form;
        if((row != pm2->pm_nrow) || (column != pm2->pm_ncol))
          {
            printf("Input images are not of same size. Exiting \n");
            exit(0);
          }

        nrow = row;     /* initialize global variables nrow and ncol *
        ncol = column;

        printf("Edge threshold :");
        scanf("%d",&edge_threshold);

        printf("Background threshold :");
        scanf("%d",&back_threshold);

        printf("Max. distance from seed region :");
        scanf("%d",&distance);


        /* read the input image and laplacian edge operated image */

        /* first read the range image */
        if(pm1->pm_form == PM_C)
          {
            pm_point = (unsigned char *) pm1->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 range_image_buffer[i][j] = *(pm_point);
                 pm_point++;
                }
          }
        else if(pm1->pm_form == PM_S)
          {
            pms_point = (short int *) pm1->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 range_image_buffer[i][j] = *(pms_point);
                 pms_point++;
                }
          }
        /* Now read laplacian operated image */

        if(pm2->pm_form == PM_C)
          {
            pm_point = (unsigned char *) pm2->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
```

```
                {
                 lap_image_buffer[i][j] = *(pm_point);
                 pm_point++;
                }
          }
        else if(pm2->pm_form == PM_S)
          {
            pms_point = (short int *) pm2->pm_image;
            for(i=0;i<row;i++)
              for(j=0;j<column;j++)
                {
                 lap_image_buffer[i][j] = *(pms_point);
                 pms_point++;
                }
          }

        /* Initialize output and temporary buffers */
/*      for(i=0;i<row;i++)
           for(j=0;j<column;j++)
             {
               third_image_buffer[i][j] =0;
               output_buffer[i][j] = 0;
               support_image_buffer[0][i][j] =0;
               support_image_buffer[1][i][j] =0;
             }
*/
        bzero((char *) &third_image_buffer[0][0],sizeof(int)*row*colu
        bzero((char *) &output_buffer[0][0],sizeof(int)*row*column);
        bzero((char *) &support_image_buffer[0][0][0],sizeof(int)*row
        bzero((char *) &support_image_buffer[1][0][0],sizeof(int)*row

        /* Open files for output and initialize buffers */
        pm_addcmt(pm1,cmt);

        pm2 = pm_alloc();    /* supporting points image */
        pm2->pm_nrow = row;
        pm2->pm_ncol = column;
        pm2->pm_form = image_format;
        pm2->pm_image = (char *) malloc(pm_psize(pm2));

        pm3= pm_alloc();    /* top most segmented object */
        pm3->pm_nrow = row;
        pm3->pm_ncol = column;
        pm3->pm_form = image_format;
        pm3->pm_image = (char *) malloc(pm_psize(pm3));


        pm1 = pm_alloc();       /* labeled image */
        pm1->pm_nrow = row;
        pm1->pm_ncol = column;
        pm1->pm_form = image_format;
        pm1->pm_image = (char *) malloc(pm_psize(pm1));

        if(image_format == PM_S)
          {
            pms_point = (short int *) pm1->pm_image;
            pms_point2 = (short int *) pm2->pm_image;
            pms_point3 = (short int *) pm3->pm_image;
          }
        else /* image format is PM_C */
          {
            pm_point = (unsigned char *) pm1->pm_image;
            pm_point2 = (unsigned char *) pm2->pm_image;
            pm_point3 = (unsigned char *) pm3->pm_image;
          }
        /* initialize the buffers */

        bzero(pm1->pm_image,pm_isize(pm1));
        bzero(pm2->pm_image,pm_isize(pm2));
        bzero(pm3->pm_image,pm_isize(pm3));


        /***   Segmentation of the picture starts    ***/

        max = -1000;
        if(image_format == PM_S)
          label = MAX_REGION;      /* starting label+1; for unlabeled
        else
          label = MAX_REGION;
        region_count = 0;          /* counts only valid regions */
        invalid_region_count = 0;  /* Counts only invalid regions */
        nextrow = nextcol = 1;     /* initialize the seed region star


        /**********  Loop for segmenting all the objects  in the rang
        do
          {
            region_count++;
            label--;

            if(region_count == 1) find_seed_region();
            else
                seed_region();

            if(max > 0)
              {
                /* call grow_region for recursive region growing */
```

```
                seedrow = row_max;/* seed region coordinates in globa
                seedcol = column_max;
                third_image_buffer[seedrow][seedcol] = 1;
                pixels=0;
                num_call = 1;
                stack_length = 0;
                current_element = 0;
                max_pixel_region = -1000;
                min_pixel_region = 1000;

                grow_region(row_max,column_max);

                while(stack_length != current_element)
                  {
                    get_pixel();        /* returns the pixel */
                    num_call = 1;
                    /*printf("AAAAA");*/
                    if(output_buffer[rownum][colnum] != label)
                      {
                        /*printf(" BBBBB "); */
                        grow_region(rownum,colnum);
                      }
                  }
                smooth_region(label);
                if(accept_region(label) == 'n')
                  {
                    region_count--;
                    invalid_region_count++;
                    region[label].number = label;
                    region[label].valid = 0;
                    region[region_count].size    = pixels;
                  }
                else
                  {
                    printf("label = %d ",label);
                    printf("Top :(%d,%d) = %d ",row_max,column_max,ma
                    printf("pixels : %d ACCEPT ",pixels);
                    printf("Max : %d Min %d \n",max_pixel_region,min_
                    region[label].number = label;
                    region[label].valid  = 1;
                    region[label].size   = pixels;
                    region[label].max = max_pixel_region;
                    region[label].min = min_pixel_region;
                    determine_support(label);
                  }

              }
            else printf("\n No more valid regions \n");
```

```
      } while((max > 0));

   /* Label all the unwanted regions as UNACCEPT_REGION */
   label++;    /* label of the last region */

   for(i=0;i<row;i++)
     for(j=0;j<column;j++)
       if(third_image_buffer[i][j] == 0)
         output_buffer[i][j] = UNACCEPT_REGION;
region[UNACCEPT_REGION].valid = 0;  /* unaccept region is inv

   max = -1000;
   for(i= ( MAX_REGION -1 );i >= label;i--)
     if(region[i].valid == 1)
       if(region[i].max > max)
         {
          max = region[i].max;
          top_region_label = region[i].number;
          max_pixel_region = region[i].max;
          min_pixel_region = region[i].min;
         }

   printf("\nTotal # of Valid regions : %d\n",region_count-1);
   printf("Total # of Invalid regions : %d\n",invalid_region_cou
   printf("Topmost region : Label = %d Max = %d Min %d \n",top_r

   /* output the segmented edge image */

   for(i=0;i<row;i++)
     {
       output_buffer[i][0] = 0;
       output_buffer[i][column-1] = 0;
     }

   for(i=0;i<column;i++)
     {
       output_buffer[0][i] = 0;
       output_buffer[row-1][i] = 0;
     }

   if(image_format == PM_C)
     for(i=0;i<row;i++)
       for(j=0;j<column;j++)
         {
          label = output_buffer[i][j];
          if(j<(column-1))
            if(output_buffer[i][j] != output_buffer[i][j+1])
              if((region[output_buffer[i][j]].valid == 1) ||
```

```
                 (region[output_buffer[i][j+1]].valid == 1))
                *pm_point = 255;
          if(i<(row-1))
            if(output_buffer[i][j] != output_buffer[i+1][j])
              if((region[output_buffer[i][j]].valid == 1) ||
                 (region[output_buffer[i+1][j]].valid == 1))
                *pm_point = 255;

          if(output_buffer[i][j] == top_region_label)
            *pm_point3 = range_image_buffer[i][j]; /*top */
/*        if(region[support_image_buffer[1][i][j]].valid == 1)*
          if(support_image_buffer[1][i][j] == top_region_label)
            *pm_point2 = support_image_buffer[0][i][j]; /*sup*/
          pm_point++;
          pm_point2++;
          pm_point3++;
         }
   else  /* image_format == PM_S */
     for(i=0;i<row;i++)
       for(j=0;j<column;j++)
         {
          label = output_buffer[i][j];
          if(j<(column-1))
            if(output_buffer[i][j] != output_buffer[i][j+1])
              if((region[output_buffer[i][j]].valid == 1) ||
                 (region[output_buffer[i][j+1]].valid == 1))
                *pms_point = 255;
          if(i<(row-1))
            if(output_buffer[i][j] != output_buffer[i+1][j])
              if((region[output_buffer[i][j]].valid == 1) ||
                 (region[output_buffer[i+1][j]].valid == 1))
                *pms_point = 255;

          if(output_buffer[i][j] == top_region_label)
            *pms_point3 = range_image_buffer[i][j]; /*top */
          if(support_image_buffer[1][i][j] == top_region_label)
/*        if(region[support_image_buffer[1][i][j]].valid == 1)*
            *pms_point2 = support_image_buffer[0][i][j]; /*sup*
          pms_point++;
          pms_point2++;
          pms_point3++;
         }

   pm_write(outfile,pm1);
   pm_write(outfile2,pm2);
   pm_write(outfile3,pm3);

}  /*  end of main program */
```

```
        pm1->pm_ncol = column;
        pm1->pm_form = image_format;
        pm1->pm_image = (char *) malloc(pm_psize(pm1));

        if(image_format == PM_S)
          {
            pms_point = (short int *) pm1->pm_image;
            pms_point2 = (short int *) pm2->pm_image;
            pms_point3 = (short int *) pm3->pm_image;
          }
        else /* image format is PM_C */
          {
            pm_point = (unsigned char *) pm1->pm_image;
            pm_point2 = (unsigned char *) pm2->pm_image;
            pm_point3 = (unsigned char *) pm3->pm_image;
          }
        /* initialize the buffers */

        bzero(pm1->pm_image,pm_isize(pm1));
        bzero(pm2->pm_image,pm_isize(pm2));
        bzero(pm3->pm_image,pm_isize(pm3));


        /***   Segmentation of the picture starts    ***/

        max = -1000;
        if(image_format == PM_S)
          label = MAX_REGION;       /* starting label+1; for unlabeled
        else
          label = MAX_REGION;
        region_count = 0;           /* counts only valid regions */
        invalid_region_count = 0;   /* Counts only invalid regions */
        nextrow = nextcol = 1;      /* initialize the seed region star


        /**********  Loop for segmenting all the objects  in the rang
        do
          {
            region_count++;
            label--;

            if(region_count == 1) find_seed_region();
            else
                seed_region();

            if(max > 0)
              {
                /* call grow_region for recursive region growing */
```

```
                seedrow = row_max;/* seed region coordinates in globa
                seedcol = column_max;
                third_image_buffer[seedrow][seedcol] = 1;
                pixels=0;
                num_call = 1;
                stack_length = 0;
                current_element = 0;
                max_pixel_region = -1000;
                min_pixel_region = 1000;

                grow_region(row_max,column_max);

                while(stack_length != current_element)
                  {
                    get_pixel();         /* returns the pixel */
                    num_call = 1;
                    /*printf("AAAAA");*/
                    if(output_buffer[rownum][colnum] != label)
                      {
                        /*printf(" BBBBB "); */
                        grow_region(rownum,colnum);
                      }
                  }
                smooth_region(label);
                if(accept_region(label) == 'n')
                  {
                    region_count--;
                    invalid_region_count++;
                    region[label].number = label;
                    region[label].valid = 0;
                    region[region_count].size    = pixels;
                  }
                else
                  {
                    printf("label = %d ",label);
                    printf("Top :(%d,%d) = %d ",row_max,column_max,ma
                    printf("pixels : %d ACCEPT ",pixels);
                    printf("Max : %d Min %d \n",max_pixel_region,min_
                    region[label].number = label;
                    region[label].valid  = 1;
                    region[label].size   = pixels;
                    region[label].max = max_pixel_region;
                    region[label].min = min_pixel_region;
                    determine_support(label);
                  }

              }
            else printf("\n No more valid regions \n");
            } while((max > 0));

        /* Label all the unwanted regions as UNACCEPT_REGION */
        label++;    /* label of the last region */

        for(i=0;i<row;i++)
          for(j=0;j<column;j++)
            if(third_image_buffer[i][j] == 0)
              output_buffer[i][j] = UNACCEPT_REGION;
        region[UNACCEPT_REGION].valid = 0;  /* unaccept region is inv

        max = -1000;
        for(i= ( MAX_REGION -1 );i >= label;i--)
          if(region[i].valid == 1)
            if(region[i].max > max)
              {
                max = region[i].max;
                top_region_label = region[i].number;
                max_pixel_region = region[i].max;
                min_pixel_region = region[i].min;
              }

        printf("\nTotal # of Valid regions : %d\n",region_count-1);
        printf("Total # of Invalid regions : %d\n",invalid_region_cou
        printf("Topmost region : Label = %d Max = %d Min %d \n",top_r

        /* output the segmented edge image */

        for(i=0;i<row;i++)
          {
            output_buffer[i][0] = 0;
            output_buffer[i][column-1] = 0;
          }

        for(i=0;i<column;i++)
          {
            output_buffer[0][i] = 0;
            output_buffer[row-1][i] = 0;
          }

        if(image_format == PM_C)
          for(i=0;i<row;i++)
            for(j=0;j<column;j++)
              {
                label = output_buffer[i][j];
                if(j<(column-1))
                  if(output_buffer[i][j] != output_buffer[i][j+1])
                    if((region[output_buffer[i][j]].valid == 1) ||
```

```
                        (region[output_buffer[i][j+1]].valid == 1))
                      *pm_point = 255;
                if(i<(row-1))
                  if(output_buffer[i][j] != output_buffer[i+1][j])
                    if((region[output_buffer[i][j]].valid == 1) ||
                        (region[output_buffer[i+1][j]].valid == 1))
                      *pm_point = 255;

                if(output_buffer[i][j] == top_region_label)
                  *pm_point3 = range_image_buffer[i][j]; /*top */
/*              if(region[support_image_buffer[1][i][j]].valid == 1)*
                if(support_image_buffer[1][i][j] == top_region_label)
                  *pm_point2 = support_image_buffer[0][i][j]; /*sup*/
                pm_point++;
                pm_point2++;
                pm_point3++;
              }
        else  /* image_format == PM_S */
          for(i=0;i<row;i++)
            for(j=0;j<column;j++)
              {
                label = output_buffer[i][j];
                if(j<(column-1))
                  if(output_buffer[i][j] != output_buffer[i][j+1])
                    if((region[output_buffer[i][j]].valid == 1) ||
                        (region[output_buffer[i][j+1]].valid == 1))
                      *pms_point = 255;
                if(i<(row-1))
                  if(output_buffer[i][j] != output_buffer[i+1][j])
                    if((region[output_buffer[i][j]].valid == 1) ||
                        (region[output_buffer[i+1][j]].valid == 1))
                      *pms_point = 255;

                if(output_buffer[i][j] == top_region_label)
                  *pms_point3 = range_image_buffer[i][j]; /*top */
                if(support_image_buffer[1][i][j] == top_region_label)
/*              if(region[support_image_buffer[1][i][j]].valid == 1)*
                  *pms_point2 = support_image_buffer[0][i][j]; /*sup*
                pms_point++;
                pms_point2++;
                pms_point3++;
              }

        pm_write(outfile,pm1);
        pm_write(outfile2,pm2);
        pm_write(outfile3,pm3);

}  /*  end of main program */
```

```
/***************************** GROW_REGION *************************
/*  following is the modified recursive call for the segmentation.
  now a pixel is examined before routine is called rather than callin
  the routine and then checking the pixel type. this was done to opti
  the stack-space which overflows in the case of large objects.
       even after this modification stack overflows if the object is
  therefore recursive region growing is not possible if the object is
*/


grow_region(row,col)
int row;
int col;
  {
        int i,j;                /* loop control variables */
        int dist;
        int cross_grad;


        if(strcmp("y",ikonas_disp) == 0)
          lwr(col,row,&value);
        output_buffer[row][col] = label;

        if(max_pixel_region < range_image_buffer[row][col])
          max_pixel_region = range_image_buffer[row][col];
        if(min_pixel_region > range_image_buffer[row][col])
          min_pixel_region =  range_image_buffer[row][col];


        pixels++;


/*      if((row < (nrow -1)) && (col < (ncol -1)))
          cross_grad =sqrt((double)
                           (squarezz(range_image_buffer[row][col] -
                                     range_image_buffer[row+1][col+1]
                            squarezz(range_image_buffer[row][col+1] -
                                     range_image_buffer[row+1][col]))
        else */
          cross_grad = 0;
        if(cross_grad !=0) cross_grad += 0;
        if(cross_grad < edge_threshold)
          {
            for(i=row-1;i<row+2;i++)
              for(j=col-1;j<col+2;j++)
                if((i != row) || (j != col))
                  if((i > 0) && (i < (nrow-1)) && (j > 0) && (j < (nc
```

```
                    /*if((i == row) || (j == col))*/
                      if(third_image_buffer[i][j] == 0)
                        {
                          dist = (int)(sqrt((double)((seedrow - i)*(s
                                           (seedcol - j)*(seedcol -
                          if (dist <= distance)
                            {
                              if((lap_image_buffer[i][j] < edge_thres
                                 (output_buffer[i][j] != label) &&
                                 (range_image_buffer[i][j] > back_thr
                                {
                                 if(gap_filler(i,j) == 0)
                                   {
                                     third_image_buffer[i][j] = 1;
                                     /* check for number of pending c
                                     num_call++;
                                     if(num_call >= MAX_NUM_CALL)
                                       store_pixel(i,j);
                                     else
                                       grow_region(i,j);
                                   }
                                 else  /* point is actually one dista
                                              from an  edge pixel*/
                                   { /* first mark the pixels visted
                                     output_buffer[i][j] = label;
                                     pixels++;
                                     third_image_buffer[i][j] = 1;
                                     if(strcmp("y",ikonas_disp) == 0)
                                       lwr(j,i,&value);
                                     /* now mark the edge pixel visit
                                     output_buffer[gaprow][gapcol] =
                                     pixels++;
                                     third_image_buffer[gaprow][gapco
                                     if(strcmp("y",ikonas_disp) == 0)
                                       lwr(gapcol,gaprow,&value);

                                   }
                                }
                              else if(lap_image_buffer[i][j] >= edge_
                                {
                                  output_buffer[i][j] = label;
                                  pixels++;
                                  third_image_buffer[i][j] = 1;
                                  if(strcmp("y",ikonas_disp) == 0)
                                    lwr(j,i,&value);
                                }
                            }
                          else  /* distance exceeded */
                            {
```

```
                                        output_buffer[i][j] = label;
                                        pixels++;
                                        third_image_buffer[i][j] = 1;
                                        if(strcmp("y",ikonas_disp) == 0)
                                          lwr(j,i,&value);
                                    }
                              }/* acceptable pixel */
                }/* cross_grad acceptable */
              num_call--;
        }    /*  end of grow_region */


/******************** STORE_PIXEL & GET_PIXEL ***********************

store_pixel(rrow,ccol)
int rrow;
int ccol;
{
  num_call--;
/*  printf(" FFFF "); */

  pixel_stack[stack_length].row = rrow;
  pixel_stack[stack_length].col = ccol;

  stack_length++;
  if(stack_length == PIXEL_STACK_SIZE) stack_length = 0;
  if(stack_length == current_element)
        printf("\n segment : Stack Collision While region growing \n

}

get_pixel()
{

  rownum = pixel_stack[current_element].row;
  colnum = pixel_stack[current_element].col;

  current_element++;
  if(current_element == PIXEL_STACK_SIZE) current_element = 0;
}

float squarezz(n)
int n;
{ float f;
  f = (float)(n);
  return(f*f);
}
```

```
/*****  gap_filler checks if the pixel can be considered as the part
      the edge . This is done by checking if the 8-connected neighbou
      has any edge pixel. If yes, it is considered a neighbour of edg
      and coordinates of edge pixel is returned in gaprow,gapcol. The
      pixel is not further grown. This procedure fills in 2-pixel gap
      without undergoing the pain of gap-filling using contour tracin
      which is computationally expensive. See peter allen's thesis fo
      performance of gap-filler (due to Nevatia & Babu). He observes
      that filling of at most 2-pixel gaps is acceptable in most case

 ****/

gap_filler(rrow,ccol)
int rrow,ccol;
{
  int i,j;

  for(i=rrow-1;i<=(rrow+1);i++)
    for(j=ccol-1;j<=(ccol+1);j++)
      if(lap_image_buffer[i][j] >= edge_threshold)
        { /* edge pixel in 8-connected nbd is found */
          gaprow = i;
          gapcol = j;
          return(1);
        }
  /* no edge pixel in 8-connected neighbourhood is found */

  return(0);
}

smooth_region(label_value)
int label_value;
{
  int i,j;

 /* for(i=0;i<nrow;i++)
    for(j=0;j<ncol;j++)
      {
        if(output_buffer[i][j] == label_value)
          {
          }

      }
  */
}

min(x,y)
int x,y;
{
```

```
/****************************** GROW_REGION *************************
/*  following is the modified recursive call for the segmentation.
  now a pixel is examined before routine is called rather than callin
  the routine and then checking the pixel type. this was done to opti
  the stack-space which overflows in the case of large objects.
      even after this modification stack overflows if the object is
  therefore recursive region growing is not possible if the object is
*/


grow_region(row,col)
int row;
int col;
  {
        int i,j;                /* loop control variables */
        int dist;
        int cross_grad;


        if(strcmp("y",ikonas_disp) == 0)
          lwr(col,row,&value);
        output_buffer[row][col] = label;

        if(max_pixel_region < range_image_buffer[row][col])
          max_pixel_region = range_image_buffer[row][col];
        if(min_pixel_region > range_image_buffer[row][col])
          min_pixel_region =  range_image_buffer[row][col];


        pixels++;


/*      if((row < (nrow -1)) && (col < (ncol -1)))
          cross_grad =sqrt((double)
                          (squarezz(range_image_buffer[row][col] -
                                    range_image_buffer[row+1][col+1]
                           squarezz(range_image_buffer[row][col+1] -
                                    range_image_buffer[row+1][col]))
        else */
          cross_grad = 0;
        if(cross_grad !=0) cross_grad += 0;
        if(cross_grad < edge_threshold)
          {
            for(i=row-1;i<row+2;i++)
              for(j=col-1;j<col+2;j++)
                if((i != row) || (j != col))
                  if((i > 0) && (i < (nrow-1)) && (j > 0) && (j < (nc
```

```
                  /*if((i == row) || (j == col))*/
                    if(third_image_buffer[i][j] == 0)
                      {
                        dist = (int)(sqrt((double)((seedrow - i)*(s
                                         (seedcol - j)*(seedcol -
                        if (dist <= distance)
                          {
                            if((lap_image_buffer[i][j] < edge_thres
                               (output_buffer[i][j] != label) &&
                               (range_image_buffer[i][j] > back_thr
                              {
                               if(gap_filler(i,j) == 0)
                                 {
                                   third_image_buffer[i][j] = 1;
                                   /* check for number of pending c
                                   num_call++;
                                   if(num_call >= MAX_NUM_CALL)
                                     store_pixel(i,j);
                                   else
                                     grow_region(i,j);
                                 }
                               else  /* point is actually one dista
                                               from an  edge pixel*/
                                 { /* first mark the pixels visted
                                   output_buffer[i][j] = label;
                                   pixels++;
                                   third_image_buffer[i][j] = 1;
                                   if(strcmp("y",ikonas_disp) == 0)
                                     lwr(j,i,&value);
                                   /* now mark the edge pixel visit
                                   output_buffer[gaprow][gapcol] =
                                   pixels++;
                                   third_image_buffer[gaprow][gapco
                                   if(strcmp("y",ikonas_disp) == 0)
                                     lwr(gapcol,gaprow,&value);

                                 }
                              }
                            else if(lap_image_buffer[i][j] >= edge_
                              {
                                output_buffer[i][j] = label;
                                pixels++;
                                third_image_buffer[i][j] = 1;
                                if(strcmp("y",ikonas_disp) == 0)
                                  lwr(j,i,&value);
                              }
                          }
                        else  /* distance exceeded */
                          {
```

```
                                    output_buffer[i][j] = label;
                                    pixels++;
                                    third_image_buffer[i][j] = 1;
                                    if(strcmp("y",ikonas_disp) == 0)
                                      lwr(j,i,&value);
                                  }
                              }/* acceptable pixel */
                 }/* cross_grad acceptable */
               num_call--;
         }    /*  end of grow_region */


/******************* STORE_PIXEL & GET_PIXEL **********************

store_pixel(rrow,ccol)
int rrow;
int ccol;
{
  num_call--;
/*  printf(" FFFF "); */

  pixel_stack[stack_length].row = rrow;
  pixel_stack[stack_length].col = ccol;

  stack_length++;
  if(stack_length == PIXEL_STACK_SIZE) stack_length = 0;
  if(stack_length == current_element)
        printf("\n segment : Stack Collision While region growing \n

}

get_pixel()
{

  rownum = pixel_stack[current_element].row;
  colnum = pixel_stack[current_element].col;

  current_element++;
  if(current_element == PIXEL_STACK_SIZE) current_element = 0;
}

float squarezz(n)
int n;
{ float f;
  f = (float)(n);
  return(f*f);
}
```

```
/*****  gap_filler checks if the pixel can be considered as the part
      the edge . This is done by checking if the 8-connected neighbou
      has any edge pixel. If yes, it is considered a neighbour of edg
      and coordinates of edge pixel is returned in gaprow,gapcol. The
      pixel is not further grown. This procedure fills in 2-pixel gap
      without undergoing the pain of gap-filling using contour tracin
      which is computationally expensive. See peter allen's thesis fo
      performance of gap-filler (due to Nevatia & Babu). He observes
      that filling of at most 2-pixel gaps is acceptable in most case

 ****/

gap_filler(rrow,ccol)
int rrow,ccol;
{
  int i,j;

  for(i=rrow-1;i<=(rrow+1);i++)
    for(j=ccol-1;j<=(ccol+1);j++)
      if(lap_image_buffer[i][j] >= edge_threshold)
        { /* edge pixel in 8-connected nbd is found */
          gaprow = i;
          gapcol = j;
          return(1);
        }
  /* no edge pixel in 8-connected neighbourhood is found */

  return(0);
}

smooth_region(label_value)
int label_value;
{
  int i,j;

 /* for(i=0;i<nrow;i++)
    for(j=0;j<ncol;j++)
      {
        if(output_buffer[i][j] == label_value)
          {
          }

      }
  */
}

min(x,y)
int x,y;
{
  if (x<y) return(x);
  else     return(y);
}

/*************************** ACCEPT_REGION  *************************
char accept_region(lab)
int lab;
{
  int i,j,k;

  if(pixels < MIN_ACCEPTABLE) return('n');
  else return('y');
}

/***************************** DETERMINE_SUPPORT ********************

determine_support(lab)
int lab;
{
  int i,j,k;

  /* determine boundary points for all rows first */

  for(i=0;i<nrow;i++)
    for(j=0;j<(ncol-1);j++)
      {
        if((output_buffer[i][j] != lab) && (output_buffer[i][j+1] ==
           det_med_support(lab,i,j+1);
        else if((output_buffer[i][j] == lab) && (output_buffer[i][j+1
           det_med_support(lab,i,j);
      }

  /* determine boundary points for all columns */

  for(j=0;j<ncol;j++)
    for(i=0;i<(nrow-1);i++)
      {
        if((output_buffer[i][j] != lab) && (output_buffer[i+1][j] ==
           det_med_support(lab,i+1,j);
        else if((output_buffer[i][j] == lab) && (output_buffer[i+1][j
           det_med_support(lab,i,j);
      }
}


/************************  DET_MED_SUPPORT  ************************

det_med_support(lab,row,col)
int lab;
```

```
int row;
int col;
{
  int i,j,k;
  int count = 0;
  int num;
  int wsize =3;
/*  printf("det_med_support for lab = %d row %d col %d called ",lab,r

  for(i=0;i<256;i++) vector[i] =0;

  for(i=(row-wsize);i<=(row+wsize);i++)
    for(j=(col-wsize);j<=(col+wsize);j++)
      if((i>=0) && (i<nrow) && (j >= 0) && (j< ncol))
        if(output_buffer[i][j] != lab)
          {
            count++;
            vector[range_image_buffer[i][j]]++;
          }

/*  num = count/2;     THis is for median */
    num = 1;           /* This picks up the smallest depth */


/*  printf("num = %d count = %d",num,count);*/

  if(num == 0)
    {
      support_image_buffer[0][row][col] = range_image_buffer[row][col
      support_image_buffer[1][row][col] = lab;
    }
  else
    {
      for(i=0;num >0;i++)
        {  num=num-vector[i];
           if (vector[i] > 0) j=i;
        }
      support_image_buffer[0][row][col] = j;
      support_image_buffer[1][row][col] = lab;
    }
}

/************************  FINISHED  ******************************

finished()
{
  int i,j,k;
  int finish = 1;
  for(i=1;i<nrow;i++)
    for(j=1;j<ncol;j++)
     if((third_image_buffer[i][j] == 0) &&
        (range_image_buffer[i][j] > back_threshold)) finish = 0;

  return(finish);
}


/********************  FIND_SEED_REGION  ***************************/

find_seed_region()
{
  int i,j,k,m,n;
  int ok_point;                     /* Boolean */
  int average_depth;              /* average depth of the 3x3 window */
  int acount;


  max = -1000;
  for(i=2;i<nrow-2;i++)
    for(j=2;j<ncol-2;j++)
      if((range_image_buffer[i][j] > back_threshold) &&
         (third_image_buffer[i][j] == 0))
        {
          acount = 0;
          average_depth = 0;
          ok_point = 1;
          if(region_count == 1)      /* do it only the first time */
            {
              for(m=i-1;m<i+2;m++)
                for(n=j-1;n<j+2;n++)
                  if((lap_image_buffer[m][n] < edge_threshold) &&
                     (range_image_buffer[m][n] > back_threshold) &&
                     (third_image_buffer[m][n] == 0))
                    {
                      acount++;
                      average_depth += range_image_buffer[m][n];
                    }
                  else ok_point = 0;
              if(acount > 8) average_image[i][j] = average_depth/acou
              else average_image[i][j] = 0;
            }

          if(ok_point == 1)
            {
              if((lap_image_buffer[i][j] < edge_threshold) &&
                 (range_image_buffer[i][j] > back_threshold) &&
                 (third_image_buffer[i][j] == 0) &&
```

```
                 (average_image[i][j] > max))
                {
                  max = average_image[i][j];
                  row_max = i;
                  column_max = j;
                }
            }
        }


} /* end of find_seed_region */

/*************************** SEED_REGION ****************************

seed_region()
{
  int i,j,done,end;
  int m,n;
  int acount;
  int cross_grad;

  done = 0;
  end = 0;

  while((done == 0) && (end == 0))
    {
      if((third_image_buffer[nextrow][nextcol] == 0) &&
         (lap_image_buffer[nextrow][nextcol] < edge_threshold) &&
         (range_image_buffer[nextrow][nextcol] > back_threshold))
        {
          acount = 0;
          for(m=nextrow-1;m<nextrow+2;m++)
            for(n=nextcol-1;n<nextcol+2;n++)
              {
/*              cross_grad =sqrt((double)
                              (squarezz(range_image_buffer[m][n] -
                                range_image_buffer[m+1][n+1])+
                        squarezz(range_image_buffer[m][n+1] -
                                range_image_buffer[m+1][n]))); */

                cross_grad = 0;

              if((lap_image_buffer[m][n] < edge_threshold) &&
                 (range_image_buffer[m][n] > back_threshold) &&
                 (cross_grad < edge_threshold) &&
                 (third_image_buffer[m][n] == 0))
                acount++;
              }
          if(acount > 8)
```

```
            {
              done = 1;
              max = range_image_buffer[nextrow][nextcol];
            }
        }
      row_max = nextrow;
      column_max = nextcol;

      nextcol++;
      if(nextcol > (ncol-2))
        {
          nextrow++;
          nextcol = 0;
          if(nextrow > (nrow - 2))
            {
              end = 1;
              max = -1000;
            }
        }
    }


}   /* end of seed_region */

/****************************** FILL THE GAPS ************************
fill_gaps()
{
  int i,j,k,l;


}/*fill_gaps */

/****************************** CONTOUR TRACING **********************
```

```
/*********************************************************************
program for reading 2 and a 1/2 D range images
            removing supporting surface,
            calibrating the points,
            adding vertical points,
            adding horizontal points,
            selecting the density of grid,
            outputing the points.

    Jan    1988 : Modified to read PM_C format files.
    Jan    1988 : Modified to add the horizontal points.
    Jan    1988 : File reading procedure replaced to read as unsigned
    Jan    1988 : Buffer declarations moved out of the program to avo
                  run time segmentation fault.
    Feb 11,1988 : To read in supporting surface image and to add poin
                 vertically instead of horizontally.
    Feb 26,1988 : Changed to read rca range image files.
                  Output points in seperate files.
                  points.orig
                  points.add
    Mar 24,1988 : Modified to read both PM_C and PM_S formats.

I/O :  run the program as:

      %rca_calib _grid_density_ _range_image_file_ {_support_points_f

      if support image file is not specified then vertical point addi
 is disabled. Otherwise user is given choice to add vertical points o
 Input images can be either in PM_S or PM_C format. Two files are out
  one having just the original points : points.orig
  one having all the desired added points ( background , vertical ,
        and horizontal )            : points.add

Notes :
  1.  Support point image should not have depth values = 255. It is r
     for the program.
  2. Backgound points are thresholded at BACK_DEPTH + TRESH.

*********************************************************************

#include <math.h>
#include <stdio.h>
#include <local/pm.h>
/*** #include "/usr/users/franc/local/pic.h" */
#include "/usr/users/alok/trial/pic.h"


#define POINTS PICDIM_X * PICDIM_Y
#include "/usr/users/franc/local/frio.h"
```

```
/*** Following values are Range-image scanner dependent. These corres
   to the SRI- test database ***/

/*#define VERTICAL 1.531 */
/*#define HORIZONTAL 1.531 */
/*#define HEIGHT 0.245 */
/*#define BACK_DEPTH 5.0 */

/* Following are for RCA range image scanner.
   measured in mm/pixel
*/

#define VERTICAL 1.8796
#define HORIZONTAL 1.8796
#define HEIGHT 0.0254

/*#define VERTICAL 1.5240*/                    /* X , varying rows 0.060
/*#define HORIZONTAL 1.8796*/                  /* Y , varying cols 0.074
/*#define HEIGHT 0.0254*/                      /* Z , depth        0.001

/* Range image scanner dependent */
#define BACK_DEPTH 320                  /* background depth */
#define TRESH 0 /* original value = 5 */

#define BORDER 10

/*** Big array declarations are moved out of the main program body to
  avoid run time memory fault. ***/
/*** Important to have the image read in as unsigned char so that pix
values are from 0 to 255 and not from -127 to +127 ***/

int picture[PICDIM_X][PICDIM_Y];
int sup_points[PICDIM_X][PICDIM_Y];

double point[POINTS][3], support[POINTS][3], T[4][4], newpoint[3], ve

/*** additional declarations for adding hidden points ***/

double vect[3], addpoint[POINTS][3], vectpoint[3];     /* horizontal
double sup_vect[3], side_add_points[POINTS][3], sup_point[3];/*vertic


pmpic *pm1;    /*** Input file is in PM-format */
int sizex;     /*** # of rows in input picture */
int sizey;     /*** # of columns in input picture */


main (argc, argv)
```

```
int argc;
char *argv[];

{

  int i, j, k, k2, k3, m, n, grid;
  double x1, y1, z1, x2, y2, z2, x3, y3, z3, a, b, c;
  double sqrt(), sq(), distance;
  char g[10],h[10],sup[10],orig[10];
  int sup_count = 0;
  int cause;
  FILE *orig_file,*add_file;

  if ((argc < 3) || (argc > 4))
    printf("usage: rca_calib grid_density inpic (sup_pic) \n");
  else
   {
     grid = atoi(argv[1]);
     read_picture(argv[2], picture);
     if (argc == 4) read_picture(argv[3], sup_points);

     make_matrix(T);

/*  compute the supporting plane from three points
*/
     x1 = 15.0;
     y1 = 5.0;
     z1 = BACK_DEPTH;
/*     z1 = (double)picture[(int)x1][(int)y1];*/
     fprintf(stderr,"z1 = %f  ",z1);

     x2 = 230.0;
     y2 = 5.0;
     z2 = BACK_DEPTH;
/*     z2 = (double)picture[(int)x2][(int)y2];*/
     fprintf(stderr,"z2 = %f  ",z2);

     x3 = 30.0;
     y3 = 165.0;
     z3 = BACK_DEPTH;
  /*   z3 = (double)picture[(int)x3][(int)y3];*/
     fprintf(stderr,"z3 = %f \n",z3);

     c = ((x3 -x1)*(x3*y2 - x2*y3) - (x3 - x2)*(x3*y1 - x1*y3))/(
         (x3*z2 - x2*z3)*(x3*y1 - x1*y3) - (x3*z1 -x1*z3)*(x3*y2 - x2
         );

     b = (-c * (x3*z1 - x1*z3) - (x3 - x1))/(x3*y1 - x1*y3);
```

```
     a = (-1 - c*z1 - b*y1)/x1;

     fprintf(stderr,"a = %f b = %f c = %f\n",a,b,c);

     fprintf(stderr,"Add hidden points horizontally (y/n)?");
     scanf("%s",h);

     if(argc == 4){ /* supporting points file present */
       fprintf(stderr,"Add hidden points vertically   (y/n)?");
       scanf("%s",sup);
     } else
       sprintf(sup,"%s","no");

     k = 0;
     k2 =0;
     k3 =0;

     for (j = BORDER; j < sizey - BORDER; j = j + grid)
      { for (i = BORDER; i < sizex - BORDER; i = i + grid)
         {
           vector[0] = j * HORIZONTAL;
           vector[1] = (239 - i) * VERTICAL;
           vector[2] = picture[i][j] * HEIGHT;
           matrix_mult(vector, T, newpoint);

           if(h[0] == 'y')
             {
               vect[0] = vector[0];
               vect[1] = vector[1];
               vect[2] = ((-1.0-a*i-b*j)/c)*HEIGHT;
               matrix_mult(vect, T, vectpoint);
             }

           distance = (a * i + b * j + c * (double)(picture[i][j]) +1
              sqrt(sq(a) + sq(b) + sq(c));

/*         fprintf(stderr,"i = %d j = % d z = %d distance = %f \n",i,

           if(distance < -TRESH)
            { point[k][0] = newpoint[0];
              point[k][1] = newpoint[1];
              point[k][2] = newpoint[2];
              if(h[0] == 'y')
                {
                  addpoint[k][0] = vectpoint[0];
                  addpoint[k][1] = vectpoint[1];
                  addpoint[k][2] = vectpoint[2];
                }
              k = k + 1;
             }
           else if (distance < TRESH)
            { support[k2][0] = newpoint[0];
              support[k2][1] = newpoint[1];
              support[k2][2] = newpoint[2];
              k2 = k2 + 1;
            }
           else {} /* points is in shadow */
         }
      }

    if(sup[0] == 'y')
      for (j = BORDER; j < sizey - BORDER; j++)
        { for (i = BORDER; i < sizex - BORDER; i++)
            {
              if(sup_points[i][j] > 0)
                {
                  sup_count++;
                  cause = 0;
                  for(m=i-grid/2;m<=i+grid/2;m++)
                    for(n=j-grid/2;n<=j+grid/2;n++)
                      if((sup_points[m][n] == 255)) cause++;
                  if(cause == 0)
                    {
                      for(m=sup_points[i][j]; m <= picture[i][j]; m=
                        {
                          sup_vect[0] = j * HORIZONTAL;
                          sup_vect[1] = (239 - i) * VERTICAL;
                          sup_vect[2] = m*HEIGHT;
                          matrix_mult(sup_vect, T, sup_point);
                          side_add_points[k3][0] = sup_point[0];
                          side_add_points[k3][1] = sup_point[1];
                          side_add_points[k3][2] = sup_point[2];
                          k3++;
                        }
                      sup_points[i][j] = 255;
                    }
                }

            }
        }

    fprintf (stderr,"Remove supporting surface (y/n)?  ");
    scanf("%s", g);

    fprintf (stderr,"Add original points ?(y/n)");
    scanf("%s", orig);
```

```
    if(orig[0] == 'y')
      {
        if((orig_file = fopen("points.orig","w")) == NULL)
          {fprintf(stderr,"Can't open output file : %s\n","points.or
           exit(0);}
        for(i = 0; i < k; i++)
          fprintf(orig_file,"%f %f %f \n", point[i][0], point[i][1],
      }

    if((h[0] == 'y') || (g[0] == 'y') || (sup[0] = 'y'))
        if((add_file = fopen("points.add","w")) == NULL)
          {printf("Can't open output file : %s\n","points.add");
           exit(0);}

    if(h[0] == 'y')   /*** hidden points to be added horizontally ?
     { for(i = 0; i < k; i++)
        fprintf(add_file,"%f %f %f \n", addpoint[i][0], addpoint[i][
     }

    if(g[0] == 'n')  /*   background to be removed */
     { for(i = 0; i < k2; i++)
        fprintf(add_file,"%f %f %f \n", support[i][0], support[i][1]
     }

    if(sup[0] == 'y')  /*   vertical points to be added */
     {
       for(i = 0; i < k3; i++)
        fprintf(add_file,"%f %f %f \n", side_add_points[i][0], side_
     }

  }
}

/*********************************************************************
function for multiplying matrix with a vector
*********************************************************************

matrix_mult(vector, matrix, result)
double vector[3], matrix[4][4], result[3];
{
  result[0] = matrix[0][0] * vector[0] +
              matrix[0][1] * vector[1] +
              matrix[0][2] * vector[2] + matrix[0][3];

  result[1] = matrix[1][0] * vector[0] +
              matrix[1][1] * vector[1] +
              matrix[1][2] * vector[2] + matrix[1][3];
  result[2] = matrix[2][0] * vector[0] +
              matrix[2][1] * vector[1] +
              matrix[2][2] * vector[2] + matrix[2][3];
}

/*********************************************************************
function for making a T matrix
*********************************************************************/
make_matrix(TR)
double TR[4][4];

{ double rx, ry, rz, x, y, z;

  x = 80.0;
  y = -180.0;
  z = 0;

  rx = 90.0;
  ry = 45.0;
  rz = -15.0;

  rx = rx * PI/180;
  ry = ry * PI/180;
  rz = rz * PI/180;

/*
homogenous transformation : Euler angles
*/

     TR[0][0] = cos(rx)*cos(ry)*cos(rz) - sin(rx)*sin(rz);
     TR[0][1] = -cos(rx)*cos(ry)*sin(rz) - sin(rx)*cos(rz);
     TR[0][2] = cos(rx)*sin(ry);
     TR[0][3] = x;

     TR[1][0] = sin(rx)*cos(ry)*cos(rz) + cos(rx)*sin(rz);
     TR[1][1] = - sin(rx)*cos(ry)*sin(rz) + cos(rx)*cos(rz);
     TR[1][2] = sin(rx)*sin(ry);
     TR[1][3] = y;

     TR[2][0] = -sin(ry)*cos(rz);
     TR[2][1] = sin(ry)*sin(rz);
     TR[2][2] = cos(ry);
     TR[2][3] = z;

     TR[3][0] = 0;
     TR[3][1] = 0;
     TR[3][2] = 0;
     TR[3][3] = 1;
}
```

```
double sq(x)
double x;
{ return(x*x);
}

read_picture(filename,buffer)
char filename[50];
int buffer[PICDIM_X][PICDIM_Y];
{
  int i,j;
  FILE *infs;
  unsigned char *pm_point;
  short int *pms_point;

  /* open input pm file */

  if ((infs = fopen(filename,"r")) == NULL)
    {
      printf("file open error :%s \n",filename);
      exit(0);
    }

/* read inputfile into the pmpic buffer */

  if((pm1 = pm_read(infs,0)) == NULL)
    {
      printf("error in reading the pmfile %s",filename);
      exit(0);
    }

  sizex = (pm1->pm_nrow);    /* # of rows */
  sizey = (pm1->pm_ncol);    /* # of columns */

  fprintf(stderr,"rows : %d ; columns : %d\n",sizex,sizey);

  if(pm1->pm_form == PM_C)
    {
      pm_point = (unsigned char *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[i][j] = *(pm_point);
            pm_point++;
          }
    }
  else if(pm1->pm_form == PM_S)
    {
      pms_point = (short int *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[i][j] = *(pms_point);
            pms_point++;
          }
    }
  else
    {
      printf("Image file in unrecognized format.Exiting.\n");
      exit(0);
    }

}/* end of read picture */
```

```
/***********************************************************************

     Program to classify the superquadric model into one of the four
  broad categories :
      flat,
      box,
      roll,
      IPP.

 Format of the input file is as output from the rec9.out program.
 Run as:
   %classify fit_*.originalpoints fit_*.addedpoints

   0.00 <=  e1,e2 <= 1.00
***********************************************************************

#include <stdio.h>
#include <math.h>

#define TIM 3               /* to implement << or >>  */
#define FLAT 1
#define BOX 2
#define ROLL 3
#define IPP 4


double a1[3],a2[3],a3[3];             /* to store a1, a2 and a3 */
double e1[3],e2[3];          /* to store e1 and e2     */
double measured_goodness1,goodness;         /* goodness of fit */
double measured_goodness2;

char dummy[100],orig[50],add[50];

int type1,type2;              /* type determined by looking at the a1
                                 and a3 values and e1 and e2 values of
                                 fitted model */
double dum;
double k_box = 10.0 ,
       k1_roll=10.0 ,
       k2_roll=15.0 ;

FILE *infs,*addfile,*outfile;

main(argc,argv)
int argc;
char *argv[];
{
  int i,j,k,l;
  int good1,good2;
```

```
  strcpy(orig,argv[1]);
  strcpy(add,argv[2]);

  if((infs = fopen(argv[1],"r")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[1]);
      exit(0);
    }

  if((addfile = fopen(argv[2],"r")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[2]);
      exit(0);
    }

  if((outfile = fopen(argv[3],"w")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[3]);
      exit(0);
    }


  fscanf(infs,"%s",dummy);

  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);
  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);
  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);

  fscanf(infs,"%f %f",&e1[1],&e2[1]);
  fscanf(infs,"%f %f",&e1[1],&e2[1]);

  fscanf(infs,"%d %d %d",&dum,&dum,&dum);
  fscanf(infs,"%s",dummy);

  fscanf(infs,"%f",&measured_goodness1);

  printf("%f,%f,%f\n",a1[1],a2[1],a3[1]);
  printf("%f,%f\n",e1[1],e2[1]);
  printf("%f\n",measured_goodness1);

  fscanf(addfile,"%s",dummy);

  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);
  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);
  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);

  fscanf(addfile,"%f %f",&e1[2],&e2[2]);
  fscanf(addfile,"%f %f",&e1[2],&e2[2]);
```

```
    fscanf(addfile,"%d %d %d",&dum,&dum,&dum);
    fscanf(addfile,"%s",dummy);

    fscanf(addfile,"%f",&measured_goodness2);

    printf("%f,%f,%f\n",a1[2],a2[2],a3[2]);
    printf("%f,%f\n",e1[2],e2[2]);
    printf("%f\n",measured_goodness2);

    /* Readin the Threshold values */

    printf("K for Box : ");
    scanf("%f",&k_box);

    printf("K1 and K2 for Roll : ");
    scanf("%f %f",&k1_roll,&k2_roll);

    printf("Goodness of fit measure : ");
    scanf("%f",&goodness);

    /* FIRST classify the object according to the a1,a2,a3,e1,e2 values

    type1 = classified(1);
    type2 = classified(2);

    good1 = good_enough(measured_goodness1);
    good2 = good_enough(measured_goodness2);

    if((good1 == 1) && (good2 == 0))
      { /* first fit is better than second fit */
        classification(1,type1);
      }
    else if((good1 == 0) && (good2 == 1))
      { /* second fit is better than the first fit */
        classification(2,type2);
      }
    else if((good1 == 1) && (good2 == 1))
      { /* both the fits are acceptable */
        volume_criterion();
      }
    else
      { /* Both the fits are unacceptable */
        classification(3,IPP);
      }

}

classified(num)
```

```
int num;
{
  int i,j,k;

  if((TIM*a3[num] < a1[num]) && (TIM*a3[num] < a2[num]) &&
      (e2[num] < 0.5) && (e1[num] < 0.5))
    return(FLAT);

  else if(((a1[num]*TIM < a3[num]) || (a2[num]*TIM < a3[num])) &&
           (e1[num] < 0.5) && (e2[num] < 0.5))
    return(FLAT);

  else if((a1[num] > k_box) && (a2[num] > k_box) && (a3[num] > k_box)
           (e1[num] < 0.5) && (e2[num] < 0.5))
    return(BOX);

  else if((a1[num] > k1_roll) && (a2[num] > k1_roll) && (a3[num] > k2
           (e1[num] < 0.5) && (e2[num] > 0.5))
    return(ROLL);

  else
    return(IPP);

}

classification(num,type)
int num;
int type;
{
  char str[50];
  char string[10];

  switch(type)
    {
    case FLAT : sprintf(string,"%s","Flat");break;
    case BOX  : sprintf(string,"%s","Box");break;
    case ROLL : sprintf(string,"%s","Roll");break;
    case IPP  : sprintf(string,"%s","Ipp");break;
    }

  if((num == 1))
    {
      printf("Points not added in the fit.\n");
      printf("Object classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",orig," fit.final ");
      system(str);
    }
  else if((num == 2))
    {
      printf("Points added to obtain the fit.\n");
      printf("Object classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",add," fit.final ");
      system(str);
    }

  else
    {
      printf("Object Classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",orig," fit.final ");
      system(str);
    }
}

volume_criterion()
{
  double vol1,vol2;

  vol1 = a1[1]*a2[1]*a3[1];
  vol2 = a1[2]*a2[2]*a3[2];

  printf("Following volume criterion \n");

  if(vol1 <= vol2)
    classification(2,type2);
  else
    classification(1,type1);

}

good_enough(goodn)
double goodn;
{

  if(goodn < goodness)
    return(1);
  else
    return(0);
}
```

```
  result[2] = matrix[2][0] * vector[0] +
              matrix[2][1] * vector[1] +
              matrix[2][2] * vector[2] + matrix[2][3];
}

/*********************************************************************
function for making a T matrix
*********************************************************************
make_matrix(TR)
double TR[4][4];

{ double rx, ry, rz, x, y, z;

  x = 80.0;
  y = -180.0;
  z = 0;

  rx = 90.0;
  ry = 45.0;
  rz = -15.0;

  rx = rx * PI/180;
  ry = ry * PI/180;
  rz = rz * PI/180;

/*
homogenous transformation : Euler angles
*/

     TR[0][0] = cos(rx)*cos(ry)*cos(rz) - sin(rx)*sin(rz);
     TR[0][1] = -cos(rx)*cos(ry)*sin(rz) - sin(rx)*cos(rz);
     TR[0][2] = cos(rx)*sin(ry);
     TR[0][3] = x;

     TR[1][0] = sin(rx)*cos(ry)*cos(rz) + cos(rx)*sin(rz);
     TR[1][1] = - sin(rx)*cos(ry)*sin(rz) + cos(rx)*cos(rz);
     TR[1][2] = sin(rx)*sin(ry);
     TR[1][3] = y;

     TR[2][0] = -sin(ry)*cos(rz);
     TR[2][1] = sin(ry)*sin(rz);
     TR[2][2] = cos(ry);
     TR[2][3] = z;

     TR[3][0] = 0;
     TR[3][1] = 0;
     TR[3][2] = 0;
     TR[3][3] = 1;
}
```

```
double sq(x)
double x;
{ return(x*x);
}

read_picture(filename,buffer)
char filename[50];
int buffer[PICDIM_X][PICDIM_Y];
{
  int i,j;
  FILE *infs;
  unsigned char *pm_point;
  short int *pms_point;

  /* open input pm file */

  if ((infs = fopen(filename,"r")) == NULL)
    {
      printf("file open error :%s \n",filename);
      exit(0);
    }

/* read inputfile into the pmpic buffer */

  if((pm1 = pm_read(infs,0)) == NULL)
    {
      printf("error in reading the pmfile %s",filename);
      exit(0);
    }

  sizex = (pm1->pm_nrow);    /* # of rows */
  sizey = (pm1->pm_ncol);    /* # of columns */

  fprintf(stderr,"rows : %d ; columns : %d\n",sizex,sizey);

  if(pm1->pm_form == PM_C)
    {
      pm_point = (unsigned char *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[i][j] = *(pm_point);
            pm_point++;
          }
    }
  else if(pm1->pm_form == PM_S)
    {
      pms_point = (short int *) pm1->pm_image;
      for(i=0;i<sizex;i++)
        for(j=0;j<sizey;j++)
          {
            buffer[i][j] = *(pms_point);
            pms_point++;
          }
    }
  else
    {
      printf("Image file in unrecognized format.Exiting.\n");
      exit(0);
    }

}/* end of read picture */
```

```
/*********************************************************************

     Program to classify the superquadric model into one of the four
  broad categories :
      flat,
      box,
      roll,
      IPP.

 Format of the input file is as output from the rec9.out program.
 Run as:
   %classify fit_*.originalpoints fit_*.addedpoints

   0.00 <=  e1,e2 <= 1.00
*********************************************************************/

#include <stdio.h>
#include <math.h>

#define TIM 3              /* to implement << or >>  */
#define FLAT 1
#define BOX 2
#define ROLL 3
#define IPP 4


double a1[3],a2[3],a3[3];             /* to store a1, a2 and a3 */
double e1[3],e2[3];          /* to store e1 and e2     */
double measured_goodness1,goodness;         /* goodness of fit */
double measured_goodness2;

char dummy[100],orig[50],add[50];

int type1,type2;              /* type determined by looking at the a1
                                 and a3 values and e1 and e2 values of
                                 fitted model */
double dum;
double k_box = 10.0 ,
       k1_roll=10.0 ,
       k2_roll=15.0 ;

FILE *infs,*addfile,*outfile;

main(argc,argv)
int argc;
char *argv[];
{
  int i,j,k,l;
  int good1,good2;
```

```
  strcpy(orig,argv[1]);
  strcpy(add,argv[2]);

  if((infs = fopen(argv[1],"r")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[1]);
      exit(0);
    }

  if((addfile = fopen(argv[2],"r")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[2]);
      exit(0);
    }

  if((outfile = fopen(argv[3],"w")) == NULL)
    {
      printf("classify : File open error : %s\n",argv[3]);
      exit(0);
    }


  fscanf(infs,"%s",dummy);

  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);
  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);
  fscanf(infs,"%f %f %f",&a1[1],&a2[1],&a3[1]);

  fscanf(infs,"%f %f",&e1[1],&e2[1]);
  fscanf(infs,"%f %f",&e1[1],&e2[1]);

  fscanf(infs,"%d %d %d",&dum,&dum,&dum);
  fscanf(infs,"%s",dummy);

  fscanf(infs,"%f",&measured_goodness1);

  printf("%f,%f,%f\n",a1[1],a2[1],a3[1]);
  printf("%f,%f\n",e1[1],e2[1]);
  printf("%f\n",measured_goodness1);

  fscanf(addfile,"%s",dummy);

  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);
  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);
  fscanf(addfile,"%f %f %f",&a1[2],&a2[2],&a3[2]);

  fscanf(addfile,"%f %f",&e1[2],&e2[2]);
  fscanf(addfile,"%f %f",&e1[2],&e2[2]);
  fscanf(addfile,"%d %d %d",&dum,&dum,&dum);
  fscanf(addfile,"%s",dummy);

  fscanf(addfile,"%f",&measured_goodness2);

  printf("%f,%f,%f\n",a1[2],a2[2],a3[2]);
  printf("%f,%f\n",e1[2],e2[2]);
  printf("%f\n",measured_goodness2);

  /* Readin the Threshold values */

  printf("K for Box : ");
  scanf("%f",&k_box);

  printf("K1 and K2 for Roll : ");
  scanf("%f %f",&k1_roll,&k2_roll);

  printf("Goodness of fit measure : ");
  scanf("%f",&goodness);

  /* FIRST classify the object according to the a1,a2,a3,e1,e2 values

  type1 = classified(1);
  type2 = classified(2);

  good1 = good_enough(measured_goodness1);
  good2 = good_enough(measured_goodness2);

  if((good1 == 1) && (good2 == 0))
    { /* first fit is better than second fit */
      classification(1,type1);
    }
  else if((good1 == 0) && (good2 == 1))
    { /* second fit is better than the first fit */
      classification(2,type2);
    }
  else if((good1 == 1) && (good2 == 1))
    { /* both the fits are acceptable */
      volume_criterion();
    }
  else
    { /* Both the fits are unacceptable */
      classification(3,IPP);
    }

}

classified(num)
```

```
int num;
{
  int i,j,k;

  if((TIM*a3[num] < a1[num]) && (TIM*a3[num] < a2[num]) &&
     (e2[num] < 0.5) && (e1[num] < 0.5))
    return(FLAT);

  else if(((a1[num]*TIM < a3[num]) || (a2[num]*TIM < a3[num])) &&
          (e1[num] < 0.5) && (e2[num] < 0.5))
    return(FLAT);

  else if((a1[num] > k_box) && (a2[num] > k_box) && (a3[num] > k_box)
          (e1[num] < 0.5) && (e2[num] < 0.5))
    return(BOX);

  else if((a1[num] > k1_roll) && (a2[num] > k1_roll) && (a3[num] > k2
          (e1[num] < 0.5) && (e2[num] > 0.5))
    return(ROLL);

  else
    return(IPP);

}

classification(num,type)
int num;
int type;
{
  char str[50];
  char string[10];

  switch(type)
    {
    case FLAT : sprintf(string,"%s","Flat");break;
    case BOX  : sprintf(string,"%s","Box");break;
    case ROLL : sprintf(string,"%s","Roll");break;
    case IPP  : sprintf(string,"%s","Ipp");break;
    }

  if((num == 1))
    {
      printf("Points not added in the fit.\n");
      printf("Object classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",orig," fit.final ");
      system(str);
    }
  else if((num == 2))
    {
      printf("Points added to obtain the fit.\n");
      printf("Object classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",add," fit.final ");
      system(str);
    }

  else
    {
      printf("Object Classified as %s \n",string);
      fprintf(outfile,"%s",string);
      sprintf(str,"%s %s %s","cp ",orig," fit.final ");
      system(str);
    }
}

volume_criterion()
{
  double vol1,vol2;

  vol1 = a1[1]*a2[1]*a3[1];
  vol2 = a1[2]*a2[2]*a3[2];

  printf("Following volume criterion \n");

  if(vol1 <= vol2)
    classification(2,type2);
  else
    classification(1,type1);

}

good_enough(goodn)
double goodn;
{

  if(goodn < goodness)
    return(1);
  else
    return(0);
}
```

```
/*********************************************************************

   Program to compute the first and second order derivatives of the r
image and finally the Gaussian and Mean curvature at all the image po
is given below. The program outputs the sign map of gaussian and mean
curvature.
   Mar 17, 1988 Interactive processing.
                Can handle PM_S and PM_C images. Outputs only PM_C im
   Mar 25, 1988 Display histogram of arbitrary parameter on IKONAS
                using quickdraw.


*********************************************************************

#include <stdio.h>
#include <math.h>
#include <local/pm.h>
#include <ik.h>
#include "/usr/users/alok/advanced/spline_include.h"


#define SCALE 1.978            /* should be same as xscale and yscale
                                  as mm/pixel ;for Gus' scanner < \/*
#define ZSCALE 1.500           /* zscale in the digitized image */
#define REGION_SIZE 1000

#define NSYS  25
#define NDATA  1000

struct region_type {
  int order;                /* order of the surface fitted */
  int surf_type;            /* classifiacation of the region surface
  float fit_error;          /* surface fit error */
  int label;                /* identifying label of the region */
  int size;                 /* # of pixels in the region */
  float normal_vector[3];   /* unit normal to the surface */
} regions[REGION_SIZE];


struct _image{
  float xu,xv,xuu,xvv,xuv;
  float fit_error;
  float gauss,mean;
  int label;
  int th_mean;
  int th_gauss;
  float q;
  float sqrtg;
```

```
  float cosphi;
} image,parm[BUFSIZE][BUFSIZE];        /* for parameters of pixels  *

float ri[BUFSIZE][BUFSIZE];   /* range image */

int buffer[BUFSIZE][BUFSIZE];
int line[BUFSIZE];
float linef[BUFSIZE];

int offx,offy;

struct mxval{
  float fit_error;
  float gauss;
  float mean;
  float q;
  float sqrtg;
  float cosphi;
  float depth;
  int label;
  int th_gauss;
  int th_mean;
}maxv,minv;                   /* stores the maximum and minumum of value


float x[1024];
float y[1024];
float value;
float xmin,xmax,ymin,ymax;
int iopt;
int npts;


  /* followind parameters are returned by the least square fitting pr

double  ix,   iy,   ixx,  iyy,  ixy,  iyx,  ixxx, iyyy, ixyy, ixxy ;
double a30,  a21,  a12,  a03,  a20,  a11,  a02,  a10,  a01,  a00 ;
double xu,xv,xuu,xvv,xuv;
double fit_error;  /* the surface fit error */
int s_order;       /* the order of the surface fitted in the nbd */

  /* following are global to this file */
int csize, rsize ;
int offsetl ;
int approx ;
int s_order;         /* fitted surface order */
double lsqerr();
FILE *dumpfile;
int todump;
```

```
char name_ext[16][20] = {        " ",      /* name-extensions to be appe
                        ".fit-error",   /* to the input file-name to
                        ".quad-var",    /* output-file-name
                        ".zero-mean",
                        ".zero-gauss",
                        ".zero-ccf",
                        ".ccaf",
                        ".sign-mean",
                        ".sign-gauss",
                        ".mag-pcd",
                        ".pda",
                        ".mgc",
                        ".mmc",
                        ".n-critical",
                        ".critical",
                        ".region"};


int mask_u[5][5] = {
  {-1,-6,-10,-6,-1},
  {-2,-20,-52,-20,-2},
  {0,0,0,0,0},
  {2,20,52,20,2},
  {1,6,10,6,1}};

int mask_v[5][5] = {
  {-1,-2,0,2,1},
  {-6,-20,0,20,6},
  {-10,-52,0,52,10},
  {-6,-20,0,20,6},
  {-1,-2,0,2,1}};

int mask_uu[5][5] = {
  {1,6,10,6,1},
 {0,8,32,8,0},
  {-2,-28,-84,-28,-2},
  {0,8,32,8,0},
  {1,6,10,6,1}};

int mask_vv[5][5] = {
  {1,0,-2,0,1},
  {6,8,-28,8,6},
  {10,32,-84,32,10},
  {6,8,-28,8,6},
  {1,0,-2,0,1}};

int mask_uv[5][5] = {
  {1,2,0,-2,-1},
```

```
  {2,12,0,-12,-2},
  {0,0,0,0,0},
  {-2,-12,0,12,2},
  {-1,-2,0,2,1}};

int op_u[3][3] = {  {-1,-4,-1},
  {0,0,0},
  {1,4,1}};

int op_v[3][3] = {
  {-1,0,1},
  {-4,0,4},
  {-1,0,1}};

int op_uu[3][3] = {
  {1,4,1},
  {-2,-8,-2},
  {1,4,1}};

int op_vv[3][3] = {
  {1,-2,1},
  {4,-8,4},
  {1,-2,1}};

int op_uv[3][3] = {
  {1,0,-1},
  {0,0,0},
  {-1,0,1}};


float weight_u = 288.0;
float weight_v = 288.0;
float weight_uu =144.0;
float weight_vv =144.0;
float weight_uv =96.0;

float convo();
float convo_1();
float abszz();

float div_u = 12.0;
float div_v = 12.0;
float div_uu= 6.0 ;
float div_vv= 6.0 ;
float div_uv= 4.0 ;


float max_mean = -1000.0;
float max_gauss= -1000.0;
float min_mean =  1000.0;
float min_gauss=  1000.0;


main(argc,argv)
int argc;
char *argv[];
{
  int i,j,k,l,m,n;                    /* Loop control variables */
  pmpic *pm1,*pm2;
  FILE *infile,*outfile;
  int row,col;
  char *cmt;
  unsigned char *pm_point_uchar;
  short int *pm_point_short;
  int option;
  float gauss,mean;
  char temp[40];
  int offset;
  pmpic *pmp[16];
  unsigned char *uchar_point[16];
  int temp_value;
  int mean_val,gauss_val;
  int bool[17];
  FILE *fp[16];
  float th_mean,th_gauss;
  float t1,t2,t3;
  float q;
  char c;
  char smooth;
  int back_threshold;
  int to_smooth;
  int to_print_files;     /* =1, if all outputs desired in a file */
  char string[30];
  float sf;
  pmpic *pm;
  FILE *fp1;
  double scale,zscale;    /* scale = yscale = xscale; zscale is for d
  u_int image_format;
  int subs;


  if((argc > 3) || (argc < 2))
    {
      printf("Usage : spline input_filename output_diagonistics_file\
      exit(0);
    }

  if((infile=fopen(argv[1],"r")) == NULL)
```

```
    {
      printf("Can't open %s\n",argv[1]);
      exit(0);
    }

  todump = 0;
  if(argc == 3)
    {
      if((dumpfile=fopen(argv[2],"w")) == NULL)
        {
          printf("Can't open %s\n",argv[2]);
          exit(0);
        }
      todump = 1;
    }

/*  if(ikopen(NULL) == -1)
    printf(" Can't open IKONAS \n");*/

  init_structure();        /* initializes the structures */

  cmt = (char *)pm_cmt(argc,argv);      /* get the command line */

  if((pm1 = pm_read(infile,0)) == NULL)
    {
      printf("Error in reading PM-Format file : %s\n",argv[1]);
      exit(0);
    }

  row = pm1->pm_nrow;
  col = pm1->pm_ncol;
  rsize = row;
  csize = col;
  offx = offy =0;

  /* copy the input image into the image */

  if(pm1->pm_form == PM_C)    /* one byte per pixel picture */
    {
      pm_point_uchar = (unsigned char *) pm1->pm_image;
      image_format = PM_C;
      zscale = ZSCALE;   /* for Gus' scanner */
      scale = SCALE;
      printf("initializing buffer \n");
      for(i=0;i<row;i++)
        for(j=0;j<col;j++)
          {
            ri[i][j] = ((float) *pm_point_uchar)*((float)(zscale/scal
            if(maxv.depth < ri[i][j]) maxv.depth = ri[i][j];
            if(minv.depth > ri[i][j]) minv.depth = ri[i][j];
            pm_point_uchar++;
          }
     }

   else if(pm1->pm_form == PM_S)  /* short integer picture */
     {
       pm_point_short = (short int *) pm1->pm_image;
       image_format = PM_S;
       zscale = 1.00;
       scale = 74.20;
       printf("initializing buffer \n");
       for(i=0;i<row;i++)
         for(j=0;j<col;j++)
          {
            ri[i][j] = ((float) *pm_point_short)*((float)(zscale/scal
            if(maxv.depth < ri[i][j]) maxv.depth = ri[i][j];
            if(minv.depth > ri[i][j]) minv.depth = ri[i][j];
            pm_point_short++;
          }
     }
   else {fprintf(stderr,"unrecognized PM format in image");
         exit(0);
       }

   /* background threshold is the background value in image as it is r
     and not in uniformly scaled ( in Z direction ) image */

   printf(" Background Threshold : ");
   scanf("%d",&back_threshold);

   back_threshold = (back_threshold * zscale)/scale;

   read_specs();      /* read specifications */

   printf("Gaussian-smooth the picture ?(1 if yes) :");
   scanf("%d",&to_smooth);

   if(to_smooth == 1) gaussian(ri,row,col);


   to_print_files = 0;
   if(to_print_files == 1)
     {
       printf("  Following outputs can be obtained :\n");
       printf("     Indicate your choice by entering integers in a lin
       printf("  1. Square root of metric determinant (edge magnitude)
       printf("  2. Quadratic Variation (flatness measure image Q.\n")
       printf("  3. Zeros of the mean curvature : H = 0\n");
```

```
       printf("  4. Zeros of the Gaussian curvature :k = 0\n");
       printf("  5. Zeros of the cosine-of-the-coordinate-function cos
       printf("  6. Cosine of the Coordinate angle Function :cos 0\n")
       printf("  7. Sign regions of mean curvature  sgn(H)\n");
       printf("  8. Sign regions of Gaussian curvature ,sgn(K)\n");
       printf("  9.Magnitude of principal curvatures difference :sqrt(
       printf("  10.Principal direction angle \n");
       printf("  11.Magnitude of Gaussian curvature K\n");
       printf("  12.Magnitude of Mean curvature H\n");
       printf("  13.Non degenerate critical points image :fu=fv=0<>Q\n
       printf("  14.Critical points image\n");
       printf("  15.Labeled regions\n");
       printf("  16.ALL OF THE ABOVE\n");
     }
       /* read in user requirements and set boolean corresponding to t

   /*      for(i=0;i<17;i++) bool[i] = 0;
           i = 0;
       while (i == 0)
         {
           scanf("%d",&n);
           getchar();
           if ((n>0)&&(n<17)) {bool[n] = 1;}
           else {i = 1;}
         }
       i = i;
       if (bool[16] == 1)
         for(i=0;i<17;i++) bool[i] = 1;
       printf("\n Outputs are:\n\n");*/

       /*  generate output filenames */

 /*      for (i=1;i<16;i++)
         if(bool[i] == 1)
           {
             strcpy(temp,argv[1]);
             strcat(temp,name_ext[i]);
             printf("  %s \n",temp);
             fp[i] = fopen(temp,"w");
             pmp[i] = pm_alloc();
             pmp[i]->pm_nrow = row;
             npmp[i]->pm_ncol = col;
             pmp[i]->pm_image = (char *) malloc(pm_psize(pmp[i]));
             uchar_point[i] = (unsigned char *)pmp[i]->pm_image;
           }
     }*/  /* segment for output file initialization */

   /* Now compute the derivatives and Gaussian and Mean curvature at e
     image point
```

```
  */

  printf("row  : %d  column %d  offset1 %d\n",row,col,offset1);
  printf("rsize : %d    csize : %d approx : %d\n",rsize,csize,approx)

  compute_amatrix();

  for(i=offset1;i<row-offset1;i++)
    {
      for(j=offset1;j<col-offset1;j++)
        if(ri[i][j] > back_threshold)
        {
          if((approx == 1) || (approx == 2) || (approx == 3))
            {
              poly2(i,j);
               xu = ix;
               xv = iy;
               xuu = ixx;
               xvv = iyy;
               xuv = ixy;
            }
          else
            if(approx == 5)  /* B-spline fitting using Kak-Hwang mask
              {
                xu  = convo(i,j,mask_u,weight_u,5);
                xv  = convo(i,j,mask_v,weight_v,5);
                xuu= convo(i,j,mask_uu,weight_uu,5);
                xvv= convo(i,j,mask_vv,weight_vv,5);
                xuv= convo(i,j,mask_uv,weight_uv,5);
              }
            else  /*without smoothing B-spline fitting using Kak-Hwan
              {
                 xu  = convo_1(i,j,op_u,div_u,3);
                 xv  = convo_1(i,j,op_v,div_v,3);
                 xuu= convo_1(i,j,op_uu,div_uu,3);
                 xvv= convo_1(i,j,op_vv,div_vv,3);
                 xuv= convo_1(i,j,op_uv,div_uv,3);
              }

          (parm[i][j].xu) = xu;
          parm[i][j].xv = xv;
          parm[i][j].xuu = xuu;
          parm[i][j].xvv = xvv;
          parm[i][j].xuv = xuv;


          gauss = (xuu*xvv-xuv*xuv)/
            ((float)(pow((double)(1+xu*xu+xv*xv),(double)(2))));
          mean  = (xuu+xvv+xuu*xv*xv+xvv*xu*xu-2.0*xu*xv*xuv)/
```

```
            ((float)(pow((double)(1+xu*xu+xv*xv),(double)(1.5))));

          if(gauss > maxv.gauss) maxv.gauss = gauss;
          if(mean  > maxv.mean ) maxv.mean  = mean;
          if(gauss < minv.gauss) minv.gauss = gauss;
          if(mean  < minv.mean ) minv.mean  = mean;

          if(fit_error >255) fit_error = 255;

          if(fit_error > maxv.fit_error) maxv.fit_error = fit_error;
          if(fit_error < minv.fit_error) minv.fit_error = fit_error;

          parm[i][j].fit_error = fit_error;
          parm[i][j].gauss = gauss;
          parm[i][j].mean = mean;

        }
    }  /* End of loop to compute derivatives and curvature values */


  /* open ikonas display */
  if(ikopen(NULL) == 1)
    printf("Can't open IKONAS \n");


  printf("ENTER > ");
  scanf("%s",string);

  while((strcmp("exit",string) != 0) && (strcmp("quit",string) != 0))
    {/* interactive loop to do things starts here */

      if(strcmp("comp",string) == 0)
        { /* compute general things */

          for(i=offset1;i<row-offset1;i++)
            for(j=offset1;j<col-offset1;j++)
              if(ri[i][j] > back_threshold)
              {
                /*** sqrt g ***/
                parm[i][j].sqrtg = (float)sqrt((double)(1+parm[i][j].
                                 parm[i][j].xu+parm[i][j].xv*parm[i][
                if(parm[i][j].sqrtg > maxv.sqrtg)
                  maxv.sqrtg = parm[i][j].sqrtg;
                if(parm[i][j].sqrtg < minv.sqrtg)
                  minv.sqrtg = parm[i][j].sqrtg;


                /***  Q   ***/
                parm[i][j].q = (float)(parm[i][j].xuu*parm[i][j].xuu
                   2*parm[i][j].xuv*parm[i][j].xu
                   parm[i][j].xvv*parm[i][j].xvv)
        if(parm[i][j].q > maxv.q)
         maxv.q = parm[i][j].q;
        if(parm[i][j].q < minv.q)
         minv.q = parm[i][j].q;



        /*** zeros of cos phi  ***/

        parm[i][j].cosphi = (float)(parm[i][j].xu*parm[i][j].
         ((float)(sqrt((double)(1+parm[i][j].xu*parm[i][j].x
               parm[i][j].xv*parm[i][j].xv +
               parm[i][j].xu*parm[i][j].xu*parm[i][j]
               parm[i][j].xv))));
        if(parm[i][j].cosphi  > maxv.cosphi )
         maxv.cosphi  = parm[i][j].cosphi ;
        if(parm[i][j].cosphi  < minv.cosphi )
         minv.cosphi  = parm[i][j].cosphi ;

       }
    }

   else if(strcmp("ikclose",string) == 0)
    ikclose();

   else if(strcmp("ikopen",string) == 0)
    ikopen(NULL);

   else if(strcmp("thresh",string) == 0)
    {
     printf("threshold for Gaussian curvature > ");
     scanf("%f",&th_gauss);
     printf("threshold for Mean curvature > ");
     scanf("%f",&th_mean);

     for(i=offset1;i<row-offset1;i++)
      for(j=offset1;j<col-offset1;j++)
       if(ri[i][j] > back_threshold)
        {
         if(fabs((double)parm[i][j].gauss) <= th_gauss)
          parm[i][j].th_gauss = 0;   /* gaussian curv = 0 *
         else if(parm[i][j].gauss < 0)
          parm[i][j].th_gauss = 2;  /* gaussian curv is -ve
         else parm[i][j].th_gauss = 1;/* gaussian curv is +v

         if(parm[i][j].th_gauss > maxv.th_gauss)
          maxv.th_gauss = parm[i][j].th_gauss;
```

```
         if(parm[i][j].th_gauss < minv.th_gauss)
          minv.th_gauss = parm[i][j].th_gauss;


         if(fabs((double)parm[i][j].mean) <= th_mean)
          parm[i][j].th_mean = 0;    /* mean curv = 0 */
         else if(parm[i][j].mean < 0)
          parm[i][j].th_mean = 2;   /* mean curv is -ve */
         else parm[i][j].th_mean = 1; /* mean curv is +ve */

         if(parm[i][j].th_mean > maxv.th_mean)
          maxv.th_mean = parm[i][j].th_mean;
         if(parm[i][j].th_mean < minv.th_mean)
          minv.th_mean = parm[i][j].th_mean;

        }
    }
   else if(strcmp(string,"label") == 0)
    {
     for(i=offset1;i<row-offset1;i++)
      for(j=offset1;j<col-offset1;j++)
       if(ri[i][j] > back_threshold)
        {
         switch(parm[i][j].th_gauss)
          {
          case 0 : switch(parm[i][j].th_mean)
           {
           case 0 : parm[i][j].label = 1;break;/* flat */
           case 1 : parm[i][j].label = 223;break;/* valley
           case 2 : parm[i][j].label = 159;break;/* ridge
           }  break;
          case 1 : switch(parm[i][j].th_mean)
           {
           case 0 : parm[i][j].label = 255;break;/* spurio
           case 1 : parm[i][j].label = 63;break; /* pit */
           case 2 : parm[i][j].label = 95;break; /* peak *
           }  break;
          case 2 : switch(parm[i][j].th_mean)
           {
           case 0 : parm[i][j].label = 31;break; /* minima
           case 1 : parm[i][j].label = 191;break;/* saddle
           case 2 : parm[i][j].label = 127;break;/* saddle
           }
          }
        if(parm[i][j].label > maxv.label)
         maxv.label = parm[i][j].label ;
        if(parm[i][j].label < minv.label)
         minv.label = parm[i][j].label;
        }
    } /* end of label */

  else if(strcmp(string,"temp") == 0)
    {
      /* put th eindicated parameter in the buffer */
      for(i=0;i<row;i++)
        for(j=0;j<col;j++)
          buffer[i][j] = parm[i][j].gauss;

    }

  else if(strcmp(string,"disp") == 0)
    {
      scanf("%d",&option);

      printf("scale factor >");
      scanf("%f",&sf);

      for(i=0;i<row;i++)
        {
          for(j=0;j<col;j++)
            {
              switch(option)
                {
                  case 1: line[j] = sf*parm[i][j].fit_error;break
                  case 2: line[j] = sf*parm[i][j].gauss;    break
                  case 3: line[j] = sf*parm[i][j].mean;     break
                  case 4: line[j] = sf*parm[i][j].label;    break
                  case 5: line[j] = sf*parm[i][j].th_gauss; break
                  case 6: line[j] = sf*parm[i][j].th_mean;  break
                  case 7: line[j] = sf*parm[i][j].q;        break
                  case 8: line[j] = sf*parm[i][j].sqrtg;    break
                  case 9: line[j] = sf*parm[i][j].cosphi;   break
                  case 10:linef[j] = sf*ri[i][j];           break

                }
            }
          lwr_n(offx,i+offy,&line[0],col);
        }
    }

  else if(strcmp(string,"offset") == 0)
    {
      scanf("%f %f",&offx,&offy);
    }

  else if(strcmp(string,"hist") == 0)
    {/* display histogram using qkdraw */
```

```
      scanf("%d",&option);

      printf("xmax , xmin : ");
      switch(option)
        {
        case 1: printf("%f ; %f",maxv.fit_error,minv.fit_error);b
        case 2: printf("%f ; %f",maxv.gauss,minv.gauss);        b
        case 3: printf("%f ; %f",maxv.mean,minv.mean);          b
        case 4: printf("%d ; %d",maxv.label,minv.label);        b
        case 5: printf("%d ; %d",maxv.th_gauss,minv.th_gauss);  b
        case 6: printf("%d ; %d",maxv.th_mean,minv.th_mean);    b
        case 7: printf("%f ; %f",maxv.q,minv.q);                b
        case 8: printf("%f ; %f",maxv.sqrtg,minv.sqrtg);        b
        case 9: printf("%f ; %f",maxv.cosphi,minv.cosphi);      b
        case 10:printf("%f ; %f",maxv.depth,minv.depth);        b

        }
      printf("xmin : xmax :");
      scanf("%f %f",&xmin,&xmax);

      printf("# of points desired >");
      scanf("%d",&npts);

      for(i=0;i<npts;i++)
        {
          x[i] = xmin + ((float)(i) * (xmax -xmin))/(float)(npts)
          y[i] = 0;
        }
      for(i=offset1;i<row-offset1;i++)
        for(j=offset1;j<col-offset1;j++)
          {
            switch(option)
              {
              case 1: value = parm[i][j].fit_error;break;
              case 2: value = parm[i][j].gauss;    break;
              case 3: value = parm[i][j].mean;     break;
              case 4: value = parm[i][j].label;    break;
              case 5: value = parm[i][j].th_gauss; break;
              case 6: value = parm[i][j].th_mean;  break;
              case 7: value = parm[i][j].q;        break;
              case 8: value = parm[i][j].sqrtg;    break;
              case 9: value = parm[i][j].cosphi;   break;
              case 10:value = ri[i][j];           break;
              }
            subs =((int)(((value - xmin) * npts)/(xmax - xmin)));
            if((subs < 1000) && (subs >= 0)) y[subs] = y[subs] +
          }
      ymin = 1000;
      ymax = -1000;
```

```
        for(i=0;i<npts;i++)
          { if(ymin > y[i]) ymin = y[i];
            if(ymax < y[i]) ymax = y[i];
          }
        printf("ymin : %f ; ymax : %f\n",ymin,ymax);
        scanf("%f %f",&ymin,&ymax);

        iopt = 0;

        qterm(4);
        qkdraw(npts,x,y,iopt,&xmin,&xmax,&ymin,&ymax);
        qdtitl(" Histogram");
        qxlabl("<-- values -->");
        qylabl("freq");

        qdone();


      }

    else if(strcmp(string,"row") == 0)
      {  /* row histogram display using qkdraw */
        scanf("%d",&option);

        printf("row :");
        scanf("%d",&i);
        while((i < row) && (i >= 0))
          {
            ymin = 1000;ymax = -1000;
            for(j=0;j<col;j++)
              {
                switch(option)
                  {
                    case 1: linef[j] = parm[i][j].fit_error;break;
                    case 2: linef[j] = parm[i][j].gauss;    break;
                    case 3: linef[j] = parm[i][j].mean;     break;
                    case 4: linef[j] = parm[i][j].label;    break;
                    case 5: linef[j] = parm[i][j].th_gauss; break;
                    case 6: linef[j] = parm[i][j].th_mean;  break;
                    case 7: linef[j] = parm[i][j].q;        break;
                    case 8: linef[j] = parm[i][j].sqrtg;    break;
                    case 9: linef[j] = parm[i][j].cosphi;   break;
                    case 10:linef[j] = ri[i][j];            break;
                  }
                if(linef[j] < ymin) ymin = linef[j];
                if(linef[j] > ymax) ymax = linef[j];
              }
            xmin = 0.0;
            xmax = col;
```

```
            printf("ymin : %f ; ymax : %f\n",ymin,ymax);
            scanf("%f %f",&ymin,&ymax);

            iopt = 0;
            npts = col;
            for(i=0;i<col;i++) x[i] = i;

            qterm(4);
            qkdraw(npts,x,linef,iopt,&xmin,&xmax,&ymin,&ymax);
            qdtitl(" ROW ");
            qxlabl("col-->");
            qylabl("Values");

            qdone();
            printf("row :");
            scanf("%d",&i);
          }
      }

    else if(strcmp(string,"save") == 0)
      { /* save in a file */

        printf("Save what ? ");
        scanf("%d",&option);

        printf("scale factor : ");
        scanf("%f",&sf);

        printf("outputfilename :");
        scanf("%s",string);

        fp1 = fopen(string,"w");

        pm = pm_alloc();
        pm->pm_nrow = row;
        pm->pm_ncol = col;
        pm->pm_form = PM_C;
        pm->pm_image = (char *) malloc(pm_isize(pm));

        pm_point_uchar = (unsigned char *) pm->pm_image;

        for(i=0;i<row;i++)
          for(j=0;j<col;j++)
            {
              switch(option)
                  {
                    case 1: *(pm_point_uchar) = (unsigned char) sf*
                    case 2: *(pm_point_uchar) = (unsigned char) sf*
                    case 3: *(pm_point_uchar) = (unsigned char) sf*
```

```
                     case 4: *(pm_point_uchar) = (unsigned char) sf*
                     case 5: *(pm_point_uchar) = (unsigned char) sf*
                     case 6: *(pm_point_uchar) = (unsigned char) sf*
                     case 7: *(pm_point_uchar) = (unsigned char) sf*
                     case 8: *(pm_point_uchar) = (unsigned char) sf*
                     case 9: *(pm_point_uchar) = (unsigned char) sf*
                     case 10:*(pm_point_uchar) = (unsigned char) sf*
                     }
                   pm_point_uchar++;
               }
           pm_write(fp1,pm);
           fclose(fp1);
         }



       printf("ENTER > ");
       scanf("%s",string);

     }  /* interactive processing loop ends */


   /* put the outputs in respective files */
 /*  printf("\n Putting results in output files \n");

   for(i=1;i<16;i++)
     {
       if((i != 10) && (bool[i] == 1))
         {
           if(pm_write(fp[i],pmp[i]) == NULL)
             {
               printf(" Can't write output files \n");
               exit(0);
             }
             }
         }
 */

 }
  /* End of main program */

 float convo(indi,indj,mask,base,size)
 int indi,indj;
 int mask[5][5];
 float base;
 int size;
 {
   int i,j,k,l;
   float sum;
```

```
   float final;

   sum = 0.0;

   for(k=0,i=indi-2;i<=indi+2;i++,k++)
     for(l=0,j=indj-2;j<=indj+2;j++,l++)
       sum += (float)mask[k][l]*(float)ri[i][j];

   final = sum/base;
   return(final);
 }

 float convo_1(indi,indj,mask,base,size)
 int indi,indj;
 int mask[3][3];
 float base;
 int size;
 {
   int i,j,k,l;
   float sum;
   float final;

   sum = 0.0;

   for(k=0,i=indi-1;i<=indi+1;i++,k++)
     for(l=0,j=indj-1;j<=indj+1;j++,l++)
       sum += (float)mask[k][l]*(float)ri[i][j];

   final = sum/base;
   return(final);
 }


 float abszz(num)
 float num;
 {
  float b;

  if(num >0) b=num; else b= -num;
   return(b);
 }


 init_structure()
 {
   int i,j;

 /* initialize the parm structure first */
```

```
  bzero(&parm[0][0],sizeof(image)*BUFSIZE*BUFSIZE);

/* initialize maxv and minv structures */

  maxv.fit_error = -1000.00;
  maxv.gauss = -1000.00;
  maxv.mean = -1000.00;
  maxv.q = -1000.00;
  maxv.sqrtg = -1000.00;
  maxv.cosphi = -1000.00;
  maxv.label = -1000;
  maxv.th_gauss = -1000;
  maxv.th_mean = -1000;
  maxv.depth = -1000.00;

  minv.fit_error = 1000.00;
  minv.gauss = 1000.00;
  minv.mean = 1000.00;
  minv.q = 1000.00;
  minv.sqrtg = 1000.00;
  minv.cosphi = 1000.00;
  minv.label = 1000;
  minv.th_gauss = 1000;
  minv.th_mean = 1000;
  minv.depth = 1000.00;


} /* end of init */
```

```
#define RTD (180.0/3.14159)
#define MAXGRAY 255
#define WINDOW 5
#define LFLOAT 4
#define NARGS 2
#define MAXORDER 3
#define NSYS 10          /* maximum # of coefficients possible */

#include <stdio.h>
#include <math.h>
#include <strings.h>
#include <local/pm.h>
#include "/usr/users/alok/advanced/spline_include.h"


char *malloc(), *strcpy() ;
int getline(), body() ;
double sqrt(), atan2() ;
double lsqerr1();

double a1[200][NSYS],a2[200][NSYS],a3[300][NSYS];
     /* matrices to store A of Ax=b ; for 1st,2nd and 3rd order fitti
extern double ix,  iy,  ixx,  iyy,  ixy,  iyx,  ixxx, iyyy, ixyy,
extern double a30,  a21,  a12,  a03,  a20,  a11,  a02,  a10,  a01,  a
extern double fit_error;
extern int s_order;
extern int csize, rsize ;
extern int offset1;
extern int approx ;
extern float r1[BUFSIZE][BUFSIZE];
extern FILE *dumpfile;
extern int todump;


read_specs()
  {
  pmpic  *area, *(newarea[4]) ;

  FILE *fdin, *fdout[3] ;

  char    buffer[BUFSIZE],
          nargs,
          *cmt, *cmd,
          *ptr, window ;
  int     i, j ,
          ncol, nrow,
          count, nfiles, nf,
          grad, mingrad, maxgrad ;
```

```
  float   *fptr;

  double  e, theta,
          scale1;

  printf("intensity is approximated locally by a polynomial.\n") ;
  printf("type 1 for bi-linear    approximation.\n") ;
  printf("     2 for quadric      \n") ;
  printf("     3 for bi-cubic          \n") ;
  printf("     4 for b-spline \n");
  printf("     5 for smooth-b-spline\n");

  printf("value = ") ;

  scanf("%d",&approx);
  if ((approx<1) || (approx>5)) {
    fprintf(stderr,"value must be 1,2,3,4 or 5.\n") ;
    exit(0) ;
    }

  getchar();
  printf("window size = ") ;
  if (getline(buffer)==0) {
    if (approx==1) window = 2 ;
    else if (approx==2) window = 3 ;
    else if (approx==3) window = 5 ;
    fprintf(stderr,"window size = %d\n", window) ;
    }
  else {
    window = atoi(buffer) ;
    if ((window/2*2==window) && (approx!=1)) {
      fprintf(stderr,"window size must be an odd number.\n") ;
      exit(0) ;
      }
    if ((approx==1) && (window<2)) {
      fprintf(stderr,"window must be >= 2.\n") ;
      exit(0) ;
      }
    if ((approx==2) && (window<3)) {
      fprintf(stderr,"window must be >= 3.\n") ;
      exit(0) ;
      }
    if ((approx==3) && (window<5)) {
      fprintf(stderr,"window must be >= 5.\n") ;
      exit(0) ;
      }
    }
  offset1 = window/2 ;
  printf("offset1 %d\n",offset1);

  nfiles = 1 ;
  scale1 = 1.0 ;

}



compute_amatrix()
{
  int i,j,k;

  k=0;
  for(i= -offset1;i<=offset1;i++)
    for(j= -offset1;j<=offset1;j++)
      {
        a3[k][7]=a2[k][3]=a1[k][0]=i;
        a3[k][8]=a2[k][4]=a1[k][1]=j;
        a3[k][9]=a2[k][5]=a1[k][2]=1;
        a3[k][4]=a2[k][0]=i*i;
        a3[k][5]=a2[k][1]=j*j;
        a3[k][6]=a2[k][2]=i*j;
        a3[k][0]=i*i*i;
        a3[k][1]=j*j*j;
        a3[k][2]=i*i*j;
        a3[k][3]=i*j*j;
        k++;
      }
}/* end of compute_amatrix */



/*------------------------------poly1--------------------------------
*/
poly1(row,col)
int row, col ;

  {
  double z, z1, z2 ;

  z =  (double)ri[row][col] ;
  z1 = (double)ri[body(rsize,row)][body(csize,col+1)] ;
  z2 = (double)ri[body(rsize,row+1)][body(csize,col)] ;

  ix = z1 - z ;
  iy = z2 - z ;
  }
```

```
/*-----------------------------poly2-----------------------------*/
poly2(row,col)

int row, col ;
{

   int x, y ;
   int r, c ;
   int x1, y1 ;
   int k;
   double z ;
   double s000, s200, s400, s220, s600, s420 ;
   double s001, s011, s021, s031, s101, s111, s121, s201, s211, s301
   double coeff1[NSYS],b_mat[100],coeff2[NSYS],coeff3[NSYS];
   double *p_averb;
   double x2,   x4,   y2 ;
   double det1, det2 ;
   double inv1[10], inv2[10] ;
   double determ() ;
   double error1,error2,error3;

   k=0;
   s000 = s200 = s400 = s220 = s420 = s600 = 0 ;
   s001 = s011 = s021 = s031 = s101 = s111 = s121 = s201 = s211 = s30



   for( y = -offset1 ; y <= offset1 ; y++ )
     for( x = -offset1 ; x <= offset1 ; x++ ) {
       c = col + x ;
       r = row + y ;
       if( c < 0 ) c = 0 ;
       else if (c >= csize) c = csize - 1;
       if( r < 0 ) r = 0 ;
       else if (r >= rsize) r = rsize - 1;
       b_mat[k] = z = (double)ri[r][c] ;
       k++;

       s000 = s000 + 1 ;
       x2 = x * x ;
       x4 = x2 * x2 ;
       y2 = y * y ;
       s200 = s200 + x2 ;
       s400 = s400 + x4 ;
```

```
        s220 = s220 + x2 * y2 ;
        s600 = s600 + x4 * x2 ;
        s420 = s420 + x4 * y2 ;

        s001 = s001 + z ;
        s011 = s011 + y * z ;
        s021 = s021 + y2 * z ;
        s031 = s031 + y2 * y * z ;
        s101 = s101 + x * z ;
        s111 = s111 + x * y * z ;
        s121 = s121 + x * y2 * z ;
        s201 = s201 + x2 * z ;
        s211 = s211 + x2 * y * z ;
        s301 = s301 + x2 * x * z ;
        }


    if (approx==1) {
      coeff1[0] = a10 = s101 / s200 ;
      coeff1[1] = a01 = s011 / s200 ;
      coeff1[2] = a00 = s001 / s000 ;
      a30 = a21 = a12 = a03 = 0.0 ;
      a20 = a11 = a02 = 0.0 ;
      fit_error = error1 = lsqerr1(a1,coeff1,b_mat,k,3,&p_averb); /* c

      }
    else if (approx==2) {
      coeff2[3] = a10 = s101 / s200 ;
      coeff2[4] = a01 = s011 / s200 ;
      coeff2[5] = a00 = s001 / s000 ;
      det2 = determ( s400, s220, s200, s400, s200, s000) ;
      inverse(s400, s220, s200, s400, s200, s000, det2, inv2 ) ;
      coeff2[0] = a20 = inv2[1] * s201 + inv2[2] * s021 + inv2[3] * s0
      coeff2[1] = a02 = inv2[4] * s201 + inv2[5] * s021 + inv2[6] * s0
      coeff2[5] = a00 = inv2[7] * s201 + inv2[8] * s021 + inv2[9] * s0
      a30 = a21 = a12 = a03 = 0.0 ;
      coeff2[2] = a11 = s111 / s220 ;
      fit_error = error2 = lsqerr1(a2,coeff2,b_mat,k,6,&p_averb);
      }
    else if (approx==3) {
      det1 = determ( s600, s420, s400, s420, s220, s200) ;
      det2 = determ( s400, s220, s200, s400, s200, s000) ;

      inverse(s600, s420, s400, s420, s220, s200, det1, inv1 ) ;
      inverse(s400, s220, s200, s400, s200, s000, det2, inv2 ) ;

      coeff3[1] = a03 = inv1[1] * s031 + inv1[2] * s211 + inv1[3] * s0
      coeff3[2] = a21 = inv1[4] * s031 + inv1[5] * s211 + inv1[6] * s0
      coeff3[8] = a01 = inv1[7] * s031 + inv1[8] * s211 + inv1[9] * s0
```

```
      coeff3[0] = a30 = inv1[1] * s301 + inv1[2] * s121 + inv1[3] * s1
      coeff3[3] = a12 = inv1[4] * s301 + inv1[5] * s121 + inv1[6] * s1
      coeff3[7] = a10 = inv1[7] * s301 + inv1[8] * s121 + inv1[9] * s1

      coeff3[4] = a20 = inv2[1] * s201 + inv2[2] * s021 + inv2[3] * s0
      coeff3[5] = a02 = inv2[4] * s201 + inv2[5] * s021 + inv2[6] * s0
      coeff3[9] = a00 = inv2[7] * s201 + inv2[8] * s021 + inv2[9] * s0

      coeff3[6] = a11 = s111 / s220 ;
      fit_error = error3 = lsqerr1(a3,coeff3,b_mat,k,10,&p_averb);
      }

   /* the program computes the least square fitting error by calling t
     lsqerr1() routine in the source file solver.c. the calling parame
         a: the n*m matrix.
         x: m*1 matrix having the values of coefficients.
         b: observed values at the n points.
         p_averb : value returned = average value at n points.

                all the variables are doble except for n and m which a
      integers.
           called as :  double lsqerr1(a,x,b,n,m,p_averb)
                        double a[][nsys],x[],b[],*p_averb;
                        int m,n;

               returns lsq error (double). */

/*    if((error1 <= error2) && (error1 <= error3))
      {
        s_order = 1;
        fit_error = error1;
        a01 = coeff1[1];
        a10 = coeff1[0];
        a00 = coeff1[2];
        a30 = a21 = a12 = a03 = 0.0 ;
        a20 = a11 = a02 = 0.0 ;
      }
    else if(error2 <= error3)
      {
        s_order = 2;
        fit_error = error2;
        a00 = coeff2[5];
        a01 = coeff2[4];
        a10 = coeff2[3];
        a11 = coeff2[2];
        a02 = coeff2[1];
        a20 = coeff2[0];
      }
      else
        {
          s_order = 3;
          fit_error = error3;
        }
   */
    if(todump == 1) printf(dumpfile,"x = %d y= %d error = %f \n",row,c
/*    if(todump == 1) printf(dumpfile,"x = %d y= %d error1 = %f error2
*/
    ix = a10 ;
    iy = a01 ;
    ixx = 2.0 * a20 ;
    iyy = 2.0 * a02 ;
    ixy = a11 ;
    iyx = a11 ;
    ixxx = 6.0 * a30 ;
    iyyy = 6.0 * a03 ;
    ixyy = 2.0 * a12 ;
    ixxy = 2.0 * a21 ;
/*    printf("ix %f iy %f ixx %f iyy %f ixy %f\n",ix,iy,ixx,iyy,ixy);*
    return(0) ;
    }  /* Main */




/*  -----    compute determinant of symmetric 3 x 3 matrix.   ----- *

double determ( b11, b12, b13, b22, b23, b33 )
double b11, b12, b13, b22, b23, b33 ;

    {
    double temp1, temp2 ;
    temp1 = b11 * b22 * b33 + b12 * b23 * b13 + b12 * b23 * b13 ;
    temp2 = b13 * b22 * b13 + b12 * b12 * b33 + b23 * b23 * b11 ;
    return( temp1 - temp2) ;
    }




/*  -----   get inverse of symmetric matrix.  -----   */

inverse( b11, b12, b13, b22, b23, b33, det, inv )
double b11, b12, b13, b22, b23, b33 ;
```

```
double det ;
double inv[] ;


    {
    inv[0] = 0.0 ;
    inv[1] =  (b22 * b33 - b23 * b23) / det ;
    inv[2] = -(b12 * b33 - b13 * b23) / det ;
    inv[3] =  (b12 * b23 - b22 * b13) / det ;
    inv[4] =  inv[2] ;
    inv[5] =  (b11 * b33 - b13 * b13) / det ;
    inv[6] = -(b11 * b23 - b12 * b13) / det ;
    inv[7] =  inv[3] ;
    inv[8] =  inv[6] ;
    inv[9] =  (b11 * b22 - b12 * b12) / det ;
    return(0) ;
    }




int body(size,x)
int size, x;

  {
  if (x<0) return(0) ;
  else if (x>=size)
    return(size-1) ;
  else
    return(x) ;
  }




getline(s)
char s[] ;
{
  int c, i ;

  i = 0 ;
  while( (c=getchar()) != '\n'  &&  c != '\0' )
    s[i++] = c ;
  s[i] = '\0' ;
  return(i) ;
  }


/*------------------------------lsqerr1------------------------------
```

```
double lsqerr1(A, x, b, m, n, p_averb)

double  A[][NSYS], x[], b[],
        *p_averb ;
int     m, n ;

  {
  int    i, j ;
  double sum,errsum,bsum ;



  errsum=bsum=0.0;
  for (i=0; i<m; i++) {
    sum = 0.0 ;
    for (j=0; j<n; j++)
      sum = sum + A[i][j]*x[j] ;
    sum = sum - b[i];
    errsum = errsum + fabs(sum);
    bsum = bsum + fabs(b[i]) ;
    }

  *p_averb = bsum / (double)m ;
  return(errsum);

  }  /* lsqerr */
```

```
/*
   Program for further segmentation of the scene obtained after label
using the sign of mean and gaussian curvatures.

  The program calls routines in solver.c to fit the surface on specif
data.

  March 30, 1988
  April 4 , 1988 : Initialize neighbour structure. Regions smaller th
                   size 6 are merged with the best fitting neighbouri
                   region at the time of initialization. The output i
                   in the form of labeled convex/concave subparts of
                   scene seperated by convex/concave/jump edges.

*/

#include <stdio.h>
#include <math.h>
#include <local/pm.h>
#include <ik.h>
#include </usr/users/alok/advanced/spline_include.h>

#define REGION_SIZE 1000           /* so many regions in the */
#define NPOINTS  10000             /* so many points in a region */
#define NSYS 20                    /* so many variables at the most *
#define MIN_REGION_SIZE 50         /* so many pixels in an acceptable
                                      seed region */
#define PIXEL_STACK_SIZE 8000     /* size of pixel-stack used for rec
                                      -iterative region growing */
#define MAX_NUM_CALL 400          /* Maximum # of pending recursive c
                                      at a given time. */
#define ACCEPT_ERROR 2.00          /* value of acceptable error */
#define THRESH_ERROR 0.20          /* threshold error that is accepta
                                      while region growing */
#define FLAT 1
#define PEAK 95                    /* spherical */
#define RIDGE 159                  /* cylinderical */
#define MIN 31                     /* minimal */
#define SADRID 127                 /* Saddle ridge */


float buffer[BUFSIZE][BUFSIZE];     /* stores input image */
int label[BUFSIZE][BUFSIZE];        /* stores labeled image */
short int lap[BUFSIZE][BUFSIZE];          /* stores laplacian image *
short int rec_image[BUFSIZE][BUFSIZE];    /* reconstructed image */
char attempt[BUFSIZE][BUFSIZE];       /* used to keep track of pixels
                                       region_grow() */
```

```
double lsqerr();

int congrowlab;
ikword ikvalue = 255;
int row,col;                        /* rows and columns in image */
int seedr,seedc;
int seedrow,seedcol;
int num_points;                     /* # of points in the region */
double avect[NPOINTS][NSYS];         /* array to store the least sq m
double bvect[NPOINTS];              /* vector to store b in Ax = b */
double result[NSYS];                 /* x in Ax = b */
int region_label;
int surf_type;
int cmin,rmin,cmax,rmax;             /* extremeties of the region */
int curr;                            /* used to indicate attempt[][]
int tr;                              /* total # of regions */
int edge_threshold;
int to_merge;


struct region_type {
  int valid;
  int label;                        /* label of the region */
  int order;                        /* order of fit */
  double fit_error;                 /* surface fit error */
  int surf_type;                    /* classification of the surface
  int size;                         /* # of pixels in the region */
  int done;                         /* boolean used by pick_up_seed()
  int center[2];                    /* origin of the region */
  float coeffs[6];
  int neighbour[500];
  int num_neigh;
  int rmin,rmax,cmin,cmax;          /* extremeties of the region */
  int dmax;                          /* maximum depth of the region *
} regions[REGION_SIZE],reg;

int dmax;                           /* keeps  track of max depth of r
int con_label[REGION_SIZE];         /* stores convex region label */
int color[REGION_SIZE];             /* store color for the convex reg
int convex_label;                   /* for labeling convex regions */

float error_in_fit();

int to_disp;                         /* == 1 if to be displayed on IK
char ikonas_disp[2];

/* for stack management during final region growing */

struct p_stack {                /* stores the open pixels in circular
```

```
  int row;
  int col;
} pixel_stack[PIXEL_STACK_SIZE];

int rownum;                       /*(rownum,colnum)  is the next pixel *
int colnum;                       /*    popped from the stack */

int num_call;                     /* number of calls pending at a given
int stack_length;                 /* =current_element if queue is empty
                                     points to the tail of the queue */
int current_element;              /* points to head of the queue */

/*********************************MAIN******************************

main(argc,argv)
int argc;
char *argv[];
{
  int i,j,k,l,m,n;             /* local variables */

  pmpic *pm1,*pm2,*pm3;        /* pmpic pointers to range and labeled im
  double scale,zscale;         /* scale of the input image */
  int image_format;            /* stores input image format */
  unsigned char *uchar_point;
  float *float_point;          /* original image is scaled and smoothed
  short int *short_point;
  FILE *imagefile,*labelfile;
  FILE *loc_file,*rec_file,*outputfile,*outfile,*lab_file,*lapfile,*c
  int want;
  double x,y,averb;
  int valid = 0,invalid = 0;
  int imageformat;
  int region_num;
  int pixel_val;
  float fit_error,min_error;
  int found;
  int lab;
  int surface_fit;                  /* =1 ; if surface fit is to be done


  if(argc != 4)
    {
      fprintf(stderr,"Usage : merge (scaled & smoothed input PM_F ima
      exit(0);
    }

  printf("Want to display region growing on IKONAS. y if yes > ");
  scanf("%s",&ikonas_disp[0]);
```

```
  printf("Edge_threshold : ");
  scanf("%d",&edge_threshold);

  if((imagefile = fopen(argv[1],"r")) == NULL)
    {
      fprintf(stderr,"Cannot open input range image file : %s \n",arg
      exit(0);
    }

  if((labelfile = fopen(argv[2],"r")) == NULL)
    {
      fprintf(stderr,"Cannot open image label file : %s \n",argv[2]);
      exit(0);
    }

  if((lapfile = fopen(argv[3],"r")) == NULL)
    {
      fprintf(stderr,"Cannot open laplacian operated file : %s \n",ar
      exit(0);
    }

  outputfile = fopen("log","w");

  if((pm1 = pm_read(imagefile,0)) == NULL)
    {
      fprintf(stderr,"Error in reading PM-format range image file : %
      exit(0);
    }

  if((pm2 = pm_read(labelfile,0)) == NULL)
    {
      fprintf(stderr,"Error in reading PM-format range image file : %
      exit(0);
    }

  if((pm3 = pm_read(lapfile,0)) == NULL)
    {
      fprintf(stderr,"Error in reading PM-format range image file : %
      exit(0);
    }

  row = pm1->pm_nrow;
  col = pm1->pm_ncol;

  if((row != pm2->pm_nrow) || (col != pm2->pm_ncol) || (row != pm3->p
     || (col != pm3->pm_ncol))
    {
      fprintf(stderr,"Rows and/or columns not same in range and label
      exit(0);
    }

  if(pm2->pm_form != PM_C)
    {
      fprintf(stderr,"Label image is not in PM_C format \n");
      exit(0);
    }

  if(pm1->pm_form == PM_F){
    float_point = (float *) pm1->pm_image;
    imageformat = PM_F;
    scale = 74.20;                /* for RCA images */
    zscale = 1.00;
    for(i=0;i<row;i++)
      for(j=0;j<col;j++)
        {buffer[i][j] = *(float_point);float_point++;}
  }
  else
    if(pm1->pm_form == PM_S){
      imageformat = PM_S;
      short_point = (short int *) pm1->pm_image;
      scale = 74.20;              /* for RCA images */
      zscale = 1.00;              /* for RCA images */
      for(i=0;i<row;i++)
        for(j=0;j<col;j++)
          {buffer[i][j] = ((float)*(short_point))*zscale/scale;short_
    }
    else
      if(pm1->pm_form == PM_C) {
        imageformat = PM_C;
        uchar_point = (unsigned char *) pm1->pm_image;
        zscale = 1.5;             /* for Gus' images */
        scale = 1.978;            /* for Gus' images */
        for(i=0;i<row;i++)
          for(j=0;j<col;j++)
           {buffer[i][j] = ((float)*(uchar_point))*zscale/scale;uchar
      }
      else {
        printf("unrecognized format in the input image \n");
        exit(0);
      }

  uchar_point = (unsigned char *) pm2->pm_image;
  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      label[i][j] = 0 - (*(uchar_point++));

  short_point = (short int *) pm3->pm_image;
```

```
  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      lap[i][j] = *(short_point++);



  if(pm1->pm_form != PM_F)
    {
      printf("want to smooth ? (1/0) >");
      scanf("%d",&want);
      if(want == 1) gaussian(buffer,row,col);
    }



  bzero((char *)&rec_image[0][0],sizeof(short int)*BUFSIZE*BUFSIZE);
  bzero((char *)&regions[0],sizeof(reg)*REGION_SIZE);

  /* initialize the structure ;
     fit a second order polynimial on every patch */
  fprintf(stderr,"starting surface fitting on individual regions \n")
  seedr = 0;
  seedc = 0;
  region_label = 0;
  surface_fit = 1;          /* no surface fitting to be done */
  ikvalue = 100;
  to_disp = 0;

  while(next_seed() == 0)   /* while there are seed regions */
    {
      surf_type = label[seedrow][seedcol];  /* label of the region */
      region_label++;
      num_points = 0;
      cmin = 1000;
      rmin = 1000;
      cmax = -1000;
      rmax = -1000;
      dmax = -1000;
      label[seedrow][seedcol] = region_label;
      grow_seed(seedrow,seedcol,surf_type,region_label);

      if(surface_fit == 1)
      if(num_points < MIN_REGION_SIZE)  /* region is invalid if # of
        {
          regions[region_label].valid = 0;
          invalid++;
        }
      else
        {
```

```
        if((0 - surf_type) == FLAT)
          {
            lsquare(avect,bvect,result,num_points,3);
            regions[region_label].fit_error = lsqerr(avect,result,bve
          }
        else
          {
            lsquare(avect,bvect,result,num_points,6);
            regions[region_label].fit_error = lsqerr(avect,result,bve
          }
        regions[region_label].coeffs[0] = result[0];/*a00,a01,a10,a02
        regions[region_label].coeffs[1] = result[1];
        regions[region_label].coeffs[2] = result[2];
        if((0 - surf_type) != FLAT)
          {
            regions[region_label].coeffs[3] = result[3];
            regions[region_label].coeffs[4] = result[4];
            regions[region_label].coeffs[5] = result[5];
            regions[region_label].order = 2;
          }
        else
          {
            regions[region_label].order = 1;
          }
        valid++;
        regions[region_label].valid = 1;

      }

      regions[region_label].label = region_label;
      regions[region_label].size = num_points;

      regions[region_label].surf_type = -surf_type;
      regions[region_label].center[0] = seedrow;
      regions[region_label].center[1] = seedcol;
      regions[region_label].num_neigh = 0;
      regions[region_label].cmin = cmin;
      regions[region_label].cmax = cmax;
      regions[region_label].rmin = rmin;
      regions[region_label].rmax = rmax;
      regions[region_label].done = 0;
      regions[region_label].dmax = dmax;
      con_label[region_label] = 0;   /* not assigned to any convex re

fprintf(outputfile," region : %d  points : %d surf_type %d (row,col)=
      if(num_points >= MIN_REGION_SIZE)fprintf(stderr," region : %d


      fprintf(outputfile," a20 : %f a11 : %f a02 : %f a10 : %f a01 :
```

```
    } /* while loop to fit surfaces */

  printf("# of regions found : %d invalid : %d valid %d\n",region_lab
  fclose(outputfile);
  tr = region_label;   /* total # of regions */


  fprintf(stderr,"Marking neighbours \n");
  /* initialize neighbours */

  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      if(label[i][j] > 0)
        {
          if(label[i][j] != label[i+1][j])
            {
              make_neighbour(label[i][j],label[i+1][j]);
              make_neighbour(label[i+1][j],label[i][j]);
            }
          if(label[i][j] != label[i][j+1])
            {
              make_neighbour(label[i][j],label[i][j+1]);
              make_neighbour(label[i][j+1],label[i][j]);
            }
        }

/*------------------ SURFACE FITTING / REGION GROWING */
if(surface_fit == 1)
  {/* TO BE DONE ONLY IF SURFACE FITTING BASED REGION GROWING DESIRED
  fprintf(stderr,"Merging invalid regions into nearest best fitting r
  /* merge invalid regions with neighbouring valid region with least
  to_merge = 0;
  if(to_merge == 1)
  for(i=1;i<=tr;i++)
    { /* for all regions do */
      if(regions[i].valid == 0)
        { /*  if  the region is invalid then do */
          /* returns the list of neighbours */
          min_error = 1000.00;
          found = 0;
          for(j=0;j<regions[i].num_neigh;j++)
            { /* find error in fitting the polynomial of neigh[j] on
              */
              if(regions[regions[i].neighbour[j]].valid == 1)
                {
                  found = 1;
                  fit_error = error_in_fit(regions[i].label,regions[i
                  if (min_error > fit_error) {
                    region_num = regions[i].neighbour[j];
                    min_error = fit_error;
                  }
                }
              }
          if(found == 1)
            {/* a suitable region has been found
                merge first region into second one */

              merge_region(regions[i].label,region_num);
            }
          else { /* no suitable valid region was found in the neighbo
                    Do nothing for the moment.*/
            fprintf(stderr,"No suitable valid region found in the nei
          }
        }
    } /* end of merging invalid regions */

  /* Main Segmentation loop starts. Bigger seed regions are merged wi
     selected set of points if the RMS error is acceptable, thatis lo
     the acceptable error of the whole region. */
/*
  fprintf(stderr,"Main segmentation starts \n");
  curr = 1;

  if(strcmp("y",ikonas_disp) == 0)
    {
      if(ikopen(NULL) == -1)
        fprintf(stderr,"Can't open IKONAS \n");
      to_disp = 1;
    }
  else to_disp = 0;

  ikvalue = 200;
  while((lab = pick_up_seed()) != -1)    */ /* returns the next seed r
/*      {
      fprintf(stderr,"Growing for %d :\n",lab);
  */    /* curr++;*/
/*      num_call = 1;
      grow_region(regions[lab].center[0],regions[lab].center[1],lab);

      while(stack_length != current_element)
        {
          get_pixel();*/        /* returns the pixel */
/*        num_call = 1;
          grow_region(rownum,colnum,lab);
        }
    }
*/
```

```
} /* END OF THE REGION TO BE DONE ONLY IF SURFACE FITTING BASED REGIO
     GROWING IS DESIRED */


  /*------------------ OUTPUT IMAGES -------- */

  /* output the reconstructed and error image */

  for(i=1;i<=(row-1);i++)
    for(j=1;j<=(col-1);j++)
      if(label[i][j] > 0)
        { /* for all pixels do */
          /* compute local error at the pixel */
          x= i - regions[label[i][j]].center[0];
          y= j - regions[label[i][j]].center[1];
          rec_image[i][j] = x*x*regions[label[i][j]].coeffs[5] +
                            x*y*regions[label[i][j]].coeffs[4] +
                            y*y*regions[label[i][j]].coeffs[3] +
                              x*regions[label[i][j]].coeffs[2] +
                              y*regions[label[i][j]].coeffs[1] +
                              1*regions[label[i][j]].coeffs[0];
        }

  /* initialize pm buffers */

  printf("Saving images. Stored as PM_S images \n");

  rec_file = fopen("recimage","w");
  loc_file = fopen("errorimage","w");
  lab_file = fopen("labelimage","w");

  pm1 = pm_alloc();
  pm1->pm_nrow = row;
  pm1->pm_ncol = col;
  pm1->pm_form = PM_S;
  pm1->pm_image = (char *) malloc(pm_isize(pm1));
  bzero(pm1->pm_image,pm_isize(pm1));

  short_point = (short int *) pm1->pm_image;

  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      { *short_point = (short int)fabs((double)(rec_image[i][j]*scale
        short_point++;
      }

  pm_write(rec_file,pm1);
  fclose(rec_file);
  bzero(pm1->pm_image,pm_isize(pm1));
  short_point = (short int *) pm1->pm_image;
  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
        { *short_point = (short int )fabs((double)(rec_image[i][j] -
          short_point++;
        }

  pm_write(loc_file,pm1);
  fclose(loc_file);

  /* output new label image */
  pm1->pm_form = PM_C;
  pm1->pm_image = (char *) malloc(pm_isize(pm1));
  bzero(pm1->pm_image,pm_isize(pm1));
  uchar_point = (unsigned char *) pm1->pm_image;

  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      { *uchar_point = regions[label[i][j]].surf_type;
        uchar_point++;
      }
  pm_write(lab_file,pm1);
  fclose(lab_file);


  if(imageformat != PM_F)
    {
      pm1 = pm_alloc();
      pm1->pm_nrow = row;
      pm1->pm_ncol = col;
      pm1->pm_form = PM_F;
      pm1->pm_image = (char *) malloc(pm_isize(pm1));
      bzero(pm1->pm_image,pm_isize(pm1));
      float_point = (float *) pm1->pm_image;
      for(i=0;i<row;i++)
        for(j=0;j<col;j++)
          {
            *float_point = buffer[i][j];
            float_point++;
          }

      outfile = fopen("image","w");
      pm_write(outfile,pm1);
      fclose(outfile);
    }

/*--------------- CONVEX PATCHES GROWING -------*/
```

```
/* mark all the regions as undone */

  for(i=1;i<=tr;i++)
    regions[i].done = 0;

  /* label convex subparts in the image */
  fprintf(stderr,"Label convex subparts in the image \n");

  convex_label = 0;
  pixel_val = 100;
  while((lab = get_next_region()) != -1)
    {
      pixel_val = pixel_val + 2;
      convex_label++;
      color[convex_label] = pixel_val;
      regions[lab].done = 1;
      congrowlab = lab;
      extend_region(lab);
    }

  /* output the convex/concave image */
  con_file = fopen("confile","w");

  fprintf(stderr,"# of convex patches found : %d",convex_label);

  pm1 = pm_alloc();
  pm1->pm_nrow = row;
  pm1->pm_ncol = col;
  pm1->pm_form = PM_C;
  pm1->pm_image = (char *) malloc(pm_isize(pm1));
  bzero(pm1->pm_image,pm_isize(pm1));
  uchar_point = (unsigned char *) pm1->pm_image;
  con_label[0] = 0;

  for(i=0;i<row;i++)
    for(j=0;j<col;j++)
      {

        if(con_label[label[i][j]] != 0)
          *uchar_point = color[con_label[label[i][j]]];
        if((con_label[label[i][j]] != con_label[label[i][j+1]]) ||
           (con_label[label[i][j]] != con_label[label[i+1][j]]))
          *uchar_point = 255;
        uchar_point++;
      }

  pm_write(con_file,pm1);
  fclose(con_file);
```

```
}/* end of main */


/********************************NEXT_SEED****************************

next_seed()
{
  int i,j,k,l;
  while((buffer[seedr][seedc] == 0) || (label[seedr][seedc] >= 0)) {
    seedc++;
    if(seedc == (col-1)) {
      seedr++;
      seedc = 0;
      if(seedr == (row-1)) return(-1);
    }
  }
  seedrow = seedr;
  seedcol = seedc;
  return(0);
}


/********************************GROW_SEED****************************

grow_seed(srow,scol,stype,slabel)
int srow;
int scol;
int stype;
int slabel;
{
  int i,j;
  double x,y;

  if(to_disp == 1) lwr(scol,srow,&ikvalue);

  if(rmin > srow) rmin = srow;
  if(rmax < srow) rmax = srow;
  if(cmin > scol) cmin = scol;
  if(cmax < scol) cmax = scol;
  if(dmax < buffer[srow][scol]) dmax = buffer[srow][scol];

  num_points++;

  x = srow - seedrow;
  y = scol - seedcol;

  avect[num_points][5] = x*x;
```

```
  avect[num_points][4] = x*y;
  avect[num_points][3] = y*y;
  avect[num_points][2] = x;
  avect[num_points][1] = y;
  avect[num_points][0] = 1;

  bvect[num_points] = buffer[srow][scol];

  for(i=srow-1;i<=srow+1;i++)
    for(j=scol-1;j<=scol+1;j++)
      if((i > 0) && (i < (row -1)) && (j > 0) && (j < (col - 1)))
        if(label[i][j] == stype)
          {
            label[i][j] = slabel;
            grow_seed(i,j,stype,slabel);
          }

} /* grow_seed */

/************************* MAKE_NEIGHBOUR ***************************
  Makes label2 neighbour of label1.
*/

make_neighbour(label1,label2)
int label1;
int label2;
{
  int i,j,k,l;
  int done;

  done = 0;

  k = 0;

  if(regions[label1].num_neigh == 0)
    {
      regions[label1].num_neigh = 1;
      regions[label1].neighbour[0] = label2;
    }
  else
  while(done == 0)
    {
      if(k == regions[label1].num_neigh)
        {/* neighbour not yet marked in the structure */
          regions[label1].num_neigh = regions[label1].num_neigh + 1;
          regions[label1].neighbour[k] = label2;
          done = 1;
        }
      else
```

```
        if(regions[label1].neighbour[k] == label2)
          {/* nothing to be done */
            done = 1;
          }
        else k++;
    }
} /* end of make neighbour */


/************************ ERROR IN FIT ***************************
  computes fit_error of fitting label1 points using label2 coefficien
*/

float error_in_fit(label1,label2)
int label1;
int label2;
{
  int i,j,k,l;
  double error;
  double averb;
  float x,y;

  k = 0;

  for(i=regions[label1].rmin;i<=regions[label1].rmax;i++)
    for(j=regions[label1].cmin;j<=regions[label1].cmax;j++)
      if(label[i][j] == label1)
        {
          x = i - regions[label2].center[0];
          y = j - regions[label2].center[1];
          avect[k][5] = x*x;
          avect[k][4] = x*y;
          avect[k][3] = y*y;
          avect[k][2] = x;
          avect[k][1] = y;
          avect[k][0] = 1;
          bvect[k] = buffer[i][j];
          k++;
        }
  result[0] = regions[label2].coeffs[0];
  result[1] = regions[label2].coeffs[1];
  result[2] = regions[label2].coeffs[2];
  result[3] = regions[label2].coeffs[3];
  result[4] = regions[label2].coeffs[4];
  result[5] = regions[label2].coeffs[5];

  error = lsqerr(avect,result,bvect,k,6,&averb);
  return((float)error);
} /* error in fit */
```

```
/****************************** MERGE REGION ************************
  merge first region into the second one .
*/

merge_region(label1,label2)
int label1;
int label2;
{
  int i,j,k,l;

  k = 0;  /* counting # of points */
  for(i=regions[label1].rmin;i<=regions[label1].rmax;i++)
    for(j=regions[label1].cmin;j<=regions[label1].cmax;j++)
      if(label[i][j] == label1)
        {
          label[i][j] = label2;
          k++;
        }

  regions[label2].size = regions[label2].size + k;
} /* end of merging regions. that was easy */

/**************************** ERODE ******************************
  Grows the parent by removing pixels from the child, only if RMS err
criterion is met and the child is of right type.
*/
erode(parent,child)
int parent;
int child;
{
  int i,j,k,l;
  int lab;

  curr++;
  switch(regions[parent].surf_type)
    {
    case 1 : /* parent region is flat. */
      {
        /* for all types of neighbours grow the region */
        attempt[regions[parent].center[0]][regions[parent].center[1]]
        grow_region(regions[parent].center[0],regions[parent].center[
      } break;
    case 91 : /* peak; sphere; convex */
    case 159 :/* ridge, cylinder,convex */
    case 31 : /* minimal, */
    case 127 :/* saddle ridge */
      {
        switch(regions[child].surf_type)
```

```
          {
          case 1 : /* flat */
          case 63: /* pit  , sphere,concave */
          case 223:/* valley, cylinder , concave */
          case 191: /* saddle valley, concave */
        attempt[regions[parent].center[0]][regions[parent].center[1]]
        grow_region(regions[parent].center[0],regions[parent].center[
            break;

          }
      }break;
    case 63: /* pit  , sphere,concave */
    case 223:/* valley, cylinder , concave */
    case 191: /* saddle valley, concave */
      {
        switch(regions[child].surf_type)
          {
          case 1 : /* flat */
          case 91 : /* peak; sphere; convex */
          case 159 :/* ridge, cylinder,convex */
          case 31 : /* minimal, */
          case 127 :/* saddle ridge */
        attempt[regions[parent].center[0]][regions[parent].center[1]]
        grow_region(regions[parent].center[0],regions[parent].center[
            break;

          }
      }

      }/* end of switch */
} /* end of erode */

/******************************GROW_REGION**************************
grows parent at the expense of the child.
*/

grow_region(nrow,ncol,parent)
int nrow;
int ncol;
int parent;
{
  int i,j;
  float x,y;
  float value;


  if(to_disp == 1) lwr(ncol,nrow,&ikvalue);

  if(label[nrow][ncol] != parent)
```

```
    { /* pixel to work on */
      x = nrow - regions[parent].center[0];
      y = ncol - regions[parent].center[1];
      value = x*x*regions[parent].coeffs[5] +
              x*y*regions[parent].coeffs[4] +
              y*y*regions[parent].coeffs[3] +
              x*regions[parent].coeffs[2] +
              y*regions[parent].coeffs[1] +
              1*regions[parent].coeffs[0];

      if(fabs((double)(value - buffer[nrow][ncol])) <=
          (fabs((double)(regions[parent].fit_error)) + THRESH_ERROR))
        {/* acceptable pixel */
          label[nrow][ncol] = parent;
          regions[parent].size = regions[parent].size + 1;
          regions[label[nrow][ncol]].size = regions[label[nrow][ncol]

          for(i=(nrow-1);i<=(nrow+1);i++)
            for(j=(ncol-1);j<=(ncol+1);j++)
              if((i >= 0) && (i<row) && (j >= 0) && (j<col))
                if((i == nrow) || (j == ncol))
                {
                  if((lap[i][j] < edge_threshold) &&
                     (attempt[i][j] != curr))
                    {
                      attempt[i][j] = curr;
                      /* check for the # of pending calls */
                      num_call++;
                      if(num_call >= MAX_NUM_CALL)
                        store_pixel(i,j);
                      else
                        grow_region(i,j,parent);
                    }
                }
        }
    }
  else
    {
      for(i=(nrow-1);i<=(nrow+1);i++)
        for(j=(ncol-1);j<=(ncol+1);j++)
          if((i>=0) && (i<row) && (j >= 0) && (j<col))
            if((i == nrow) || (j == ncol))
            {
              if((lap[i][j] < edge_threshold) &&
                 (attempt[i][j] != curr))
                {
                  attempt[i][j] = curr;
                  num_call++;
                  if(num_call >= MAX_NUM_CALL)
```

```
                    store_pixel(i,j);
                  else
                    grow_region(i,j,parent);
                }
            }

        }
num_call--;
}/* region_grow */


/******************* STORE_PIXEL & GET_PIXEL **********************

store_pixel(rrow,ccol)
int rrow;
int ccol;
{
  num_call--;

  pixel_stack[stack_length].row = rrow;
  pixel_stack[stack_length].col = ccol;

  stack_length++;
  if(stack_length == PIXEL_STACK_SIZE) stack_length = 0;
  if(stack_length == current_element)
        printf("\n segment : Stack Collision While region growing \n

}

get_pixel()
{

  rownum = pixel_stack[current_element].row;
  colnum = pixel_stack[current_element].col;

  current_element++;
  if(current_element == PIXEL_STACK_SIZE) current_element = 0;
}


/******************************PICKUPSEED**************************
returns the seed label.
*/

pick_up_seed()
{
  int i,j,k,l;

  /* first look for flat,spherical,cylidericalregions */
```

```
  for(i=1;i<=tr;i++)
    {
      if(((regions[i].surf_type == FLAT) /*|| (regions[i].surf_type =
          (regions[i].surf_type == RIDGE)*/) &&
         (regions[i].done == 0) &&
         (regions[i].fit_error <= ACCEPT_ERROR) &&
         (regions[i].size > MIN_REGION_SIZE))
        {
          regions[i].done = 1;
          return(i);
        }
    }
/* Now look for any type of acceptable region */

  for(i=1;i<=tr;i++)
    {
      if((regions[i].done == 0) && (regions[i].size > MIN_REGION_SIZE
         (regions[i].fit_error <= ACCEPT_ERROR)*/)
        {
          regions[i].done = 1;
          return(i);
        }
    }

/* No suitable seed region is available */
return(-1);
} /* pickupseed */

/****************************GET NEXT REGION***********************
returns the label of next region to be grown as convex region
*/

get_next_region()
{
  int i,j,k,l;
  int max;
  int tlabel;

  max = -1000;

  for(i=1;i<=tr;i++)
    {
      if((regions[i].done == 0) && ((regions[i].surf_type == FLAT) ||
                                    (regions[i].surf_type == PEAK) ||
                                    (regions[i].surf_type == RIDGE))
         (regions[i].size >= MIN_REGION_SIZE) &&
         (regions[i].dmax > max))
        {
          max = regions[i].dmax;
          tlabel = i;
        }
    }

  if(max != -1000) return(tlabel);
  else return(-1);
}


/*****************************EXTEND REGION*************************
used to extend a convex region recursively at the region level.
*/

extend_region(lab)
int lab;
{
  int i,j;
  int n;

  con_label[lab] = convex_label;
  for(i=0;i<regions[lab].num_neigh;i++)
    {
      n = regions[lab].neighbour[i];
      if((regions[n].done == 0) &&
         /*(regions[congrowlab].dmax > regions[n].dmax) &&*/
                                    ((regions[n].surf_type == FLAT) |
                                    /*(regions[n].surf_type == PEAK)
                                    (regions[n].surf_type == RIDGE)/*
                                    (regions[n].surf_type == SADRID)|
                                    (regions[n].surf_type == MIN)*/))
        {
         if(regions[n].size >= MIN_REGION_SIZE)
           {
             regions[n].done = 1;
             extend_region(n);
           }
         else
           {
             regions[n].done = 1;
             con_label[n] = convex_label;
           }
        }
    }
}
```

```
 /*
   Used for calculating the least square  fit-error in the grad.c
  program.

   Caution, Warning, Danger:
      1) Include the following in the main program.

           #define NSYS  <n>
           #define NDATA  <m>


      2) If you want to compute least-squares error,
         you MUST have the following in the calling program:
            double lsqerr();

         It returns E = |Ax-b| * 100




   Parameters passed to the least square program are:
     A[][], x[], b[], m, n
   where
     A x = b.



   To check the sigularity, small constant 'epsilon' is used.
   Current value is set to 0.00001.
   This is O.K. for most application, but depending on your
   application, you may want to change the value.



*/

#include <stdio.h>
#include <math.h>
#include "/usr/users/alok/advanced/spline_include.h"

#define NSYS  20
#define NDATA  10000


int prnt = 1;              /* = -1 for printing else no printing */
double epsilon = 0.00001;
```

```
/*--------------------------------Lsquare------------------------------
int  lsquare (A, b, x, m, n)
double  A[][NSYS], b[], x[] ;
int     m, n ;

{
  double  ATA[NSYS][NSYS], ATb[NSYS] ;
  int     order ;

  if (m<n) {
    if (prnt==-1) fprintf(stderr,"insufficient # of points.\n") ;
    return(1) ;
    }
  product(A, ATA, m, n) ;
  mult(A, b, ATb, m, n) ;
  if((order=solver(ATA,ATb,x,n)) < n) {
    return(order) ;
    }
  return(0) ;
  }  /* Lsquare */







/*--------------------------------Lsqsol------------------------------
int  lsqsol (A, b, x, m, n, n1)
double  A[][NSYS], b[], x[] ;
int     m, n, n1 ;

{
  double  ATA[NSYS][NSYS], ATb[NSYS] ;
  int     order, i ;

  if (m<n) {
    if (prnt==-1) fprintf(stderr,"insufficient # of points.\n") ;
    return(1) ;
    }
  product(A, ATA, m, n) ;
  mult(A, b, ATb, m, n) ;
  for (i=0; i<n; i++) x[i] = 0.0 ;
  order = solver(ATA,ATb,x,n) ;

  if(order<n) {
    if (order<n1) return(order) ;
    product(A,ATA,m,nl) ;
    mult(A,b,ATb,m,nl) ;
    for (i=0; i<n; i++) x[i] = 0.0 ;
    order = solver(ATA,ATb,x,nl) ;
    return(order) ;
    }
  return(0) ;
  }  /* Lsquare */




/*------------------------------lsqerr-------------------------------
double lsqerr(A, x, b, m, n, p_averb)

double  A[][NSYS], x[], b[],
        *p_averb ;
int     m, n ;

  {
  int    i, j ;
  double sum,errsum,bsum ;


  errsum=bsum=0.0;
  for (i=0; i<m; i++) {
    sum = 0.0 ;
    for (j=0; j<n; j++)
      sum = sum + A[i][j]*x[j] ;
    sum = sum - b[i];
    errsum = errsum + fabs(sum);
    bsum = bsum + fabs(b[i]) ;
    }

  *p_averb = bsum / (double)m ;
  return(errsum/m);

  }  /* lsqerr */




/*------------------------------lsqrel-------------------------------
double lsqrel(A, x, b, m, n)

double  A[][NSYS], x[], b[] ;
```

```
int     m, n ;

  {
  int    i, j ;
  double sum, errsum, err, relerr ;

  errsum=0.0;
  for (i=0; i<m; i++) {
    sum = 0.0 ;
    for (j=0; j<n; j++)
      sum = sum + A[i][j]*x[j] ;
    err = fabs(sum-b[i]) ;
    if (fabs(b[i])>epsilon)
      relerr = err/fabs(b[i]) ;
    else if (fabs(sum)>epsilon)
      relerr = err/fabs(sum) ;
    else
      relerr = 0.0 ;
    errsum = errsum + relerr ;
    }
  return(errsum);

  }  /* lsqrel */




/*------------------------------Solver------------------------------
/*   The system is given by :    A x  =  b
     Returns rank of the Matrix.
*/
int  solver (A, b, x, n)

double A[][NSYS], b[], x[] ;
int    n ;

{
  int    i, j, k ;
  int    p[NSYS] ;
  double AS[NSYS][NSYS] ;

  if (prnt== -1)
    for (i=0; i<n; i++) {
      for (j=0; j<n; j++)  printf(" %f", A[i][j]) ;
      printf("   %f\n", b[i]) ;
      }
  for (i=0; i<n; i++) {
    for(j=0; j<n; j++)  AS[i][j] = A[i][j] ;
    AS[i][n] = b[i] ;
    x[i] = 0.0 ;
    }

  if ((k=gauss(AS,p,n))!=0) {
    if(prnt==-1) printf("Singular Matrix. Order = %d.\n", k) ;
    }
  else
    k = n ;
  backsub(AS,p,x,n,k) ;

  return(k) ;
  }  /* Solver */




/*------------------------------- Gauss ------------------------------
/*  Gaussian elimination with full pivoting.
*/

int gauss (A, p, n)

double A[][NSYS] ;
int    p[], n ;

{
   int    i, j, k, row, col ;
  int    itemp ;
  double pivot, ratio, dtemp ;
  double epsilon ;
  epsilon = 0.0000001 ;

  /*  Initialize permutation vector.  */
  for (i=0; i<n; i++) {
    p[i] = i ;
    }


  for (k=0; k<n-1; k++) {

    /*  Find the next pivot element.  */
    pivot = A[k][k] ;
    row = col = k ;
    for (i=k; i<n; i++)
    for (j=k; j<n; j++) {
```

```
      if(fabs(pivot)<fabs(A[i][j])) {
        pivot = A[i][j] ;
        row = i ;
        col = j ;
        }
      }
    if(fabs(pivot)<epsilon) return(k) ;



    /* Exchange row */
    if (k != row) {
      for (i=0; i<=n; i++) {
        dtemp = A[k][i] ;
        A[k][i] = A[row][i] ;
        A[row][i] = dtemp ;
        }
      }

    /* Exchange column */
    if (k != col) {
      itemp = p[col] ;
      p[col] = p[k] ;
      p[k] = itemp ;
      for (i=0; i<n; i++) {
        dtemp = A[i][k] ;
        A[i][k] = A[i][col] ;
        A[i][col] = dtemp ;
        }
      }


    /*  Elimination.  */
    for (i=k+1; i<n; i++) {
      ratio = A[i][k] / pivot ;
      A[i][k] = 0.0 ;
      for (j=k+1; j<=n; j++)
        A[i][j] = A[i][j] - ratio * A[k][j] ;
      }
    }

  if (fabs(A[n-1][n-1])<epsilon) return(n-1) ;
  return(0) ;
  }  /* Gauss */
```

```
/*--------------------------Backsub---------------------------------
/*  Back substitution.
*/

backsub (A, p, soln, N, n)

double A[][NSYS], soln[] ;
int    p[], N, n ;

{
  int   i, j, k ;
  double sum, sol[NSYS] ;


  for (k=n-1; k>=0; k--) {
    sum = 0.0 ;
    for (j=k+1; j<n; j++)
      sum = sum + A[k][j] * sol[j] ;
    sol[k] = (A[k][N] - sum) / A[k][k] ;
    }


  for (k=0; k<n; k++) {
    i = p[k] ;
    soln[i] = sol[k] ;
    }


  return ;
  }  /* Backsub */






/*------------------------------Product-----------------------------
product (B, C, m, n)
double  B[][NSYS], C[][NSYS] ;
int     m, n ;

{
  int  i, j, k ;
  double sum ;
```

```
  for (i=0; i<n; i++)
  for (j=0; j<n; j++) {
    sum = 0.0 ;
    for(k=0; k<m; k++)
      sum = sum + B[k][i]*B[k][j] ;
    C[i][j] = sum ;
    }
  return ;
  }  /* Product */




/*-----------------------------Mult---------------------------------
mult (A, b, c, m, n)
double  A[][NSYS], b[], c[] ;
int     m, n ;

  {
  int    i, j ;
  double sum ;

  for (i=0; i<n; i++) {
    sum = 0.0 ;
    for (j=0; j<m; j++)
      sum = sum + A[j][i]*b[j] ;
    c[i] = sum ;
    }
  return ;
  }  /* Mult */
  for (i=0; i<n; i++) {
    for(j=0; j<n; j++)  AS[i][j] = A[i][j] ;
    AS[i][n] = b[i] ;
    x[i] = 0.0 ;
    }

  if ((k=gauss(AS,p,n))!=0) {
    if(prnt==-1) printf("Singular Matrix. Order = %d.\n", k) ;
    }
  else
    k = n ;
  backsub(AS,p,x,n,k) ;

  return(k) ;
  }  /* Solver */




/*------------------------------- Gauss ------------------------------
/*  Gaussian elimination with full pivoting.
*/

int gauss (A, p, n)

double A[][NSYS] ;
int    p[], n ;

{
   int    i, j, k, row, col ;
  int    itemp ;
  double pivot, ratio, dtemp ;
  double epsilon ;
  epsilon = 0.0000001 ;

  /*  Initialize permutation vector.  */
  for (i=0; i<n; i++) {
    p[i] = i ;
    }


  for (k=0; k<n-1; k++) {

    /*  Find the next pivot element.  */
    pivot = A[k][k] ;
    row = col = k ;
    for (i=k; i<n; i++)
    for (j=k; j<n; j++) {
```

```
      if(fabs(pivot)<fabs(A[i][j])) {
        pivot = A[i][j] ;
        row = i ;
        col = j ;
        }
      }
    if(fabs(pivot)<epsilon) return(k) ;



    /* Exchange row */
    if (k != row) {
      for (i=0; i<=n; i++) {
        dtemp = A[k][i] ;
        A[k][i] = A[row][i] ;
        A[row][i] = dtemp ;
        }
      }

    /* Exchange column */
    if (k != col) {
      itemp = p[col] ;
      p[col] = p[k] ;
      p[k] = itemp ;
      for (i=0; i<n; i++) {
        dtemp = A[i][k] ;
        A[i][k] = A[i][col] ;
        A[i][col] = dtemp ;
        }
      }


    /*  Elimination.  */
    for (i=k+1; i<n; i++) {
      ratio = A[i][k] / pivot ;
      A[i][k] = 0.0 ;
      for (j=k+1; j<=n; j++)
        A[i][j] = A[i][j] - ratio * A[k][j] ;
      }
    }

  if (fabs(A[n-1][n-1])<epsilon) return(n-1) ;
  return(0) ;
  }  /* Gauss */
```

```
/*-------------------------Backsub---------------------------------
/*  Back substitution.
*/

backsub (A, p, soln, N, n)

double A[][NSYS], soln[] ;
int    p[], N, n ;

{
  int   i, j, k ;
  double sum, sol[NSYS] ;


  for (k=n-1; k>=0; k--) {
    sum = 0.0 ;
    for (j=k+1; j<n; j++)
      sum = sum + A[k][j] * sol[j] ;
    sol[k] = (A[k][N] - sum) / A[k][k] ;
    }


  for (k=0; k<n; k++) {
    i = p[k] ;
    soln[i] = sol[k] ;
    }


  return ;
  }  /* Backsub */







/*----------------------------Product-----------------------------
product (B, C, m, n)
double  B[][NSYS], C[][NSYS] ;
int     m, n ;

{
  int  i, j, k ;
  double sum ;
```

```
  for (i=0; i<n; i++)
  for (j=0; j<n; j++) {
    sum = 0.0 ;
    for(k=0; k<m; k++)
      sum = sum + B[k][i]*B[k][j] ;
    C[i][j] = sum ;
    }
  return ;
  }  /* Product */




/*-----------------------------Mult--------------------------------
mult (A, b, c, m, n)
double  A[][NSYS], b[], c[] ;
int     m, n ;

  {
  int    i, j ;
  double sum ;

  for (i=0; i<n; i++) {
    sum = 0.0 ;
    for (j=0; j<m; j++)
      sum = sum + A[j][i]*b[j] ;
    c[i] = sum ;
    }
  return ;
  }  /* Mult */
  for (i=0; i<n; i++) {
    for(j=0; j<n; j++)  AS[i][j] = A[i][j] ;
    AS[i][n] = b[i] ;
    x[i] = 0.0 ;
    }

  if ((k=gauss(AS,p,n))!=0) {
    if(prnt==-1) printf("Singular Matrix. Order = %d.\n", k) ;
    }
  else
    k = n ;
  backsub(AS,p,x,n,k) ;

  return(k) ;
  }  /* Solver */




/*------------------------------- Gauss ------------------------------
/*  Gaussian elimination with full pivoting.
*/

int gauss (A, p, n)

double A[][NSYS] ;
int    p[], n ;

{
   int    i, j, k, row, col ;
  int    itemp ;
  double pivot, ratio, dtemp ;
  double epsilon ;
  epsilon = 0.0000001 ;

  /*  Initialize permutation vector.  */
  for (i=0; i<n; i++) {
    p[i] = i ;
    }


  for (k=0; k<n-1; k++) {

    /*  Find the next pivot element.  */
    pivot = A[k][k] ;
    row = col = k ;
    for (i=k; i<n; i++)
    for (j=k; j<n; j++) {
```

```
      if(fabs(pivot)<fabs(A[i][j])) {
        pivot = A[i][j] ;
        row = i ;
        col = j ;
        }
      }
    if(fabs(pivot)<epsilon) return(k) ;



    /* Exchange row */
    if (k != row) {
      for (i=0; i<=n; i++) {
        dtemp = A[k][i] ;
        A[k][i] = A[row][i] ;
        A[row][i] = dtemp ;
        }
      }

    /* Exchange column */
    if (k != col) {
      itemp = p[col] ;
      p[col] = p[k] ;
      p[k] = itemp ;
      for (i=0; i<n; i++) {
        dtemp = A[i][k] ;
        A[i][k] = A[i][col] ;
        A[i][col] = dtemp ;
        }
      }


    /*  Elimination.  */
    for (i=k+1; i<n; i++) {
      ratio = A[i][k] / pivot ;
      A[i][k] = 0.0 ;
      for (j=k+1; j<=n; j++)
        A[i][j] = A[i][j] - ratio * A[k][j] ;
      }
    }

  if (fabs(A[n-1][n-1])<epsilon) return(n-1) ;
  return(0) ;
  }  /* Gauss */
  for (i=0; i<n; i++) {
    for(j=0; j<n; j++)  AS[i][j] = A[i][j] ;
    AS[i][n] = b[i] ;
    x[i] = 0.0 ;
    }

  if ((k=gauss(AS,p,n))!=0) {
    if(prnt==-1) printf("Singular Matrix. Order = %d.\n", k) ;
    }
  else
    k = n ;
  backsub(AS,p,x,n,k) ;

  return(k) ;
  }  /* Solver */




/*-------------------------------- Gauss -----------------------------
/*  Gaussian elimination with full pivoting.
*/

int gauss (A, p, n)

double A[][NSYS] ;
int    p[], n ;

{
   int    i, j, k, row, col ;
  int    itemp ;
  double pivot, ratio, dtemp ;
  double epsilon ;
  epsilon = 0.0000001 ;

  /*  Initialize permutation vector.  */
  for (i=0; i<n; i++) {
    p[i] = i ;
    }


  for (k=0; k<n-1; k++) {

    /*  Find the next pivot element.  */
    pivot = A[k][k] ;
    row = col = k ;
    for (i=k; i<n; i++)
    for (j=k; j<n; j++) {
```

```
      if(fabs(pivot)<fabs(A[i][j])) {
        pivot = A[i][j] ;
        row = i ;
        col = j ;
        }
      }
    if(fabs(pivot)<epsilon) return(k) ;



    /* Exchange row */
    if (k != row) {
      for (i=0; i<=n; i++) {
        dtemp = A[k][i] ;
        A[k][i] = A[row][i] ;
        A[row][i] = dtemp ;
        }
      }

    /* Exchange column */
    if (k != col) {
      itemp = p[col] ;
      p[col] = p[k] ;
      p[k] = itemp ;
      for (i=0; i<n; i++) {
        dtemp = A[i][k] ;
        A[i][k] = A[i][col] ;
        A[i][col] = dtemp ;
        }
      }


    /*  Elimination.  */
    for (i=k+1; i<n; i++) {
      ratio = A[i][k] / pivot ;
      A[i][k] = 0.0 ;
      for (j=k+1; j<=n; j++)
        A[i][j] = A[i][j] - ratio * A[k][j] ;
      }
    }

  if (fabs(A[n-1][n-1])<epsilon) return(n-1) ;
  return(0) ;
  }  /* Gauss */
```

```
/*---------------------------Backsub-----------------------------------
/*  Back substitution.
*/

backsub (A, p, soln, N, n)

double A[][NSYS], soln[] ;
int    p[], N, n ;

{
  int   i, j, k ;
  double sum, sol[NSYS] ;


  for (k=n-1; k>=0; k--) {
    sum = 0.0 ;
    for (j=k+1; j<n; j++)
      sum = sum + A[k][j] * sol[j] ;
    sol[k] = (A[k][N] - sum) / A[k][k] ;
    }


  for (k=0; k<n; k++) {
    i = p[k] ;
    soln[i] = sol[k] ;
    }


  return ;
  }  /* Backsub */
```

```
/*-------------------------------Product------------------------------
product (B, C, m, n)
double  B[][NSYS], C[][NSYS] ;
int     m, n ;

{
  int  i, j, k ;
  double sum ;
```

```
  for (i=0; i<n; i++)
  for (j=0; j<n; j++) {
    sum = 0.0 ;
    for(k=0; k<m; k++)
      sum = sum + B[k][i]*B[k][j] ;
    C[i][j] = sum ;
    }
  return ;
  }  /* Product */
```

```
/*-------------------------------Mult---------------------------------
mult (A, b, c, m, n)
double  A[][NSYS], b[], c[] ;
int     m, n ;

  {
  int    i, j ;
  double sum ;

  for (i=0; i<n; i++) {
    sum = 0.0 ;
    for (j=0; j<m; j++)
      sum = sum + A[j][i]*b[j] ;
    c[i] = sum ;
    }
  return ;
  }  /* Mult */
```