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AN OBJECT-CENTERED THREE-DIMENSIONAL MODEL BUILDER

CLAYTON ALBERT DANE III

A DISSERTATION

in

Computer and Information Science

sented to the Graduate Faculties of the University
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ABSTRACT

AN OBJECT-CENTERED THREE-DIMENSIONAL MODEL BUILDER

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A method of building a three-dimensional model of gid object using information from many views is described anar and quadric surface primitives describe the object' rface in an object-centered reference frame. The exten a primitive is defined by the intersection of th imitive with its neighbors. An edge graph defined b ese intersections implicitly expresses spatia lationships between surface primitives.

The model builder's input consists of groups of dat ints corresponding to different views. Each data poin ntains spatial and orientation information about th ject's surface at a discrete location. A set c gistered arrays is used to summarize input information i cal areas. Mathematical principles from differentia ometry are applied to determine local surface properties region-growing technique is applied to this information t entify data points which then are represented by a surfac

primitive. Edges and corners are computed based on intersections of surface primitives. The results from analysis of the various views are transformed to a comm arbitrary reference frame for integration into a glo model. The final object-centered reference frame established based on the center of gravity and moments inertia of the object as determined from the complete mod

The goal of model building has applications in fields of pattern recognition, computer vision, roboti computer-aided design and computer-aided manufacturing. model using surface primitives appears as a natural fi step in describing an object because surfaces are obvi visual features. The strengths and weaknesses of t surface model are explored.

Keywords:

Surface Representation, Three-Dimensional Object Representation, Object-Centered Description, Compute Vision, Pattern Recognition, Robotics, Computer-Aide Design, Computer-Aided Manufacturing.

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Graduate Group Chairperson

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This work is a reflection of me and indirectly a reflect on the world I live in. Without the understanding and c of the people in that world, I could not exist. I stood the shoulders of giants for support while doing this wo For fear of failing to acknowledge everyone justly, I of to all a collective, simple thank you.

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CHAPTER ONE

INTRODUCTION

A method of building a model of a rigid object i escribed. It utilizes information from many views coverin ne complete surface of the object. The model i hree-dimensional in nature and is expressed in a bject-centered reference frame. Planar and quadric surfa rimitives are used in conjunction with an edge graph escribe the object's surface structure. There are oth ays to represent an object. However, a surface mod ppears as a natural first description because surfaces a ne most obvious visual features. The goal of mod uilding has applications in the fields of patte ecognition, computer vision, robotics, computer-aid esign and computer-aided manufacturing. The strengths a eaknesses of this surface model are explored.

The purpose of a model is to organize or structu nformation to facilitate the solution of a problem. The re many varieties of models from which to choose wh onsidering three-dimensional objects. At present, there o universally "best" model for representation of hree-dimensional object. Models are divided into t ineral categories: surface and volume. There are surve ipers in the literature that discuss representatic IADLER/BAJCSY78], [MARR/NISHIHARA77], [REQUICHA80; >wever, there is no set of rules or algorithm to use t sleet the "correct" representation.

What are the properties of a "good" represent ati< :heme? It should be able to express all the informati< squired to solve the problems of interest. Importai iformation should be accessible easily from the model. '. lould be practical to implement, given the availab! achnology and computer environment. Another aspect of ti ^presentation is the level of abstraction. As the lev< icreases, specific information about the object is replac* Lth concepts that convey the essential information.

There are many aspects of representation which c ffect the solution to a problem. If a surface or volu; epresentation uses primitives, the number of differe rimitives and their properties can affect the usefulness he representation. Consider the following two volu rimitives. The first primitive is a simple sphere. It otationally invariant and has been used successfully odel the human body [0'ROURKE/BADLER79]. Algorithms f anipulating a model of spheres are relatively simp ecause all the instances of primitives can be handled t ame way. A single primitive can be a weakness, also, for anar object is difficult to represent with spheres, ai lere are no alternatives in this representation. 1 >ntrast, the use of the class of generalized cylinders < rimitives permits a large variety of volumes to cpressed. However, algorithms dealing with the! rimitives are more complex because of the added variety ai \e increased complexity of individual primitives. Anothi spect of representation involves the method used ^compose the object into its primitive parts. Is t ssult of the decomposition unique? Are the primitiv lique? Are they permitted to overlap? How are t Dundaries defined? Are they implicitly or explicit tated? What are the costs and benefits of the vario ptions? All these aspects of representation emphasize t sed to study methods of representation.

The purpose of this work is to develop a comput lgorithm which automatically builds models of rig hree-dimensional objects. The algorithm is not intended elp one build a model from the mind's eye. Rather, it ntended that three-dimensional data obtained from a re bject be input to the algorithm. The final description ntended for use in display, manufacture, recognition a urther analysis by man or machine. This goal is a b ask, too large for a single dissertation. A number uidelines help concentrate the effort into a problem iasonable size for a single dissertation.

The intended uses of the model are many and variec it, all appear to share a common need for geometrj lformation about the shape and structure of the object ince the model's intended use is varied, it should preser^ 5 much information as possible and avoid transformatioi lat are not reversible. The proposed model is classifi* 3 low level because the details of the object can 1 ^constructed from the model. This fact is necessary if tl)del is to be used for display or manufacture.

In a real environment, complete information is seld< bailable instantaneously. People compensate for the la< c information by utilizing previously determined modeli i this work, no supporting information, such as models < imilar objects, is available nor is all the informati- bout the current object available at once to the mod- jiilder. The model builder has a finite capacity to reta ad actively analyze raw input data, but may make nrestricted number of requests for information abo- pecific local areas of the object during the analysis. T nformation provided in response to a request is on artial, much like our human view of things.

Real world objects of interest are three-dimensional :
tture. They may have flat or curved surfaces. They may 1
>cally convex or concave in shape. They may be classifi
:om simple to complex. The objects used here are motivate
r the desire to model man-made objects from the offi<
ivironment. It is desirable to have a modelling syst<
lat handles objects in a real environment. However, th:
>al is very difficult to achieve and not essential to tl
^presentation problem. In order to simplify the situatioi
ily single objects in isolation are considered. This fa<
*rmits a concentration of effort on representati
roblems. Other problems such as separating several unknoi
bjects are not of interest and are not considered here.

The model building process described uses four prima
Lews as a general survey of the object. For each vie
^formation about the location and orientation of points
lie surface is summarized and analyzed. Based on t
esults of the analysis, groups of data points are form
or representation by a planar or quadric surface. A lea
quares fit of the data points in the group determines t
oefficients defining the surface. Once a data point
sed to determine a surface, it is removed from furth
onsideration. The process of summarizing and grouping
epeated until there are no unused data points remaining
he remaining data points cannot be grouped. Once all t

ossible surfaces in a view have been extracted, the ntersections can be computed mathematically and t xistence of edges verified in the input data. This proce f determining edges was not implemented because of t imilarity to work done previously by others [LEVIN76]. T ormation of a local edge graph completes the analysis he view. The results of the local analyses are integrat nto a global description. This process requires a chan rom the local viewer-dependent coordinate system to rbitrary global or world coordinate system. Given th hange of coordinates, the integration process mu ecognize when two surface primitives from different vie epresent the same underlying surface. If the proposed ed raph were available, this decision could be made based urface shape, number of edges, and shape of adjace urfaces. As implemented, the decision is based on surfa hape alone.

An object-centered coordinate system is one where t osition of the origin and the orientation of the axes a ixed relative to the object. An object-centered coordina ystem is important if the description is to be used f ecognition from any view. The world coordinate system us uring integration is viewer-independent but it is n bject-centered. It is proposed that the final coordina ystem used to describe the model have its origin at t

enter of gravity and its axes aligned with the princip
oments of inertia. There are many other possib
oject-centered coordinate systems, but this one is chos
bove the others because it appears feasible to compute i
ocation based on the global object description.

The motivation for studying how to build a descripti
f a three-dimensional rigid object has been presented.
hapter two the major issues of modelling are raised a
onfronted. Results from other investigations are cited
rder to help resolve them. Chapter three describes
roposed surface model without regard to use. It highligh
he organization and structure of the model. Chapters fo
nd five share a common structure of topics. Chapter fo
escribes a method of building an instance of the mode
hapter five goes a step further by providing implementati
etails about the method described in chapter four. Chapt
ix reports the results of testing some of the key ide
resented. An approximation of a telephone handset is t
ost challenging object tested. The results for le
omplex, artificial objects are presented also in order
ighlight the strengths and weaknesses of the metho
inally, chapter seven presents conclusions and ideas f
uture work.

CHAPTER TWO

BACKGROUND

The goal of object description by a machine has bee irsued over the years with varying degrees of success. 1 classic paper by Roberts [ROBERTS65], many fundaments >ncepts required for the analysis of three-dimension* >jects are reported. Complex planar objects ai ^presented using a combination of basic three-dimension*)lume primitives: cube, wedge and hexagonal prisi)iogeneous coordinates are used to facilitate tl spression of projective camera transformations from tl iree-dimensional model data to the two-dimensional imai ata. The location of object vertices in the image atermined based on extracted edge information. It ssumed that the two-dimensional vertex information of t nage is translated from the three-dimensional vert nformation of a primitive by a perspective projection. T rimitive associated with the transformation having t east error is selected to model that part of the objec iven such a transformation, only a scale factor remains e determined in order to specify completely the object osition, orientation and size. This final scale factor termined based on the camera's height. This work o berts was the starting point from which the compute sion field developed.

This chapter is divided into two major sections. Th rst section discusses methods of three-dimensional da quisition for static scenes. This topic is not of dire oncern to the work. However, a survey of methods resented in order to establish the feasibility of obtaini hree-dimensional data. The second section discusse epresentational schemes. It raises major representationa ssues and reviews previous research for possible solution

.1 Data Acquisition

Methods of three-dimensional data acquisition may rouped using various criteria. One criterion is the ty f information obtained: spatial information about depth rientation information about shape. However, th riterion is not useful in all cases because some metho ay provide both spatial and orientation information. etter criterion may be the property or feature used in t rocess of obtaining the results. Three differe pproaches for obtaining orientation information a xamined. One approach depends on the photometr roperties of the surfaces present and the lighting source second approach depends on the interpretation o-dimensional data assuming a three-dimensional source f der to obtain orientation information. A third approac pends on directly "feeling" or sensing the surface using ctile sensor. Four different approaches for obtainir atial information are examined. The first approac pends on correlating intensities of pixels in a stere age pair. A second approach depends on detecting ar tching edges of various strengths in a stereo image pai third approach depends on identifying artificially create atures in an image. Finally, the fourth approach directl asures the spatial information using a tactile sensor.

.1.1 Orientation Information -

The term orientation information refers to tl nformation about the local orientation of a surface. Tl irection of the surface normal at a particular locati xpresses the local surface orientation in quantitati rms. In contrast, shape information describes tl urface's behavior over a larger area. Horn pioneered tl evelopment of methods to determine a surface's shape a rientation from observed shading [HORN75]. The initi ethod utilizes constraints imposed by the reflectivi unction of the object's surface and the location of t amera and the lighting source. The reflectivity functi sed models lambertian reflectance. Methods that make u

this basic idea are referred to as reflectance ma
chniques. From the initial method, a more refined an
phisticated technique has been developed [HORN77].
dition, techniques that take advantage of specia
nstraints, such as the availability of multiple images
ve been developed [WOODHAM77] [WOODHAM7
ORN/WOODHAM/SILVER78]. Generally, these methods work be
en the environment is controlled so that the assumption
mbertian reflectance is true.

A two-dimensional projection of three-dimension
formation retains many clues that can be used
construct or infer the original three-dimensional shape
object. The next five works examined utilize vario
ues to infer the original orientation information. T
le that texture and contours play in visual perception
rface shape has been explored [STEVENS79]. The idea th
e relationship between a contour generator and t
sulting contour on a surface can be used to reconstru
ther, knowing the other under certain constraints,
udied. The use of contour constraints is develop
rther to infer surface shape from image contou
ITKINS80]. The idea that contours are a combination
ape information and projective transformation distortio
th of which are regular in behavior, is advanced.
thod for surface reconstruction based on this idea whi

xplains the contour best and which produces a smoot urface is used to obtain a surface and its orientation.

The use of texture elements is another way to obser erspective distortion and to estimate surface orientatio ender showed that the identification of similar textu lements at different orientations is feasible [KENDER77 keuchi confirmed the method's validity by recovering t hape of a golf ball using the texture of small circl resent on its surface [IKEUCHI80]. The use of this meth s limited by the need for a consistent texture over t urface of the object.

Kanade identifies geometric assumptions which perm ystematic recovery of three-dimensional shape fr wo-dimensional images [KANADE79]. The idea of "skewe ymmetries is introduced formally as a two-dimension inear affine transformation of a traditional real symmet n three-dimensions. The work of Stevens [STEVENS7 resents evidence to support this concept but does not u t. A technique to recover surface orientation based apping regularities in the image, like parallel lines a skewed" symmetries, into constraints on shape emonstrated.

A tactile sensor provides a relatively direct method < staining orientation information by observing the pressui fferences between various sites on the sensor. Tl essure differences can be used to produce an accurat itimate of local surface orientation. However, the size < le sensor is small when compared to the whole area of tl)ject's surface. This fact is a major disadvantage becaui le sensor needs to be moved physically to many positions i)tain a representative sample of orientation informati< rev the* object. The development of tactile sensors for ui th computers is in progress [W0LFELD81] [HILLIS81].

»1.2 Spatial Information - ' • .

Stereo images can be used to obtain spatial informatii bout the three-dimensional location of surface points* 0: f the major problems in using stereo is the corresponden roblem. The correspondence problem involves identifyi he same feature in the two images. Once this problem olved, photometric techniques can be applied to triangula lie location [WOLF74]. Solutions to the corresponden roblem have been demonstrated using pixel informati irectly [HANNAH74] [GENNERY79]. Such methods depend orrelation techniques to tell when a match has been foun he methods work best when the picture is composed iverse areas. When areas are similar, these metho

roduce less impressive results. A typical example of
tuation where these methods may perform poorly is i
nding corresponding points along an edge formed betwee
le textured leaf surface of a tree and a background of sky
le reason for the difficulty is that there are many loca
tches that appear equally acceptable along such an edge
lditional global information is necessary to improve th
esults.

Recently, a theory of human vision was propose
MARR/POGGIO77]. In this theory, the matching is done o
dges instead of directly on intensity. A computer visio
ystem has been developed and implemented to support th
easibility of the theory [GRIMSON80]. The accuracy of th
esulting three-dimensional data depends in part on how we
le edges can be located. A hierarchy of edges is define
y a measure of edge strength. This hierarchy is used in
equential process to build incrementally a stereo dispari
ap. The method works best in scenes containing many edg
r texture.

Methods that employ artificial means of creati
eatures have been used to obtain spatial information.
arly method that creates features by projecting lig
atterns has been reported in the literatu
WILL/PENNINGTON72]. More recently, a similar method h
een reported that projects a grid pattern of light onto

>ject to create artificial features [FREEMAN/POTMESIL79
le projection of the intersection of two lines of the gr:
>rms a feature on the surface of the object. Such featun
:e easily found in two images of a stereo image pair ai
itched. Each feature permits the location of one point t
le surface to be determined. These surface points then a:
sed to generate a surface patch which represents tl
3ject. In this case, the grid of light projected need m
> known precisely because it is not used directly
jasure the geometric properties of the object. Rather,
5 used only to make the solution of the corresponden
roblem easier. If a grid and its projection are kno^
recisely, then spatial information can be computed from
Lngle image. This computation uses two rays of light, o
tirough the camera lens and the other through the lig
ource, to triangulate the position of the surface at t
ntersection of the two rays. A scanning laser sens
ystem uses such a computation to determine range da
NITZAN/BRAIN/DUDA77]•

A tactile sensor, in addition to supplying orientati
nformation, can be considered to supply spati
nformation. A major disadvantage remains the requireme
o move the sensor physically to many positions. T
echanism used to position the sensor is the real source
he spatial information. However, in any practical tacti

stem, the sensor and the positioning mechanism ar tegrated and operate together.

2 Object Representation

From Roberts' early work followed many works whic terpreted lines derived from images as edges in ree-dimensional world. Typical of the achievements i is "line" research are Guzman's efforts [GUZMAN68]. Vali ree-dimensional object interpretations are derived fro e two-dimensional regions present in a single image. T hieve this, Guzman considers evidence suggested by th ructure of image regions and their relationships with eac her. Recognition of an object is done without referenc estimates of three-dimensional measurements o ordinates. Many of Guzm&n's techniques are ad hoc, base observation of what appears to work most consistently hers [HUFFMAN71] [CLOWES71] developed rules to label an scribe accurately line drawings. Waltz [WALTZ75] enhance id refined the performance of this type of analysis t •proaching the problem in a systematic manner. Ambiguitie used by cracks, obscure edges or shadows are no longer mse for gross mis-interpretation. A catalog of possib] ne/junction interpretations guides the analysis. Tt :enes that Huffman, Clowes and Waltz deal with are limits Ld not representative of the real world. It is assume

at perfect line drawings of solid planar objects whe
ery corner is formed by exactly three planar surfaces a
ailable. Kanade's origami world expands the domain
anar objects handled by considering constraints imposed
rfaces as well as edges [KANADE78]. It effectively dea
th line drawings that are less perfect and more realisti
e extension of line drawing interpretation to inclu
rved surfaces is another important step in understandi
enes. One representative work of this type is reported
ien and Chang [CHIEN/CHANG74]. As the scenes handl
come more realistic, applications to industrial assemb
ne tasks seem more feasible. However, all the works
ne drawings presented here produce qualitati
scriptions of shape and use a single view only. They la
e quantitative description present in engineering drawin
nd are not suitable for CAD/CAM systems. They are just t
nitial step in understanding three-dimensional sha
escription. The next step is to investiga
epresentations that are more quantitative in nature.

Object representations based on volumes have be
nvestigated. The use of a generalized cylinder as a volu
rimitive was suggested [BINFORD71]. A generalized cylind
s characterized roughly as the volume created by sweeping
ross sectional area along an axial curve. The generaliz
ylinder has been used to model objects like a torus, a co

AGIN/BINFORD73], or a piece of pottery [HOLLERBACH75 ore recently, the generalized cylinder has been used odel the three-dimensional structures found in biomedica ata [SOROKA79]. The use of spheres to represent three imensional objects has been reported als O'ROURKE/BADLER79]. One great advantage of using th phere as a primitive is that it is invariant to rotatio his work is motivated by the medial axis transfo BLUM67]. The transform produces a skeleton-lik epresentation of an object or figure by determining th enters of maximal spheres. The maximal spheres' radi etermine the "thickness" of the object.

A major drawback to the medial axis is that sha ngular changes in the boundary produce "spurs" in t esulting skeleton. Attempts to minimize such behavi sing smoothing and a relaxed definition of the transfo ave produced some success [BADLER/DANE79]. An alternati pproach to the medial axis transform has been report MOHR81]. In this work, non-overlapping spheres are pack nto the volume. A skeleton like representation is obtain y connecting the centers of adjacent tangent spheres. Th epresentation can assume a hierarchical structure based he radius of the spheres. If a coarse model is desire he skeleton is formed by connecting only tangent spher ith a relatively large radius. As greater detail equired, the radius restriction is relaxed to produce odel of greater detail.

One unanswered question in a representation usi rimitives is how many primitives are enough? Most of t epresentations prefer to have too many. Anoth epresentation proposed has just three primitiv SHAPIRO/et.al.81]. The three primitives are sticks, plat nd blobs. Each instance of a primitive is modified pecific description values. The representation is used orm three-dimensional object models. The goal is to stu imilarity of objects based on relational distance measure

The question of object representation is not unique mage analysis. A volume representation was used by MAGI roduce "computer generated perspective views of thre imensional objects" [GOLDSTEIN/NAGAL71]. There were ni rimitive volumes which could be combined in an algebra anner to form complex objects. An alternative approach epresenting an object as a network of surface patches w eported by [BRAID75]. Using this method to represe omplex objects has the difficulty of computing a rocessing the resulting intersecting surfaces. The work raid has been applied to CAD/CAM [WOO77]. The goal of th ork is to study the roles of positive and negative soli n creating cavities needed to link the volumetric desi pproach with existing numerically controlled tools.

Modelling three-dimensional objects using polyhedra <
Lnimal area is proposed [0'R0URKE81]. An algorithm f<
itermining such a polyhedron given a set of vertices :
ascribed and results are presented. However, a method <
itermining the set of vertices and the sensitivity of tl
ithod to different sets of vertices is not addressed.

The use of spatial information in conjunction" wi
-flectance data has been reported [DUDA/NITZAN/BARRETT79
scene segmentation procedure for finding planar surface
3 described. It is intended for use in the recognition <
bjects modeled as polyhedra. Many of the low-levi
Derations are applicable to both spatial and orientati*
iformation.

Another method of representation using cubic B-spli:
irves and Coons surface patches is report
Z0RK/HANS0N/RISEMAN81]. The method is capable of modelli
oth polyhedral and curved objects. A layered network
ntities is used to structure the model. Instances
bjects have been designed interactively and a method
atching has been tested. No method of automatical
uilding such a model from a real object is advanced.

The desirability of a viewpoint independent model h
een pointed out. Such a model is only one step toward
anonical representation reported [HINT0N81]. A method

etermining a canonical, object-based reference frame i
utlined. The method independently chooses the referenc
rame and generates a description, making it an idea
andidate for implementation as a parallel computation.

The Gaussian image is a representation used to organi
ocal surface orientation information. It is formed
gnoring spatial information and concentrating the uni
urface normals at the origin. An extension to thi
epresentation called the extended spherical image has bee
roposed [SMITH79]. In it, a single representative norma
hose length is proportional to the surface area at tha
rientation, replaces coincidental normals of simila
irection. This representation is informative becau
ertain classes of surfaces can be identified by the
xtended spherical images. For example, planar surfac
ppear as isolated normals of large length. Cylinde
ppear as arcs of great circles in the spherical image.

Work describing many three-dimensional objects in
ingle scene using planar and quadric surfaces has be
eported [OSHIMA/SHIRA79]. The three-dimension
oordinates of the surface points in a regular pattern a
ecovered. Overlapping surface elements formed by fitti
lanar surfaces to groups of eight by eight surface poin
re defined. Using a region growing process, adjace
lements are merged into larger elementary regions which a

›proximately planar. The resulting regions are classifie
; planar, curved or undefined based on the variance of th
ırface element's normals in the region and the size of th
:gion. A second region growing process merges adjacen
ırved regions into curved global regions if they ar
›nnected locally and smoothly. Quadric surfaces are fitte
› represent the curved global regions using the origina
ıderlying data points. Once the global regions ar
;tablished, regions' properties and relationships betwee
:gions are determined. The method of building a scen
:scription deals with multiple objects in a single scene
: should be noted that the curved surfaces are develope
ased on statistical parameters that indirectly reflect th
ırface in a qualitative fashion rather than on quantitati
:ometric properties like surface curvature. In additio
ingle views appear to be considered in isolation. I
ttempt is made to move from a viewer-centered referen
rame to an object-centered reference or to combi
nformation from several views. A second paper describi
he use of the scene description in recognition has appear
OSHIMA/SHIRA81].

The use of information from multiple views in t
nalysis of static scenes has been explored to a ve
imited extent. The analysis of solid planar convex objec
n isolation is reported [UNDERWOOD/COATES75]. The meth

squires input in the form of accurate line drawi ascriptions. The description of each view : ro-dimensional in nature and consists of a set of ed{ igments. A description of faces, edges and junctions : »veloped. A ratio of line segments' lengths that : lvariant under rotational, scaling and translation; ransformations is computed from two intersecting lines. 5 assumed that no significant perspective distortion exis' i the views. The two intersecting lines are defined)ur reference points determined by junctions of edges. T] lape of a face with four or more edges can be categorizi sing this ratio. The invariant ratio is used to identi le same surface in different views. No explicit knowled slating the different views is needed. However, t[1] Bstrictions on .the sequence of views used in learning t bject are imposed. The first restriction is that two ore surfaces in the new view must match * known surface his restriction eliminates the need to merge two disjoi escriptions of an object by insuring a single connect escription. The second restriction is that a new view mu ontain some new information to be learned. The results his method are qualitative in nature much like Waltz esults [WALTZ75].

Another method of analysis that uses multiple views fo
lid bodies bounded by quadric or planar faces has bee
ported [SHAPIRA/FREEMAN77]. The input for each view is
ne drawing description also. There are severa
strictions, such as corners which are formed by exactl
ree surfaces and a general camera position, that simplif
is complex problem. Unlike the method of Underwood an
ates, parameters relating the different views are know
d used. This information is needed to identify the sam
rner or junction in different views. The resultin
scription is in the form of face groups. Each face grou
scribes the boundary of a single face in three-dimensiona
rms. The results are more quantitative in nature but d
t capture the shape of the surface between the boundaries

A great variety of representational schemes have bee
oposed for many purposes. It is only natural to compar
e schemes, their properties and their uses. A pragmati
mparison of representational schemes based on th
erations that can be performed using them and th
pability and cost of converting between them is presente
ADLER/BAJCSY78]. The general categories of volume ar
rface models are used to help structure and clarify th
lationships between the various schemes. Many of th
sues raised are motivated by problems found in both th
mputer graphics and computer vision fields.

Marr and Nishihara examine representational constraint iposed by the application and by the computational problem ilated to processing retinal images [MARR/NISHIHARA77; tey identify three criteria as being useful in judging ipresentational scheme. The accessibility criterion J ;ed to judge if a representation can express the require iformation in a usable form. The scope and uniquene* riterion addresses the issue of the domain of objects th< in be represented and the number of possible descriptioi >r the same object. The stability and sensitivil riterion measures the continuity and resolution of ^presentation. Aspects of the representation including tl)ordinate system used to express representation; rimitives and their organizational structure are studie« le desirability of an object-centered, modular descripti tilizing volume primitives is expressed. The bas rocesses of using such a representational scheme f iilding models and recognizing objects are presented. T ignificance of the paper is not in the specific mod dvanced, but rather it is the identification epresentational properties that contribute to finding roblem's solution.

Another paper looks at representation from t ndustrial computer-aided design and manufacturing viewpoi ith its need for designing more reliable and versati stems [REQUICHA80]. It provides a summary of importan presentational issues, compares known schemes o presentation and presents a design for a geometri delling system. In the paper, the study of representatio tivated by specific applications is advocated.

3 Knowledge Driven Systems

One of the earliest knowledge driven systems foun lhouettes of the human head [KELLY71]. The edges we rst found in an image of reduced resolution. Thi formation then was used as a guide in finding the edges e original image. This work used two ideas which will en again: planning and the data pyramid.

More recently, a knowledge driven system using regio s reported [FREUDER76]. In low level vision, the use bsolute threshold values can be disastrous because of t reat variation possible in different images. To avoid th roblem, Freuder's work used relative thresholds based e currently known regions.

Sloan created a knowledge driven system to analy tdoor scenes [SLOAN77]. It used a production system whi aried the techniques applied based on the availabl urrent knowledge. The behavior of the production syst as determined by a set of rules and the current state owledge.

Other knowledge driven systems similar to Kelly' stem have been developed for use with aerial scenes ALLARD/BROWN/FELDMAN78] [ROSENTHAL78]. In both cases rtain features were being searched for in the images owledge about where the features normally appeared wa ed to limit the search area. For example, if one wer oking for a car, then one looked on roads or parking lots t not in an open field. Rosenthal's work used the dat ramid to good advantage to reduce computation also.

CHAPTER THREE

A SURFACE MODEL

A detailed description of the static nature of tt roposed surface model is presented. The basic element < le model is the surface primitive. A model may use ai imber of surface primitives to describe the object irface. These elements are cemented together by an edj raph. The resulting model captures the three-dimension* iture of a real object better than either the surfa< rimitives or the edge graph individually can.

.1 Surface Primitives

The surface primitive is a basic element of the mode: primitive is a planar or quadric* surface. An instance i tie model may use one or more primitives to describe ti bject's surface. Each primitive represents a finite an i the surface of the object. The area of the primitive c; e infinite in theory. In reality, the extent of t rimitive is defined by the intersection of the primiti ith its neighbors.

The use of planar and quadric surfaces as primitives
otivated by two reasons. Many man-made objects can
odelled accurately using only planar and quadric surface
PT, a language for numerically controlling machine tool
ncludes planar and quadric surfaces in its surfa
efinitions. Also, the ease of mathematical manipulati
hen compared to higher order surfaces is a factor in usi
lanar and quadric primitives. The complexity of t
urfaces to be fitted affects the process of fitti
urfaces to the groups of data points, and this process
n integral part of the model builder. A least squar
ethod of fit is used to determine the coefficients from t
aw data. As surface primitive complexity increases fr
lanar through quadric toward higher order surfaces, t
umber of coefficients required to define the primiti
ncreases and so does the size of the least squares proble
n addition, a model composed of quadric surface primitiv
ffers an advantage in determining object symmetries. A
uadric surfaces have at least one plane of symmetry. So
uadric surfaces, like ellipsoids, have three planes
ymmetry.

A surface primitive can be expressed as an implic
quation of the form

$$f(x,y,z) = 0$$

here f is a scalar function of order two or less in t iriables x, y, and z. The location of a point in tV irtesian space is represented by the three-tuple (x,y,z] id the point lies on the surface if the equatic [x,y,z) = 0 is satisfied. The surface divides the spac ito two half spaces. In one half space the function f j Lways positive, and in the other half space the function j Lways negative. A surface defined by an implicit form j Dt unique because if f(x,y,z) • 0 then c*f(x,y,z) » 0 whei is any real constant. It is necessary to add a constraii D insure that a surface has only one form.

Efficiently testing whether a point is on a surface ai ciiquely defining surfaces are two advantages in usii nadric surfaces. Consider a surface defined by arametric form such as

F(u,v)=P

here F is a vector function of rank three and order two < ess in the parametric variables u and v. P is a point he surface determined by the values of u and v in estricted domain. One can express the same surface in ma ifferent ways using a parametric form. In general, the s no systematic method for determining the equivalence wo equations. In addition, there is no simple method est whether a given point lies on a parametric surface, ight of these facts, the implicit form of the equation sed to represent the surface primitive.

2 The Edge Graph

The edge graph is essential for the accurat epresentation and reconstruction of the object by th erived model. A surface primitive expresses the basi hape of part of the object. However, a primitive ma ecify implicitly a surface that is larger than intende or example, four coefficients define a plane of infinit rea. Only a small portion of that plane is a vali epresentation for a planar face of a finite object. Th lge graph contains explicit information about bounda: irves which define the valid extent of each surfa rimitive.

The information contained in the edge graph is define y the intersections of adjacent surface primitive omputation of the intersection of two or three quadr urfaces has been investigated [LEVIN79]. The cur esulting from the intersection of two quadric surfaces li n the surface of a ruled quadric and can be expressed in anonical parametric equation. An edge is represented he equation that describes the X, Y, and Z coordinates he edge as a parameter is varied over a range of value n endpoint or corner of an edge is determined by t ntersection of the surfaces that meet there. In order ompute corner locations, a trace of the sequence eighboring surface primitives encountered along t

oundary of the primitive is required. The intersection o
wo sequential neighboring surface primitives from the trac
nd the original surface primitive determine a corner. Onc
he corners are found, the model need record only th
oefficients of the edge equation and the extreme points o
he range in order to reproduce the boundary of the surfac
rimitive.

.3 The Model Structure

There are four units or records of information that a
ombined to form an instance of the model.

Each object model has one object record. It contai
lobal information about the object such as the number
urface primitives, the number of edges, and the number
orners. In addition, it contains a list of pointers to t
urface primitive records.

Each surface primitive is represented by a separa
ecord. The surface primitive record contains a set
oefficients which define the surface. The coefficients
he surface equation are defined such that an outwa
ointing normal is obtained by partial differentiation.
ddition, there are three sequences of pointers: one f
eighboring surface primitives, another for edges and t
ast for corners. A sequence differs from a list in that

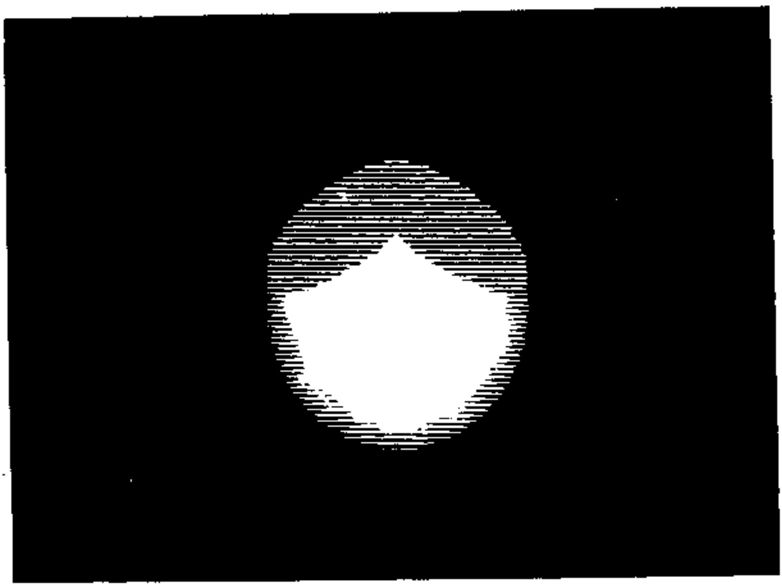
equence implies a specific order. The reason for requiri
n ordering is that there is a correspondence amo
eighbors, edges and corners. For example, the intersecti
f the i-th neighboring primitive and the current primiti
orms the i-th edge. Also, the i-th edge begins at the i-
orner and ends at the i+1-th corner.

An edge record describes an edge between two surfa
rimitives. It contains edge coefficients, parametric lim
alues and pointers to the associated corner records. T
oefficients define a parametric vector equation. Th
quation defines the edge in spatial coordinates. The t
arametric limit values represent the extreme range
arametric values for the edge equation. In addition, ea
dge record contains pointers to the associated corn
ecords.

A corner record expresses explicitly the spati
ocation of the intersection of three or more surfa
rimitives. This information is implicitly available v
he parameter limit values and edge equation of the ed
ecord.

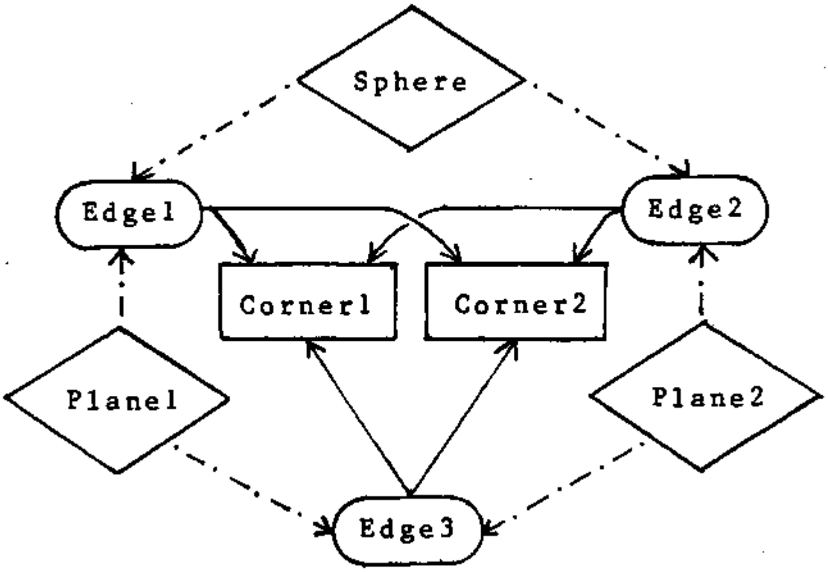
.4 An Example

Figure 3-1 shows an object that may be described as phere with two flattened planes. Figure 3-2 shows ti ecord structure of the proposed model in this instance.



A View of an Object

Figure 3-1



Model Structure

Figure 3-2

CHAPTER FOUR

BUILDING A SURFACE MODEL

A method for building an instance of the surface model is described. An outline of the presented in a set of stylized procedures. Words in procedure titles which are prefixed with a denote parameters specified by the use of the proc discussion of the method includes a descriptio desired and its source, the local analysis of dat single view, the integration of results from analyses into a global description, and the tran to an object-centered reference frame. Cha provides in corresponding sections additional deta in implementation.

The procedure "build surface model" describes level processing of the method.

```
OCEDURE: BUILD SURFACE MODEL
FOR each primary view
  - Input data for the current view
  - Analyze the current view
  IF a partial global description exists
    THEN
      - Integrate the current results into
        the global description
    ELSE
      - Make the current results into
        the global description
  END-IF
END-FOR
ND-PROCEDURE
```

.1 Input Data

The input consists of groups of data points. Each su roup, like a photograph, contains only partial informati rom a specific point of view. The information in ea roup is expressed in its own local coordinate syste nere are many possible groups corresponding to differe iews. A group is specified by "viewing" parameters in rbitrary but fixed global reference frame. This glob eference frame is the bridge that links together the loc oordinate systems of different views. These inp sumptions are consistent with methods of data acquisitio three-dimensional information.

1.1 Sources Of Data -

There are many methods of obtaining three-dimensiona ata about objects. For developmental purposes, it i esirable to use a method that produces "clean" data wit ittle or no error. Also, the ability to generat epeatedly the exact same data is useful for debuggi rograms. An artificial data generation program is neede o produce both spatial and orientation information abou oints on the surface of an object. In the field omputer graphics, programs that generate shaded images odelled objects are required to generate simila nformation [GOLDSTEIN/NAGAL71]. As an expedient soluti o constructing an artificial data generator, such a shad mage algorithm is used as the basis for the computation he input data.

The topic of three-dimensional data acquisition h een discussed generally. There appear to be two practic ethods of obtaining the desired input data from real wor ituations. The first method obtains data from pairs tereo images. A second method involves the use of actile sensor under computer control.

1.2 A View -

The basic unit of input is the point. Each point in
•oup is assumed to lie on the surface of the object. 1
Idition, it is assumed that there are no intervenii
irfaces present between the surface point and some fixe
>int in space. This assumption permits one to think of tl
•oup of data points as appearing in a single photograi
iken by a camera located at the fixed point in space
mce, the use of the word "view" to describe a group <
ita points. Also, like a camera, the resolution of tl
ita is a function of the distance between the fixed poii
id the center of the object.

Each group or view expresses its information in its 01
seal coordinate system. The origin of this system
)cated at the camera position. The orientation of tl
fstem is such that the object is located along the negati
-axis (see Figure 4-1). For each point, the X, Y, and
)ordinates and the local surface orientation at the poi
re known. The orientation of the local coordinate syst
ith respect to the camera position and the obje
marantees that the Z components of all the surface norma
re always positive. So, it is possible to express t
urface orientation in terms of a unit surface normal wi
nly two numbers. The two numbers are interpreted as the
nd Y components of the unit surface normal.

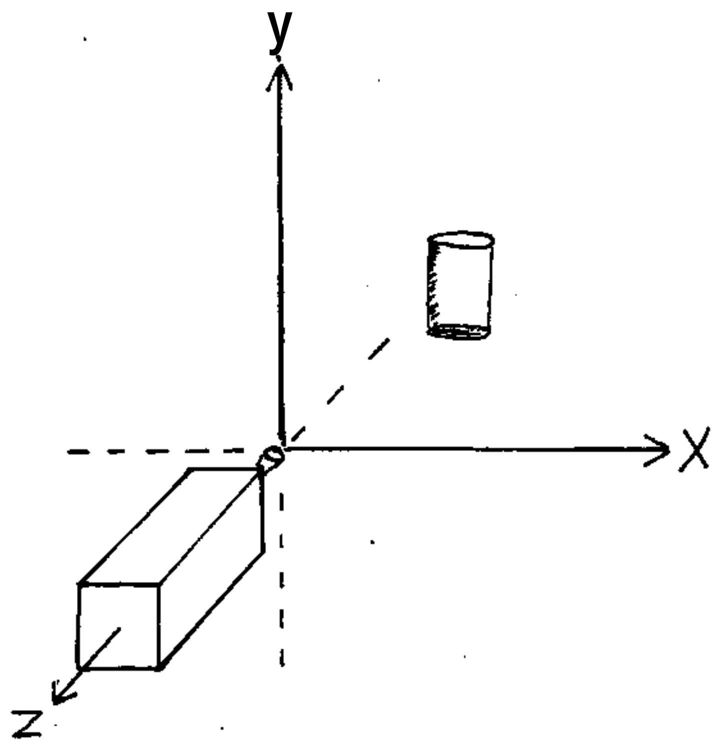
The data points in each group are assumed to b
iformly scattered relative to the local X-Y plane
tuitively, this assumption minimizes local blind spots du
sampling. However, it does not guarantee their tota
sences. No systematic spatial inter-point relations amon
ta points, such as a regular grid pattern of points, i
sumed* This fact permits a greater variety of inpu
urces to be used. Without this systematic relationship
wever, there is no easy way to determine a given point'
ighbors.

The analysis has available, for use at any one time,
oup of data points corresponding to a single view
wever, there is no restriction placed on the number o
ews or the points of view used. Initially, data from fou
imary views are investigated. Currently, the mode
ilder processes views sequentially. Since the primar
ews are intended as a general survey of the object, tli
cal analysis of the primary views could proceed i
rallel. It is expected that features may be discovere
iat require supplementary exploration.

Each primary view corresponds to an image seen by
mera at a vertex of a tetrahedron, with the earner
inting toward the center of the tetrahedron. It i
Ltended that the views overlap a small amount in order t
arantee the model builder sees complete informatic

entually. Complete coverage of the surface is necessa
order to obtain closure of the object description a
event "loose ends". An arbitrarily oriented glob
ference frame whose origin is near the object is used
ecify the viewing parameters. These parameters may
terpreted as a camera position and a camera orientation
ace. If the information from a primary view is used
nerate a shaded image, the object would appear to fi
ughly ninety percent of the image, and it would
ntered in the field of view.

In a primary view, the object is framed against t
ckground. In a supplemental view, there is no requireme
hat the field of view include the whole object. Data fr
upplemental views may be requested dynamically as t
nalysis proceeds. The need for supplemental views aris
hen a primary view contains ambiguous or insufficie
nformation about a local area. Therefore, it is expect
hat a supplemental view contains information about
imited part of the object. The analysis of supplement
iews occurs after the primary view's analysis is complet
o evidence exists as to whether it is better to merge t
upplemental results into the primary results befo
ntegration into the global description or to integrate t
upplemental results directly.



Local Coordinate System

Figure 4-1

4.2 Analysis Of A Local View

The local analysis is described by the pro "analyze local view". There are two major tasks performed in the analysis of a single view. First analysis forms subgroups of data points and dete surface primitives which adequately represent them, second task is to compute the location of edges indi from the intersections of surface primitives and their existence in the data.

```
PROCEDURE: ANALYZE THE *local VIEW
  - Obtain data about the *local view
  - Determine the *local surface primitives
  - Determine the *local edge graph
  IF the *local description is not complete internally
    THEN
      REPEAT
        - Determine a supplemental view
        - Analyze the supplemental view
        - Integrate the supplemental results into
          the *local description
      UNTIL the *local description is complete internall
        OR maximum resolution is obtained
  END-IF
END-PROCEDURE
```

4.2.1 Determining Surface Primitives -

The procedure "determine the local surface primiti describes the process of finding surface primitive represent groups of data points.

```
PROCEDURE: DETERMINE THE LOCAL SURFACE PRIMITIVES
  REPEAT
    - Summarize the unused data points
    - Group the data points based on the curvature and
      depth continuity reported in the data summary
    FOR each group found
      - Determine a surface primitive by a least squares
        fit of the original data points
      - Remove the used data points from
        further consideration
    END-FOR
  UNTIL there are no unused data points remaining
    OR no new primitives are found
END-PROCEDURE
```

4.2.1.1 Structuring Input Data -

In order to organize the input data, an array struc is utilized. Each property of interest is represented separate, two-dimensional array. Corresponding elements a set of registered arrays contain different informa about the same volume in the domain represented. Use o stack of registered arrays has been proposed as a para computational model [BARROW/TENENBAUM79B]. Its use here for sequential processing, and there is no immed modification of existing values in the various arrays eserve consistency.

The input data provided has no systematic structui
Lich permits it to be expressed using the array structui
rectly. To facilitate the use of an array structure,
imber of regularly spaced rectangular volumes is definec
ich side of these volumes is orthogonal to one of the thr<
>cal coordinate axes. The front of the volume is the plai
=+0O and the back of the volume is the plane Z=-0O . Tl
rojection of the volumes onto a local X-Y plane produces
*o-dimensional grid which serves as a basis for mapping tl
)lumes into an array structure. Each array eleme;
"presents all the data points within the corresponds
illular volume.

The use of an array to summarize local property
stermined by several data points is an interesting use of
ierarchical data structure. The use of such a da
tructure is not new to vision systems. See [R0SENTHAL7
or additional details. There are three primary purpos
or using the array structure as the second level of t
ierarchy. First, it allows for a systematic way
etermine a cell's closest neighbor. The implicit knowled
f the array's structure makes this operation possibl
econd, a cell value represents information about sever
ata points. This reduction of data saves memory space a

hosen carefully, the reliability of the data may be increased. It is desirable to utilize properties that depend on all the values, not just one. Two examples of statistical properties that depend on all the data points are the average value and standard deviation. In contrast, the statistical properties of minimum and maximum value may be affected adversely by a single bad data point. During the local analysis, decisions based on single points are avoided.

.2.1.2 Types Of Properties -

The properties represented by arrays are divided into two groups: observed properties and derived properties. Table 4-1 describes the observed properties and Table 4- describes the derived properties. The observed properties are statistics computed directly from the original input data. The derived properties require the use of some special knowledge about geometry in order to compute their value.

Observed Properties

- Number of data points in local area
- Average and standard deviation of local Z values
- Average and standard deviation of X component of local surface normals
- Average and standard deviation of Y component of local surface normals

Table 4-1

Derived Properties

- Local curvature in an X-Z plane
- Local curvature in a Y-Z plane
- Surface orientation continuity
- Surface depth continuity

Table 4-2

2.1.3 Growing Groups Of Data Points -

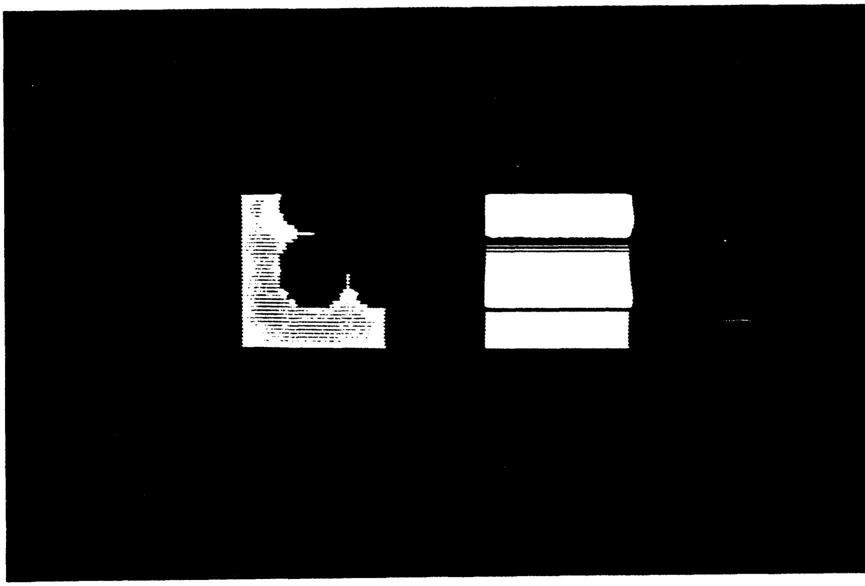
One of the parts of the local analysis groups dat oints for representation by surface primitives. There a vo methods for doing this task. A general purpose meth described first. It works for both planar and quadr urfaces. A specialized method for only planar surfaces escribed after the general, but computationally mo xpensive, method. In both methods, evidence that indicat he presence of the same type of surface in local adjace ells is sought in order to grow groups of data points.

.2.1.3.1 Quadric Surfaces -

The general method is based on two assumptions. T irst assumption is that as a single surface is traversed ny direction, the sequence of surface normals should chan moothly. For surfaces of uniform curvature, the componen f the normal vary linearly. This fact has been observ efore and used to reconstruct spherical or cylindric urfaces [BARROW/TENENBAUM79A] Also, the change in t ırface normals should be consistent. For example, conside raversing the curve formed by the intersection of a sphe nd an X-Z plane in the positive X direction defined by t ocal coordinate system. The surface is not a full sphe ıt rather a hemisphere because of the partial da vailable to a viewer. The planar curve of intersection art of a circle and has two endpoints if the degenera ase of a plane tangent to a sphere is not allowe tarting at the negative X end of the curve, the X compone f the surface normal is largely negative. As the X val ncreases as the curve is traversed, the X component of t ormal increases in value toward the positive. The fin ormal has the most positive value of the X component f ll the surface normals on the curve. The value of the omponent of the surface normal changes smoothly as t urve is traversed, and the change is consistently in t ame direction. It should be noted that the plane ntersection used to determine the curve examined iewer-centered rather than object-centered. Therefore, t urve is not one of intrinsic importance to describing t hape of the object. This expedient approach is take owever, because it is assumed that nothing is known of t bject's shape. It works because the goal to identi sameness" is modest. If a more ambitious goal dentification of surface type is selected, this simp pproach would not be sufficient.

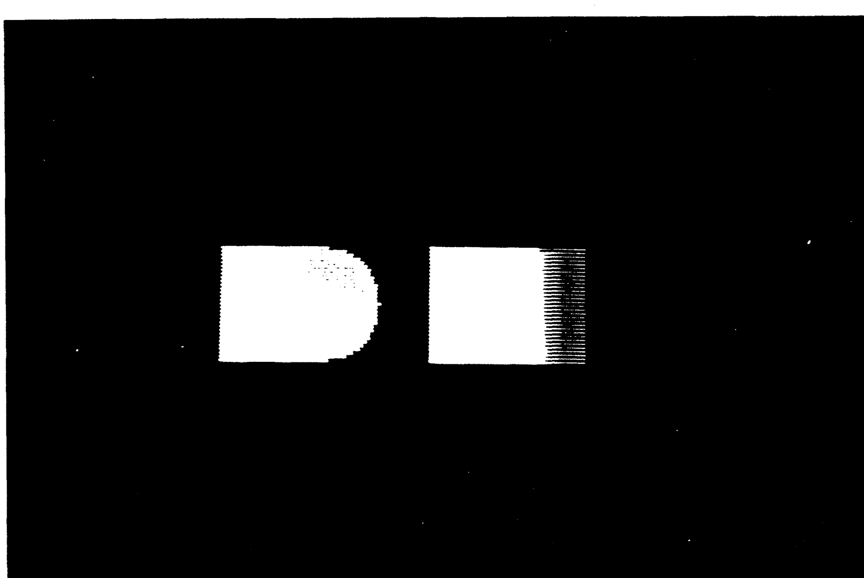
The second assumption is that a single surface shou]
tve a smooth surface as reflected in the depth or Z valu<
: the data points*. It is assumed that the underlyii
trface is not changing greatly in a small local area ai
lat the range of surface Z values in such an area can 1
;timated successfully knowing the average surfai
rientation. Evidence of the presence of more than 01
lrface is indicated when the observed range of Z valui
Lgnificantly exceeds the estimated range. Again, tl
/idence collected seeks to identify "sameness".

These two assumptions are complementary in nature. T
irst deals with orientation information, and the seco
eals with spatial information. Either, by itself, may fa
0 detect the presence of two surfaces. Figure 4-2 shows
nage with two surfaces in different spatial locations whe
tie first assumption fails because the surfaces have simil
rientation. Figure 4-3 shows an image with two differe
urfaces where the second assumption fails because t
urfaces are located close together.



Similar Surface Orientation

Figure 4-2

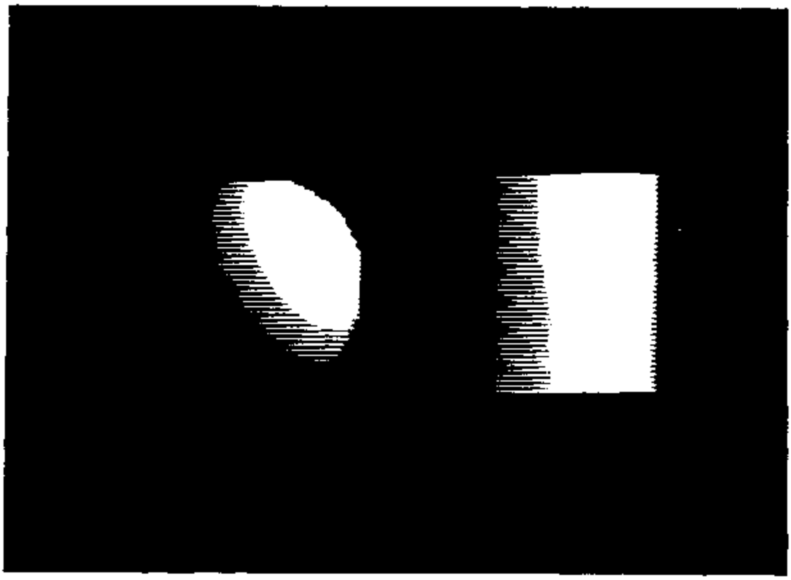


Similar Spatial Location

Figure 4-3

2.1.3.1.1 Orientation Continuity -

The first assumption is implemented as a local sha
ıbelling process. The goal is to label each cell in th
rray structure with a name that is characteristic of th
ıape of the surface within the local area and to identi
ırger areas of local shape continuity. Labels like conve
oncave, flat or unknown are not adequate, and a richer s
labels is needed. As an illustration of this nee
onsider the difference in shape between the sphere and t
ylinder of Figure 4-4. Both objects may be described
ıe label convex, yet there is a significant difference
ıape. By examining the curvature of two curves determin
y the perpendicular planes X=0 and Y=0, the difference
ıown. The careful selection of the planes contribut
ignificantly to the example's clarity. If the planes X+Y
nd X-Y=0 had been selected, a single pair of planes wou
ot be sufficient to show clearly the difference in shap
ortunately, the local analysis has information about ma
lanes parallel to the two selected on which to base i
ctions.



A Study In Curvature

Figure 4-4

.1.3.1.2 Depth Continuity -

The second assumption is implemented in two steps. The st step checks for surface continuity within a local 1. An estimate of the range of Z values under the umption that only a single surface is present is puted. When the observed range of Z values significantly eeds the estimated range, the presence of more than one face is indicated. The second step checks for continuity ween adjacent cells. When the Z values in the two acent cells differ significantly, the presence of more n one surface is indicated.

2.1.3.2 Planar Surfaces -

A simpler method for planar surfaces has bee
ıplemented based on the fact that planar surfaces are flat
ıis flatness property is reflected directly in the range c
ılues the components of the surface normals assume. Al
ıe normals from a single planar surface point in a singl
.rection. Ideally, any cell of the array containing dat
oints from a single planar surface has no variation, an
ıe range of values for the components of the surfa
ormals is zero.

Adjacent cells with similar average values for th
omponents of the surface normals and with zero ranges ar
onsidered for representation by a single planar surface
owever, the evidence reflects only orientation informatio
t is necessary to check that two surfaces of simil
rientation are not present. This situation is checked
ransforming the data points belonging to the region
uestion into a new coordinate system where the surfa
ormals are aligned with the new Z axis. If only one plan
urface is present, then there should be only one comm
alue for the transformed Z coordinate of the data points.

.2.1.4 Surface Fitting -

After a group of data points has been selected, ırface is fitted. The growing process provides the initia roup of data points to be represented and the general typ primitive required: planar or quadric. The data point re drawn from a limited area of the total surface are ecause of the conservative nature of the growing process nis fact makes the accurate estimation of the surfac arameters more difficult. Errors in the data point ırther complicate the problem. Two criteria, spatial an rientation, are combined to determine the value of th ırface parameters.

.2.1.4.1 Fitting Criteria -

A least squares fit of the observed data points is use o estimate the underlying mathematical surface. Tw riteria are used: spatial and orientation. Consider ea ype separately and independently. Ideally, for spati nformation, the intuitive geometric idea of minimizing t um of the square of the distance between the data poin nd the surface is desirable. For orientation informatio he angular difference between the observed and comput urface normals should be minimized. Nothing is known he surface, so it is difficult to implement these criter irectly.

Instead, less intuitive criteria are used. In th
miting case where there is no error, both sets of criteri
ad to the same estimation of surface parameters. Howeve
th imperfect data, no such claim can be made.

2.1.4.1.1 Spatial Criterion -

Let a quadric surface be expressed implicitly as

$$aX^2 + bY^2 + cZ^2 + dXY + eYZ + fZX + gX + hY + jZ + k = 0$$

Q(X,Y,Z)=0 for short. For an individual point, th
patial criterion chosen to be minimized can be expressed a

$$Q(X,Y,Z)*Q(X,Y,Z) \qquad \text{(Expression 4-1)} .$$

 there is no error in the data and its source is a quadri
urface, then the minimum value of Expression 4-1 is zer
owever, there is no direct intuitive geometr
nterpretation of the error in cases where the minimum val
s greater than zero.

The spatial criteria used for fitting surfaces
elected to simplify the mathematics involved with the lea
quares fit. However, the errors associated with the f
annot be used directly to determine the goodness of f
ecause the error measure is affected by the value of t
urface coefficients. A measure of goodness of fit

absolute terms, such as Euclidean distance, is importan bound on the Euclidean distance error measure usin error criterion of Expression 4-1 is developed.

Let P0 be the location of a point on the surface Q that Q(P0)=0 . Assume that an error in position, Δ introduced during the observation process. Let P1 be observed location corresponding to P0. Assume that not on the surface, so that $Q(P1)\neq 0$. Now, consider a order approximation of Q(P0) obtained by a Taylor's s expansion of the function Q about the point P1,

$$Q(P0) \triangleq Q(P1) + \Delta P \cdot \nabla Q(P1) .$$

Since Q(P0) = 0 ,

$$Q(P1) \triangleq -\Delta P \cdot \nabla Q(P1) .$$

Substituting the definition of the dot product, expression is

$$Q(P1) = - \|\Delta P\| * \|\nabla Q(P1)\| * \cos\theta ,$$

and squaring both sides yields

$$Q(P1)^2 = \|\Delta P\|^2 * \|\nabla Q(P1)\|^2 * \cos^2\theta .$$

Since

$$0 \leq \cos^2\theta \leq 1 ,$$

$$\|\Delta P\|^2 * \|\nabla Q(P1)\|^2 \geq Q(P1)^2$$

$$\| \Delta P \|^2 \geq \frac{Q(P1)^2}{\| \nabla Q(P1) \|^2} .$$

his last inequality shows that the spatial error criteri f Expression 4-1 can be expected to be a consiste stimate of the error as long as the value of $\nabla Q(P1)$ nd the angle θ are relatively constant over the range ata points. In addition, the estimate of the Euclide rror distance can be used to place the residual errors ifferent primitives on a common scale for comparison of t ccuracy of the underlying data points.

.2.1.4.1.2 Orientation Criterion -

Let A be a vector representing the actual surfa ormal and let B be a vector representing the observ urface normal. The observed surface normal is a un ector, so $\| B \| = 1$. The normal of the fitted surface, s derived from Q by differentiation, and its length is n ecessarily one. Consider the expression

$$N(X,Y,Z)^2 = \| A \|^2 - (A \cdot B)^2 \quad \text{(Expression 4-2)}$$

xpanding the expression using the definition of dot produ

Lelds

$$N(X,Y,Z)^2 = ||A||^2 - (||A||*(|B|*\cos B))^2$$

lere 0 is the angle between the observed and actu<
3rmals. Further simplification leads to

$$N(X,Y,Z)^2 = ||A||^2 * (1 - \cos^2 9)$$

r

$$N(X,Y,Z)^2 = ||A||^2 * \sin^2 8 .$$

lis expression obtains a minimum value of zero when the t\
actors are parallel and is positive otherwise. Also, noi
fiat the magnitude of A, $||A||$ can be written as $||\nabla Q(P)$
Dr any point P.

•2.1.4.2 Minimization -

The error criterion used is of the form

$$\sum_{i=1}^{n} Q(X_i,Y_i,Z_i)^2 + \sum_{i=1}^{n} N(X_i,Y_i,Z_i)^2$$

alues for the coefficients a, b, c, d, e, f, g, h, j, and
re desired which minimize this expression. There are ma
olutions to this problem since any surface defined
(X,Y,Z)=0 is defined equally well by 1*Q(X,Y,Z)=0, where

$$a^2 + b^2 + c^2 + d^2 + e^2 + f^2 + g^2 + h^2 + j^2 + k^2 = 1$$

introduced in order that a unique solution may be determined.

The problem is now a constrained minimization which may be solved using the theory of Lagrange multipliers [FULK69]. The theory guarantees that a function F takes on a local extreme value subject to a constraint function G=0 when

$$\nabla F - \lambda \nabla G = 0 \qquad \text{(Equation 4-3)} .$$

Setting

$$F = \sum_{i=1}^{n} Q(X_i, Y_i, Z_i)^2 + \sum_{i=1}^{n} N(X_i, Y_i, Z_i)^2$$

and

$$G = a^2 + b^2 + c^2 + d^2 + e^2 + f^2 + g^2 + h^2 + j^2 + k^2 - 1$$

permits the theory to be applied to this problem. The solution associated with the minimum lambda is the desired one. The vector equation of 4-3 can be expressed as ten scalar equations. Each one of the scalar equations contains partial derivatives with respect to one of the ten unknown coefficients. Implementation of a method of solution is facilitated by observing that finding a solution to Equation 4-3 is an eigenvalue problem. Methods for determining eigenvalues are well known and standard software packages xist which produce acceptable solutions. If a differen onstraint equation is chosen, this fact may not be true.

.2.2 The Local Edge Graph -

After all the primitives have been determined, th econd task of the local analysis is to determine the edge nd corners. The procedure "determine local edge graph escribes briefly this process. Ideally, the intersectio f adjacent surface primitives defines the boundary o xtent of the primitives. This determination is mor ccurate than a direct estimation from the original sampli f the three-dimensional data. Once an edge's location i omputed, it can be verified in the input data and can recorded explicitly in the object description.

In a local view, the appearance of adjacency based he X and Y location does not insure that two surfa rimitives form a real edge. The depth continuity proper rray discussed previously can provide evidence to refu he existence of a common boundary. When two primitiv orm an edge, it is desirable to express their comm oundary in terms of a parametric equation and a pair arameter values denoting the range of the boundary. his information is determined for each pair of surfa rimitives, a graph of edges and corners can be buil lso, knowing the exact extent of the surface primitiv

trmits the reconstruction of an accurate shaded image <
le object from the description.

Surface primitive boundary closure is important. Oi
ght assume that after having found all the edges that ti
^suiting boundaries of the surface primitives in the loc<
Lew would be closed. In general, this is not tru<
xrface primitives adjacent to depth discontinuities
acking an adjacent neighbor along part of their bounda
scause of local perspective do not have closed boundarie
le missing part of the boundary can be filled in
^formation from another view. Also, the corners associat
ith edges adjoining a missing boundary may not be tr
orners, but virtual corners resulting from the loc
erspective. It is important to include some knowled
bout these virtual edges and corners in the local analys
n order to avoid mistaking them for the real thing. T
art of the edge graph where a virtual edge or corner see
o "appear[11] should be marked as incomplete.

```
PROCEDURE: DETERMINE THE LOCAL EDGE GRAPH
  FOR each primitive
    WHILE "walking" around the boundary of
      the primitive in the x-y space
      - Compute the intersection of the primitive
        with its neighbor
      - Verify the edge exists in the original data
      - Update the edge graph with information about
        the "real" edge just found
    END-WHILE
  END-FOR
END-PROCEDURE
```

4.3 View Integration

After the local analysis of a view is complete, results are integrated into a global description o object. This integration is characterized by se distinct steps: transformation of information from a coordinate system to a global coordinate system, comput of a measure of similarity between two surf identification of identical surfaces, and the modific of surface parameters based on new information. procedure "integrate the local results into the next- description" describes briefly this process.

ROCEDURE: INTEGRATE THE *local RESULTS

INTO THE *next-level DESCRIPTION

- Transform the *local results into the *next-level's reference frame
- Identify the *local primitives in the *next-level's results based on primitive similarity and edge information
- Update the *next-level's description to reflect the matched information and append new information

ND-PROCEDURE

.3.1 Transformation To A Common Coordinate System -

The original data and information derived from t ocal analysis is expressed in the local coordinate syste here is some global reference frame or coordinate syst sed to specify the different camera positions. The actu lobal coordinate system used is less important than t elationships between the various views. Knowing the elationships, transformations that map information fr ach of the local coordinate systems into a common glob oordinate system may be computed. The change of referen rame from the local, viewer-centered one to an arbitrar lobal one is the first critical step toward achieving escription that is viewer independent.

.3.2 Surface Identification -

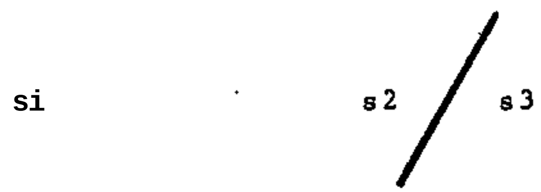
A major issue in view integration is the determinatio whether or not a surface primitive from the local vie as been seen before. Intuitively, the locatio rientation and basic shape of the surface are factors onsider. In addition, information provided by the ed raph is of value.

.3.2.1 The Types Of Surface -

Each surface primitive is categorized by the loca nalysis as planar or quadric. In the global descriptio he category of quadric is refined into ellipsoi yperboloid of one sheet, hyperboloid of two sheet lliptic paraboloid, hyperbolic paraboloid, cone, ylinder. Membership in a refined category is based umerical properties of the surface. The coefficients he surface are mapped into a continuous decision space. et of hypersurfaces divides the space into regions defini he categories. Each surface receives the label of t egion into which it maps. For additional details abo etermining a surface's type see [LEVIN76].

The refinement process for surface types transforms t escription by abstraction, and it can be misleadin onsider the three surfaces depicted in Figure 4-

rfaces si and s2 lie in the same region and are separate
r a relatively large distance. In contrast, surfaces s
id s3 lie in different regions but are relatively close
> while si and s2 share a common label, s2 and s3 are mu<
>re similar geometrically• For this reason, generic ty
\ not used as a measure of two surfaces' similarity.



Decision Space

Figure 4-5

.3.2.2 Measure Of Surfaces' Similarity -

In order to decide if a new surface matches an existi
urface in the description, a measure of similarity
omputed. Such a measure is computed between the n
urface and each existing surface in the object descriptio
f no measure falls below a predefined minimum thresho
alue, then the new surface is assumed to be unique and
dded to the object description. Otherwise, the old surfa
ith the lowest similarity value is assumed to match the n

ırface. The new information can be used to modify th
xisting surface description. The measure of similarity i
omputed as the weighted sum of the square of th
fferences of the corresponding surface parameters.

The measure of similarity used is an unsophisticate
irst attempt which lacks an intuitive, geometri
nterpretation. A more sophisticated measure whic
xplicitly considers the shape of the surface and it
ocation and orientation in space is seen as the next step
or quadric surfaces, there are methods of extracting an
eparating these pieces of information from the surfac
oefficients [LEVIN76]. Given this new measure, it shoul
e possible to predict the sensitivity and robustness of th
easure in geometric terms.

.3.2.3 The Role Of The Edge Graph -

The identification of the same surface primitive fr
ifferent points of view does not depend on the measure
urface similarity alone. During each local analysis,
dge graph can be developed which contains informati
elating adjacent surface primitives. Once tentati
dentification is made based on similarity, the adjacen
nformation is checked for consistency. The ability
erge the local and global edge graphs in the absence
onflict provides additional support for the curre

cal/global identification.

3.3 Description Updating -

Integration of a new local analysis result shoul
nprove the global description. If a local primitive ha
ot been seen before, the global description is expanded t
nclude it. If a local primitive is judged to exist in th
lobal description already, it still may be necessary t
odify the global description. The shape of the surfa
rimitive may differ between the local result and the o
lobal description. The question of how best to combine th
wo pieces of information in order to create a more accura
hape description is not addressed in this work.

The information contained in a single view is on
artial. In general, several views are required in order
btain a complete description. The global description
uilt incrementally. After a local analysis is complet
he derived surface primitives and the edge graph a
ntegrated into the global description. While it is n
equired that the global and local descriptions bei
ntegrated share some common features, it is desirable.
hey do, conflicts in descriptions can be detected a
esolved immediately. The new global description is th
ne of a single, connected surface area rather than t
isjoint areas. Having disjoint surface areas within

)bal description is not fatal because, at sometime, a nev :al view will provide information linking the two areas. ?ever, an integration of a view that joins two disjoint *as is more complex and difficult than an integration that Is a view to a single area description.

i The Final Reference Frame

The final form of the object description uses -< ference frame whose origin lies at the center of gravity the object and whose axes are aligned with the principal aents of inertia. The center of gravity and moments oi artia can be obtained by several methods. One method uses a surface primitives as the basic unit of mass t< proximate these values. Another method requires th< aversion of the surface model to a voxel representation uses the voxel as the basic unit of mass to approximati e center of gravity and moments of inertia. Once th< liter of gravity and the moments of inertia are known, th< nal transformation from the arbitrary global referenci ame to the object-centered reference frame can be compute" d applied to the model. The last transformation result the final reference frame of the description being tie the structure of the object rather than to the loca rspective of the viewer or some arbitrary reference frame

CHAPTER FIVE

IMPLEMENTATION

This chapter provides additional information which
equired in a practical implementation but is not releva
irectly to the understanding of the basic method of th
odel builder. Many of the comments presented here are th
irect result of experience gained in implementing or usi
omputer programs to test the ideas presented. Howeve
ome comments are based indirectly on results and may
peculative in nature.

.1 Input Data

Implemented computer programs use input data that
rocessed by groups or views. Each group is limited to
6-bit words of memory. A data point consists of five re
umbers: three numbers expressing spatial information a
wo numbers expressing orientation information. Therefor
ach data point requires ten words of memory, and a group
imited to a maximum of 409 data points.

1.1 Sources Of Data -

Artificially generated data is obtained from a dat
meration program based on a graphics system calle
JADRICS. Real input data can be obtained from the analysi
: pairs of stereo images or a tactile sensor. Currently
ita sources providing information about real objects ai
>t available locally for use with this work, but they ai
^ported in the literature.

•1.1.1 Artificial Data -

The QUADRICS system is a constructive geometri
xdelling system that permits the production of shad<
aages. In the course of constructing the images, the ty]
: three-dimensional information desired here as input
aerated. The system models objects using volui
rimitives whose surfaces are quadric or planar. The*
irfaces are represented in the program in an implicU
jnctional form. The volume primitives are defined by tl
itersection of half spaces associated with these surface!
le user is not concerned with surfaces but rather wi
rimitive volumes. The volumes may be combined usi
oolean-like operators of NOT and OR to produce convex a
oncave objects. However, the valid grammar for combini
olumes is restricted because primitive volumes may not

e original QUADRICS system may be found in [STRAUSS80] dditional information about similar modelling systems i vailable in [GOLDSTEIN/NAGEL71].

A data generation program is needed to produce bot patial and orientation information about points on th urface of an object. While QUADRICS and the dat eneration program needed here have different goals, the hare many similar requirements. For example, both need t ompute surface normal information for a given point on urface. The QUADRICS program generates such information b omputing the partial derivatives of the surface from a mplicit second order equation. As an expedient solution onstructing a data generation program, QUADRICS wa orrowed and modified. Both programs share a comm xternal form of model representation. The shaded ima eneration algorithm is the basis for the computation of t patial and orientation information. In the case of t ata generation program, this computation runs under progr ontrol rather than human direction, and the results a umeric rather than graphic. The effect of different vie s obtained by transforming groups of primitives. T riginal QUADRICS system is used to generate a model of est object under human direction. The data generati rogram reads a file created by QUADRICS and generates roup of three-dimensional data points from a view specifi r the analysis program.

•1.1.2 Real Data -

Methods of obtaining three-dimensional data have bee ^viewed in chapter two. The purpose of this section is I stimate the quality of the data obtained from the* *thods. In the case of stereo, it is assumed that tl)ordinate system expressing the data is oriented such th; tie Z axis is parallel to the average of the two optic< ices associated with the stereo pair of images. Ea< iree-dimensional data point is determined by * citersection of two lines of sight, one from each earner; f these lines are close to being parallel, then the ran; r Z value is expected to contain the major portion of tl rror. The physical layout of the data acquisition systi ill determine the allowable camera positions; hence, ill affect the accuracy of the data. Section 10.6 DUDA/HART73] presents an error analysis for stereoscop erception. See [DERISI81] for additional details relat o the implementation of a stereo algorithm.

The tactile method is capable of producing data reater accuracy. Assuming the tactile sensor is n onstrained in its orientation for a given position and th t is free to make the best use of its abilities, the err

lues. This method appears to be able to produce the typ
id quantity of information required more easily than th
ereo method. The tactile sensor offers a uniqu
portunity for the interleaving of data acquisition an
ialysis because the rate of acquisition is limited by th
ility to move the sensor quickly. The sequential analys
data as it becomes available and the ability to chang
ie acquisition strategy in progress to take advantage
ie new information remain large unresolved problems. The
re not considered here because of their size an
mplexity. See [WOLFELD81] for additional details on th
ictile sensor.

Obtaining orientation information directly
ifficult. Orientation or shape has been recover
uccessfully from intensity data in a controlled environme
HORN75]. In an uncontrolled environment, other metho
ust be used. An alternative approach for obtaini
rientation information estimates the surface norma
athematically from depth information. This proce
nvolves fitting surface patches to local areas a
omputing partial derivatives from the patches to estima
he normals. A patch may be planar, quadric, bi-cubic,
ny other one that is computed easily. The planar patch
avored since minimal effort is desirable. The accuracy
he normal estimate depends on the location and error of t

ints used in fitting the patch. In order to insure th ndependence of the spatial and orientation errors, point sed to determine the normal estimate should not be use lso as other actual data points in the group. This fac kes it necessary to over sample the surface in order t mpensate for the lack of orientation information. Th ate of sampling depends on the accuracy of the orientatio nformation desired.

.1.2 A View -

Artificial data is obtained from the data generati rogram. The underlying process involves the computation spatial and orientation information used to form a 64 by ixel shaded image. The data points generated are many mber and regularly spaced in a grid. In fact, the 40 tentially available data points are more than the memo f the PDP11/60 can hold practically at one time. Some he potential data points are not realized because the ocation corresponds to the background in the image. rder to conform to the input requirements mentioned abov pproximately 400 data points are selected at random fr he ones available. The system-supplied random numb enerator, RANDU, is used as the basis of the selecti rocess. The same initial seeds are used on every view ANDU to insure reproducible input data for debuggi ırposes.

The ability to examine a part of the whole is ıluable tool in the analysis of objects. Previously, ıe description of the model builder, the use and purpose :imary and supplemental views was discussed. Tl nplemented computer programs consider only primary view: ıe local analysis generates requests for supplement ıews, but they are not honored. The incomplete results ıe local analysis are integrated into the glob: escription. In many cases, redundant information fr ther local analyses fills in the gap.

.2 Analysis Of A Local View

The analysis of a single view has been implement artially. The second task of determining the edges ntersections of surfaces has not been attempted because he similarity to work done by Levin [LEVIN76].

.2.1 Determining Surface Primitives -

The ability to determine efficiently surface primitiv s a key step in the analysis.

2.1.1 Structuring Input Data -

The original data is divided into local areas by igular grid of cells. Registered arrays organize tt immary information for systematic access. Each arr*)ntains information about a different observed or compute roperty. All the elements of an array refer to the sat roperty but for different local areas. Correspondii Lements in different arrays refer to the same local are< le cell boundaries are defined so that a cell contains fi^ ata points on the average. In practice, a cell may conta: ly number of points because of the data point distribute ssumption. However, cells with two or less points a: amoved from consideration by the local analysis.

.2.1.2 Types Of Properties -

Properties are recorded in arrays of bytei iformation is coded into numerical values with a maximi ange of 256.

.2.1.3 Growing Groups Of Data Points -

The implementation of algorithms to grow groups of da oints revealed many unexpected cases that required speci onsideration.

2.1.3.1 Quadric Surfaces -

The grouping of data points generated by underlyii tadric surfaces is relatively straightforward. However, j le underlying surface is of higher order, it is a much moi .fficult problem to find "reasonable" groups f< ^presentation by a quadric surface.

.2.1.3.1.1 Orientation Continuity -

The goal is to characterize the shapes of local are; id identify larger areas of local shape continuity. T] se of shape labels like convex, concave, flat and unknoi ave been shown by the example of Figure 4-4 to aadequate. A richer set of labels which depends on t! rray structure has been developed. The shape lab ttached to a local cell depends on the properties of t ocal cell and its four-connected neighbors. At the lowe evel, an estimate of the curvature of a curve on t urface of the object connecting the center of two adjace ells is desired. Such a curve is defined by t ntersection of the object's surface with either an X-Z -Z plane. An estimate of the curvature at the mid-point oundary between the adjacent cells is computed as t ifference of the average surface normals of the two cell s implemented, the curvature is labelled as positive, ze r negative. The zero label is attached when the differen s within a tolerance of true zero. In addition, the labe f unknown is required because a cell may have less than th our neighbors due to its location in the array or due to ack of sufficient data which disqualifies a cell.

By combining two estimates of curvature from opposit ides of a cell, an idea of the shape of the curve formed b he intersection of the surface with the plane is obtained abels reflecting estimates of the shape of two curve ormed from the intersection of orthogonal planes with th urface are determined for each cell. A label representin he shape of the surface in the local area is assigned base n these two shape estimates. It should be noted that th abelling process is done conservatively. That is, the cel s labelled as mixed if any doubt exists about its shape an t is removed from consideration in the growing proces djacent cells with similar labels are grouped together fo ossible representation by a single surface primitive.

.2.1.3.1.2 Depth Discontinuity -

The estimate for the range of Z values within a sing ell is based on the assumption that a single planar surfa s present. The estimate is a function of the cell siz he average value of the Z component of the surface norm nd the range of the Z components of the surface norma his estimate is approximate and subject to error becau ırfaces are not limited to planar surfaces.

Discontinuity between adjacent cells is indicated whe
ıe magnitude of the difference of the two average Z value
ːgnificantly exceeds the average of the two range values
. When both tests for discontinuity are used together,
eliable indication of discontinuity is obtained.

.2.1.3.2 Planar Surfaces -

Identification of data points for representation by
lanar surface depends on finding points whose surfa
rientations are the same. In practice, some error
xpected. Therefore, points with similar, not identica
ırface orientations are considered. Here, the criteria f
imilar is a small range of values in the range of values
he surface orientation data.

.2.1.4 Surface Fitting -

The criterion for the fitting of surfaces appears
oc at first. It is an expedient solution. However, wh
xamined in greater detail, the mystery of why it works
ll can be explained.

.2.1.4.1 Fitting Criteria -

The criteria for fitting surfaces has been stated. Tw ndependent criteria for fitting the surface primitives hav een developed and combined. However, the issue of th elative importance of the spatial versus the orientatio nformation has not been addressed. The expression

$$\|\Delta P\|^2 * \|\nabla Q\|^2$$

as been developed as an approximation to the spatial par f the quantity minimized, where ΔP is the Euclidea istance error. Also, the expression

$$\|\nabla Q\|^2 * \sin^2 \theta$$

as been developed as the orientation part of the quanti inimized, where θ is the angle between the observed a ctual surface normals. The expression

$$\|\nabla Q\|^2 * (\|\Delta P\|^2 + \sin^2 \theta)$$

epresents an approximation of the quantity minimize owever, the combination is questionable because the t arts are not expressed in the same units of measure. T riteria used implies an arbitrary equivalence between o nit of linear measure and one unit of angular measure. ustification for this mix of spatial and orientati nformation is offered. Rather, it is presented in order how explicitly the mix used. Experiments using parti tta of known surfaces in isolation without error show* iat the use of both spatial and orientation informatic 'oduced better results than just spatial information alone lall changes in the relative weights of the spatial ai rientation information appear to have affected the resuli ttle.

.2.1.4.2 Minimization -

The solution to the minimization problem may 1 imputed using a standard eigenvalue subroutine from any < le many scientific subroutine libraries available. T1 Lgenvector associated with the minimum eigenvalue is tl ssired solution to Equation 4-3.

.2.1.4.2.1 The Wrong Point In The Right Place -

The estimation of the surface parameters is only ood as the data points used in the computation. Should umber of "bad[11] data . points be included, the resulti stimation of the surface parameters would be poor. Sin oints are grouped based on the average properties of ell, "bad" points may be selected because a majority good" points mask their presence. The error associat ith an individual point does not indicate absolute hether it is good or bad. However, if there are only a f ad points, the set of points with large errors includes t

it of "bad" points. By removing a subset of data point
th large errors from the original set, the number of "bac
ita points can be reduced, possibly to zero. This assume
tat the number of "bad" data points is relatively small
iis strategy has two major disadvantages. Even under idea
mditions, some good data points are discarded i
:tempting to remove "bad" data points. Also, an additions
irface fitting is required to determine the primitive. *Se*
riSCHLER/BOLLES81] for additional ideas on how to hand]
Lmilar problems.

In a practical implementation of the above strateg}
lere are two questions of importance to be considered. 1
lere are no "bad" data points, how good should the fit b«
le answer to this question depends mainly on the source <
le three-dimensional data. Each type of sensor introduce
3me noise or error in the data acquisition process.
*cision to apply the above strategy can be made based <
le observed fit error as compared to the expected f:
rror. An estimate of the expected fit error may be derive
j theoretical analysis or from empirical evidence. If :
s necessary to apply the strategy, how many "bad" da
Dints are there in the original set? It is assumed th
he method of selecting the original set has limited t
umber of "bad" data points to a relatively sma
ercentage. The estimate of expected error may be used as

ide to removing points. Another approach is to assu
hat a fixed percentage of data points should be remove
his latter approach is the one implemented. This goal
chieved by comparing a data point's error to a thresho
alue. In either case, however, it is difficult to predi
ow the fit and residual errors are affected by the remov
f data points without refitting.

In the process described above, a threshold is used
etermine when to remove a "bad" point. This threshold
ased on observed error computed using the error measure
quation 4-1. This error measure is not absolute. Howeve
his fact has little adverse effect so long as the da
oints are within the region around the origin where t
hreshold value was developed for use. If the data
utside this region, a different threshold value must
etermined.

.2.1.4.2.2 The Right Point In The Wrong Place -

The initial process used to define surfaces produc
roups of data points, and each group is represented by
ingle surface. The groups are chosen conservatively
rder to minimize the probability of points from t
ifferent actual surfaces being placed in the same grou
s a result, many data points near the boundaries whe
urfaces meet are not used in the original surface paramet

timation. Once a surface's parameters have bee stimated, a second pass through the data points is made t nd these undiscovered points. New points are included i ie group if they meet the following criteria:

$$Q(X_i, Y_i, Z_i)^2 < STOL \quad \text{and} \quad N(X_i, Y_i, Z_i)^2 < OTOL$$

iere STOL is an error tolerance based on the origina irface fit and OTOL is an angular error tolerance of fixe ignitude. The STOL tolerance is subject to the sai roblems discussed in the previous section. To insure ingle connected surface, only points from cells adjacent ells with known members are checked for new members. Afte ie expansion is complete, a new estimation of the surfac irameters is computed based on all the members of tl roup.

.2.1.4.2.3 A Substitute For Better Resolution -

Many times, one surface may mask the presence nother surface. The underlying masked surface may n ontribute a significant number of data points because on small part of the surface is visible in the view. As wi umans, a second look is helpful. This idea is implement s an iterative process. After a surface is fitted, t oints represented by it are removed from furth onsideration. When all the initial surface candidates ha

een checked, new values for properties are computed base
n the unresolved points. The removal of resolved point
ay clarify the type of surface to use for representing th
emaining points. This new information is analyzed fo
dditional surface candidates.

This iterative approach makes possible th
dentification of underlying surfaces that do not exten
ver a large number of cells in the registered arrays. Th
ame results could be obtained by increasing the number o
ells in the registered arrays. This increase in resoluti
ould require a corresponding increase in the number of da
oints. A tradeoff between the increased processing time o
he iterative approach versus the requirement of more inpu
ata can be made to achieve a given effective resolution.

.3 View Integration

Implementation of the view integration is limit
ecause the edge graph information is not generated by t
ocal analysis.

.3.1 Transformation To A Common Coordinate System -

Integration of local view information requires a chan
n the coordinate reference frame. This change
ccomplished by expressing information in homogeneo

oordinates and using general matrix transformations. ompound transformation composed of simple transformation uch as translation, rotation and scaling, can be formed a pplied using matrix products. This fact permits compl hanges to be computed efficiently. The use of homogeneo oordinates and such transformations are used extensively he field of computer graphics [ROGERS/ADAMS76].

.3.2 Surface Identification -

In the previous discussion on similarity, the need f more intuitive measure which explicitly considers shap rientation and location was identified. The followi iscussion attempts to motivate a method of determini anonical forms of quadric surfaces to achieve this goa he canonical forms are the same as those in solid geomet DRESDEN64]. A summary of one method is reported LEVIN76]. In that method, a surface defined by Q(X,Y,Z) s expressed in matrix form by

$$p * Q * \text{transpose}(p) = 0$$

here p is a point in homogeneous coordinates of the fo X,Y,Z,1), and Q is a four by four symmetric matrix defin y the original coefficients as

$$Q = \begin{bmatrix} a & d/2 & f/2 & g/2 \\ d/2 & b & e/2 & h/2 \\ f/2 & e/2 & c & j/2 \\ g/2 & h/2 & j/2 & k \end{bmatrix}.$$

canonical matrix C is derived from Q by factorii)tational and translational information specific to tl istance of the surface into explicit matrix multiplier* le original form of

p * Q * transpose(p)

ly be expressed as

> * R * T * C * transpose(T) * transpose(R) * tran.spose(p

lere C is the canonical form of Q, R is a rotation matri: id T is a translation matrix.

.3.3 Description Updating -

If all surface primitives do not have closed boundari eflected in the edge graph at the conclusion of t ntegration of the four primary views and their subordina upplemental views, then closure of the description has n ccurred, and some detail has been missed. To complete t escription, supplemental views can be requested based he lack of boundary closure.

.4 The Final Reference Frame

The center of gravity and moments of inertia need to b etermined from the input data or the global descriptior n approximation to this information can be computed easily iven a voxel representation, each full voxel is considere s a point mass of unity at the center of the voxel. Th omputation involves sums of products. Two possible methoc f obtaining a voxel representation are described.

At present, the input data for the surface descripti uilder is obtained artificially from a modified graphi lgorithm. This algorithm with additional modification ca erve as the basis for generating voxel data from the glob escription. During the shaded image generation, a dep uffer for each pixel in the image is computed. The dep uffer is an ordered list by Z value of surfa ntersections with a ray parallel to the Z axis. Each pix ses a different ray. In the case of the graphics syst nd the artificial data generation program, only the fir ntry in the depth buffer is of interest. All the entri re of interest when generating voxel data. It is possib o determine which parts of the ray are inside the volume xamining the depth buffer's entries sequentiall nitially, all the voxels are considered as empty. Ea epth buffer will supply the information required etermine which voxels pierced by the ray should be fille

By carefully selecting the size of the image and modelling space viewed, a voxel representation of des resolution may be computed.

Another method of obtaining a voxel representation to create it directly from the input data of the sur description builder. Initially, all the voxels in the s are considered full. As input data from a view considered, evidence is obtained that certain voxels empty. Specifically, voxels enclosing a ray connecting camera position with a visible surface point are em Also, voxels enclosing a ray starting at the camera and intersecting the object are empty. Simply, each supplies information to cut away matter much like a scul carving a statue. The resolution in the voxel space dep on the sampling density of the input data.

CHAPTER SIX

RESULTS

The key ideas proposed have been implemented an
sted. The results of that effort are presented here. Th
ograms implemented in support of these ideas are writte
FORTRAN. A 16-bit mini-computer, a PDP11/60 using an RS
erating system, serves as the test bed. The idea
plemented and tested include the finding of groups of dat
ints for representation by surface primitives, the fittin
surfaces to these groups via a least squares technique
e transformation of information from the loca
ewer-dependent reference frame to a viewer-independen
ference, and the identification via shape in tha
ference frame of the same surface from different points o
ew.

1 Presentation Of Input Data

The input data for each local view is presented in tw
rms. A pair of pictures showing the same data points i
e two forms is shown in a single figure. Both form
present a data point as a dot. A point's local X and
atial values determine its position in the picture. Th

ightness of the dots in the left, or upper, pictu
epends on the Z value of the point. Points closer to th
ewer appear brighter. This method of intensity modulatio
called depth cueing. The brightness of the dots in th
ght, or lower, picture depends on the orientation of th
rface normal. Points with surface normals pointing towa
e viewer appear brighter. This method of intensit
dulation is referred to as orientation cueing.

.2 Presentation Of Surface Primitives

The results of the grouping process are presented in
imilar fashion to the input data. Each picture in a figu
air shows a group of data points that is represented by
ingle primitive surface. Points not in the group appear
immed dots. This type of display permits one to maintain
ense of perspective and structure on the whole.
ddition, each picture contains a set of lines forming
rid. The grid denotes the approximate boundaries th
efine the local regions or cells in the registered arrays

.3 Test Cases

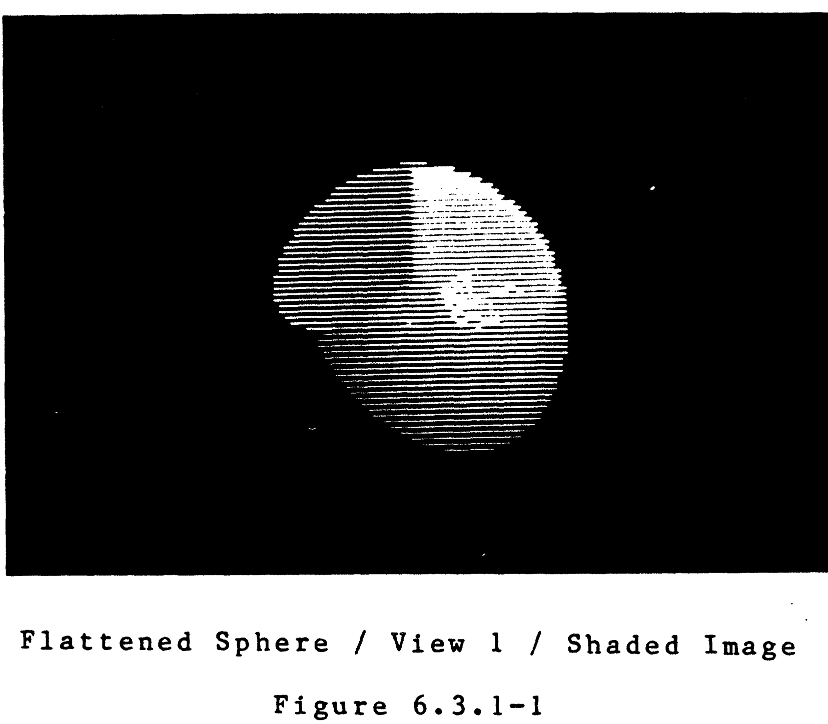
During the testing of nine objects, the programs ma
ne error in the analysis of the thirty-six local view
here were many views with unused data points and reques
or supplemental information. These requests were n

)nored, and the view integrations were done using tl
icomplete local results. In all but one case whei
icomplete local results were used, the missing informatic
is seen and recorded in the results of another loc<
aalysis and a complete global description was developed.

Requests for supplemental information resulted when tl
Deal analysis was not able to find new surface primitiv<
it there were remaining unused data points. There we:
tiree reasons found to cause this problem. The first reas<
as that there were too few data points remaining to fit ai
nrface. These data points came from a surface th<
ppeared to cover a smstll area in the view. They we
lustered together in one or two cells of the summary repo
nd could not be identified by the shape labelling proces
he second reason was that the remaining data points were
ufficient number to define a primitive but were so spre
ut over several cells in the summary report as to create
istorted and inaccurate picture. The shape labelli
rocess was unable to identify a consistent surface. T
hird reason was related to a constraint of the analysi
o prevent parts of cylinders from being misrepresented
lanar surfaces that were long and narrow, these surfac
ere rejected as primitives. It seemed better to reque
upplemental information and look at the area in great
etail before committing to a primitive.

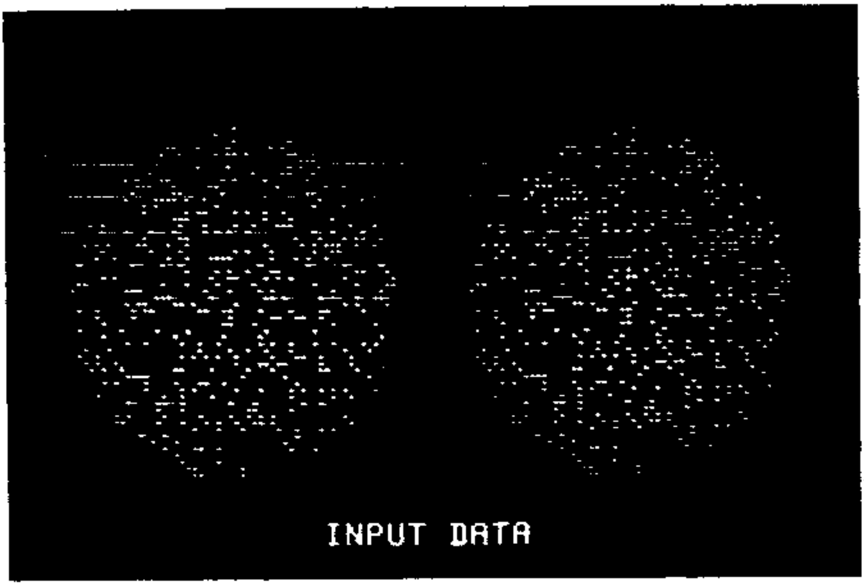
.3.1 Flattened Sphere -

The test object labelled "flattened sphere" is a sing phere with two adjoining planar sections removed. T urpose of the object is to test the ability to recov imple, relatively large planar and quadric surfaces and ntegrate them into a consistent global description. T nalyses of the four primary views were completed witho ifficulty. The integration of the results of these loc nalyses produced an accurate description of the objec 'he final global description consisted of one spheric rimitive and two planar primitives.



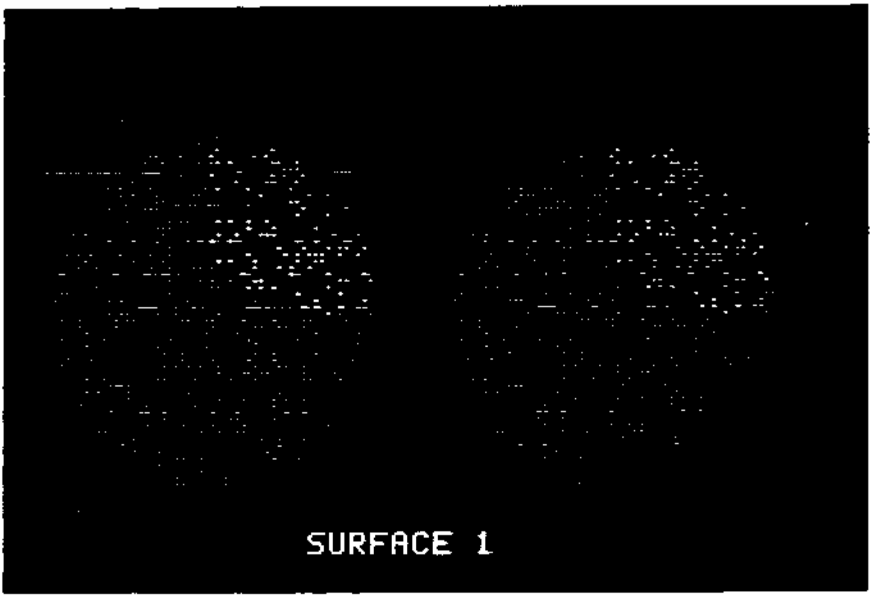
Flattened Sphere / View 1 / Shaded Image

Figure 6.3.1-1



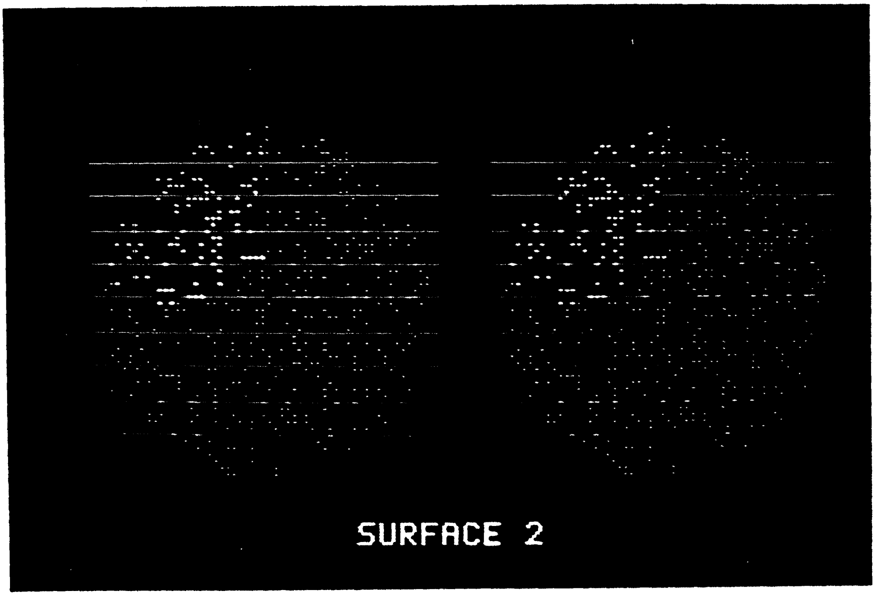
Flattened Sphere / View 1 / Input Data

Figure 6.3.1-2



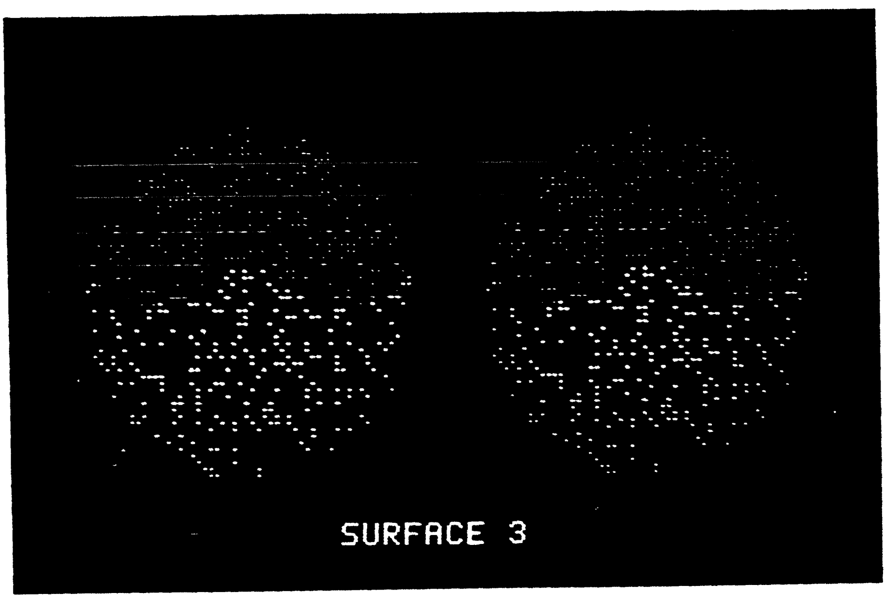
Flattened Sphere / View 1 / Surface 1

Figure 6.3.1-3



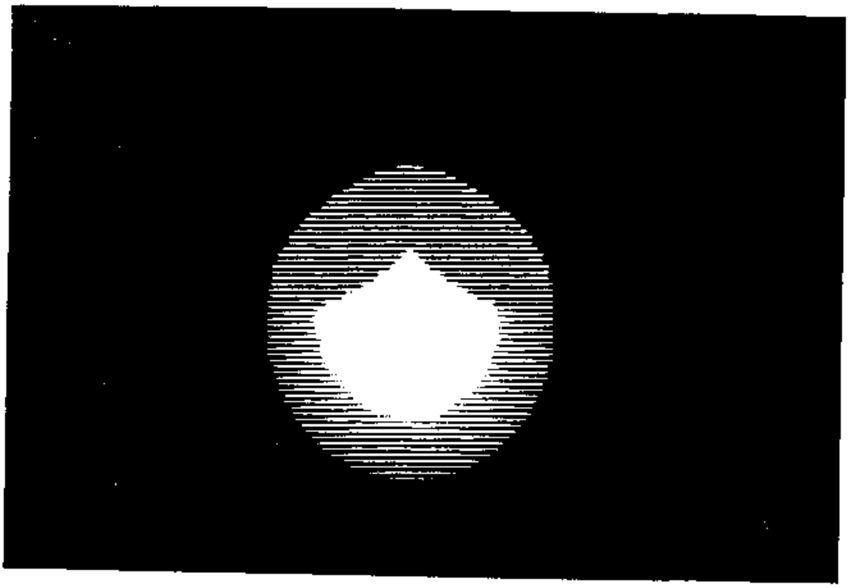
Flattened Sphere / View 1 / Surface 2

Figure 6.3.1-4



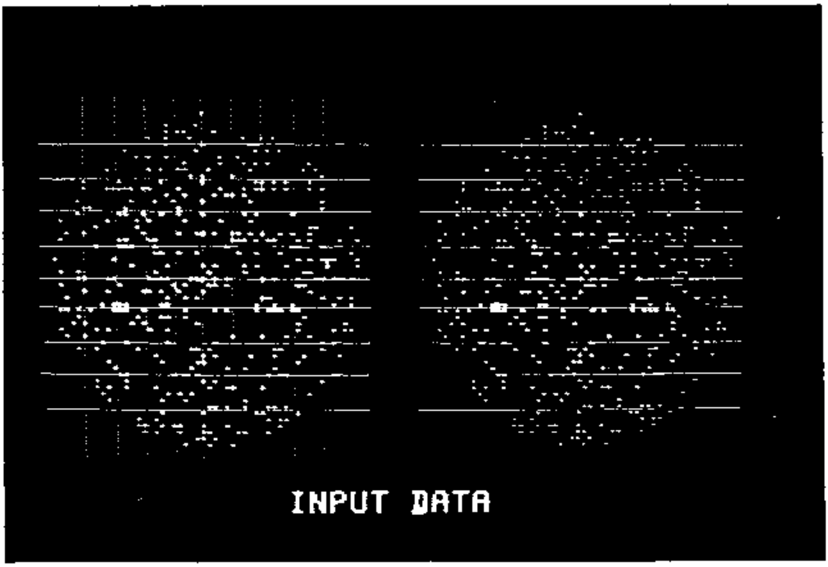
Flattened Sphere / View 1 / Surface 3

Figure 6.3.1-5



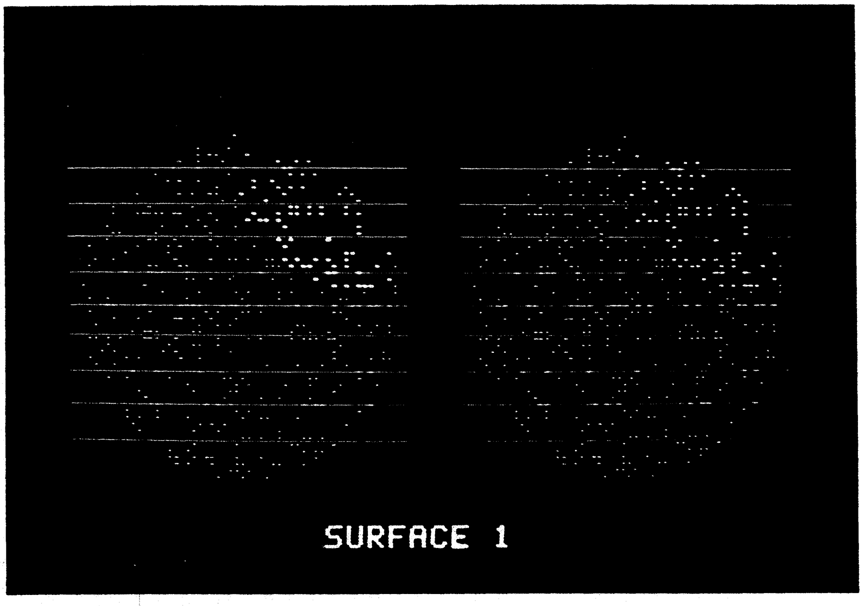
Flattened Sphere / View 2 / Shaded Image

Figure 6.3.1-6



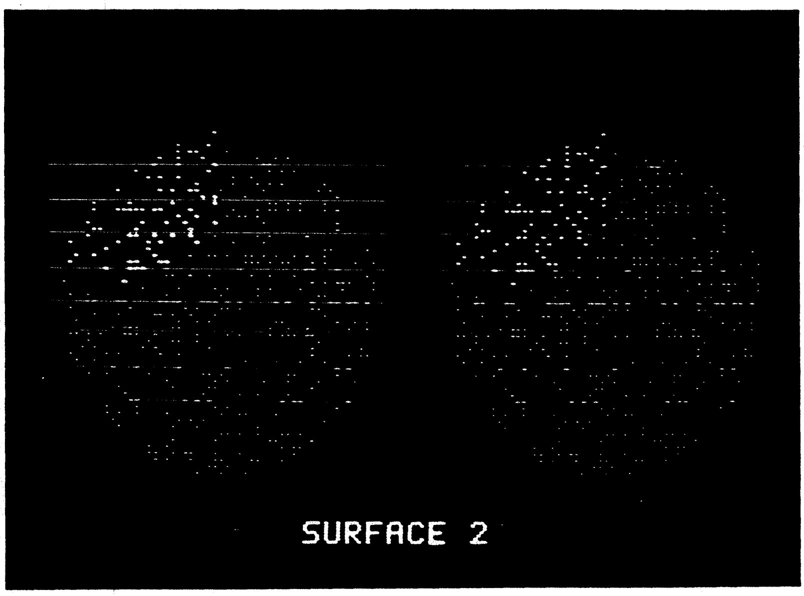
Flattened Sphere / View 2 / Input Data

Figure 6.3.1-7



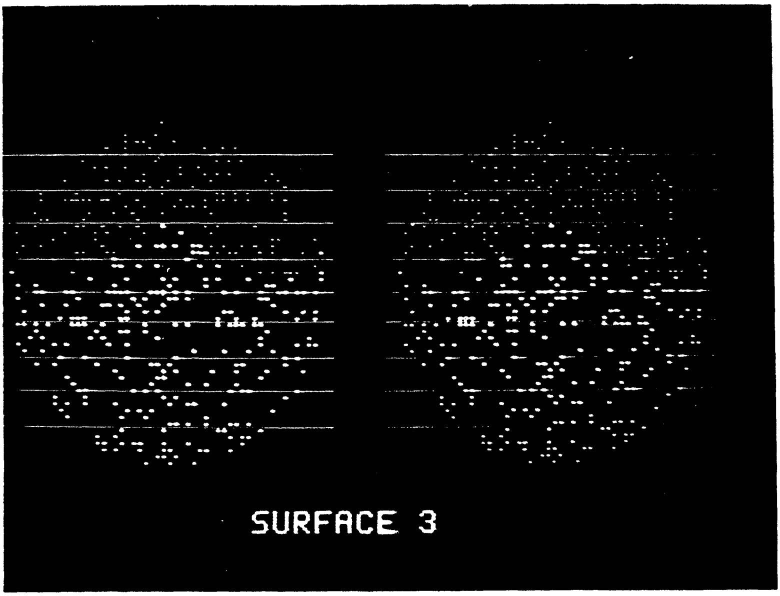
Flattened Sphere / View 2 / Surface 1

Figure 6.3.1-8



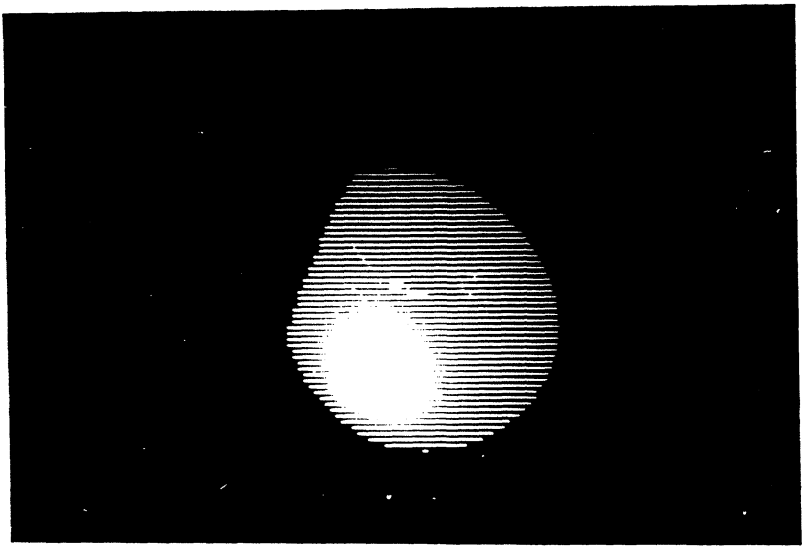
Flattened Sphere / View 2 / Surface 2

Figure 6.3.1-9



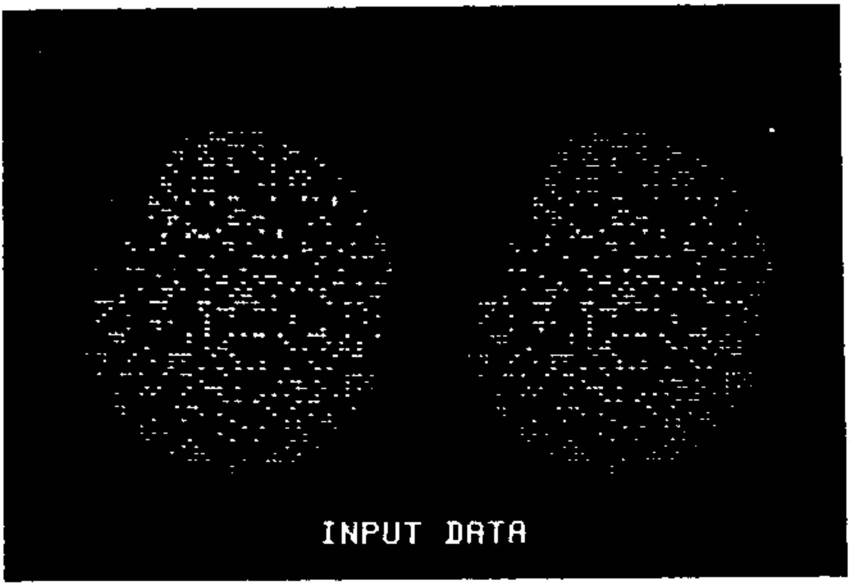
Flattened Sphere / View 2 / Surface 3

Figure 6.3.1-10



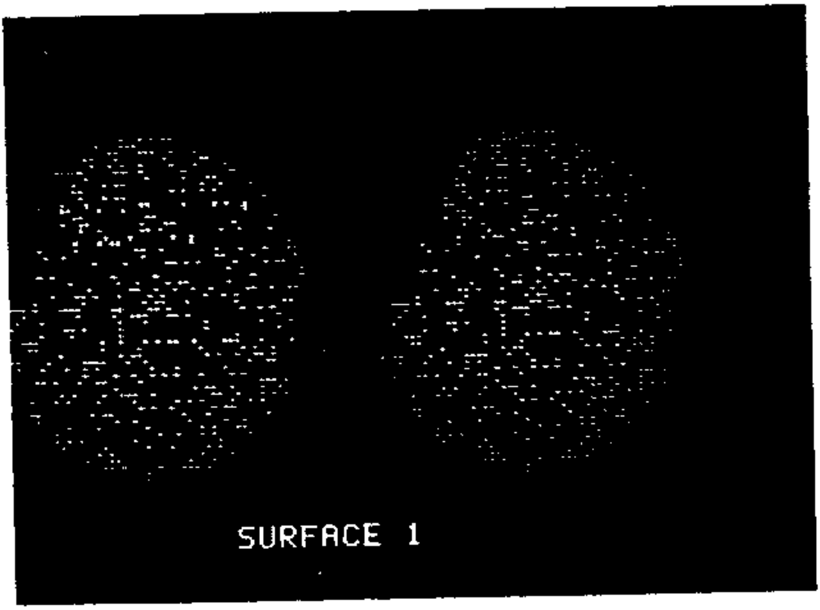
Flattened Sphere / View 3 / Shaded Image

Figure 6.3.1-11



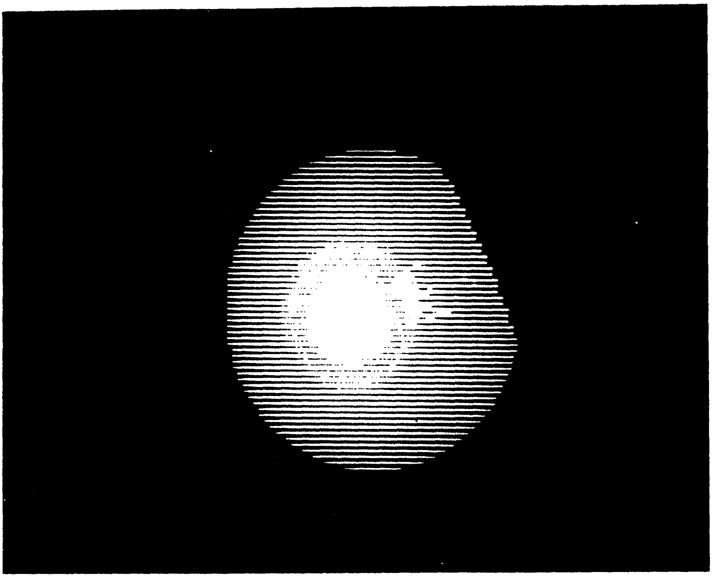
Flattened Sphere / View 3 / Input Data

Figure 6.3.1-12



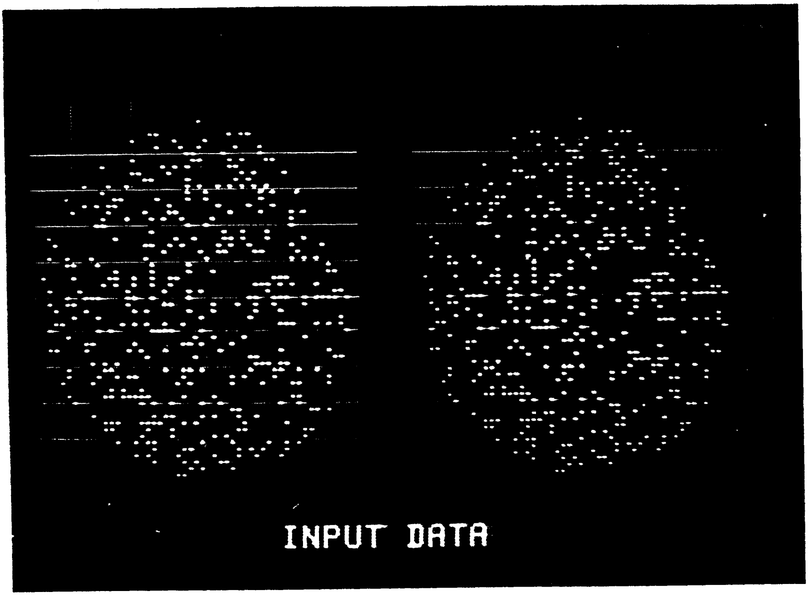
Flattened Sphere / View 3 / Surface 1

Figure 6-3.1-13



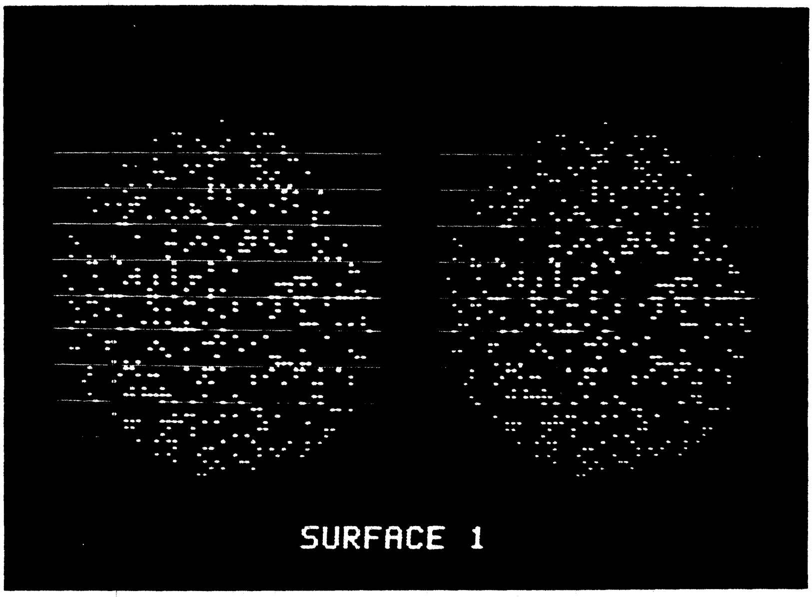
Flattened Sphere / View 4 / Shaded Image

Figure 6.3.1-14



Flattened Sphere / View 4 / Input Data

Figure 6.3.1-15

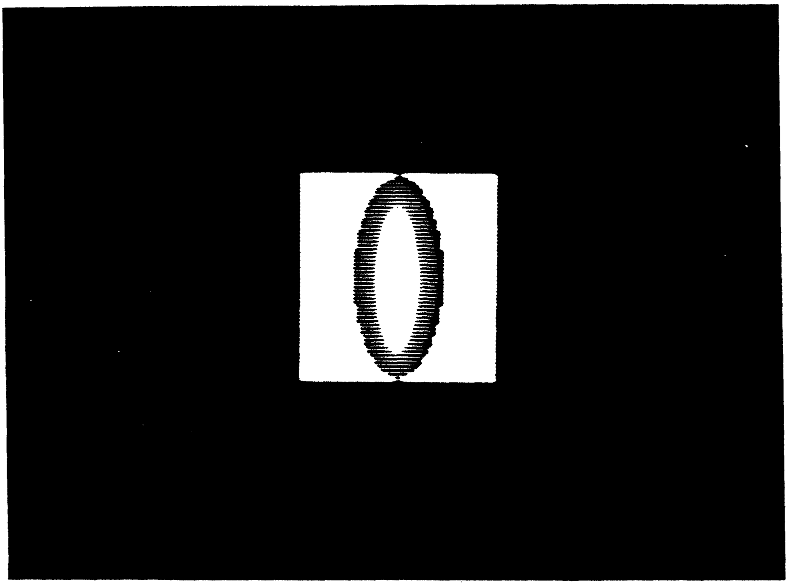


Flattened Sphere / View 4 / Surface 1

Figure 6.3.1-16

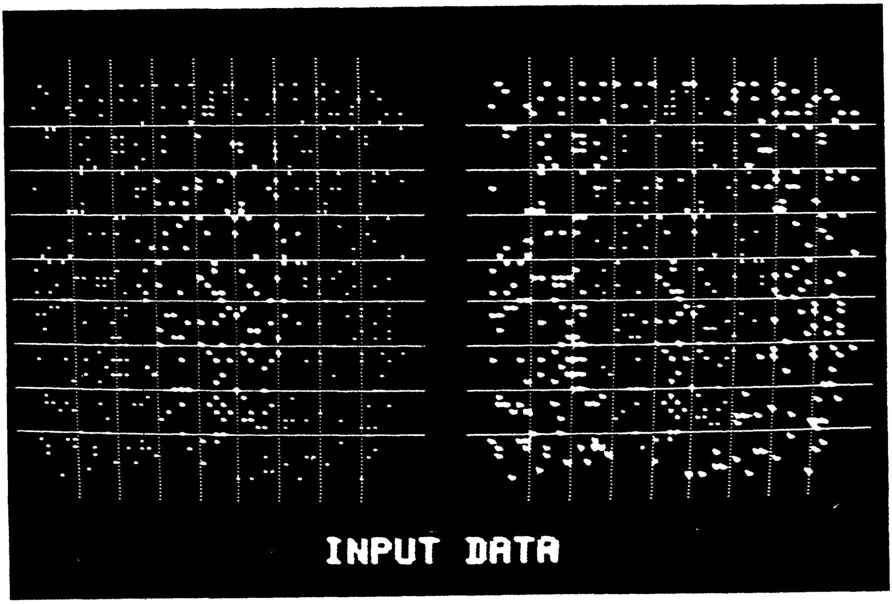
•3.2 Cube And Ellipsoid -

The test object labelled "cube and ellipsoid" is a cut Lth half an ellipsoid protruding from one of the cube' Lanar faces. The purpose of the object is to test tl bility to grow surface primitives across narrow necks j le presence of other surfaces such as in view one. Tt nalyses of views one, two and four were completed withoi Lfficulty. In view three, a request was made f< ipplemental information about the area of the ellipsoi< lere were seventeen cells covering the unidentified are< id this should have been enough for the labelling procei o function. However, five of the cells had only 01 iderlying data point and were discarded. In addition, fi' ther cells had only two underlying data points. The: ells contained information of a doubtful nature. The sha] abelling process produced several candidates for surfa rimitives. However, they all contained too few data poin o fit a primitive accurately. The integration of t esults of the local analyses produced an accura escription. The unidentified surface of view three w een and recorded in other local results. The final glob escription consisted of six planar primitives and o llipsoid primitive.



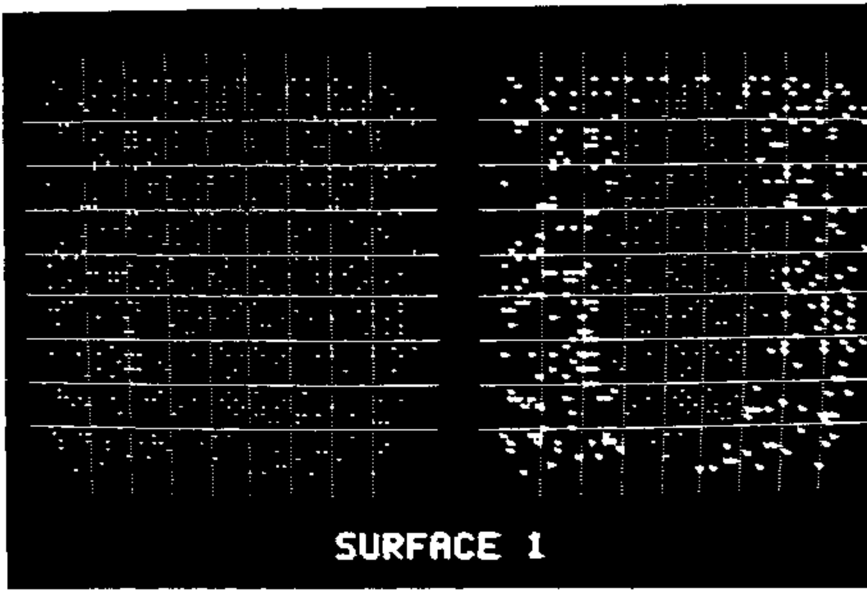
Cube and Ellipsoid / View 1 / Shaded Image

Figure 6.3.2-1



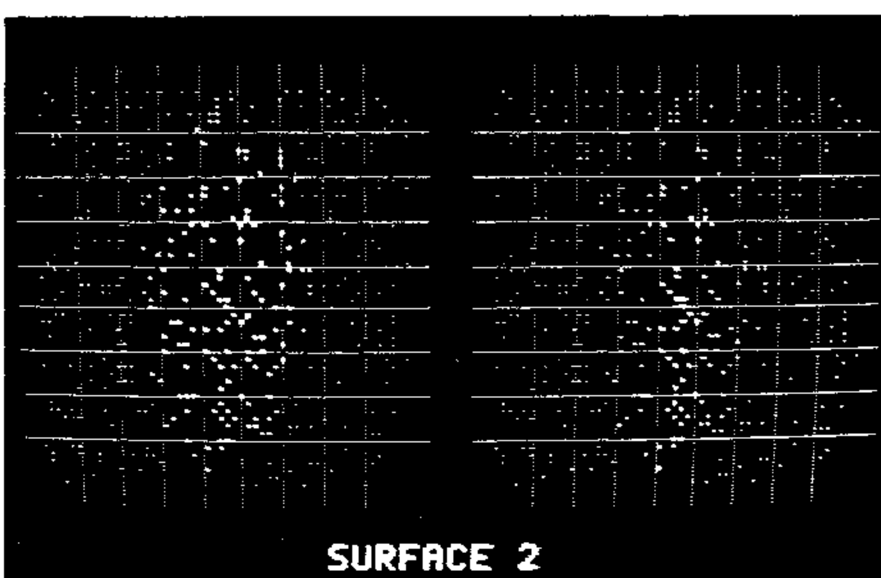
Cube and Ellipsoid / View 1 / Input Data

Figure 6.3.2-2



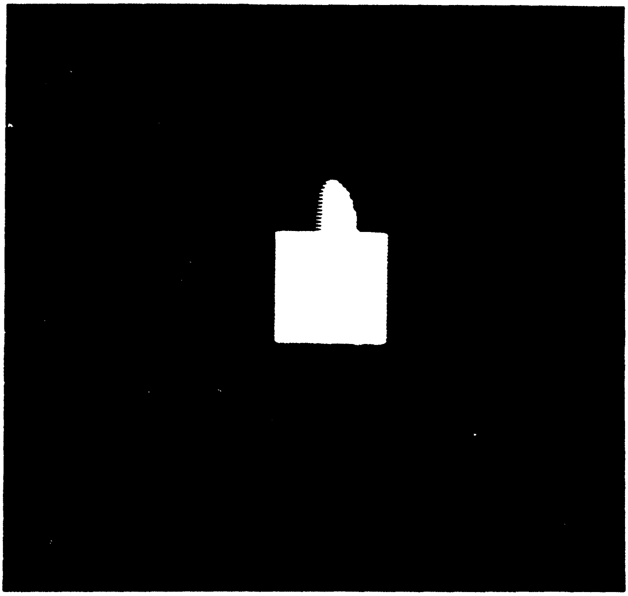
Cube and Ellipsoid / View 1 / Surface 1

Figure 6.3.2-3



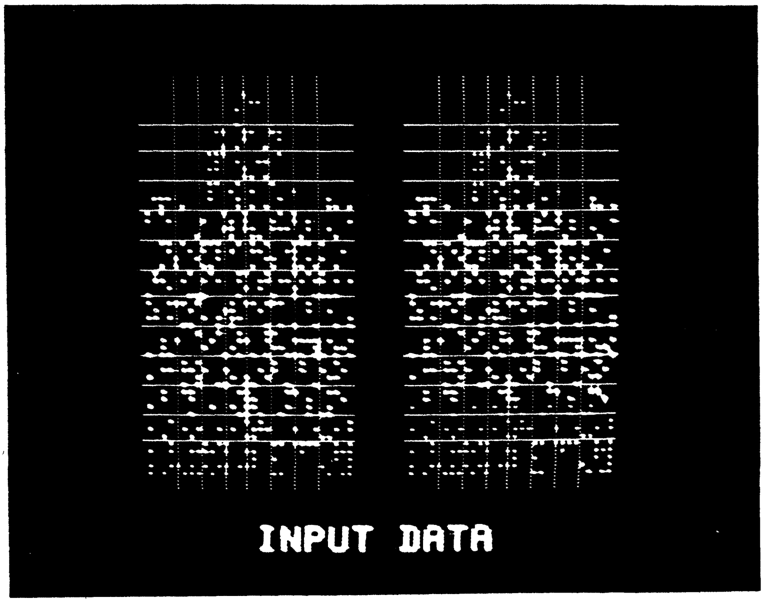
Cube and Ellipsoid / View 1 / Surface 2

Figure 6.3.2-4



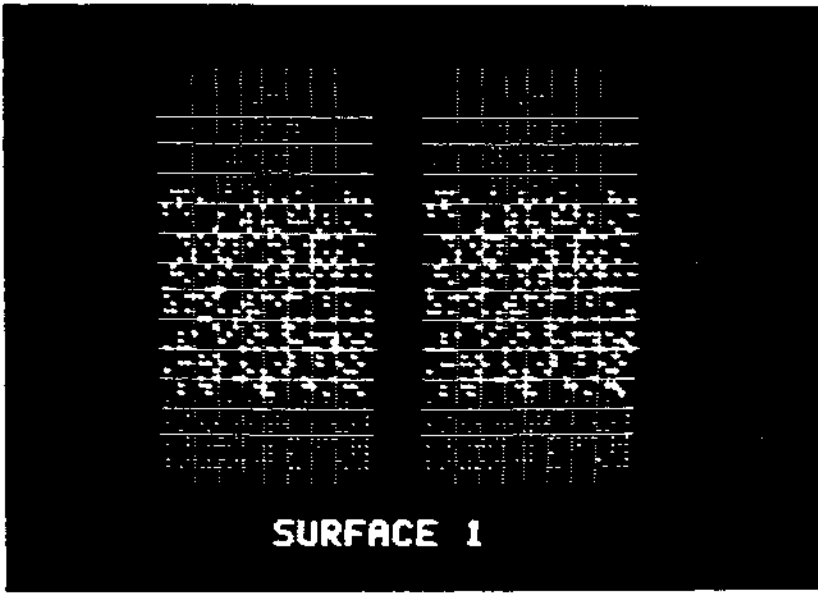
Cube and Ellipsoid / View 2 / Shaded Image

Figure 6.3.2-5



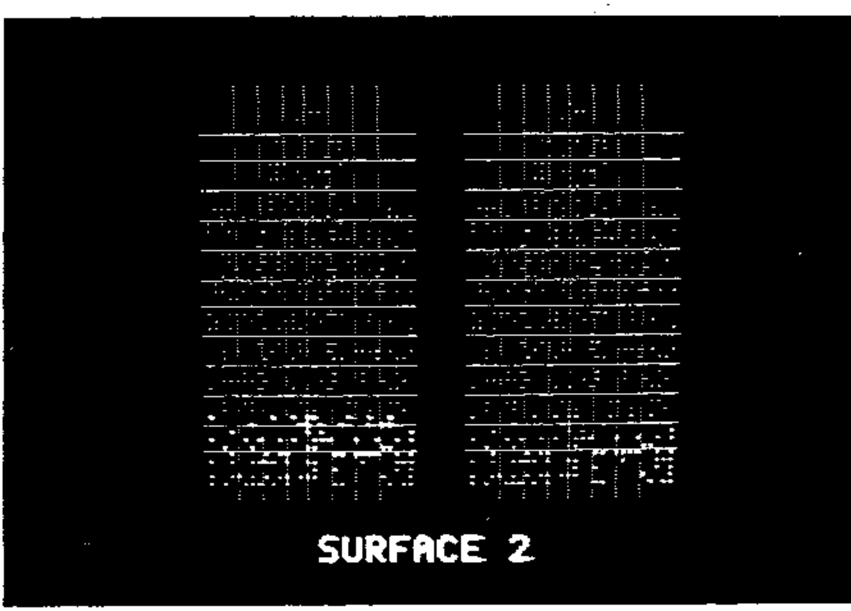
Cube and Ellipsoid / View 2 / Input Data

Figure 6.3.2-6



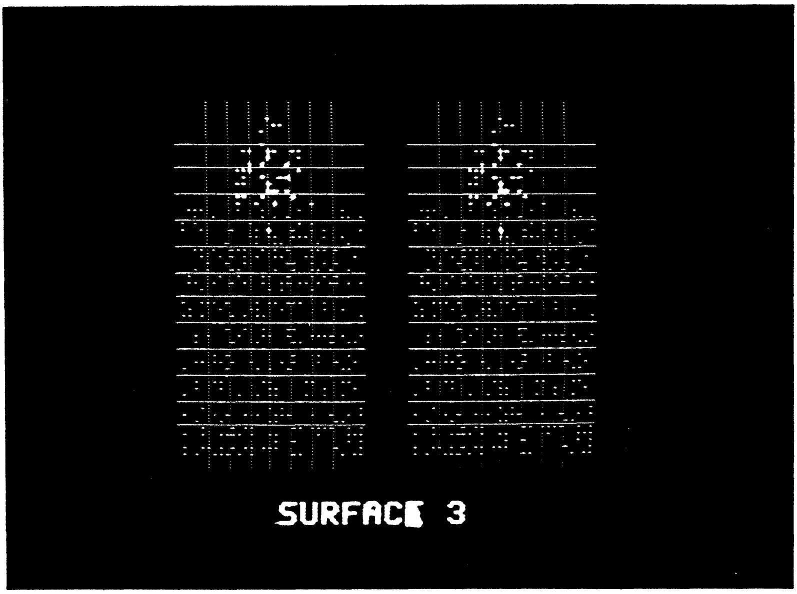
Cube and Ellipsoid / View 2 / Surface 1

Figure 6.3.2-7



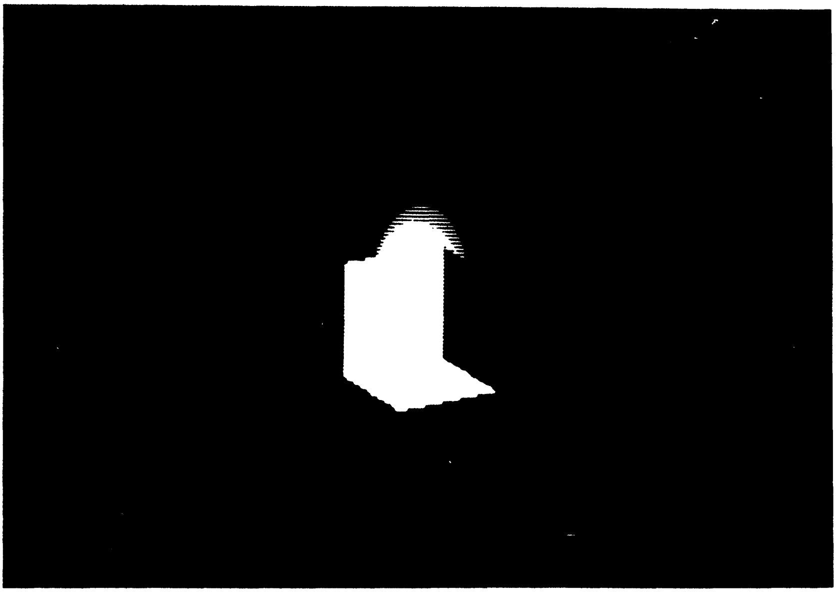
Cube and Ellipsoid / View 2 / Surface 2

Figure 6.3.2-8



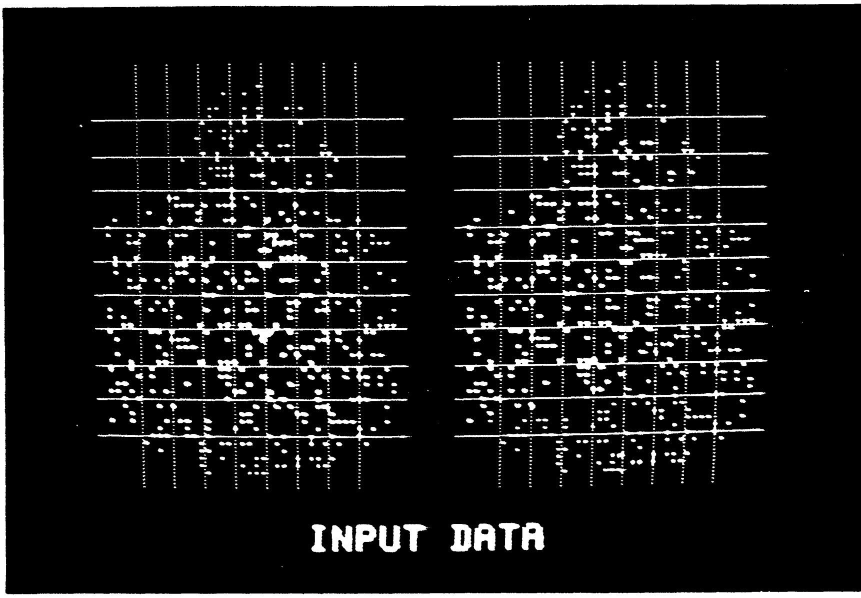
Cube and Ellipsoid / View 2 / Surface 3

Figure 6.3.2-9



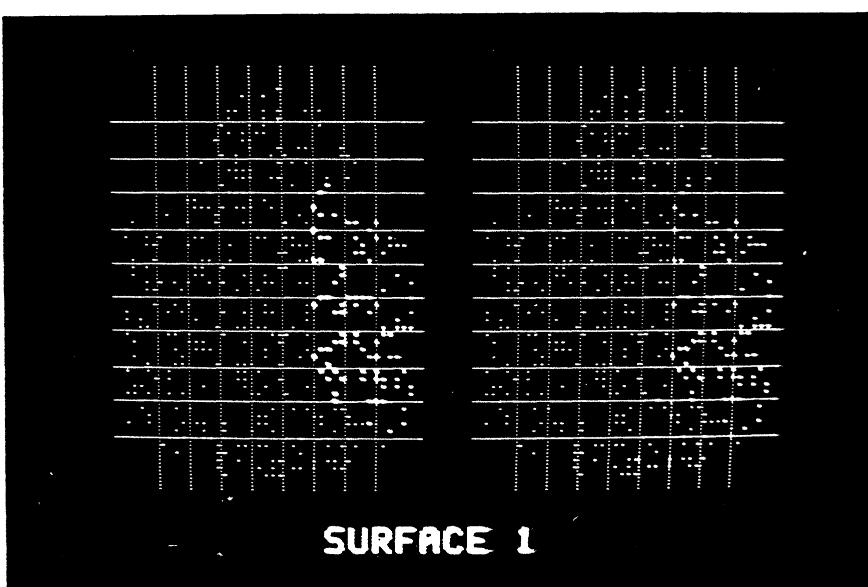
Cube and Ellipsoid / View 3 / Shaded Image

Figure 6.3.2-10



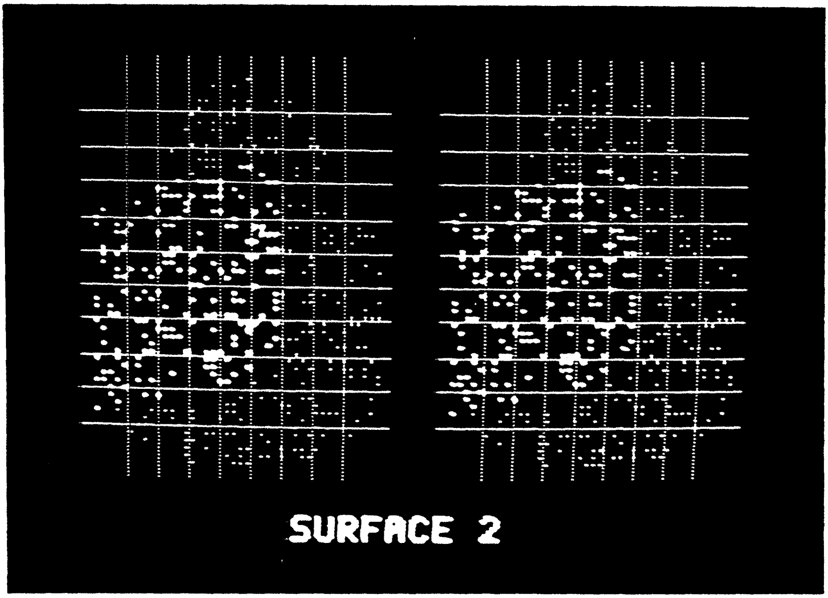
Cube and Ellipsoid / View 3 / Input Data

Figure 6.3.2-11



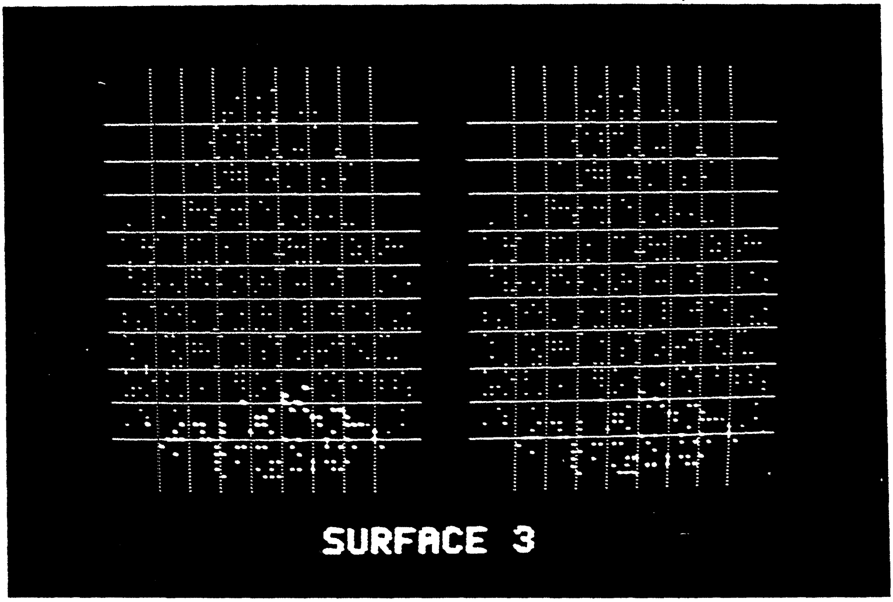
Cube and Ellipsoid / View 3 / Surface 1

Figure 6.3.2-12



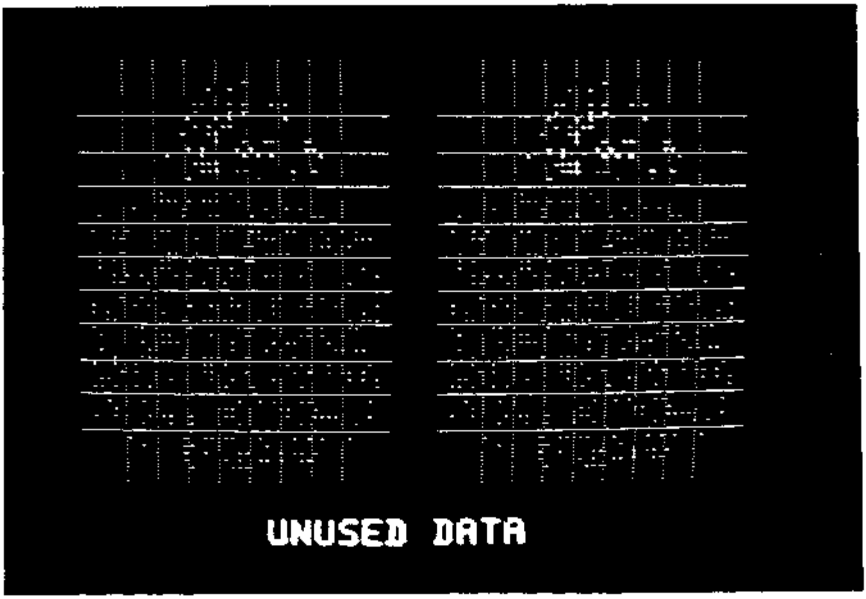
Cube and Ellipsoid / View 3 / Surface 2

Figure 6.3.2-13



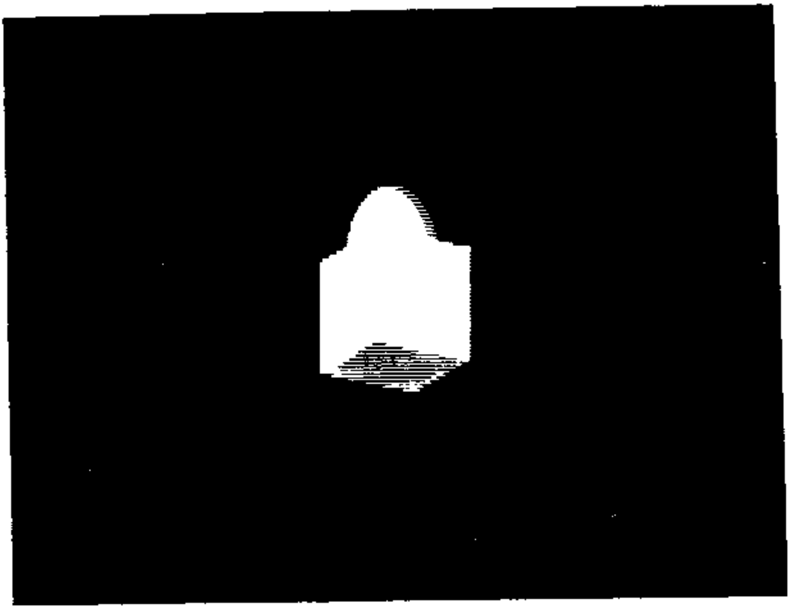
Cube and Ellipsoid / View 3 / Surface 3

Figure 6.3.2-14



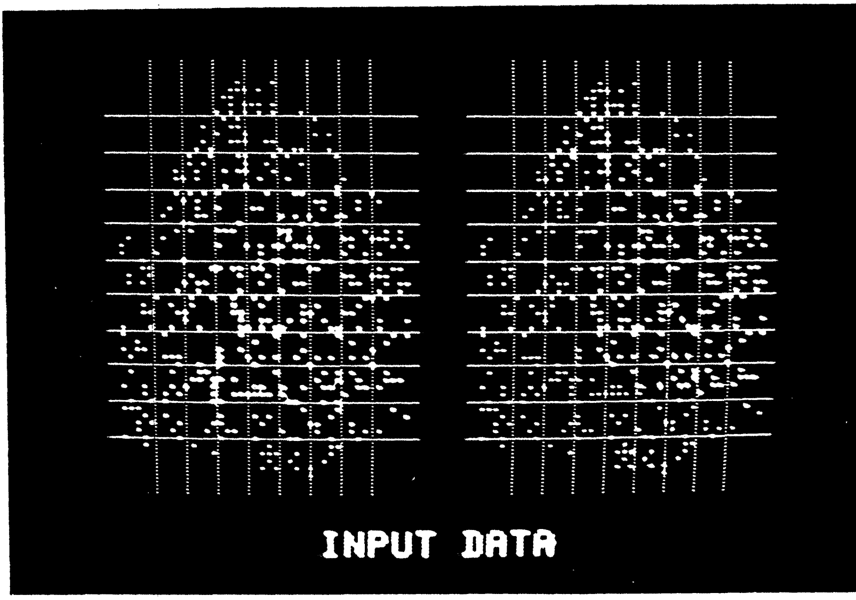
Cube and Ellipsoid / View 3 / Unused Data

Figure 6.3.2-15



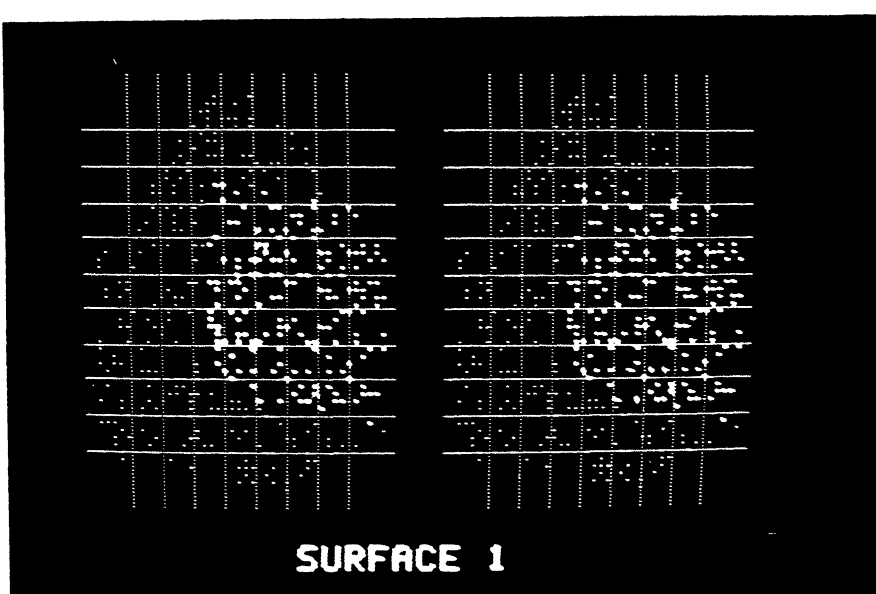
Cube and Ellipsoid / View 4 / Shaded Image

Figure 6.3.2-16



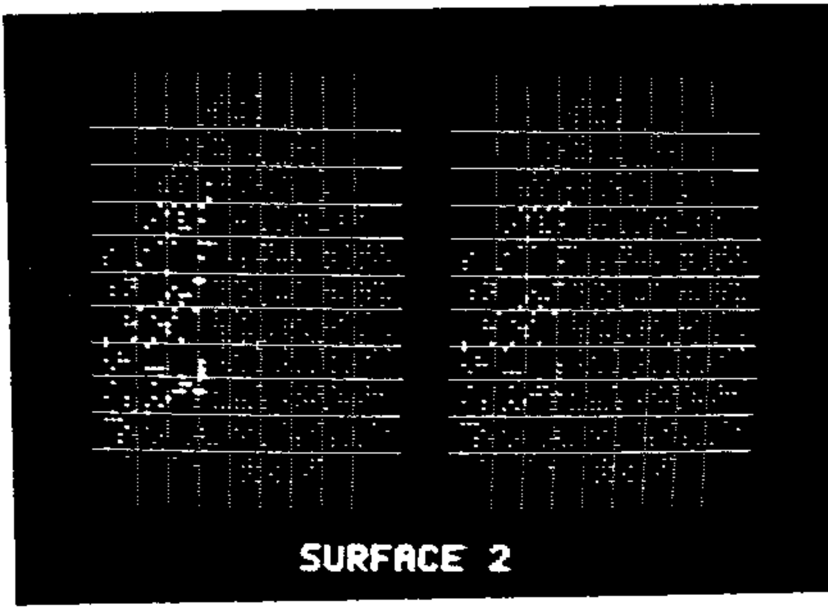
Cube and Ellipsoid / View 4 / Input Data

Figure 6.3.2-17



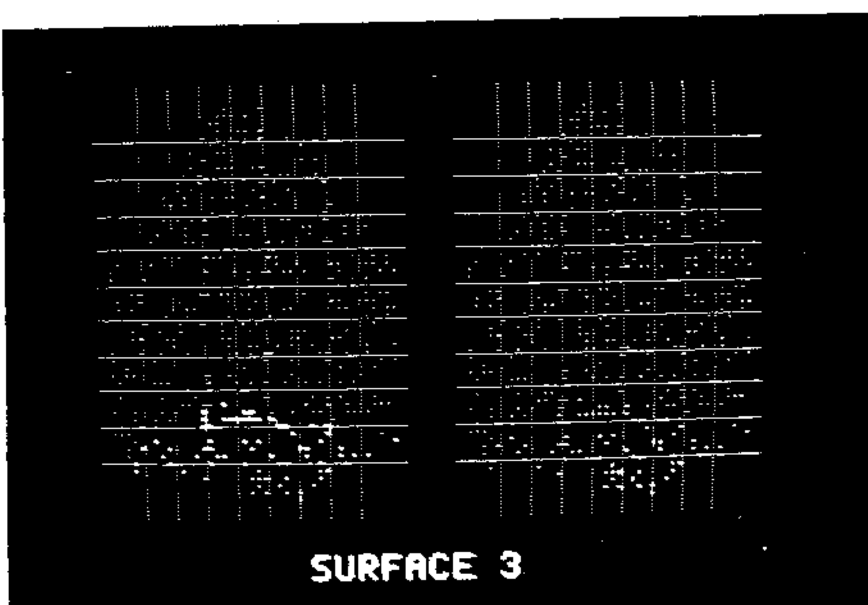
Cube and Ellipsoid / View 4 / Surface 1

Figure 6.3.2-18



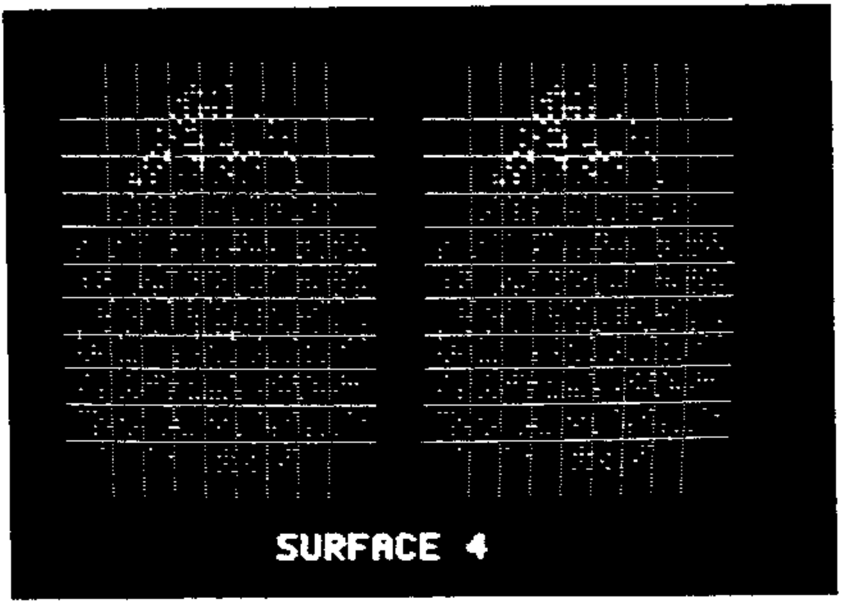
Cube and Ellipsoid / View 4 / Surface 2

Figure 6.3.2-19



Cube and Ellipsoid / View 4 / Surface 3

Figure 6.3.2-20

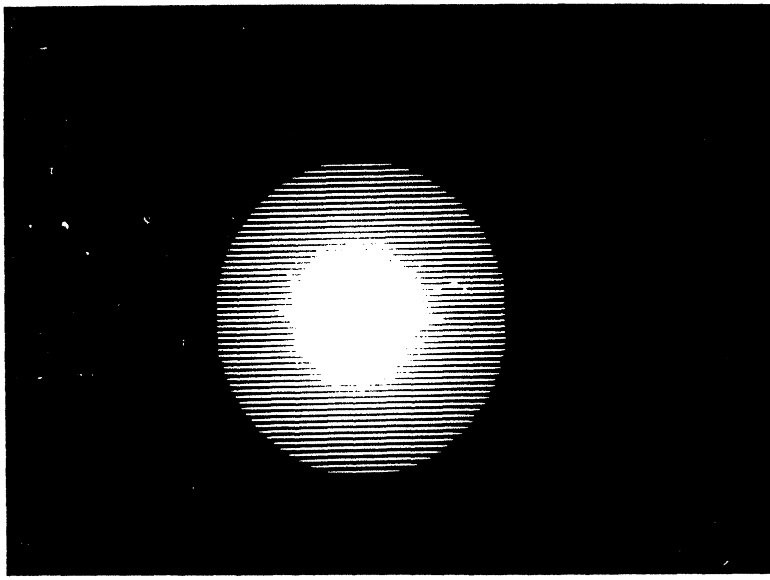


Cube and Ellipsoid / View 4 / Surface 4

Figure 6.3.2-21

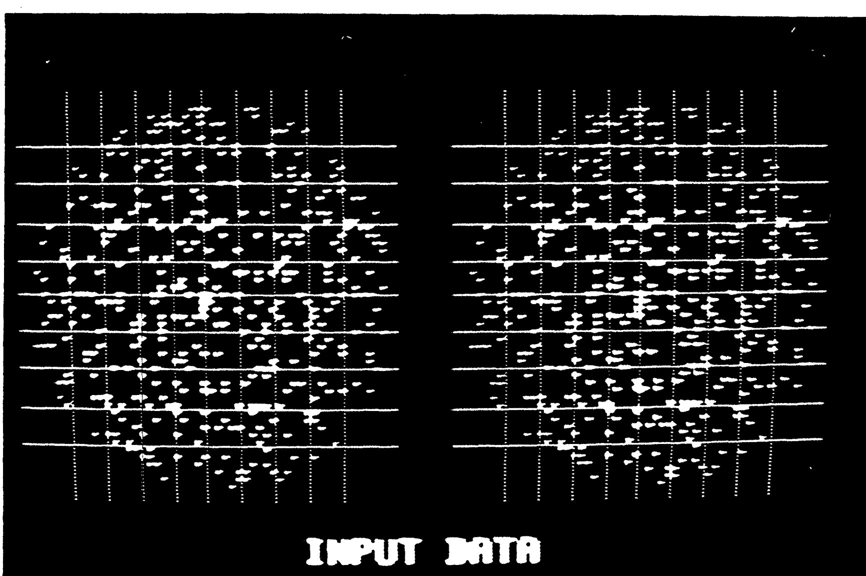
3.3 Cylinder And Sphere -

The test object labelled "cylinder and sphere" i
mposed of a cylinder with one of its ends adjoined to
misphere. The purpose of the object is to test th
bility to distinguish the change from one quadric surfac
another quadric surface. The analyses of views one, tw
d four was completed without difficulty. In view three a
rror occurred in the analysis of the planar surface tha
orms the bottom of the cylinder. On the first pass ove
e data points, the bottom of the cylinder was detected a
long, narrow planar surface and was rejected because o
e cylinder restriction. The extent of the surface was no
ruly so but appeared in the summary as such because th
djacent cylinder masked its presence in the adjoini
ells. After finding the cylinder and sphere, it attempte
mmediately to fit a quadric surface to the underlyi
lanar surface points. This resulted in only half the da
oints being used. In the next pass after the used da
oints were removed and a new summary computed, it found th
lanar surface based on the remaining data points. Th
ntegration of the local results produced an inaccura
escription with internal inconsistencies.



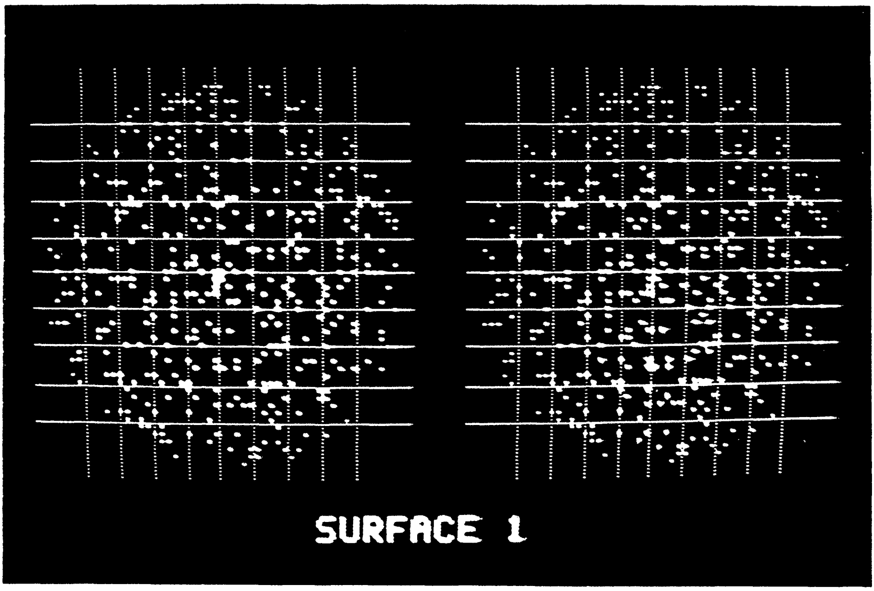
Cylinder and Sphere / View 1 / Shaded Image

Figure 6.3.3-1



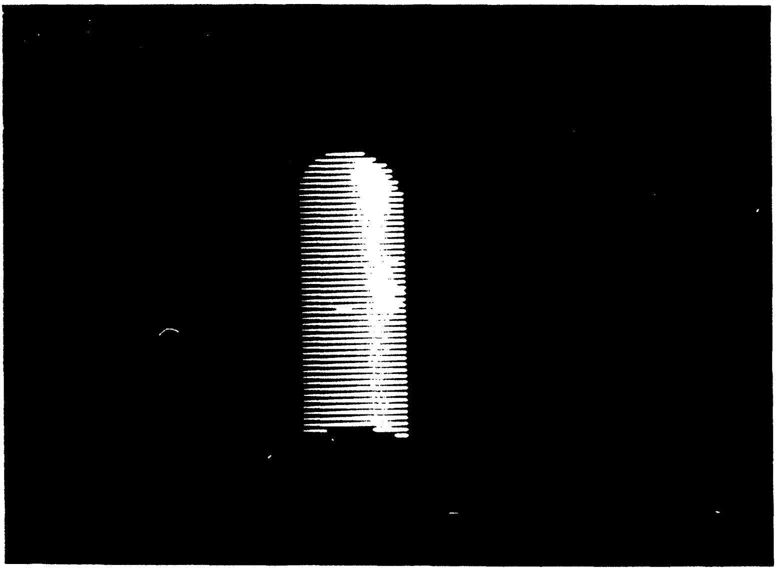
Cylinder and Sphere / View 1 / Input Data

Figure 6.3.3-2



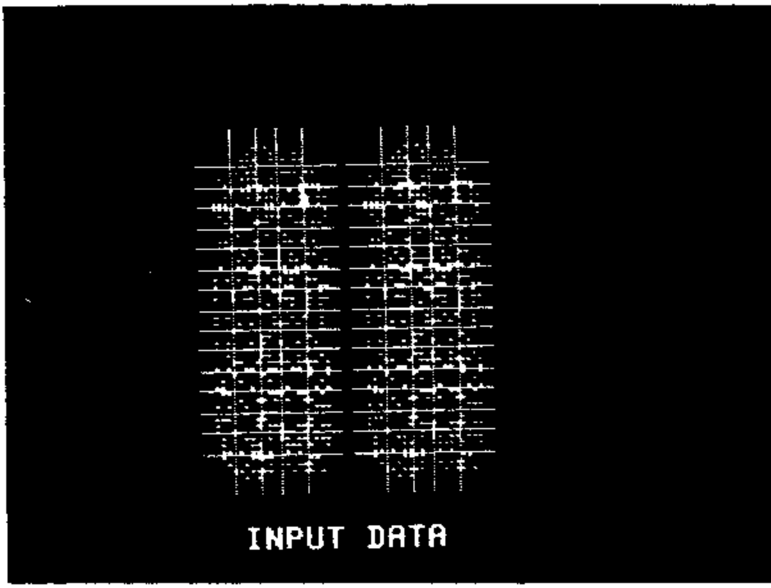
Cylinder and Sphere / View 1 / Surface 1

Figure 6.3.3-3



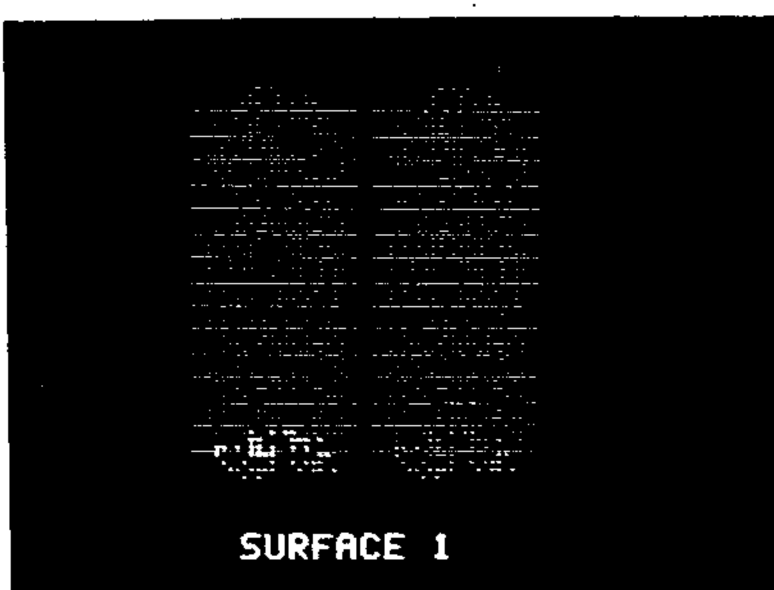
Cylinder and Sphere / View 2 / Shaded Image

Figure 6.3.3-4



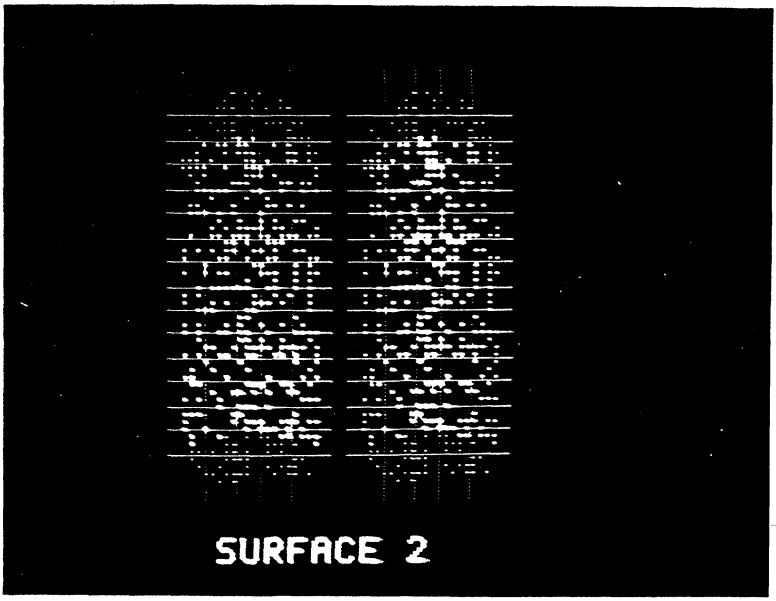
Cylinder and Sphere / View 2 / Input Data

Figure 6.3•3-5



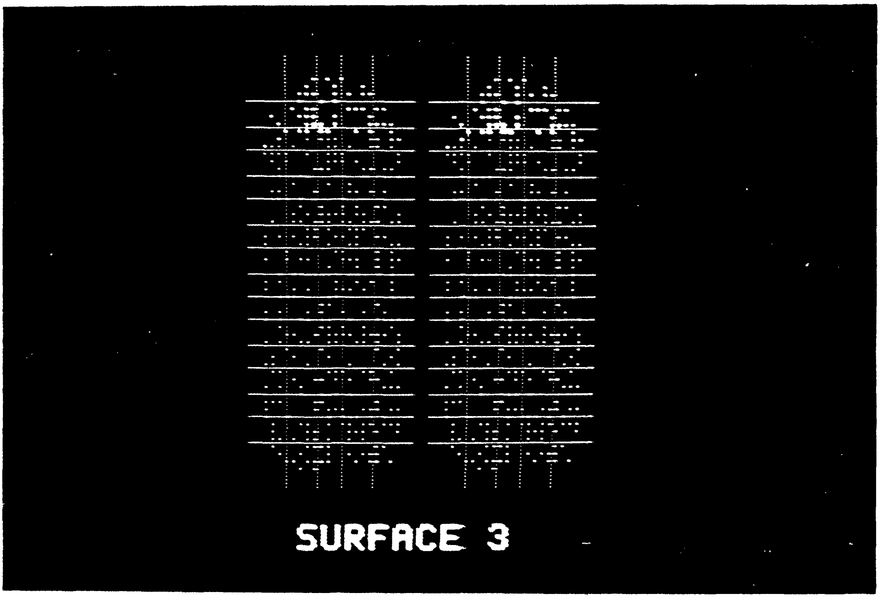
Cylinder and Sphere / View 2 / Surface 1

Figure 6.3.3-6



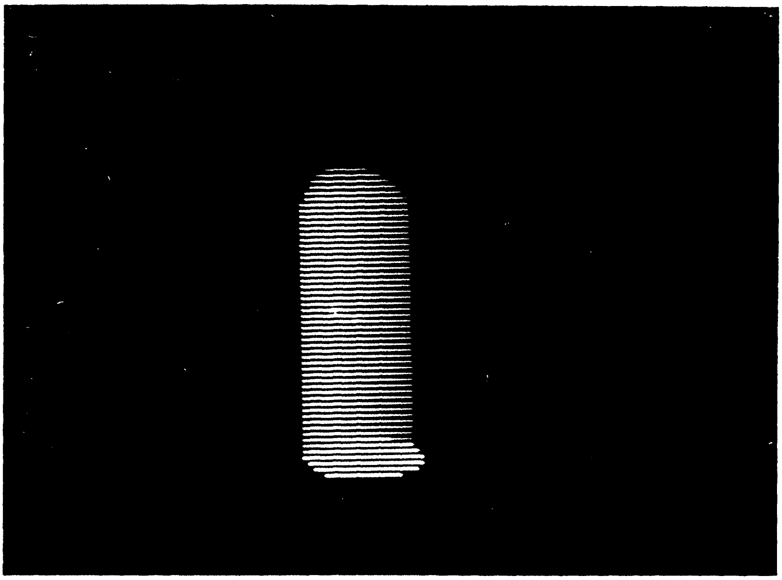
Cylinder and Sphere / View 2 / Surface 2

Figure 6.3.3-7



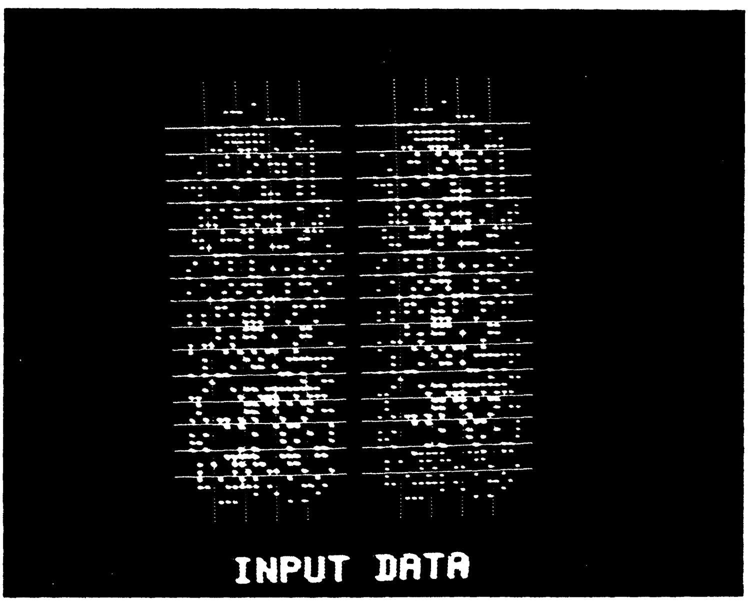
Cylinder and Sphere / View 2 / Surface 3

Figure 6.3.3-8



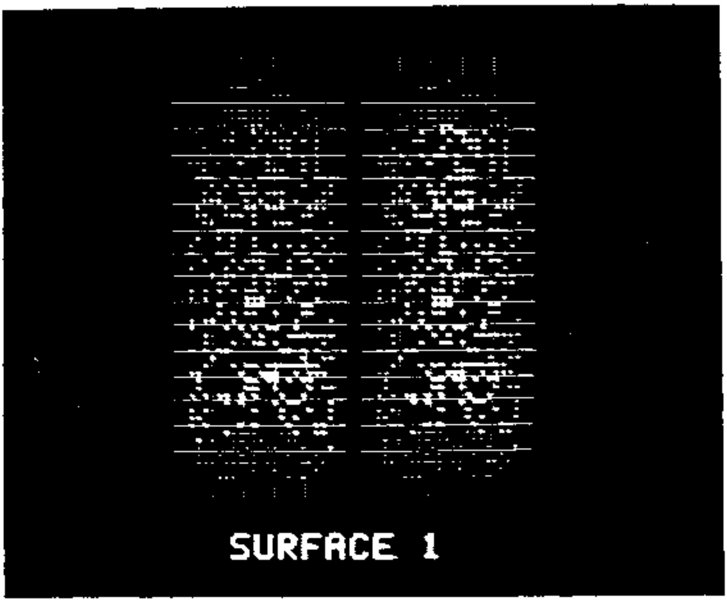
Cylinder and Sphere / View 3 / Shaded Image

Figure 6.3.3-9



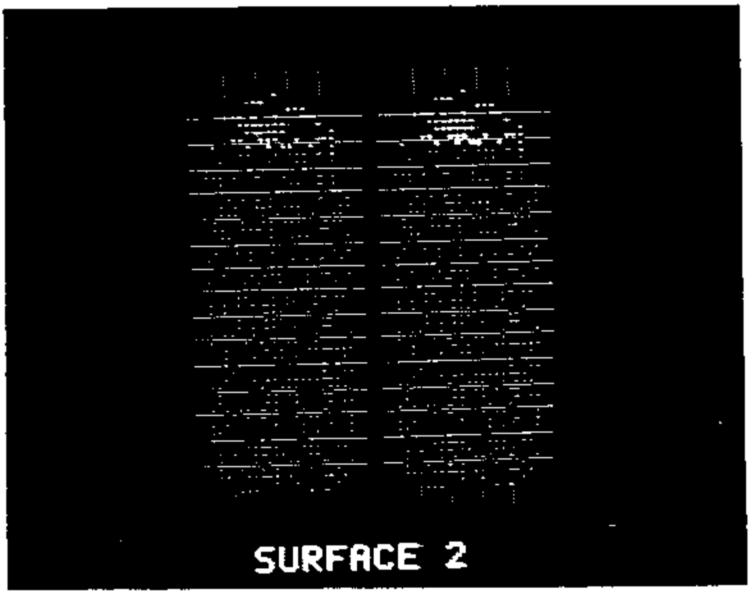
Cylinder and Sphere / View 3 / Input Data

Figure 6.3.3-10



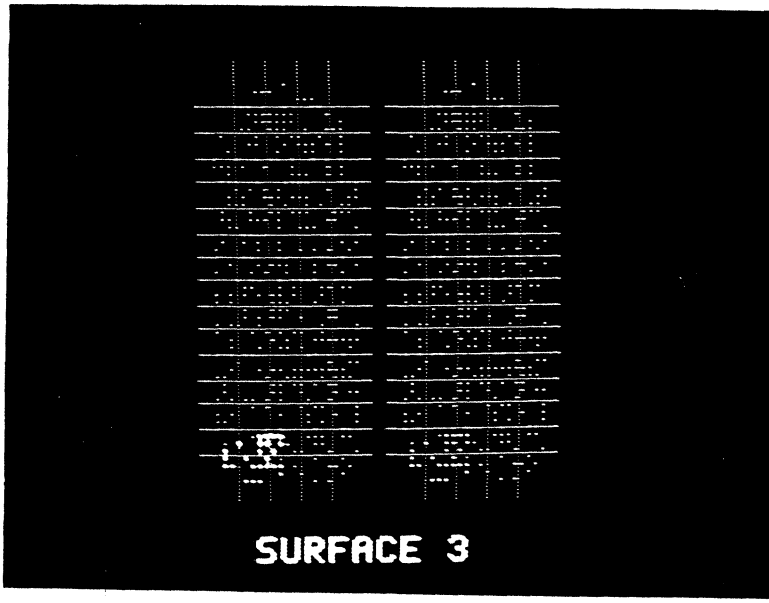
Cylinder and Sphere / View 3 / Surface 1

Figure 6.3.3-11



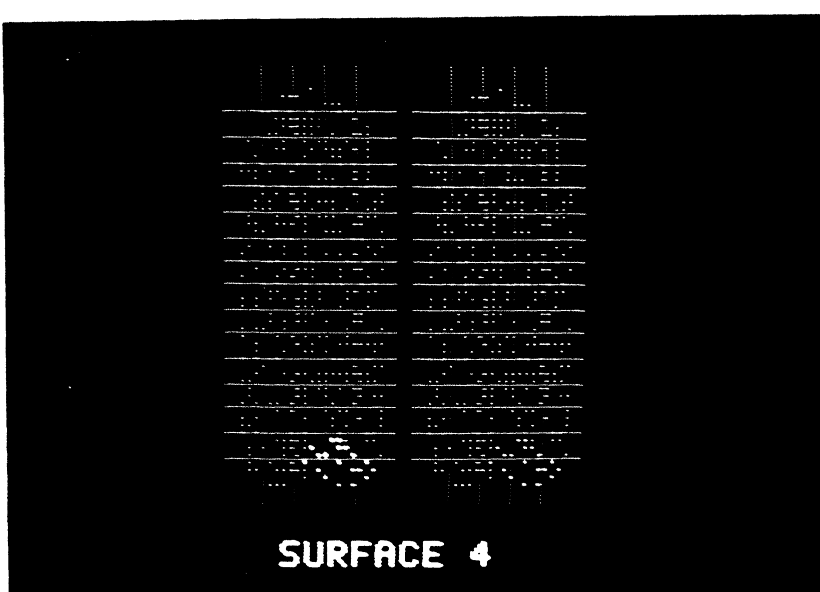
Cylinder and Sphere / View 3 / Surface 2

Figure 6.3.3-12



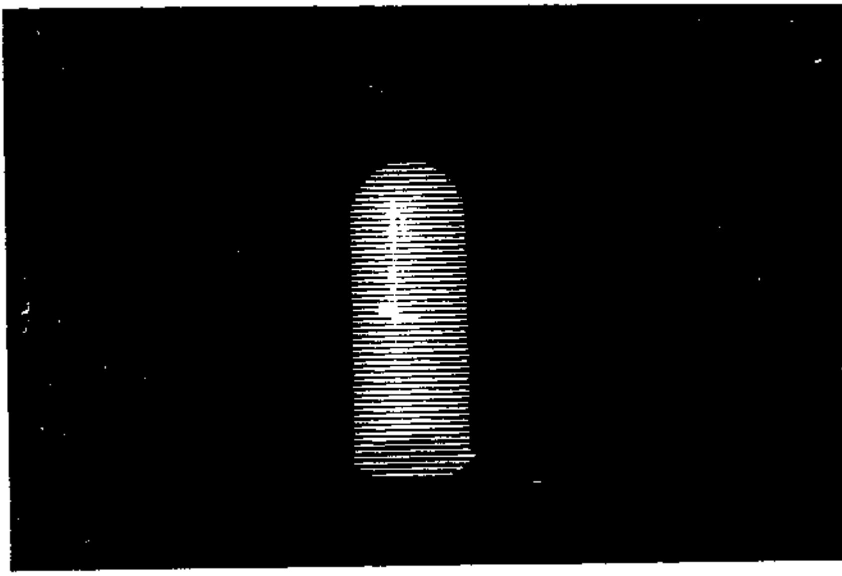
Cylinder and Sphere / View 3 / Surface 3

Figure 6.3.3-13



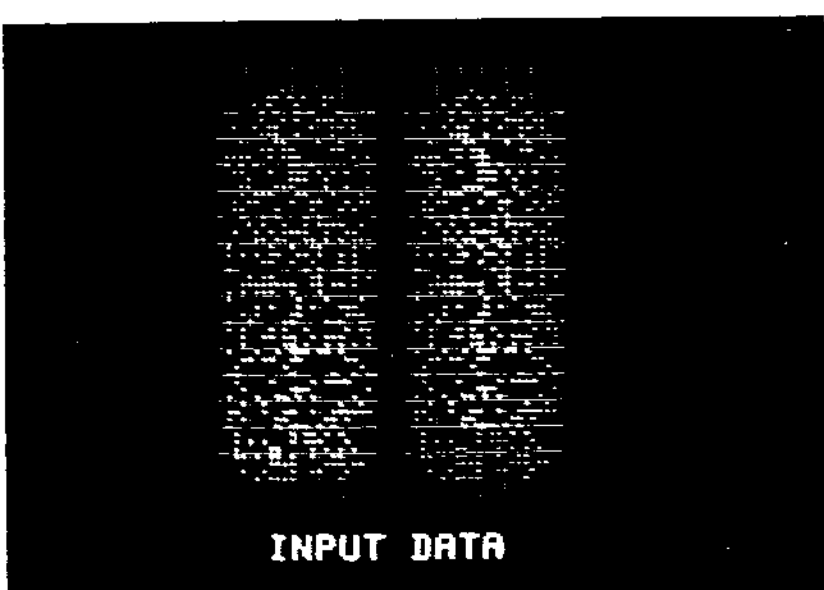
Cylinder and Sphere / View 3 / Surface 4

Figure 6.3.3-14

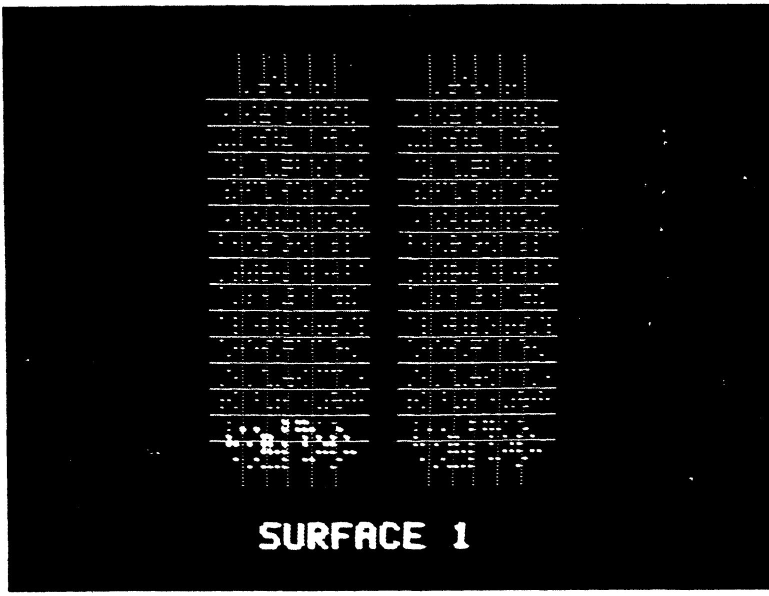


Cylinder and Sphere / View 4 / Shaded Image

Figure 6.3.3-15

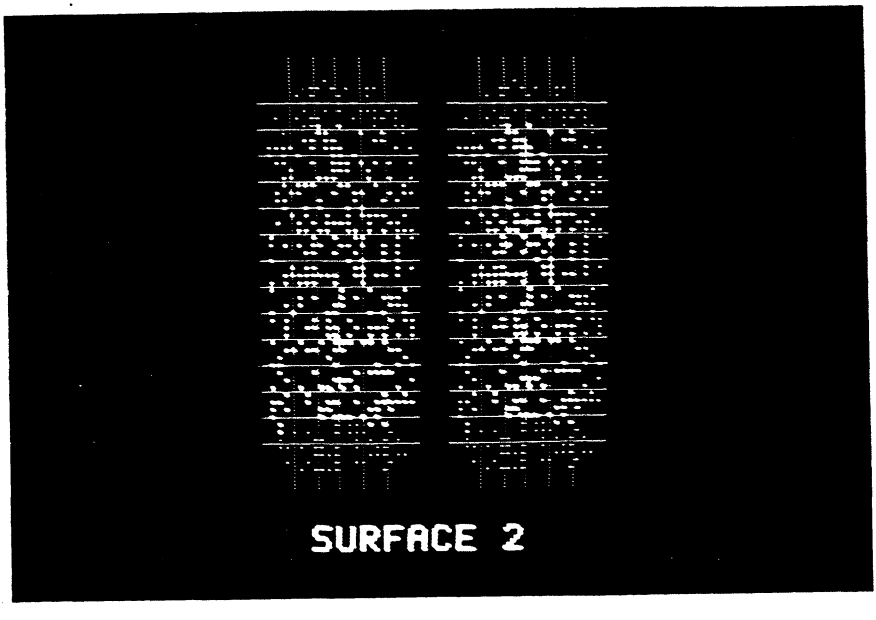


Cylinder and Sphere / View A / Input Data



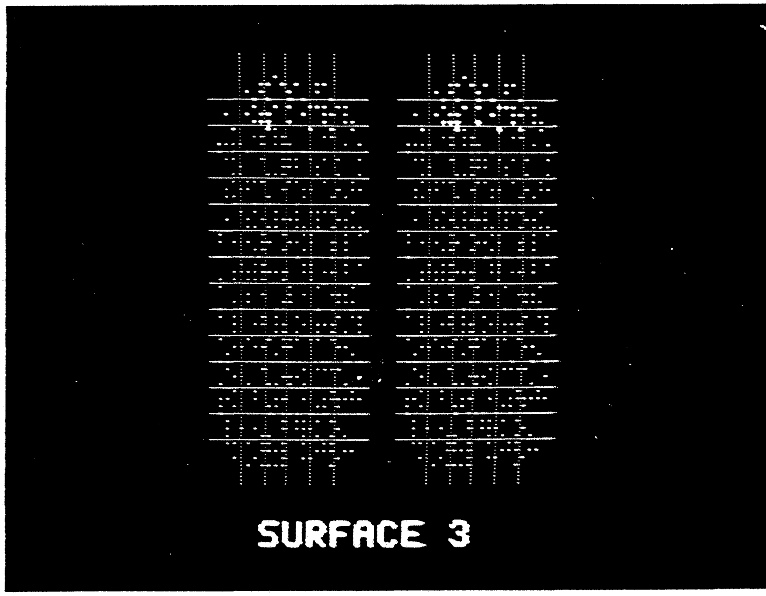
Cylinder and Sphere / View 4 / Surface 1

Figure 6.3.3-17



Cylinder and Sphere / View 4 / Surface 2

Figure 6.3.3-18

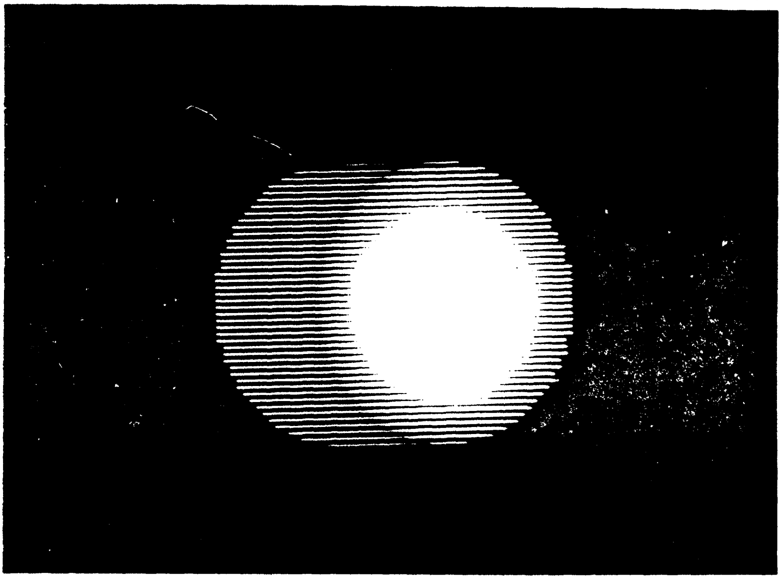


Cylinder and Sphere / View 4 / Surface 3

Figure 6.3.3-19

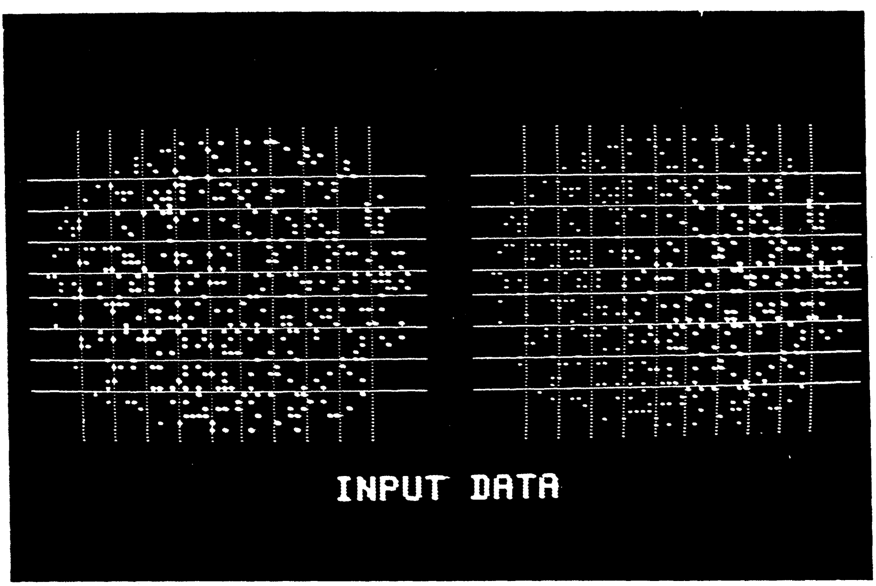
.3.4 Cylinder And Negative Sphere -

The test object labelled "cylinder and negative spher s a cylinder with half a sphere removed from one end. T urpose of the object is to test the ability to identify arge concave surface of a simple object. The analyses he first three views were completed without difficulty. iew four, a request for supplemental information about t ottom area of the cylinder was made. The analysis detect nd rejected a long, narrow region because of the cylinc estriction. It failed to make an error similar to t rror in the cylinder and sphere example because the plar urface was represented by a smaller number of data point he integration of the results of these four local analys roduced an accurate description of the object. The surfa ot identified in view three was seen and recorded in oth ocal results. The final global description consisted ne spherical primitive, one cylindrical primitive and lanar primitive.



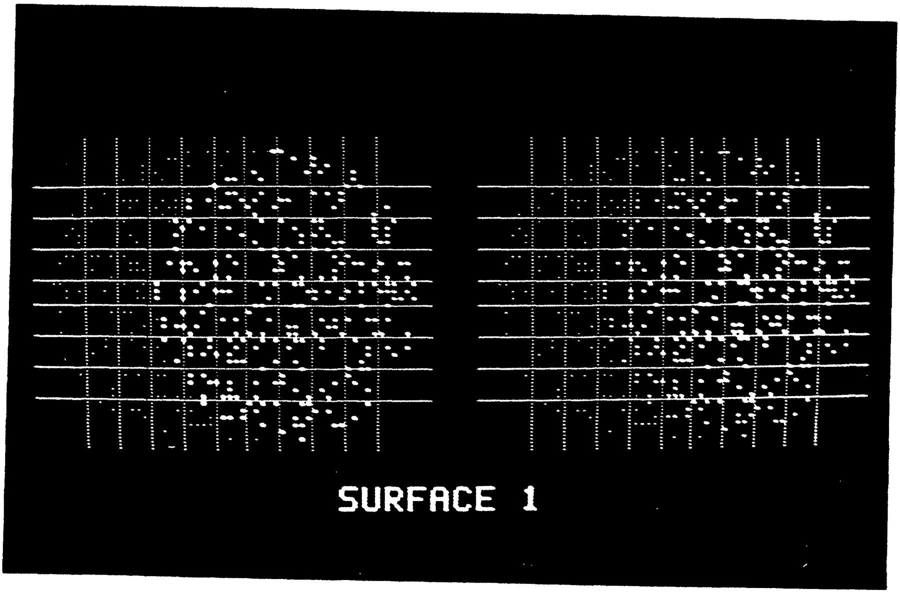
Cylinder and Negative Sphere / View 1 / Shaded Image

Figure 6.3.4-1



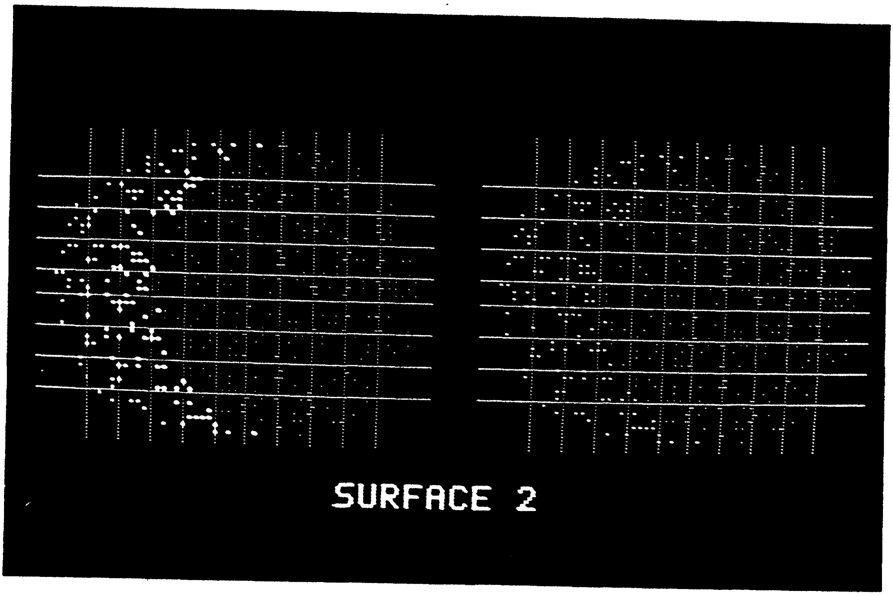
Cylinder and Negative Sphere / View 1 / Input Data

Figure 6.3.4-2



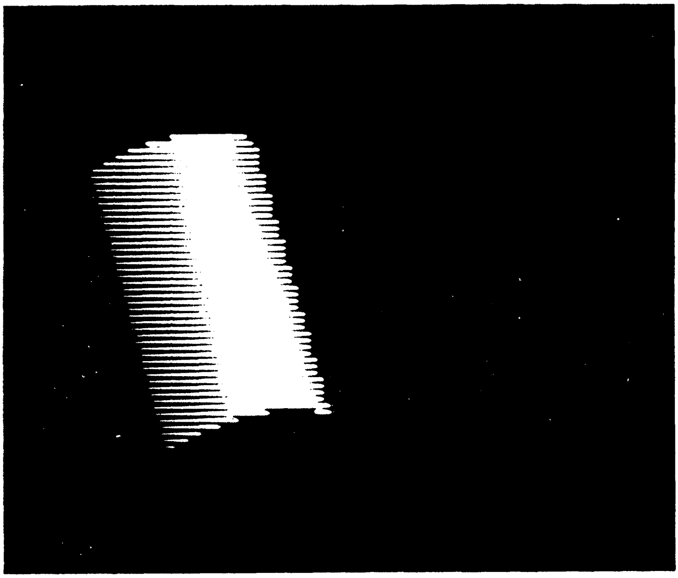
Cylinder and Negative Sphere / View 1 / Surface 1

Figure 6.3.4-3



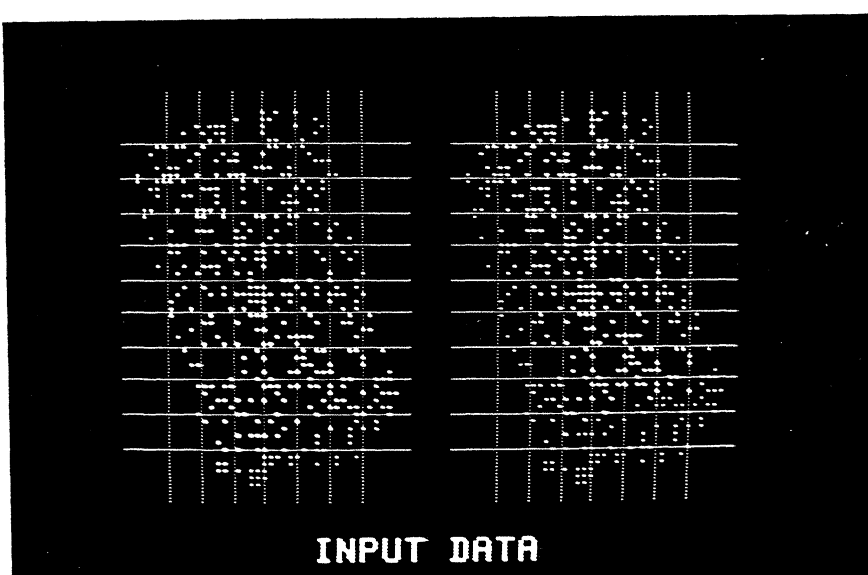
Cylinder and Negative Sphere / View 1 / Surface 2

Figure 6.3.4-4



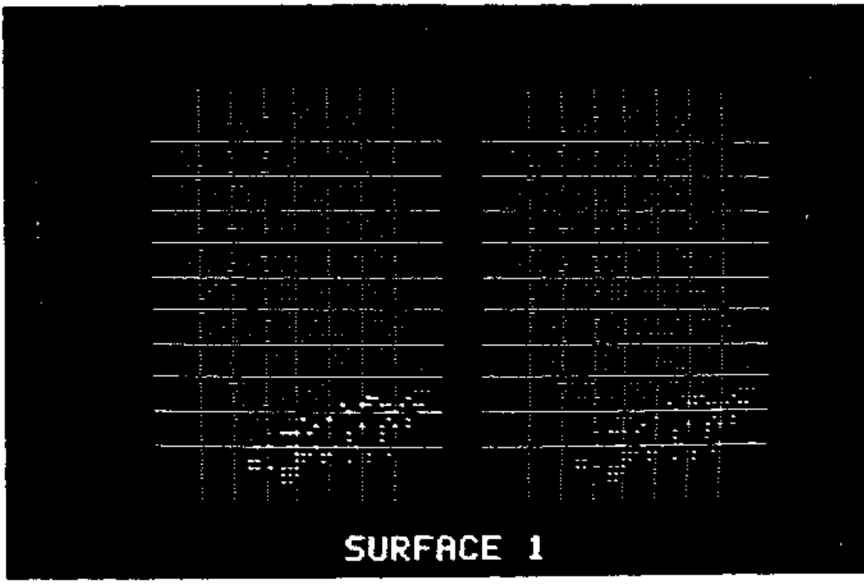
Cylinder and Negative Sphere / View 2 / Shaded Image

Figure 6.3.4-5



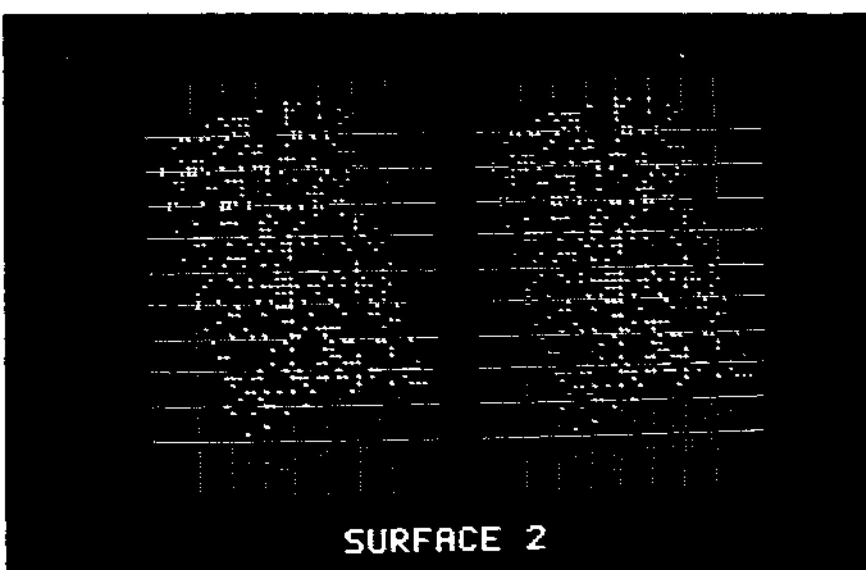
Cylinder and Negative Sphere / View 2 / Input Data

Figure 6.3.4-6



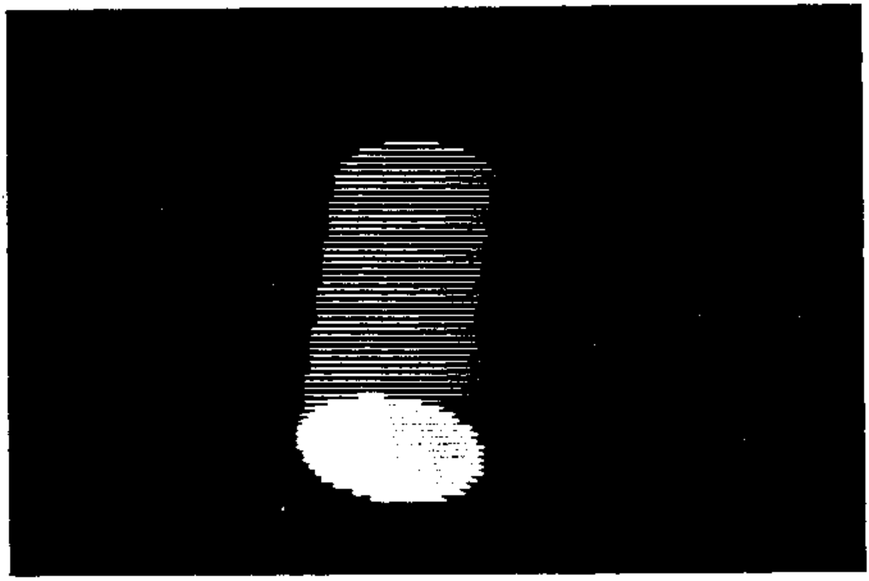
Cylinder and Negative Sphere / View 2 / Surface 1

Figure 6.3.4-7



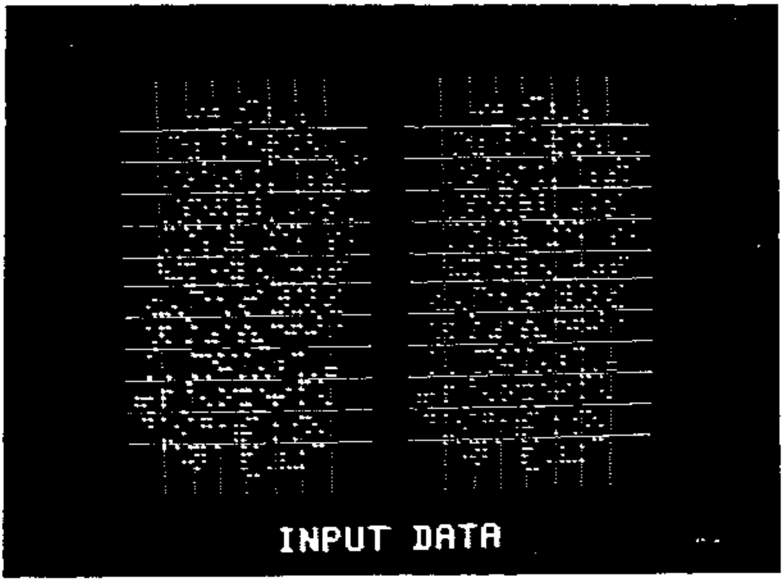
Cylinder and Negative Sphere / View 2 / Surface 2

Figure 6.3.4-8



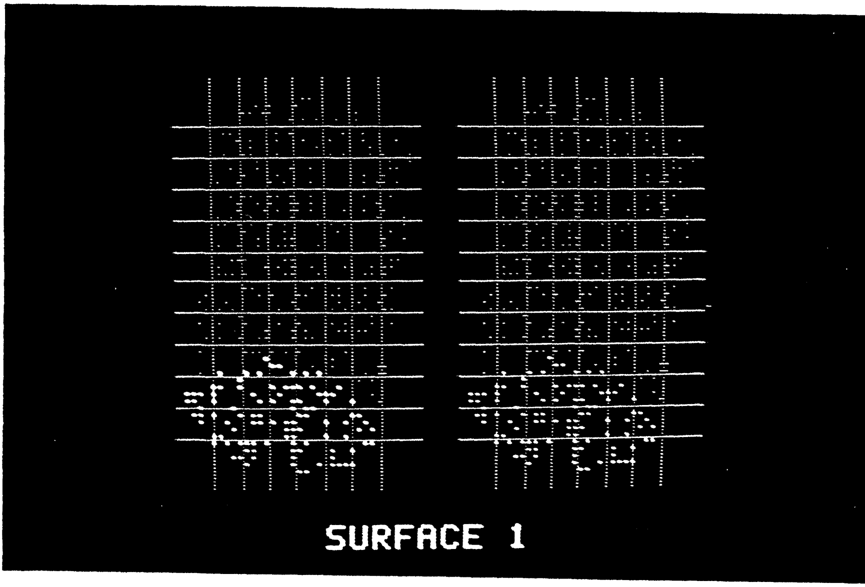
Cylinder and Negative Sphere / View 3 / Shaded Image

Figure 6.3.4-9



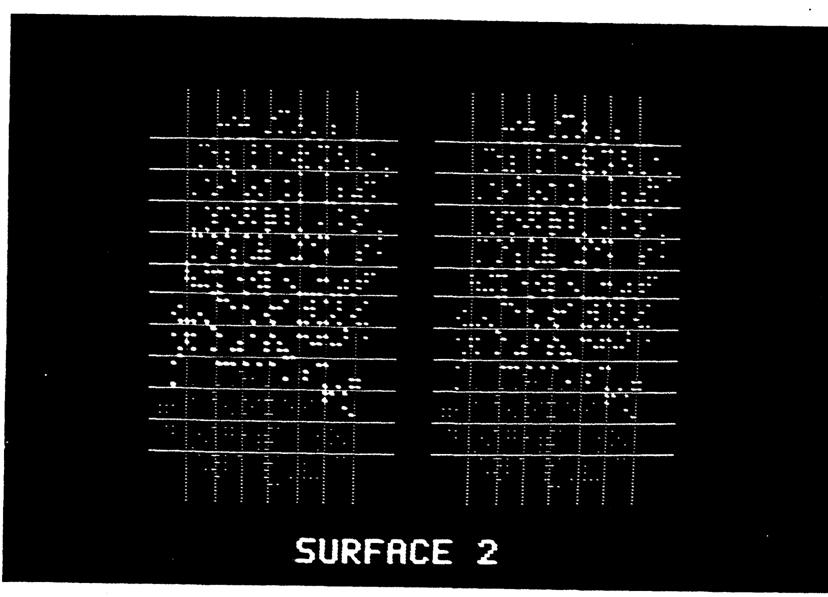
Cylinder and Negative Sphere / View 3 / Input Data

Figure 6.3.4-10



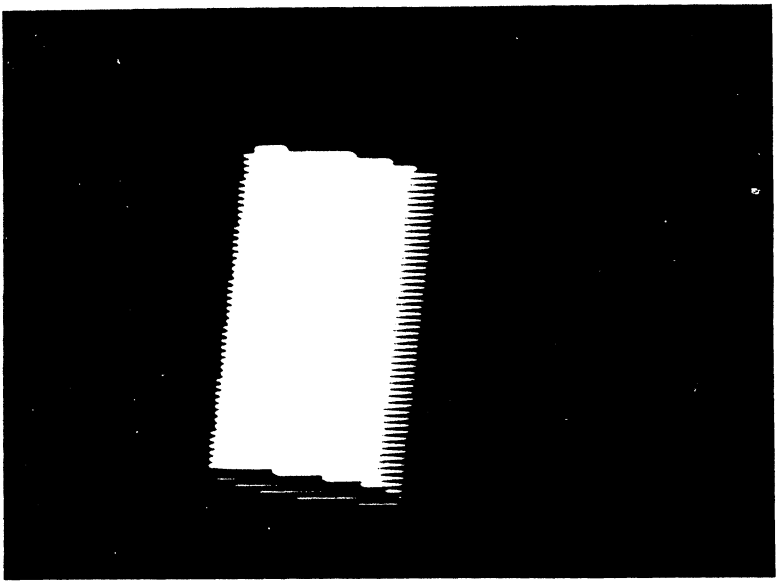
Cylinder and Negative Sphere / View 3 / Surface 1

Figure 6.3.4-11



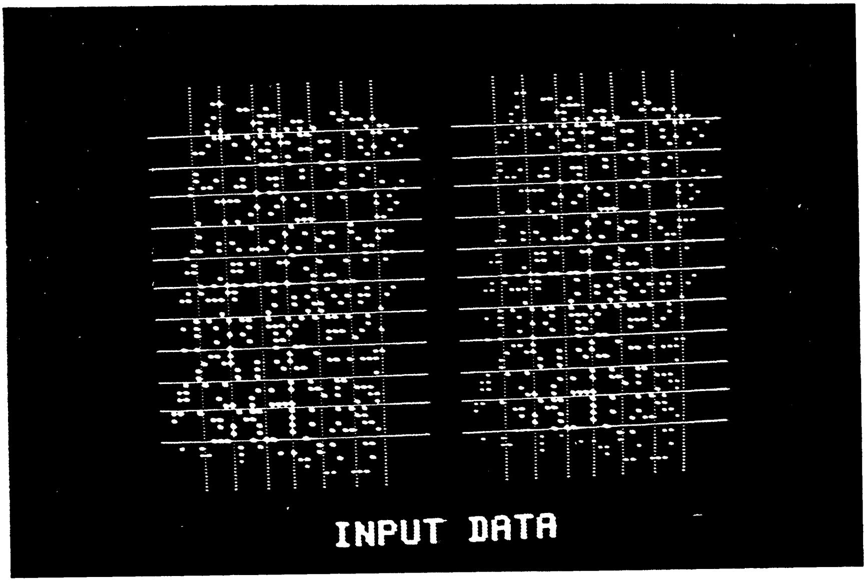
Cylinder and Negative Sphere / View 3 / Surface 2

Figure 6.3.4-12



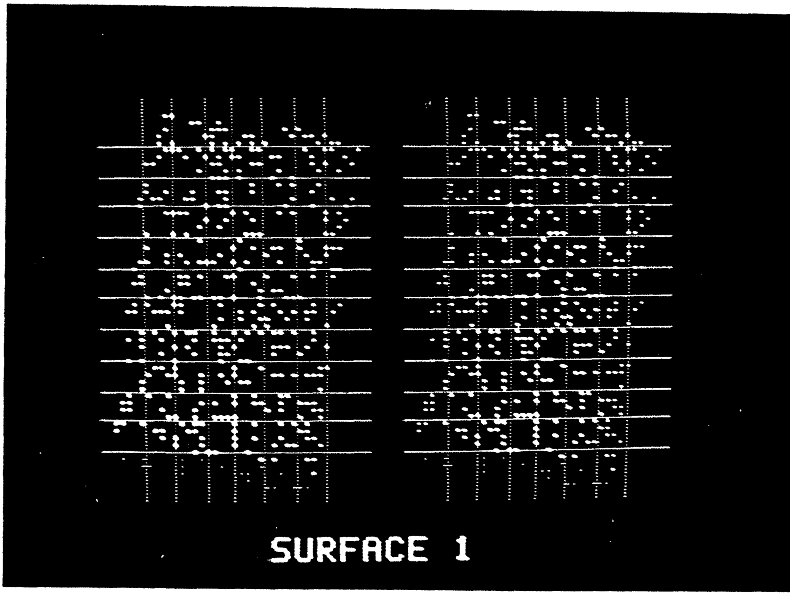
Cylinder and Negative Sphere / View 4 / Shaded Image

Figure 6.3.4-13



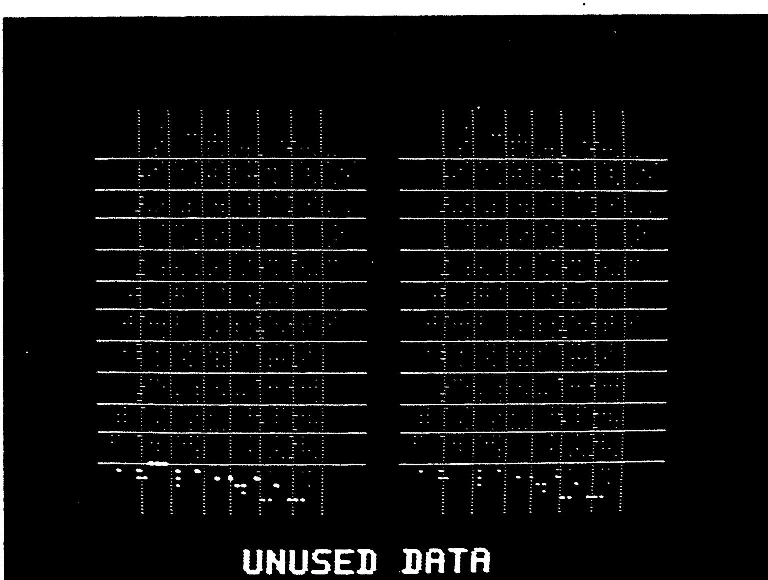
Cylinder and Negative Sphere / View 4 / Input Data

Figure 6.3.4-14



Cylinder and Negative Sphere / View 4 / Surface 1

Figure 6.3.4-15

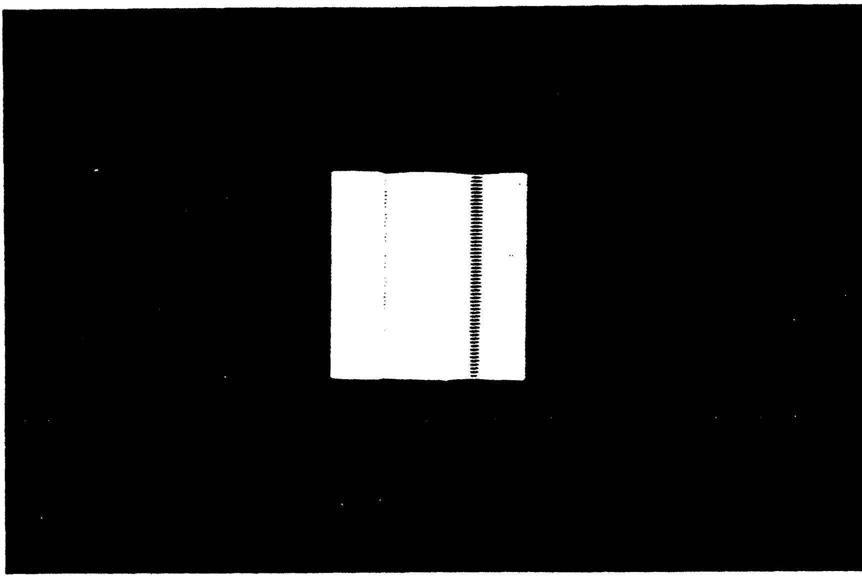


Cylinder and Negative Sphere / View 4 / Unused Data

Figure 6.3.4-16

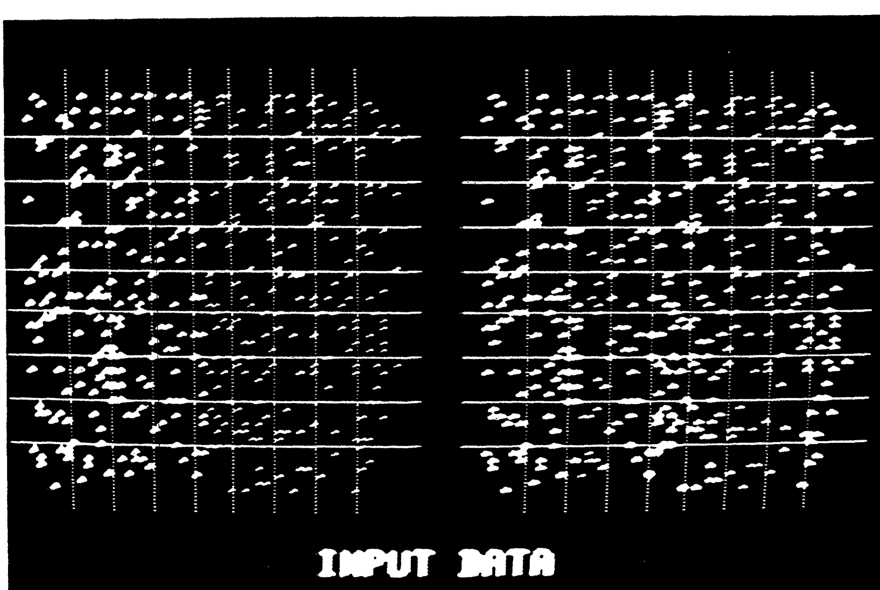
.3.5 Cube And Negative Cylinders -

The test object labelled "cube and negative cylinder
s composed of a cube with three negative cylinders align
ith the faces. The negative cylinders remove more than o
uarter of the cube's volume. The purpose of the object
o test the ability to identify concave surfaces in
omplex object. The analyses of the first two views we
ompleted without difficulty. In view three, a request w
ade for supplemental information in the center ar
ontaining the cylindrical surface. The surface w
epresented by too few data points to be identified.
iew four, a request was made again for supplement
nformation. The area of interest contained thr
ylindrical surfaces but their presences could not
esolved in the cell labelling process. The integration
he results produced an accurate description of the objec
he surfaces not identified in views three and four we
een and recorded in other local results. The final glob
escription consisted of six planar primitives and thr
ylindrical primitives.



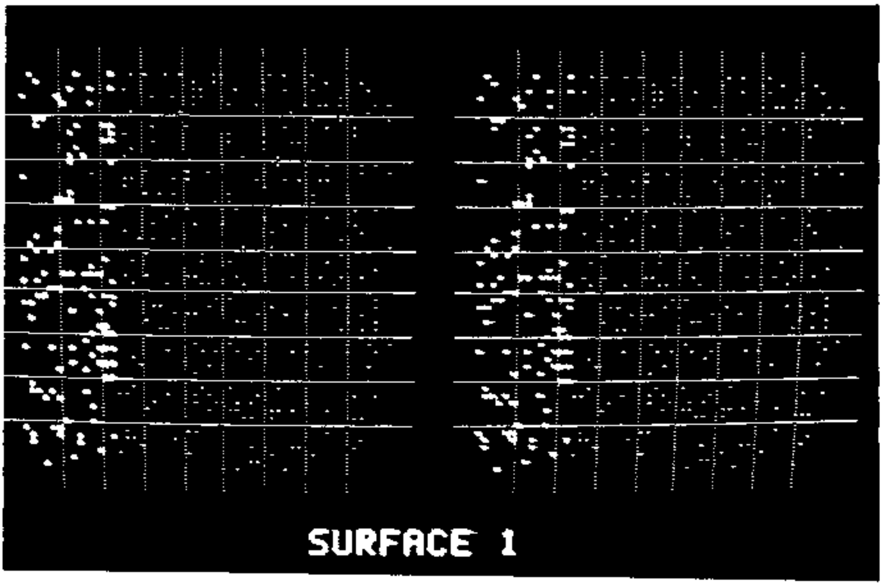
Cube and Negative Cylinders / View 1 / Shaded Image

Figure 6.3.5-1



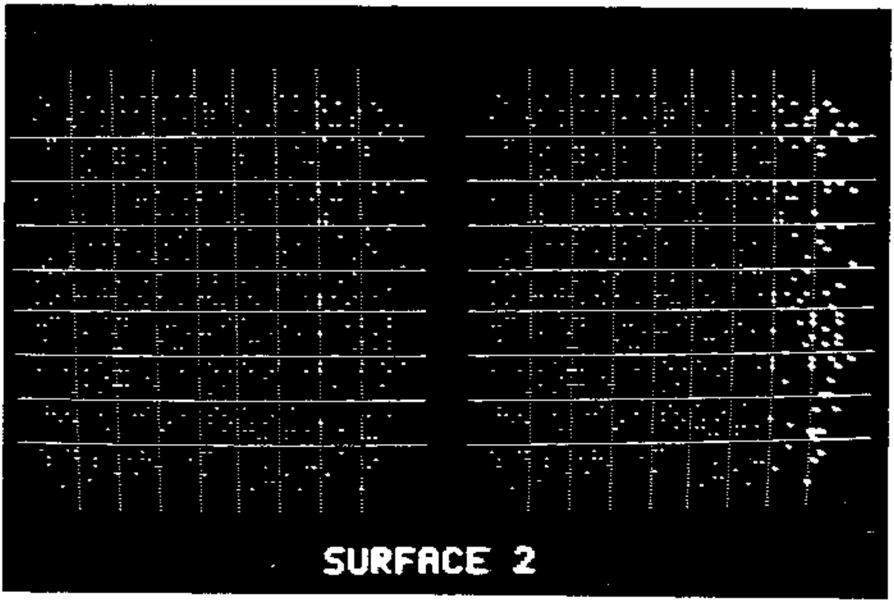
Cube and Negative Cylinders / View 1 / Input Data

Figure 6.3.5-2

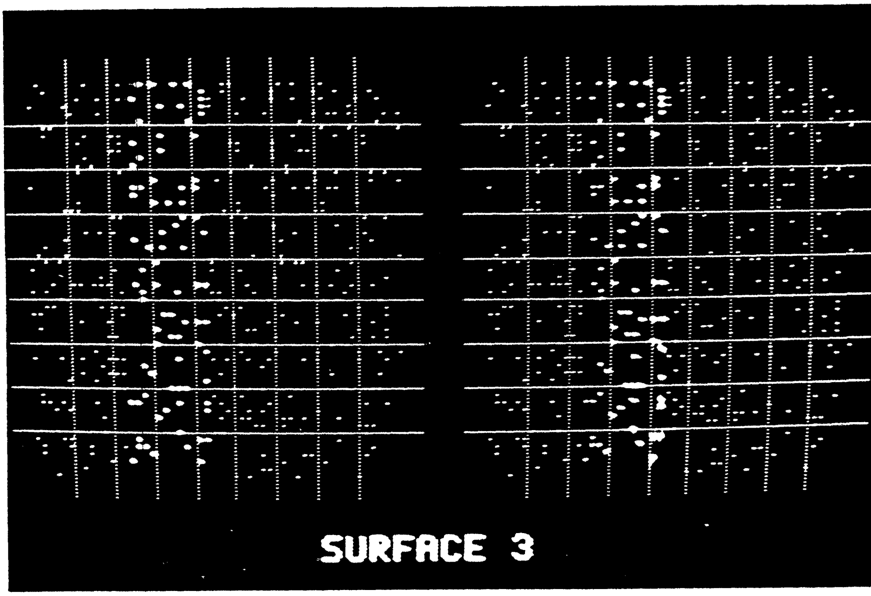


Cube and Negative Cylinders / View 1 / Surface 1

Figure 6.3.5-3

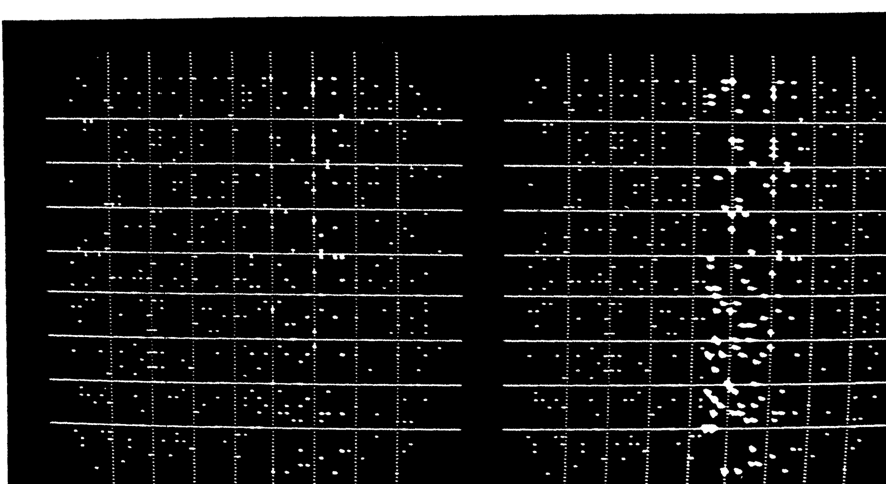


Cube and Negative Cylinders / View 1 / Surface 2



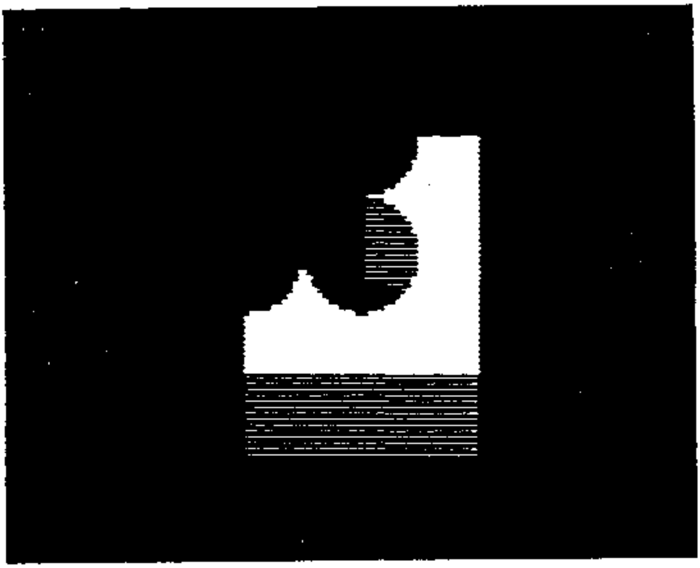
Cube and Negative Cylinders / View 1 / Surface 3

Figure 6.3.5-5



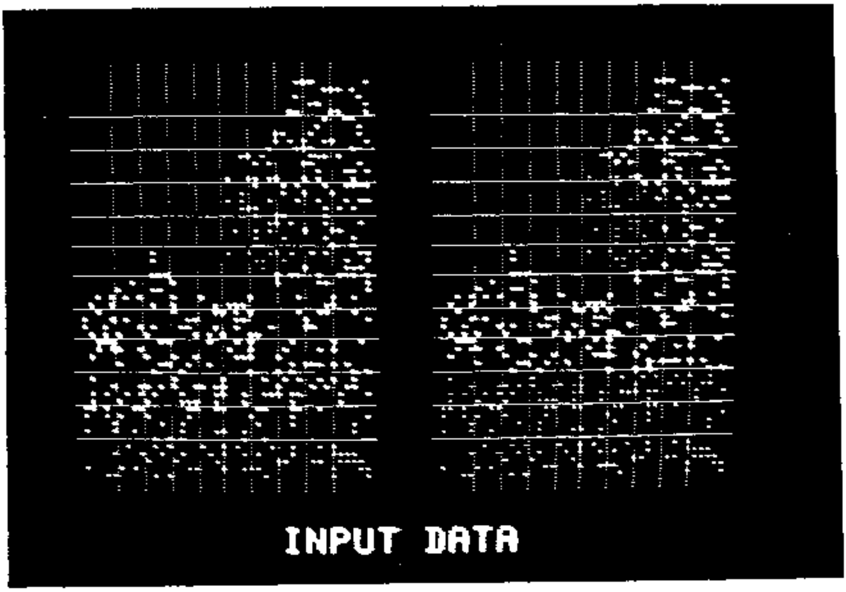
Cube and Negative Cylinders / View 1 / Surface 4

Figure 6.3.5-6



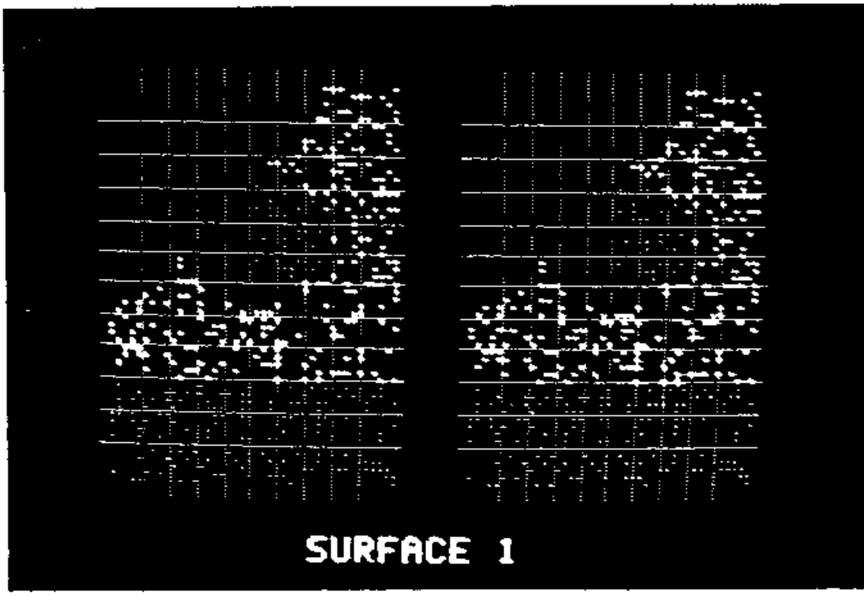
Cube and Negative Cylinders / View 2 / Shaded Image

Figure 6.3.5-7



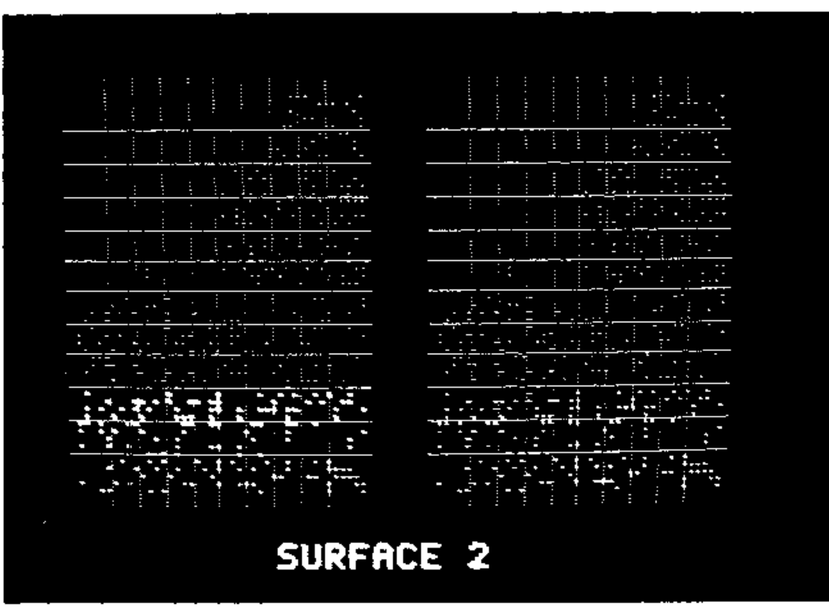
Cube and Negative Cylinders / View 2 / Input Data

Figure 6.3.5-8



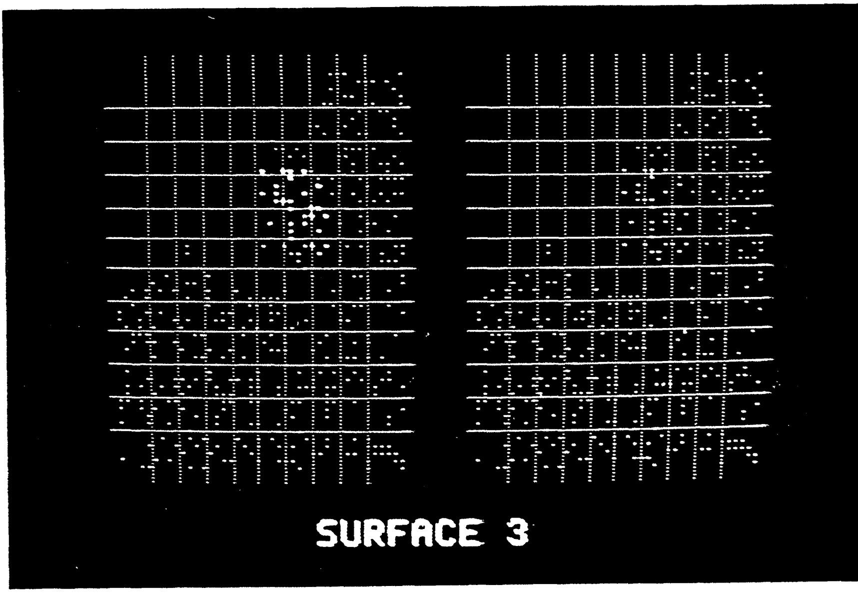
Cube and Negative Cylinders / View 2 / Surface 1

Figure 6.3.5-9



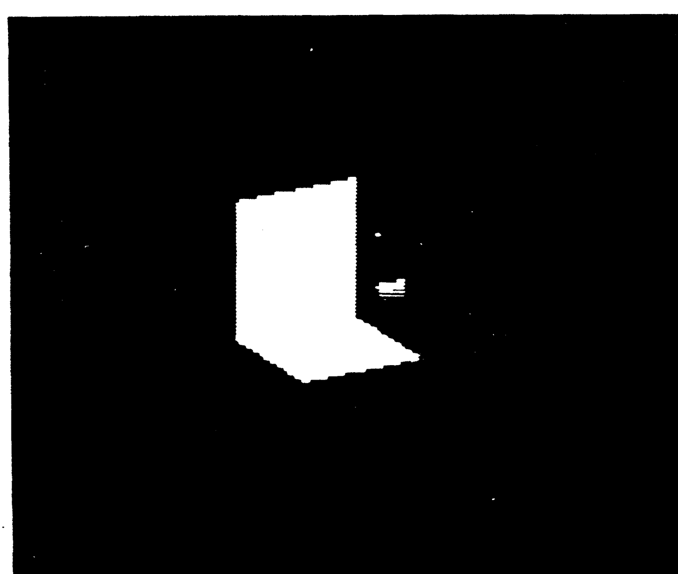
Cube and Negative Cylinders / View 2 / Surface 2

Figure 6.3.5-10



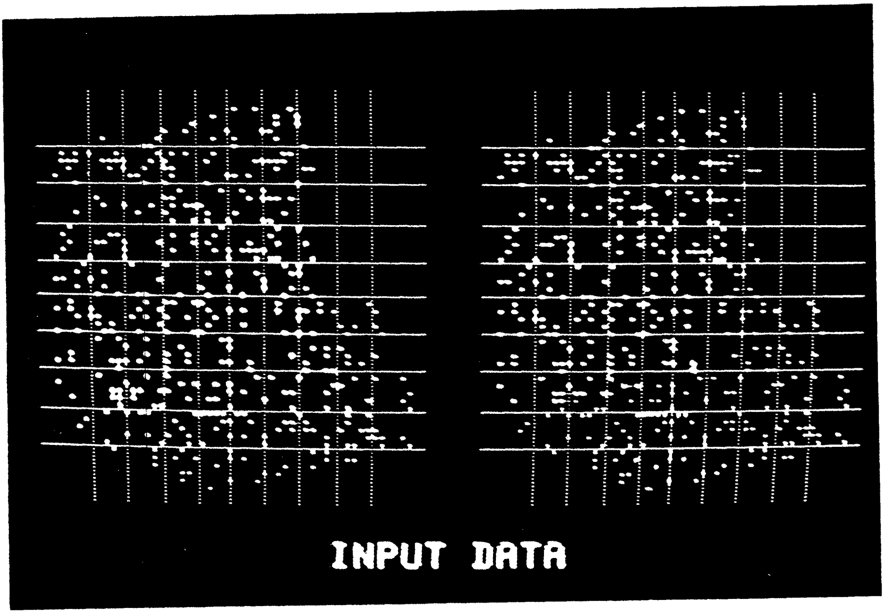
Cube and Negative Cylinders / View 2 / Surface 3

Figure 6.3.5-11



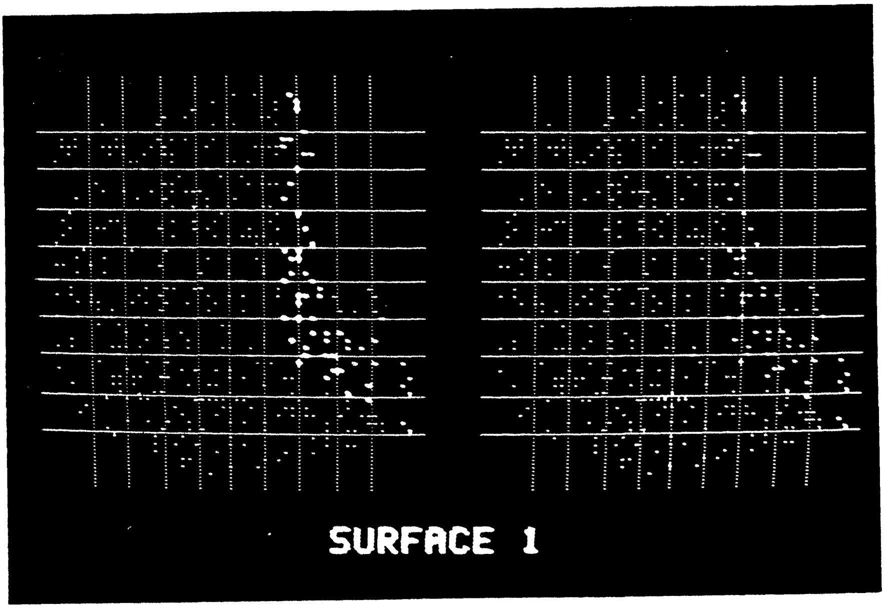
Cube and Negative Cylinders / View 3 / Shaded Image

Figure 6.3.5-12



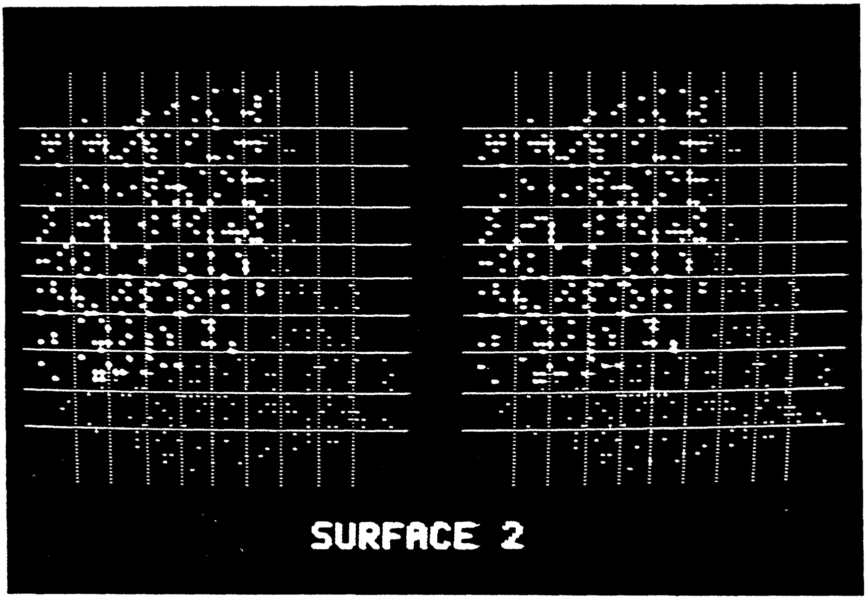
Cube and Negative Cylinders / View 3 / Input Data

Figure 6.3.5-13



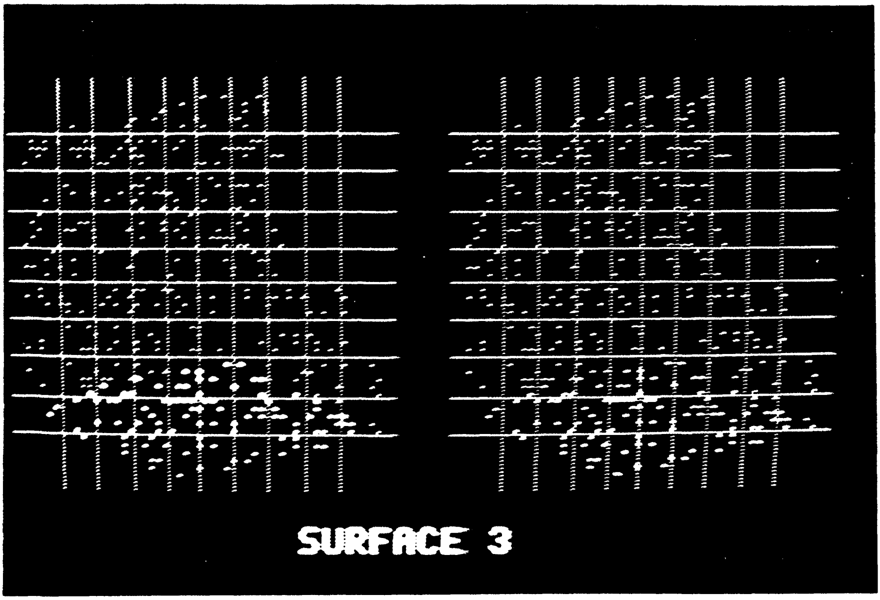
Cube and Negative Cylinders / View 3 / Surface 1

Figure 6.3.5-14



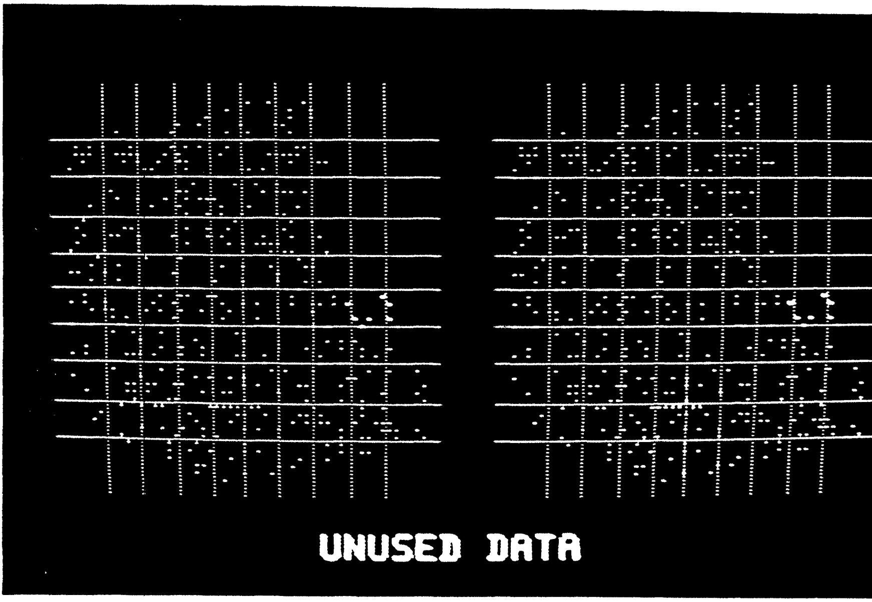
Cube and Negative Cylinders / View 3 / Surface 2

Figure 6.3.5-15



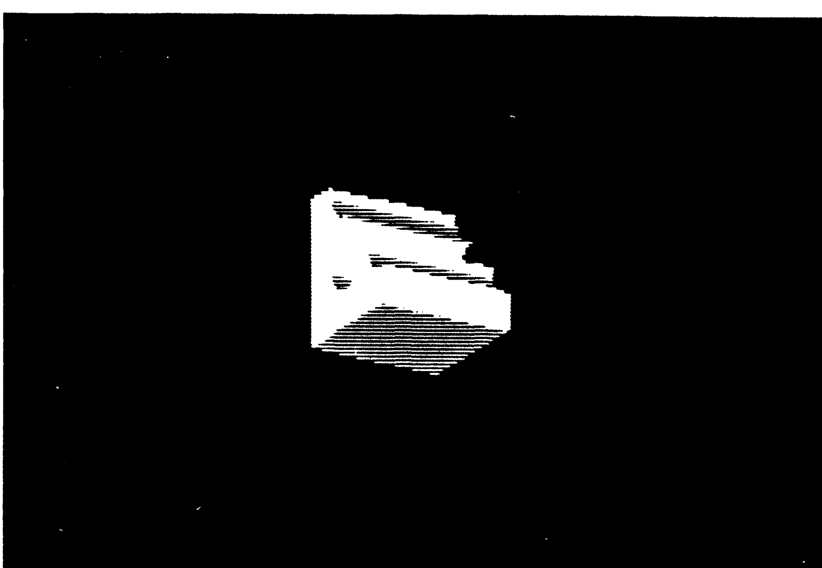
Cube and Negative Cylinders / View 3 / Surface 3

Figure 6.3.5-16



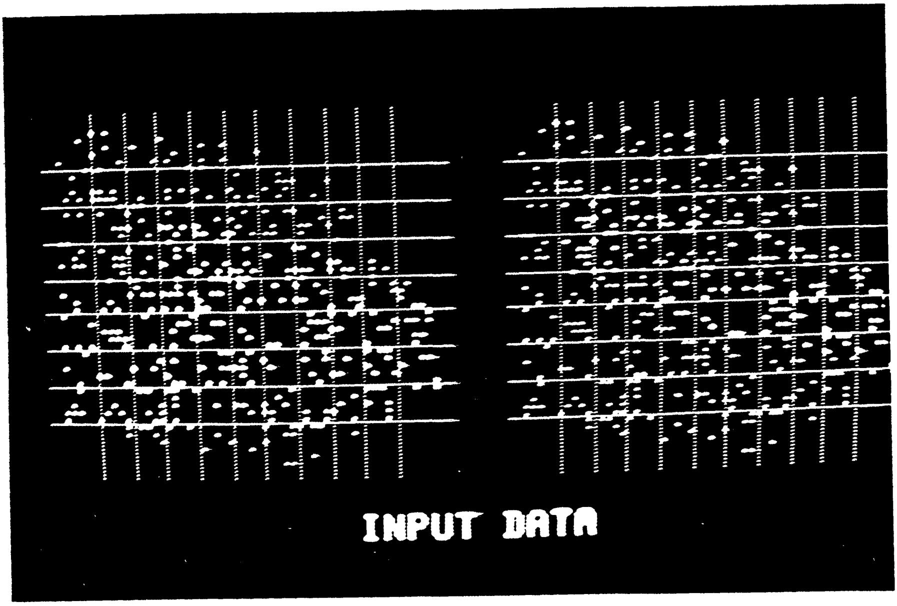
Cube and Negative Cylinders / View 3 / Unused Data

Figure 6.3.5-17



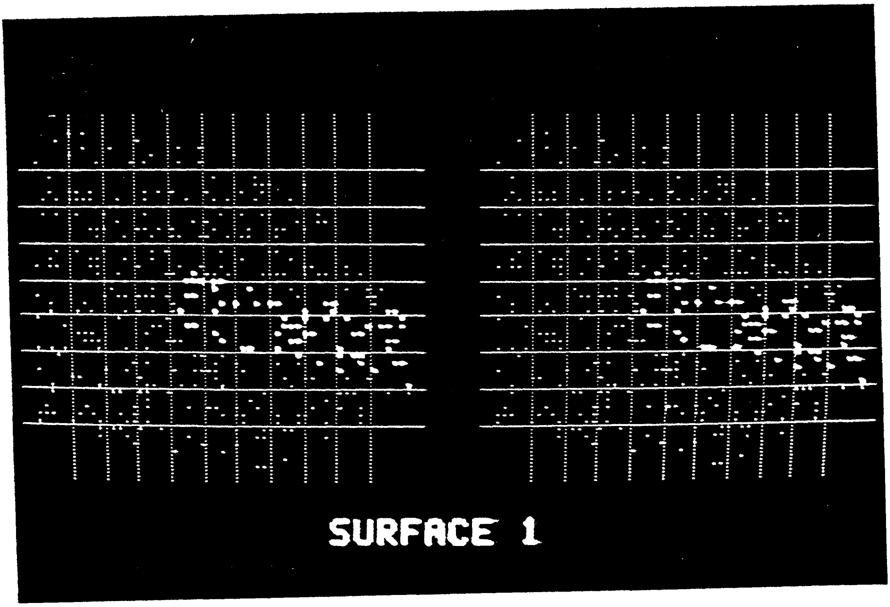
Cube and Negative Cylinders / View 4 / Shaded Image

Figure 6.3.5-18



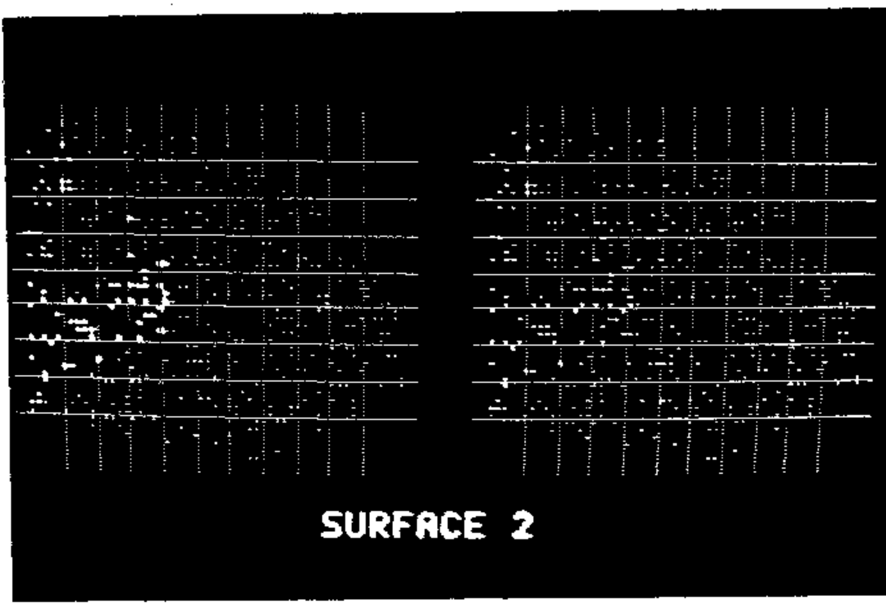
Cube and Negative Cylinders / View 4 / Input Data

Figure 6.3.5-19



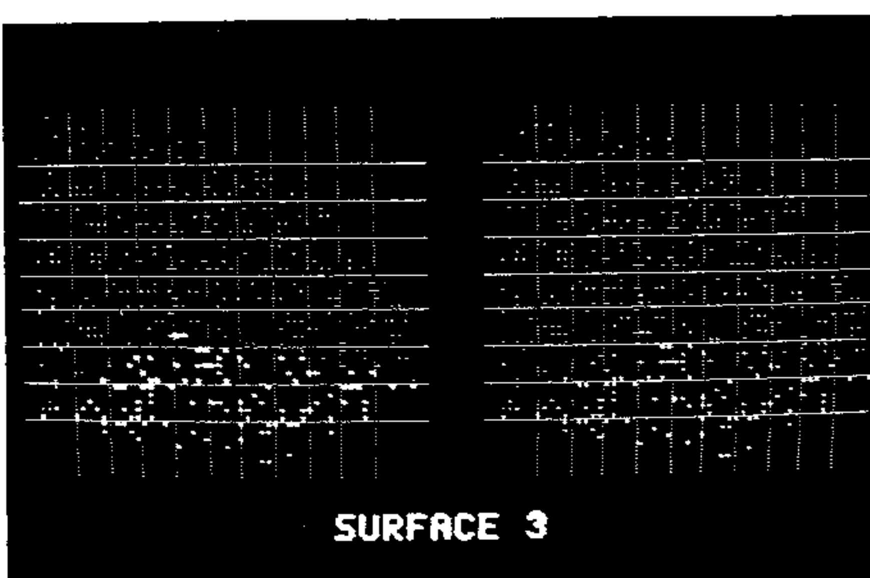
Cube and Negative Cylinders / View 4 / Surface 1

Figure 6.3.5-20



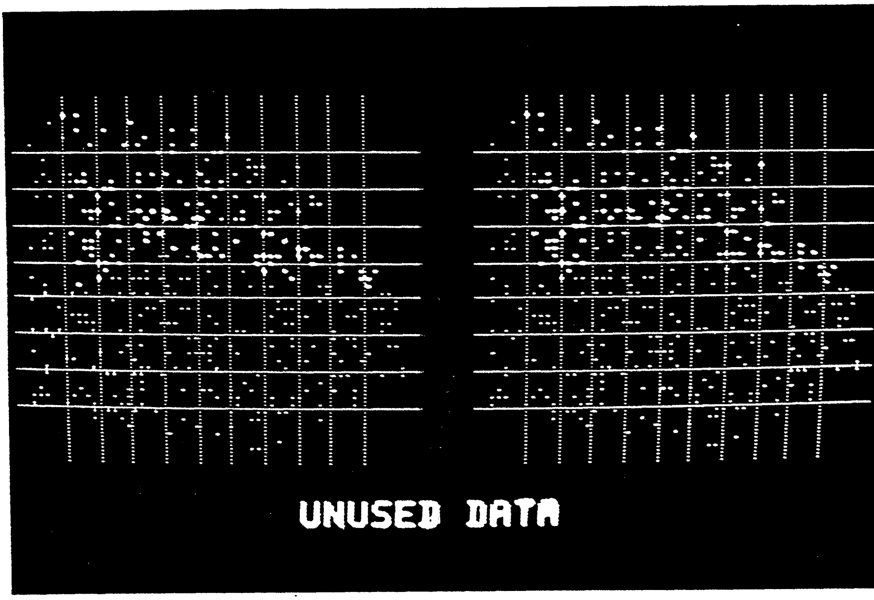
Cube and Negative Cylinders / View 4 / Surface 2

Figure 6.3.5-21



Cube and Negative Cylinders / View 4 / Surface 3

Figure 6.3.5-22

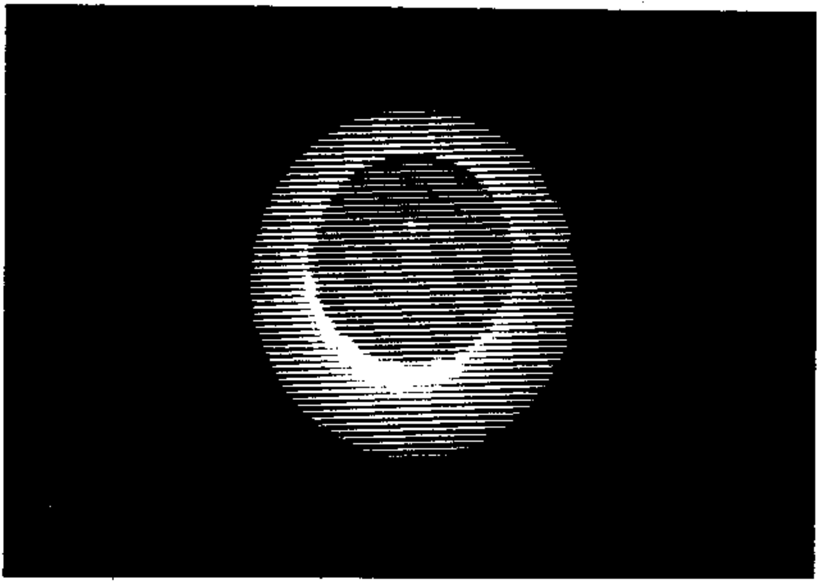


Cube and Negative Cylinders / View 4 / Unused Data

Figure 6.3.5-23

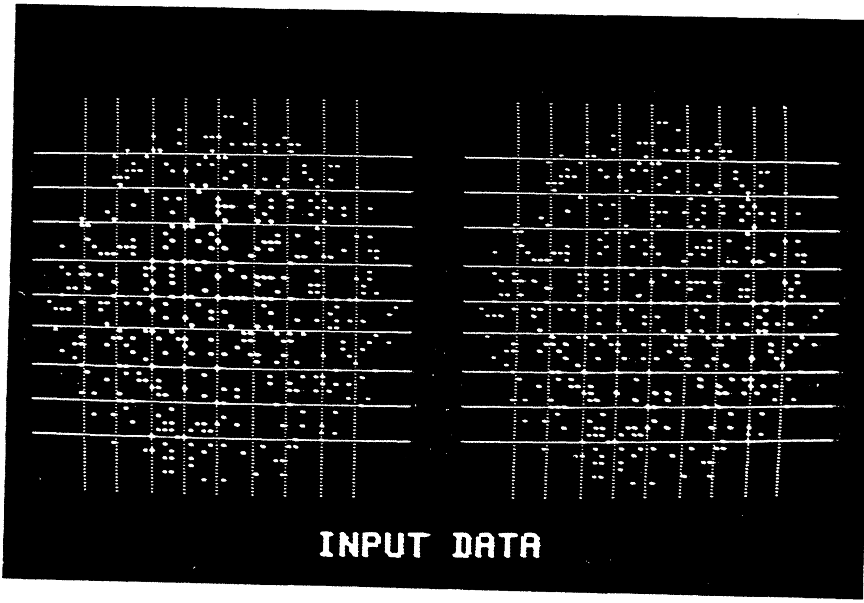
3.6 Ice Cream Cone -

The object labelled "ice cream cone" is composed of ne with its base adjoined to a hemisphere. The purpose o e object is to test the ability to identify the smoot ange from one quadric surface to another quadric surface e analyses of the four primary views were complete thout difficulty. The integration of the results produce accurate description of the object. The final globs scription consisted of one spherical primitive and or nic primitive.



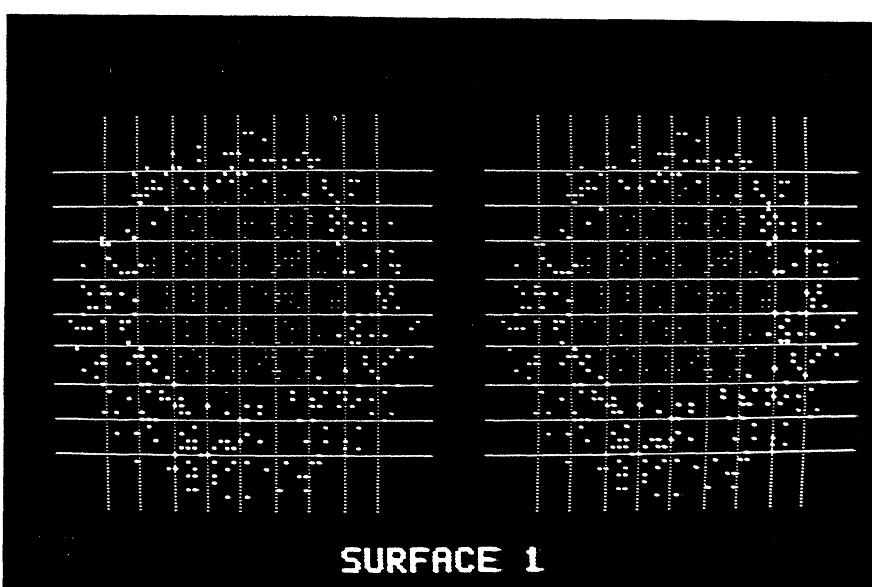
Ice Cream Cone / View 1 / Shaded Image

Figure 6.3.6-1



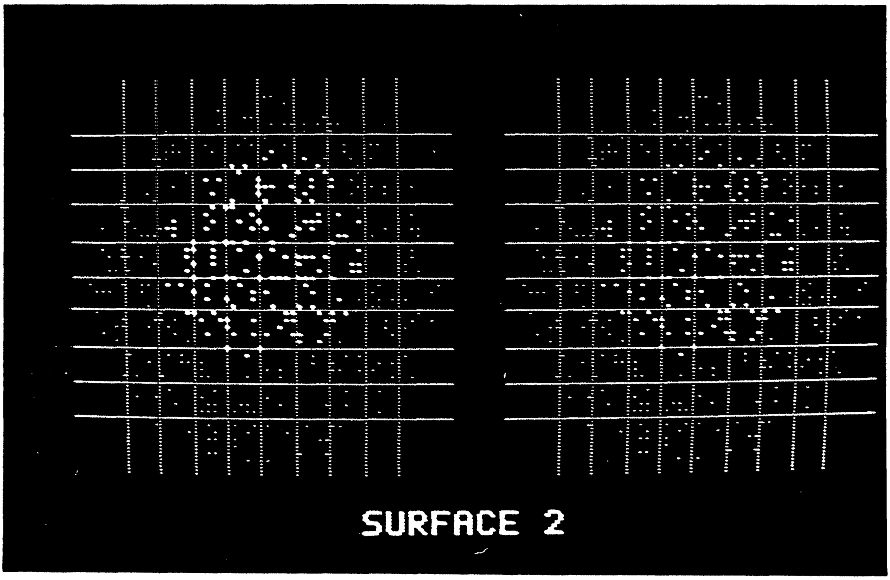
Ice Cream Cone / View 1 / Input Data

Figure 6.3.6-2



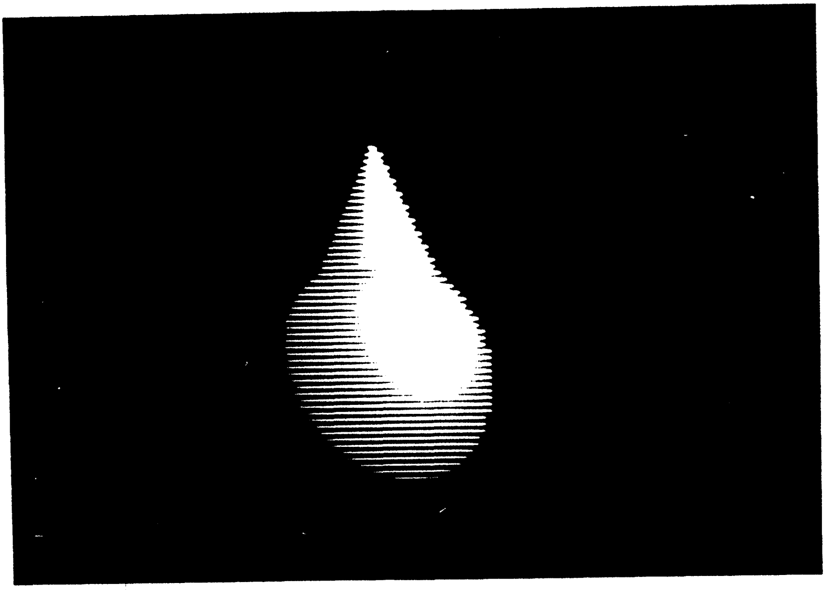
Ice Cream Cone / View 1 / Surface 1

Figure 6.3.6-3



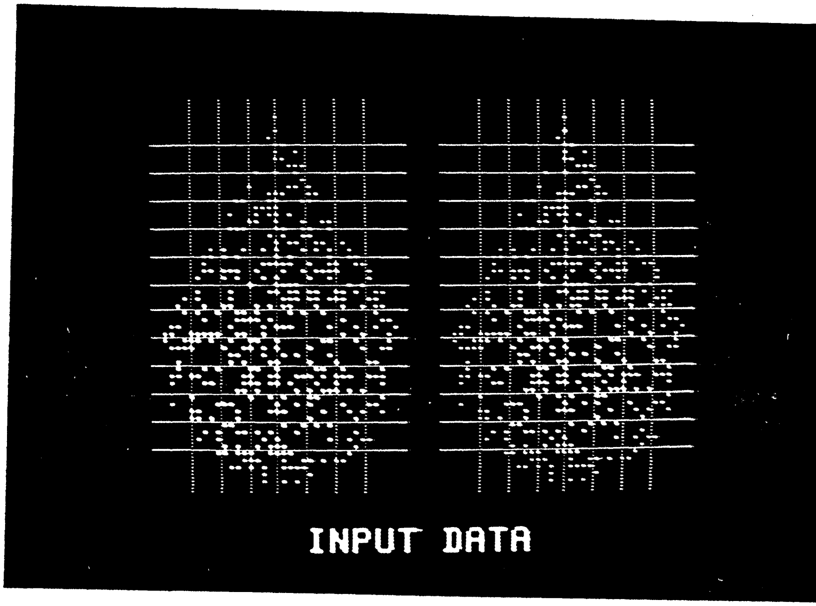
Ice Cream Cone / View 1 / Surface 2

Figure 6.3.6-4



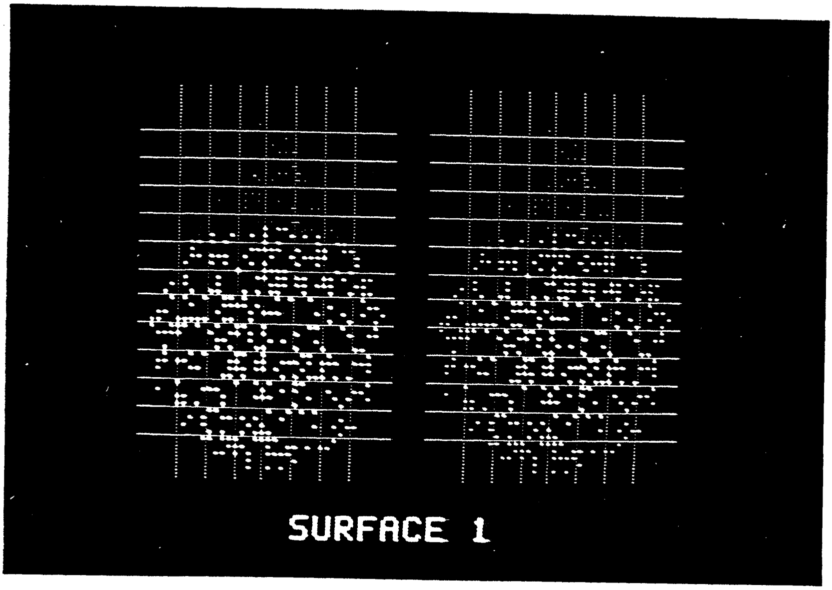
Ice Cream Cone / View 2 / Shaded Image

Figure 6.3.6-5



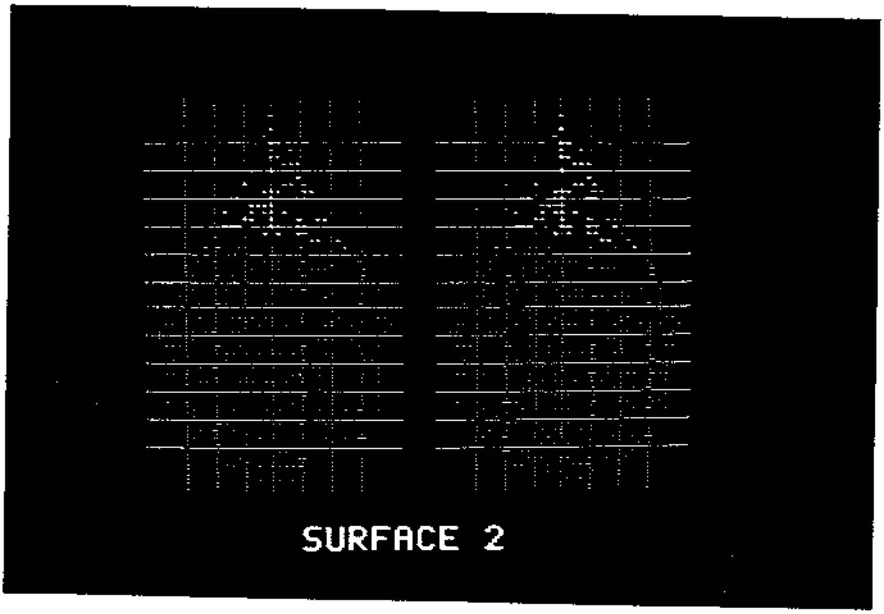
Ice Cream Cone / View 2 / Input Data

Figure 6.3.6-6



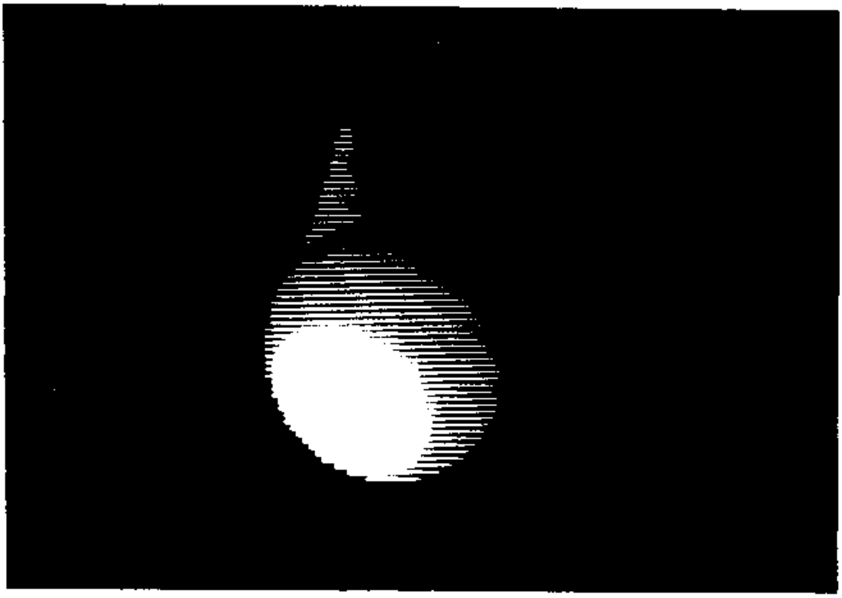
Ice Cream Cone / View 2 / Surface 1

Figure 6.3.6-7



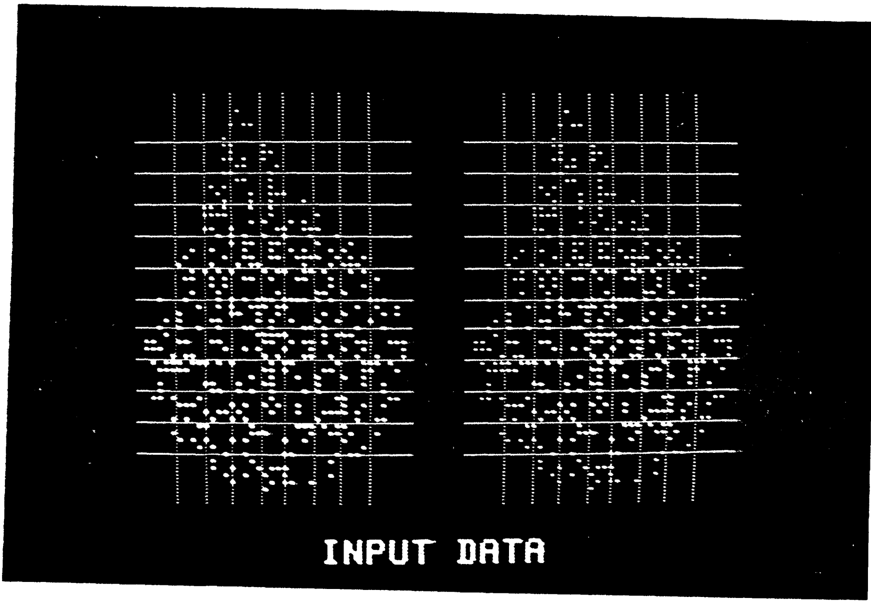
Ice Cream Cone / View 2 / Surface 2

Figure 6.3.6-8



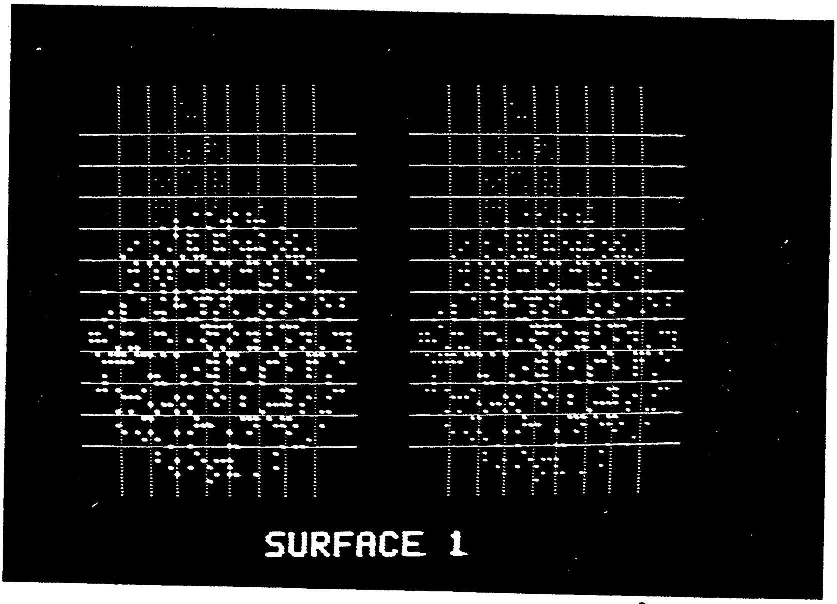
Ice Cream Cone / View 3 / Shaded Image

Figure 6.3.6-9



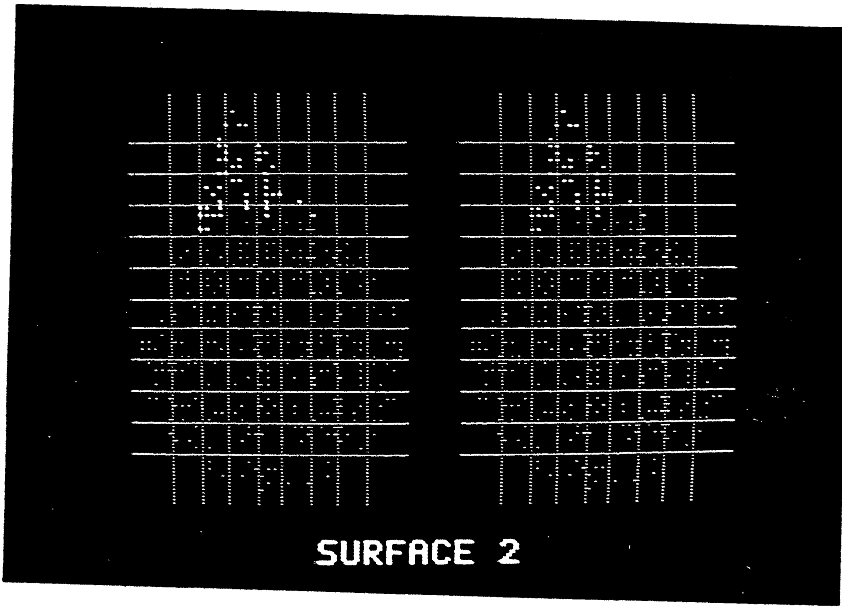
Ice Cream Cone / View 3 / Input Data

Figure 6.3.6-10



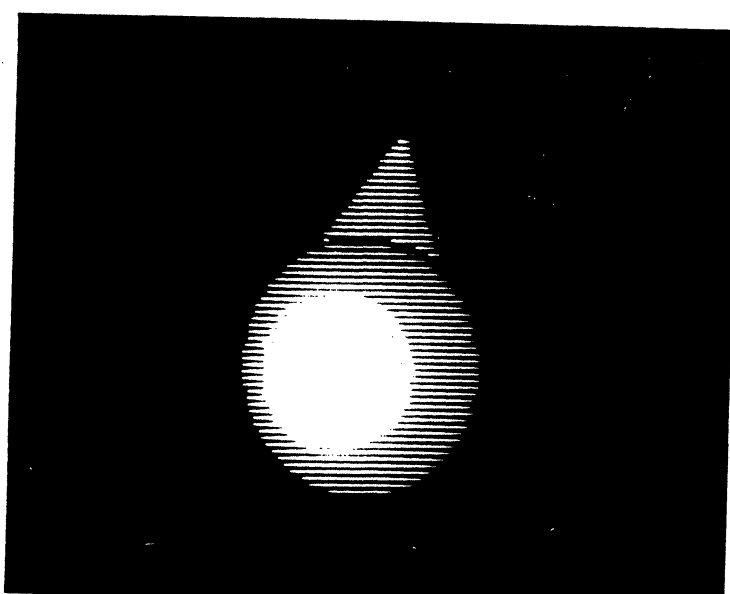
Ice Cream Cone / View 3 / Surface 1

Figure 6.3.6-11



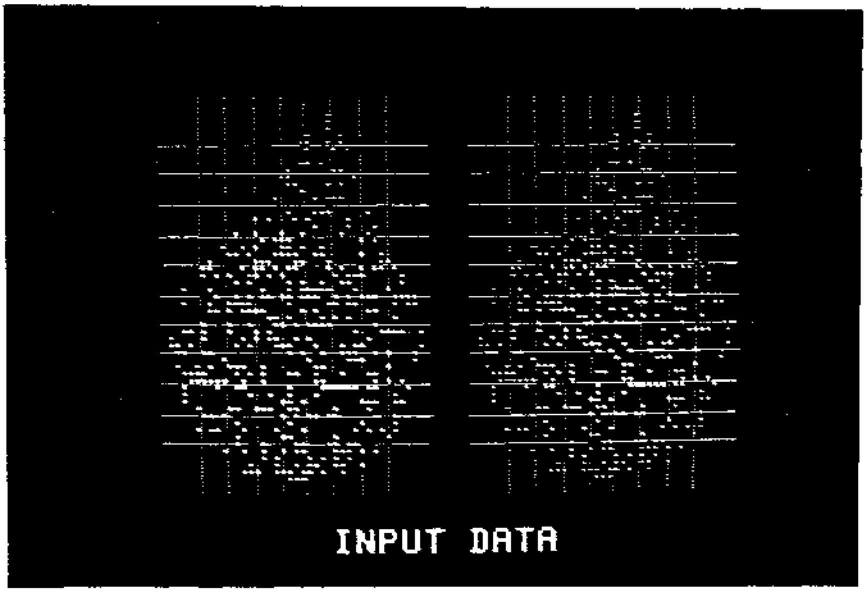
Ice Cream Cone / View 3 / Surface 2

Figure 6.3.6-12



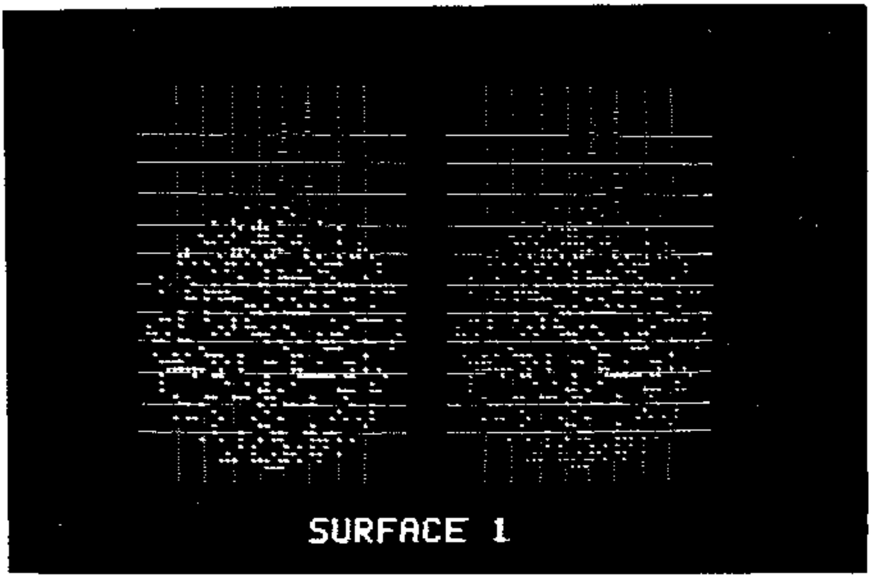
Ice Cream Cone / View 4 / Shaded Image

Figure 6.3.6-13

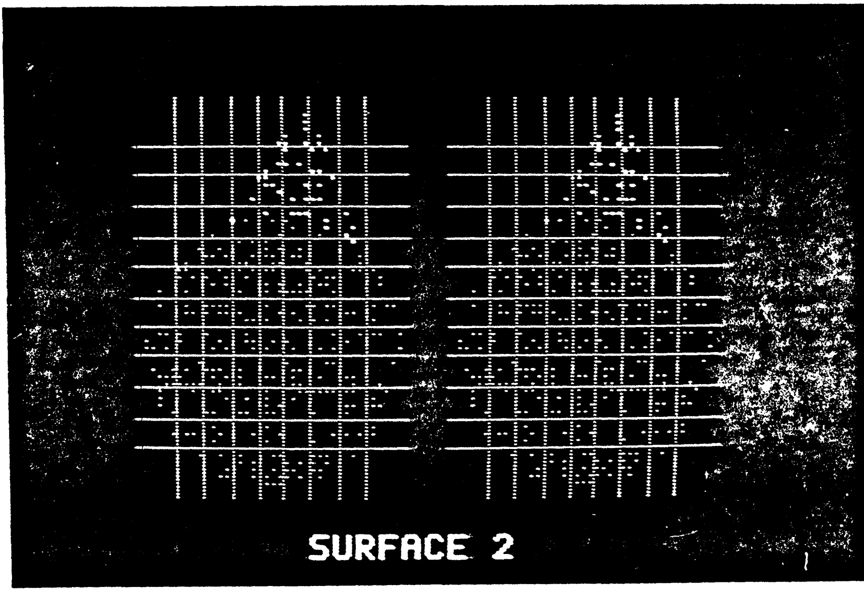


Ice Cream Cone / View 4 / Input Data

Figure 6.3.6-14



Ice Cream Cone / View 4 / Surface 1

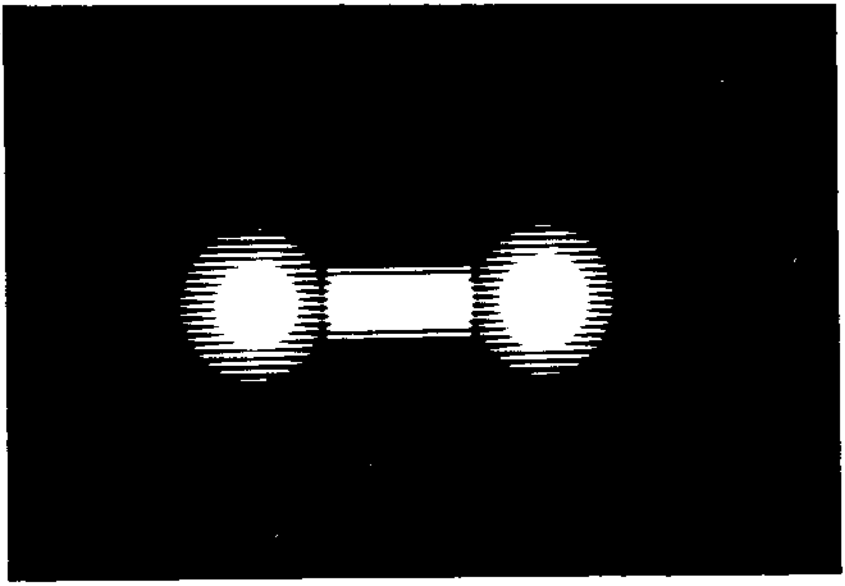


Ice Cream Cone / View 4 / Surface 2

Figure 6.3.6-16

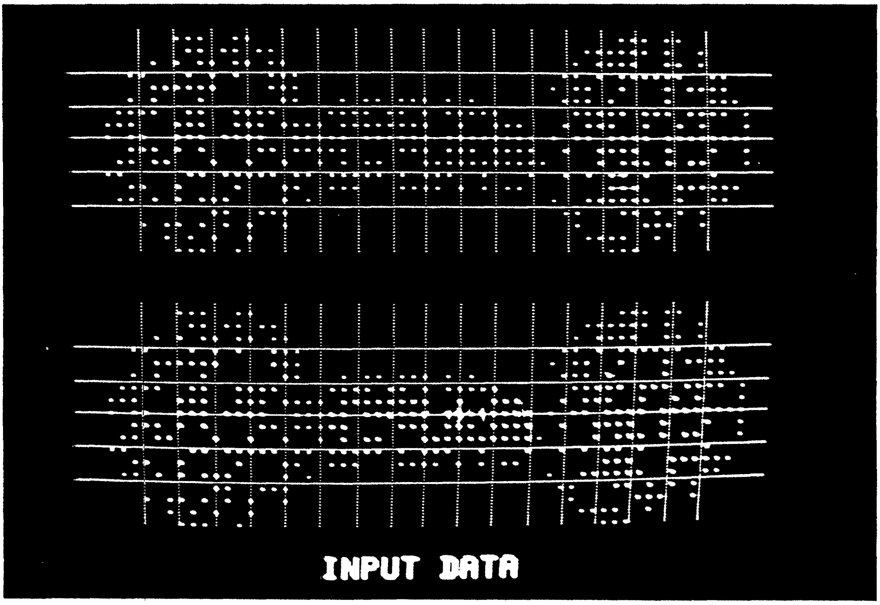
3.7 Barbell -

The test object labelled "barbell" is composed of thre
nnected parts. The two end parts are spheres, and th
nter part is a circular cylinder. The purpose of th
iject is to test the integration process with similarl
taped primitives in different locations. The analyses o
ie four primary views were completed without difficulty
e integration of the results produced an accurat
sscription of the object. The final global descriptio
insisted of two spherical primitives and a cylindrica
imi t ive .



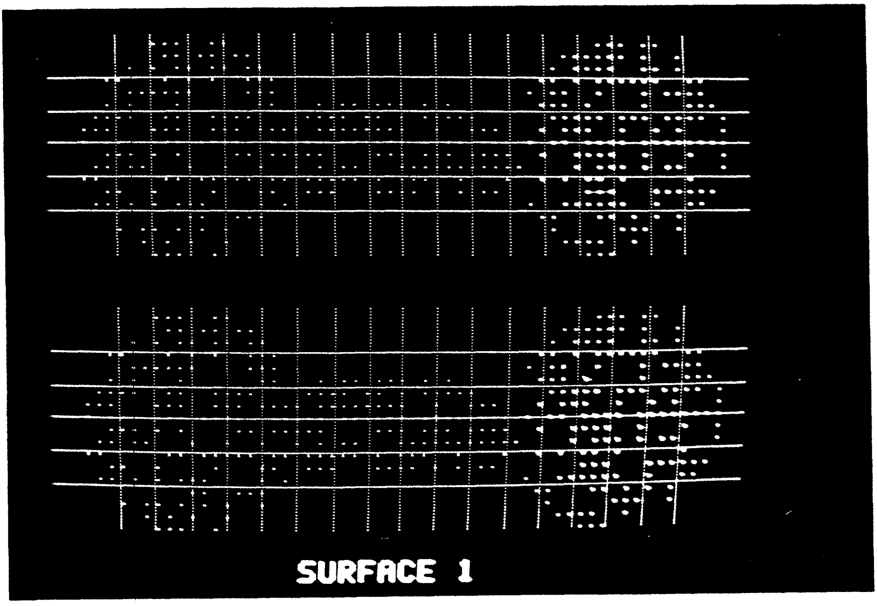
Barbell / View 1 / Shaded Image

Figure 6.3.7-1



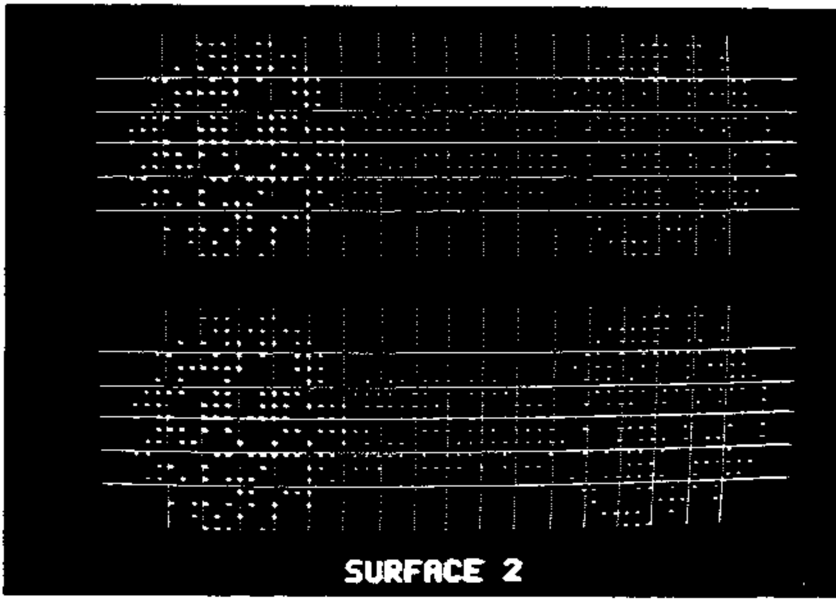
Barbell / View 1 / Input Data

Figure 6.3.7-2



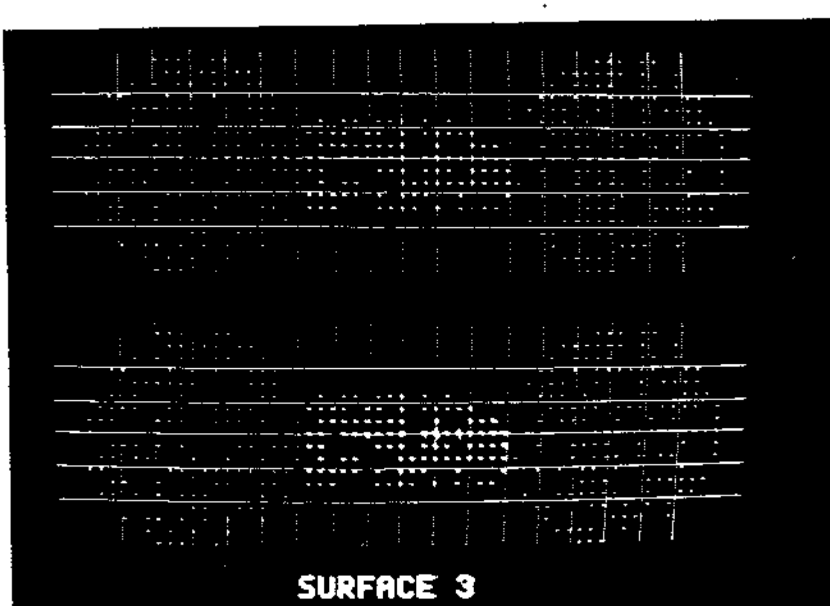
Barbell / View 1 / Surface 1

Figure 6.3.7-3



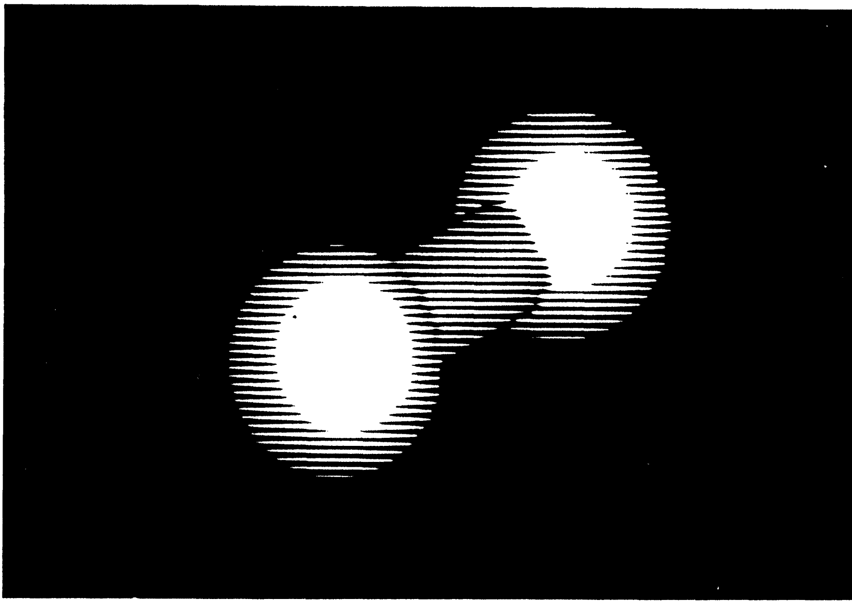
Barbell / View 1 / Surface 2

Figure 6.3.7-4



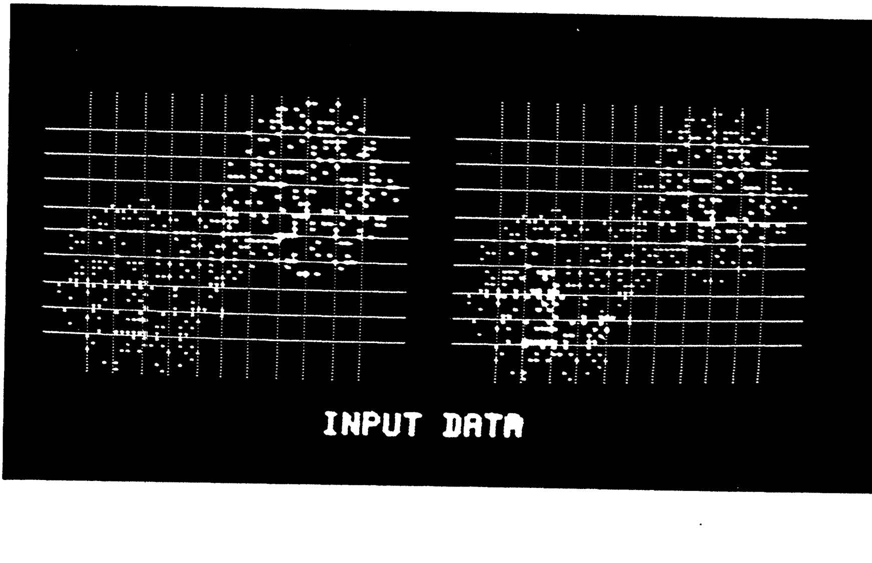
Barbell / View 1 / Surface 3

Figure 6.3.7-5



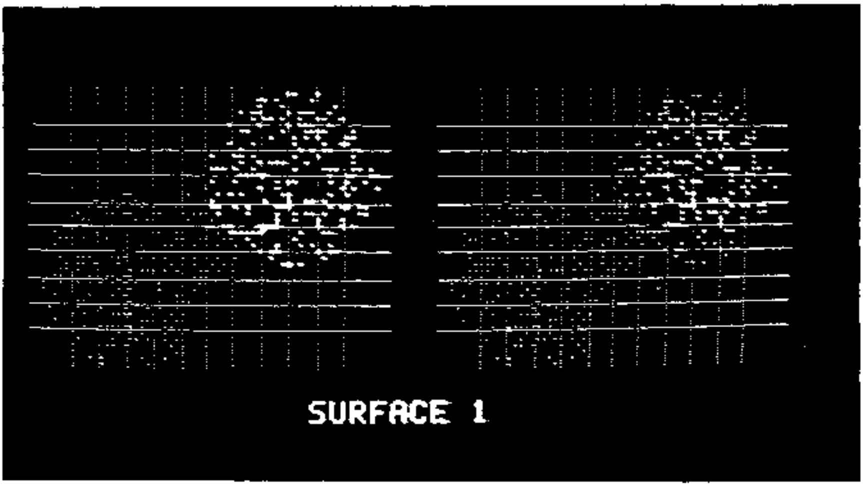
Barbell / View 2 / Shaded Image

Figure 6.3.7-6



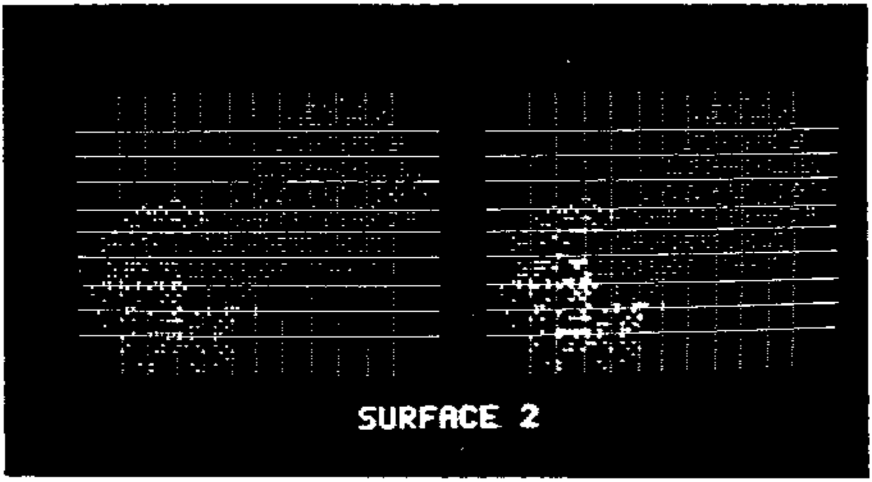
Barbell / View 2 / Input Data

Figure 6.3.7-7



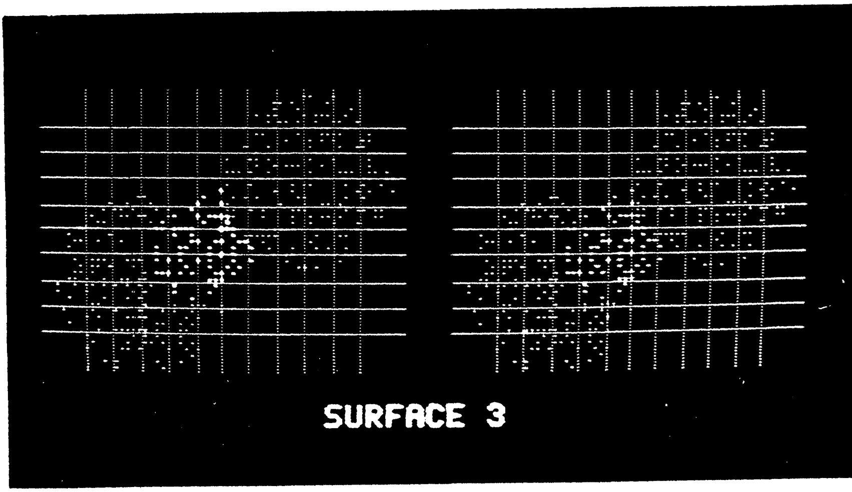
Barbell / View 2 / Surface 1

Figure 6,3.7-8



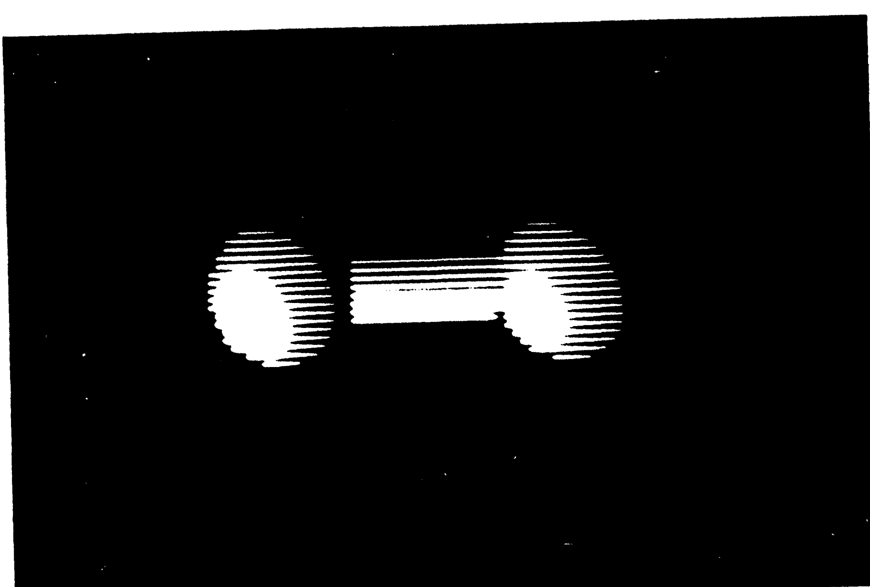
Barbell / View 2 / Surface 2

Figure 6.3.7-9



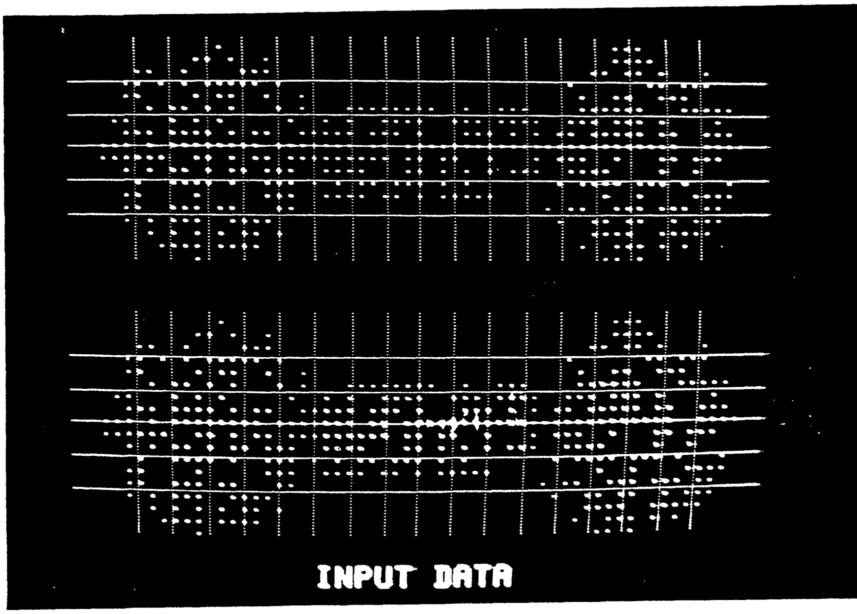
Barbell / View 2 / Surface 3

Figure 6.3.7-10



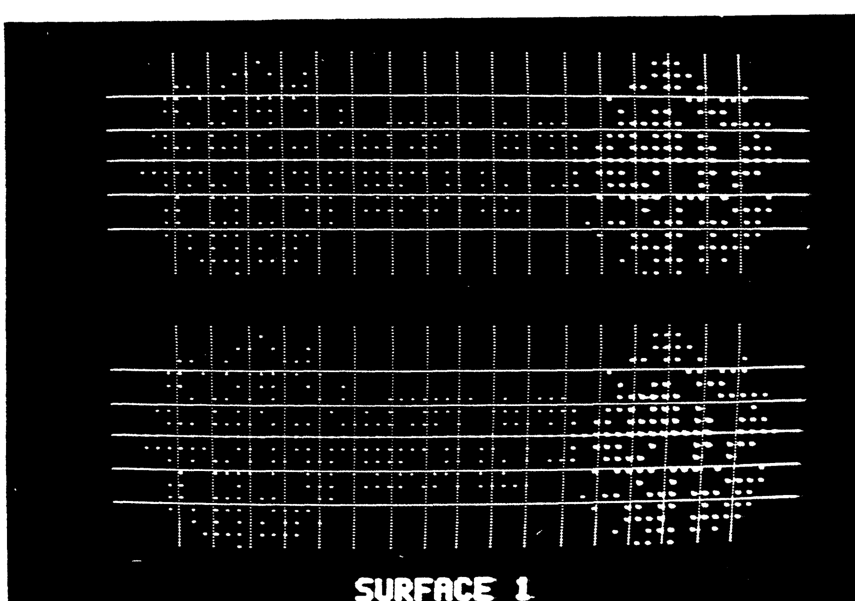
Barbell / View 3 / Shaded Image

Figure 6.3.7-11



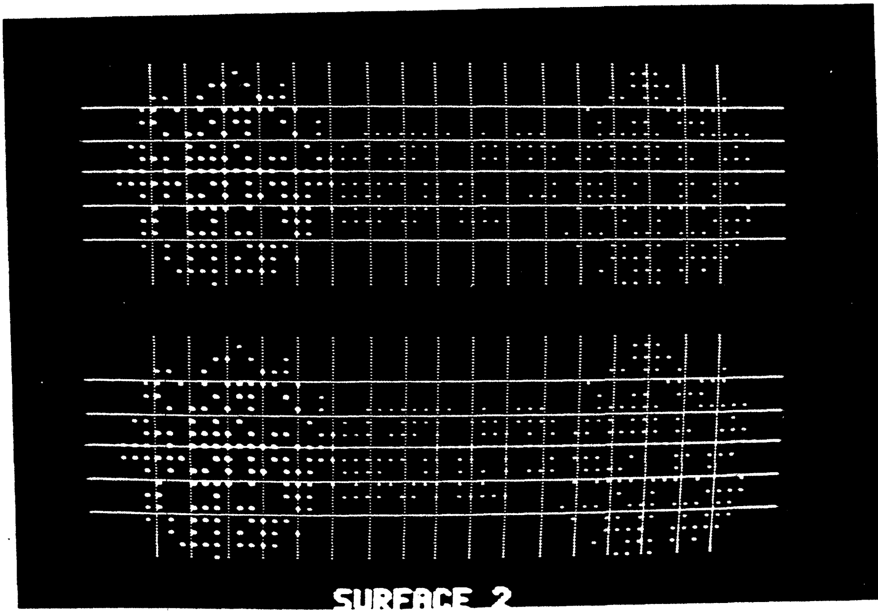
Barbell / View 3 / Input Data

Figure 6.3.7-12



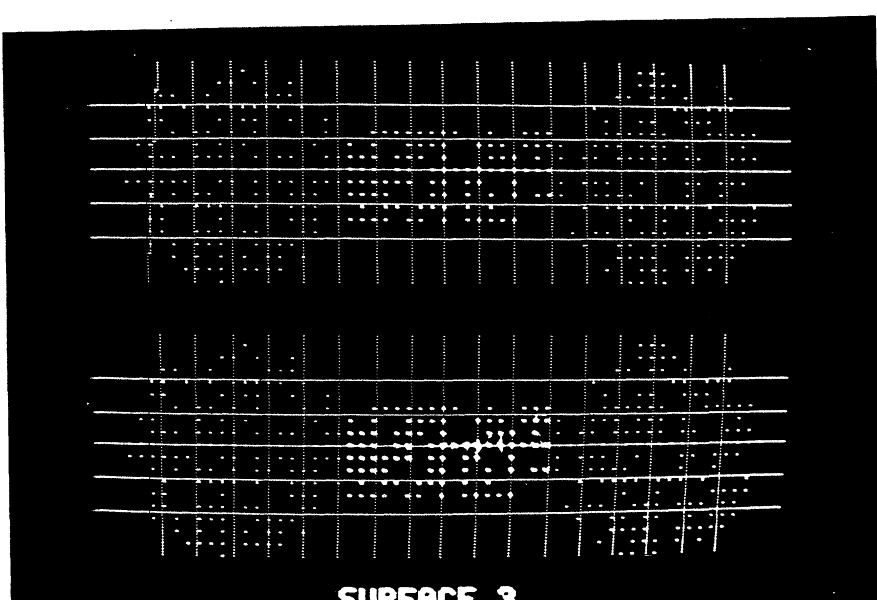
Barbell / View 3 / Surface 1

Figure 6.3.7-13



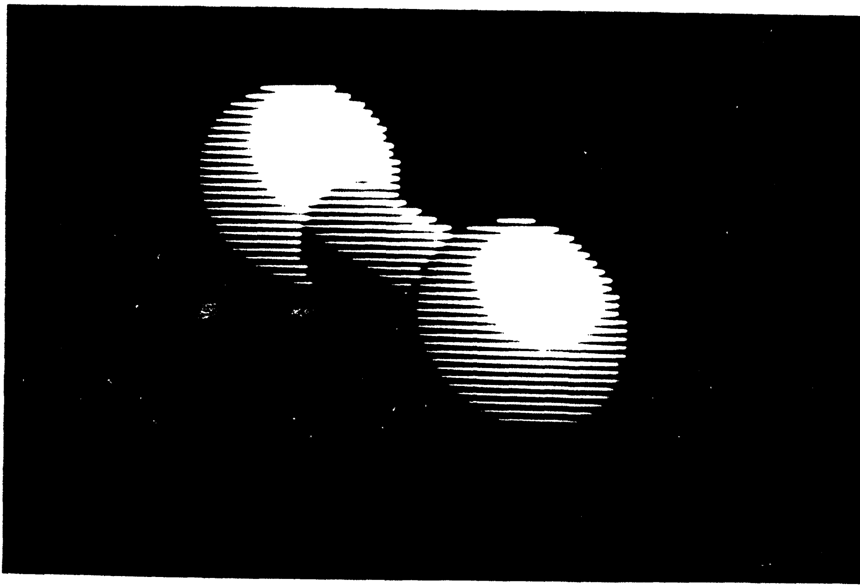
Barbell / View 3 / Surface 2

Figure 6.3.7-14



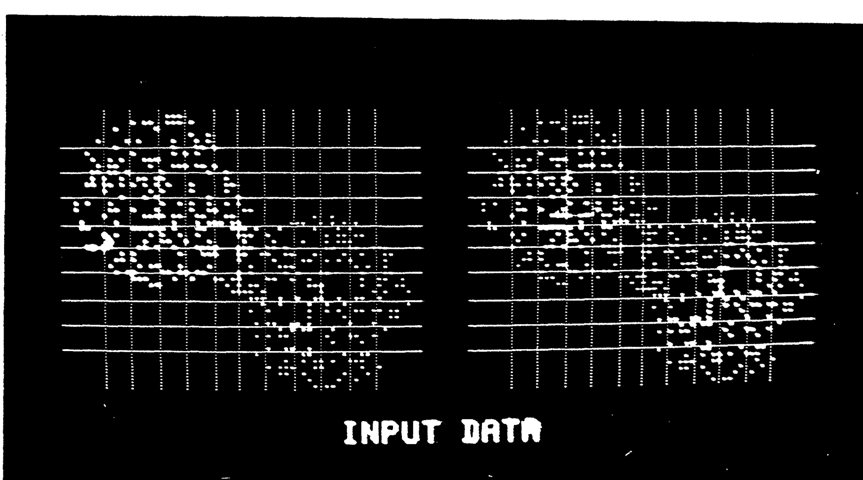
Barbell / View 3 / Surface 3

Figure 6.3.7-15

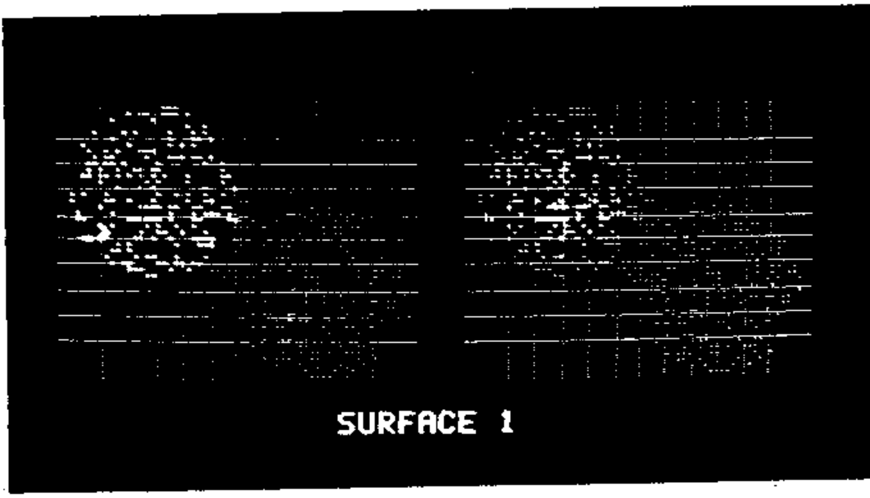


Barbell / View 4 / Shaded Image

Figure 6.3.7-16

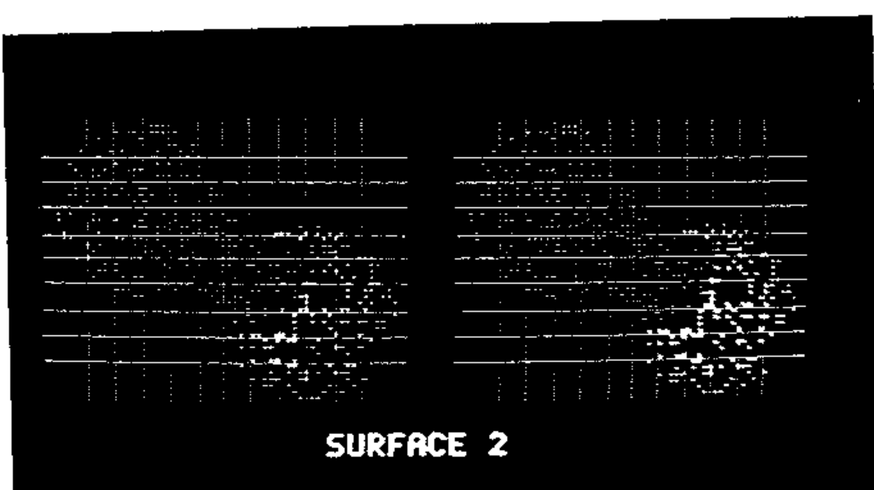


Barbell / View 4 / Input Data



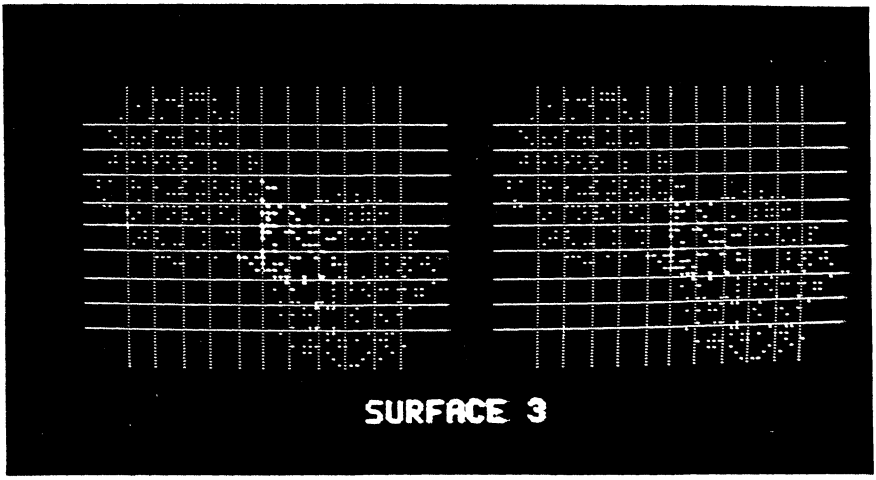
Barbell / View 4 /Surface 1

Figure 6.3.7-18



Barbell / View 4 / Surface 2

Figure 6.3.7-19



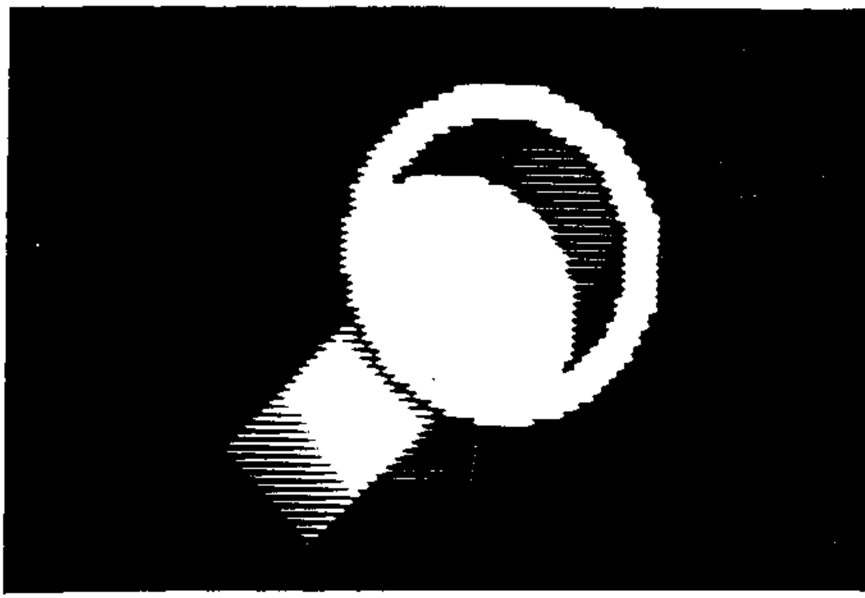
Barbell / View 4 / Surface 3

Figure 6.3.7-20

3.8 Mug -

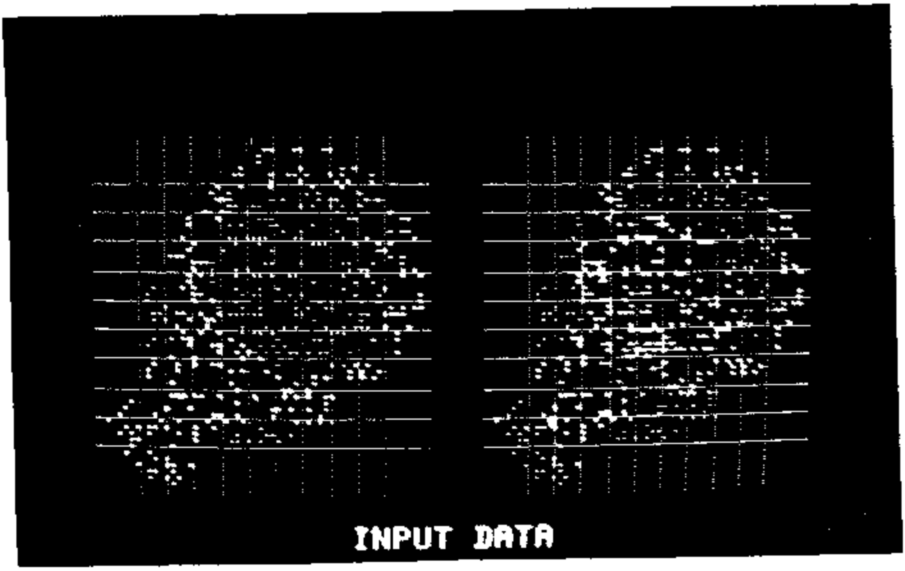
The test object labelled "mug" is composed of a handl
ıd a cup part. Two cylinders, one positive and oı
:gative form each part. For the cup part, the cylinde
:e arranged to form a closed bottom of the mug. For tl
ındle, the negative cylinder completely removes the cent
:ction of the positive cylinder to form a hole. Tl
ırpose of the object is to test the ability to describe
›mplex object with a hole in it. The analyses of the fo
:imary views did not use all the data points in any cas
ı all views, requests were made for additional informatio
ı view one, the data lacked sufficient number of cells
:rmit the shape labelling process to identify the t
ıadric surfaces forming the outside of the cup and handl
n view two, there were not enough data to identify t
nside of the handle. In view three, the side of the hand
ppeared as a long, narrow plane surface and was reject
ecause of the cylinder restriction. In view four, t
eparate requests for supplemental information were ma
orresponding to the areas of the bottom outside and the t
nside of the handle. In both cases there were too few da
oints for identification. The integration of resul
roduced an incomplete description of the object. T
nside cylindrical surface of the handle was not identifi
n any view. The final global description consisted

iree cylindrical primitives and five planar primitives.



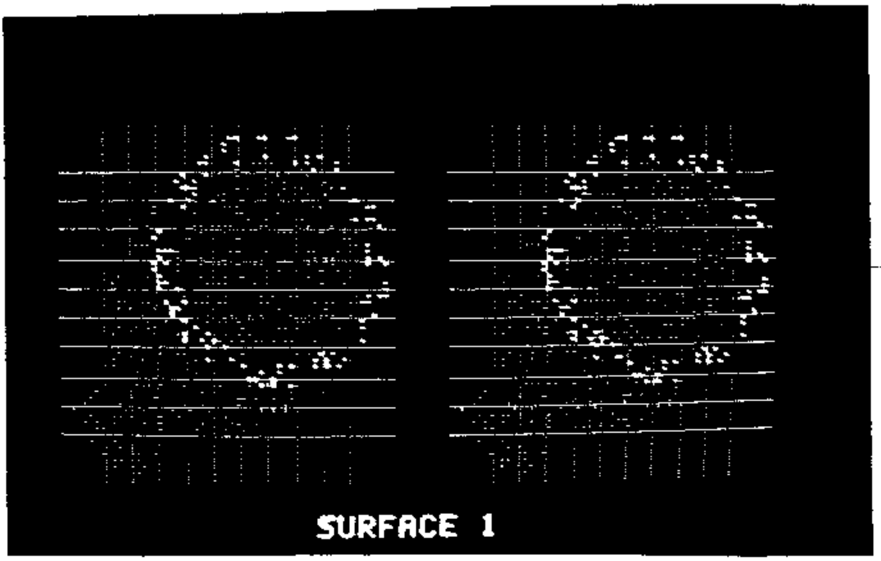
Mug / View 1 / Shaded Image

Figure 6.3.8-1



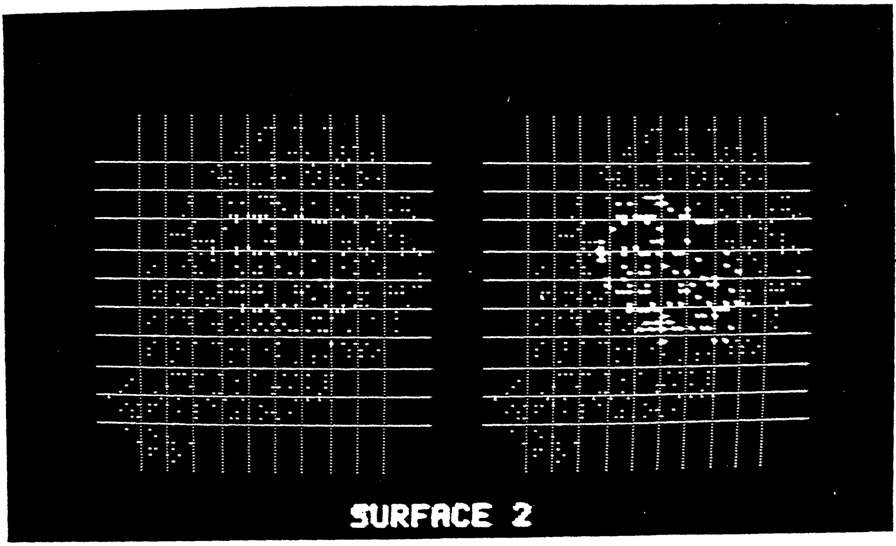
Mug / View 1 / Input Data

Figure 6*3.8-2



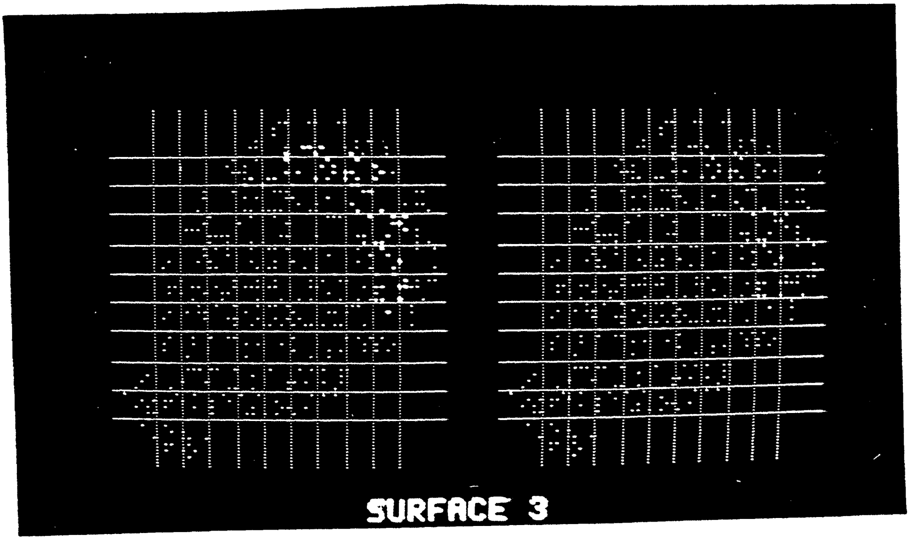
Mug / View 1 / Surface 1

Figure 6.3.8-3



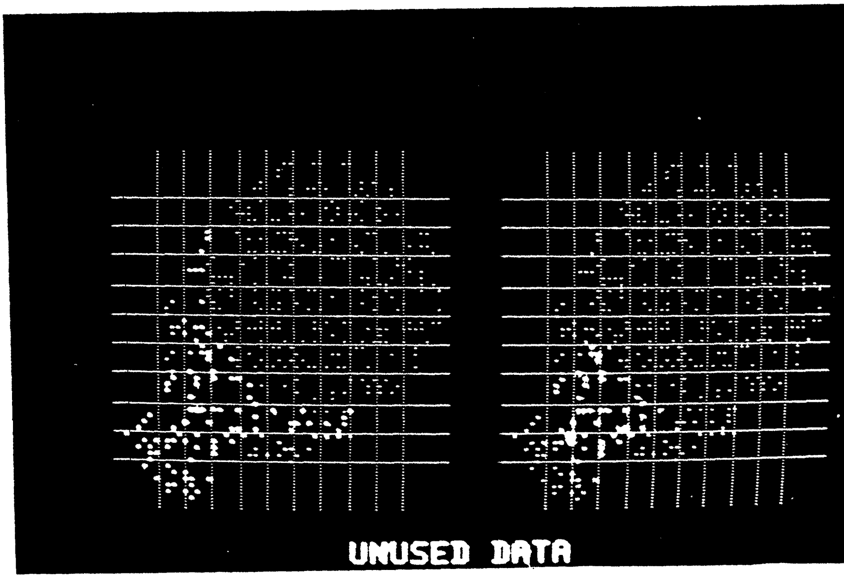
Mug / View 1 / Surface 2

Figure 6.3.8-4



Mug / View 1 / Surface 3

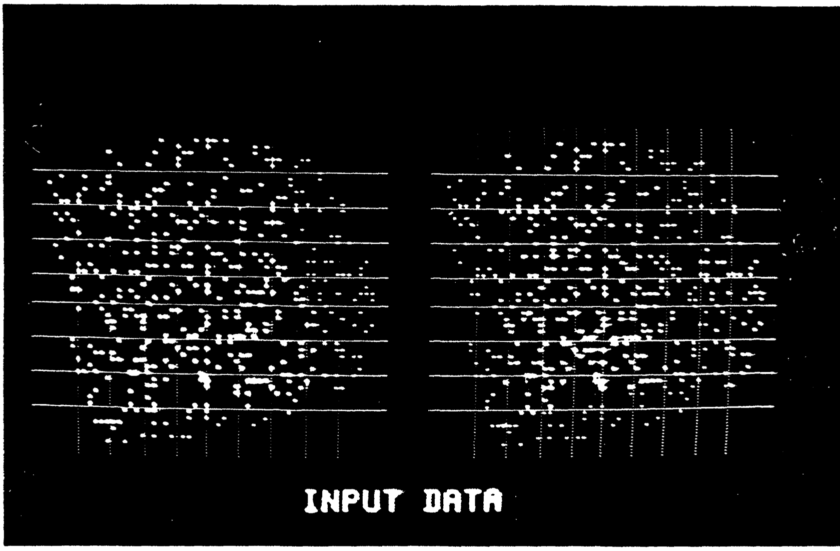
Figure 6.3.8-5



Mug / View 1 / Unused Data

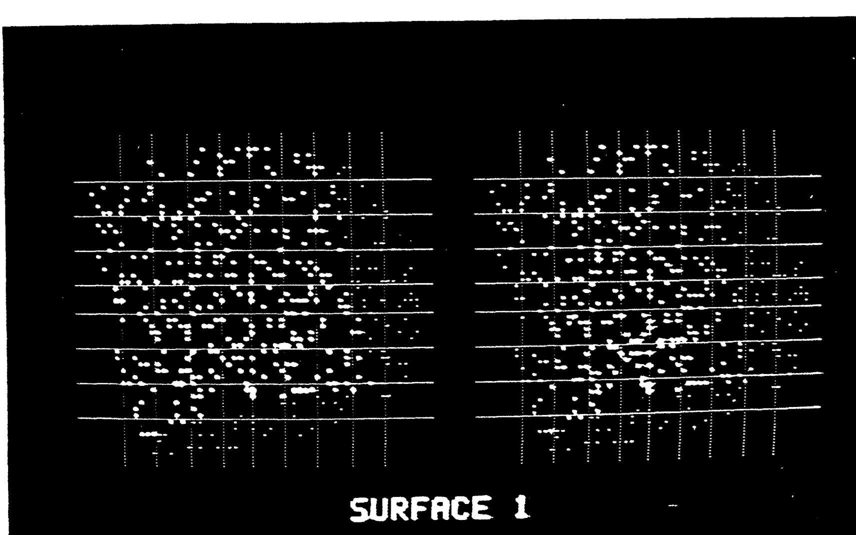
Figure 6.3.8-6

Mug / View 2 / Shaded Image

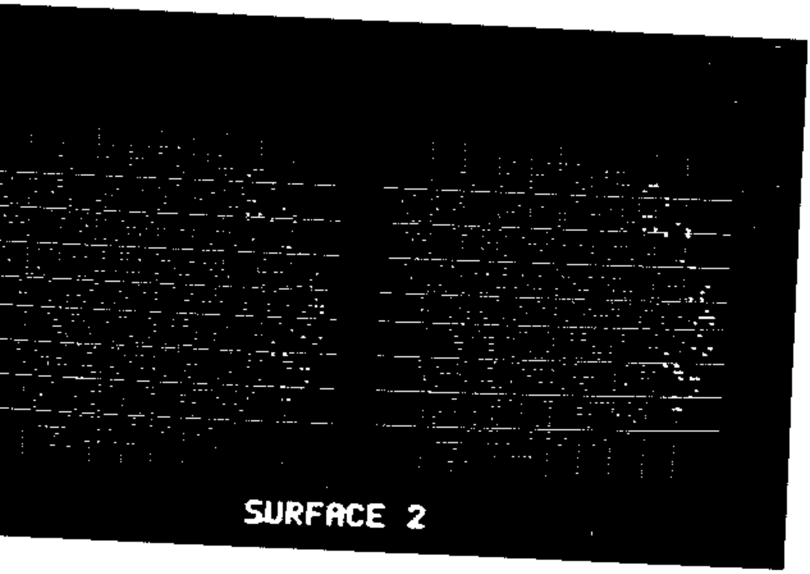


Mug / View 2 / Input Data

Figure 6.3.8-8

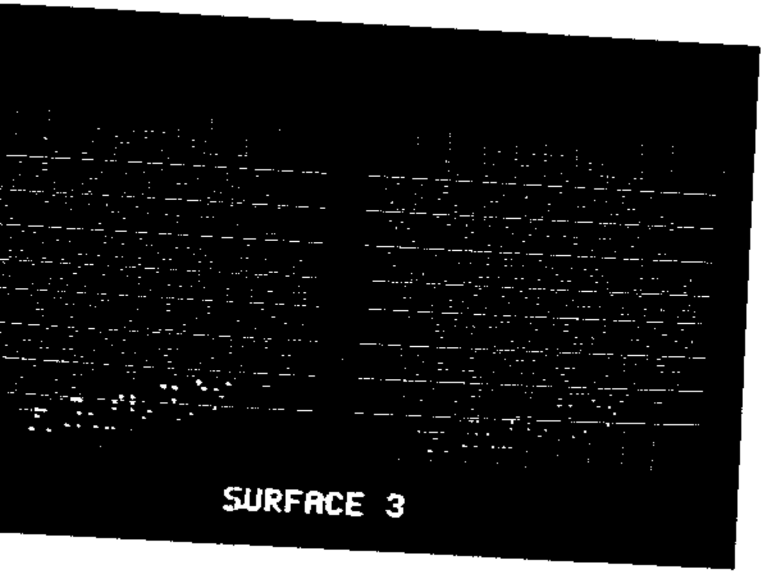


Mug / View 2 / Surface 1



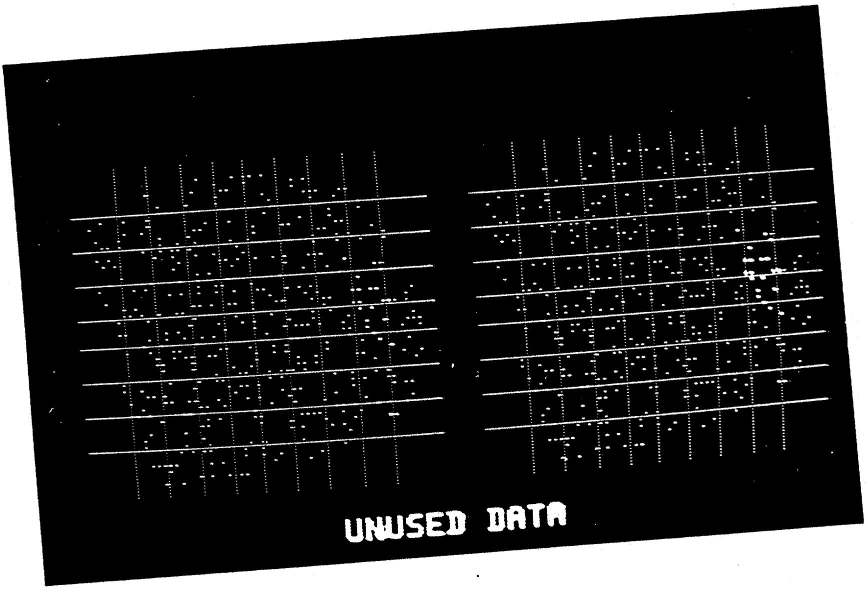
MU8 / Vl«" 2 / surface 2

Figure 6.3.8-10



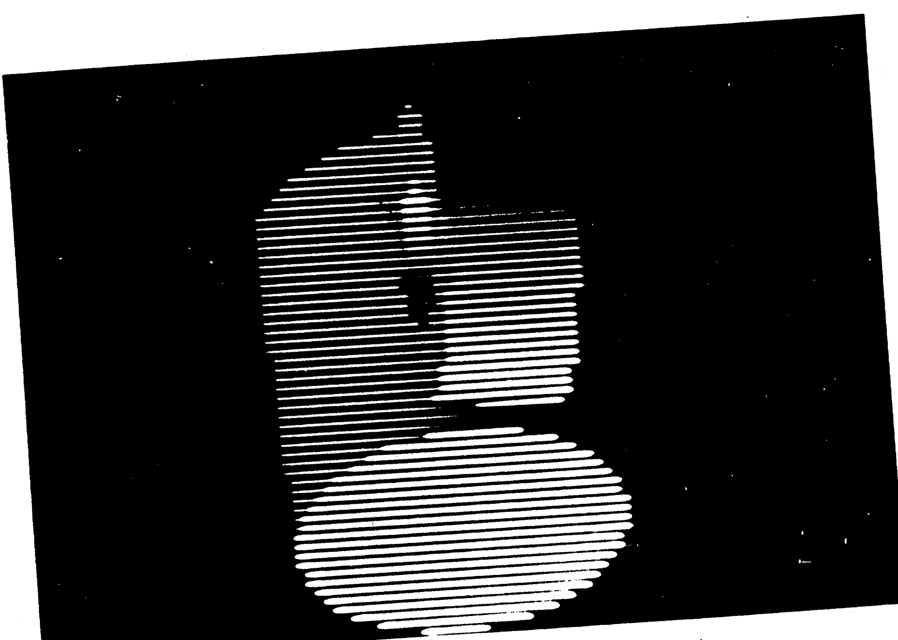
Mug / View 2 / surface 3

Figure 6.3.8-11



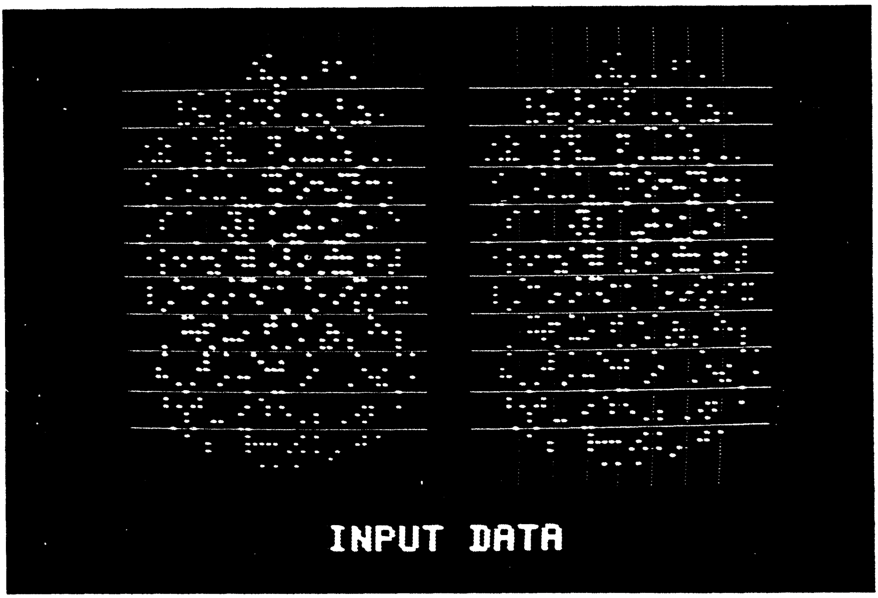
Mug / View 2 / Unused Data

Figure 6.3.8-12



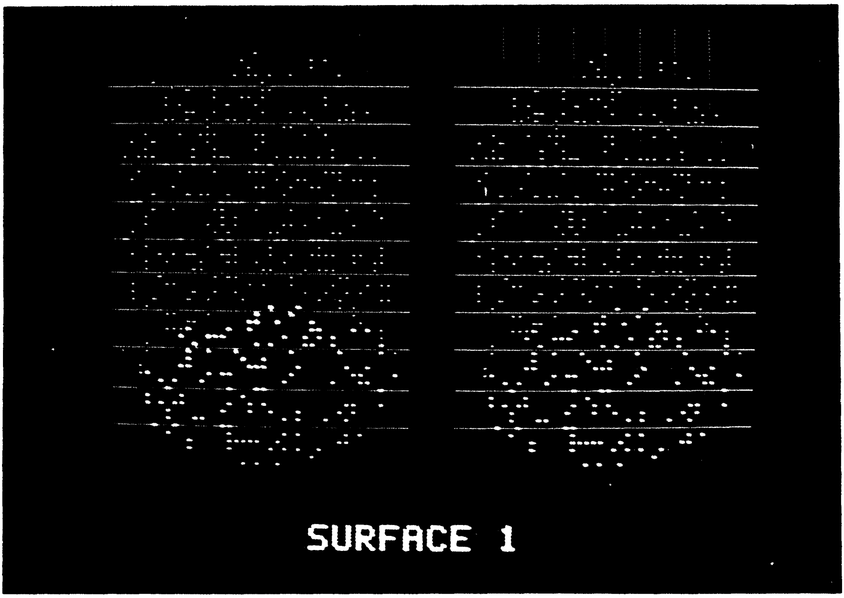
Mug / View 3 / Shaded Image

Figure 6.3.8-13

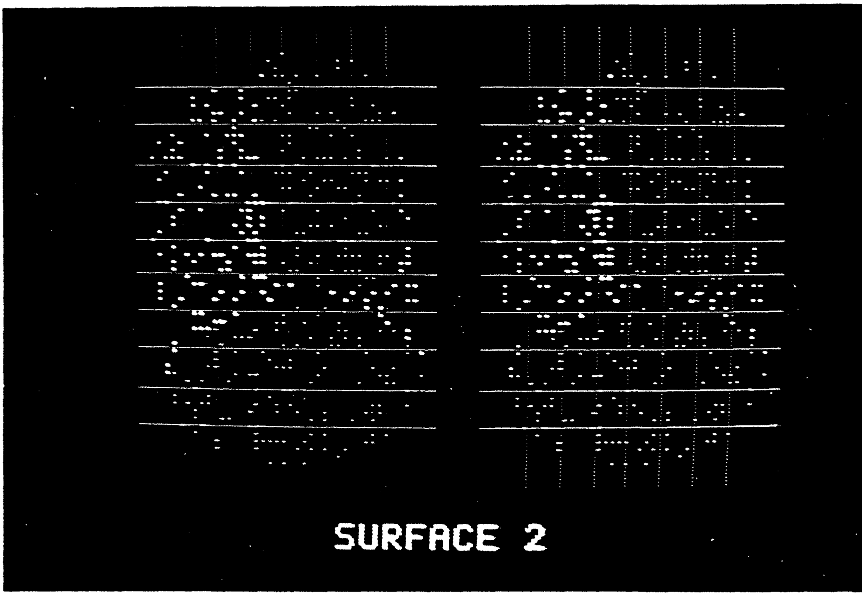


Mug / View 3 / Input Data

Figure 6.3.8-14

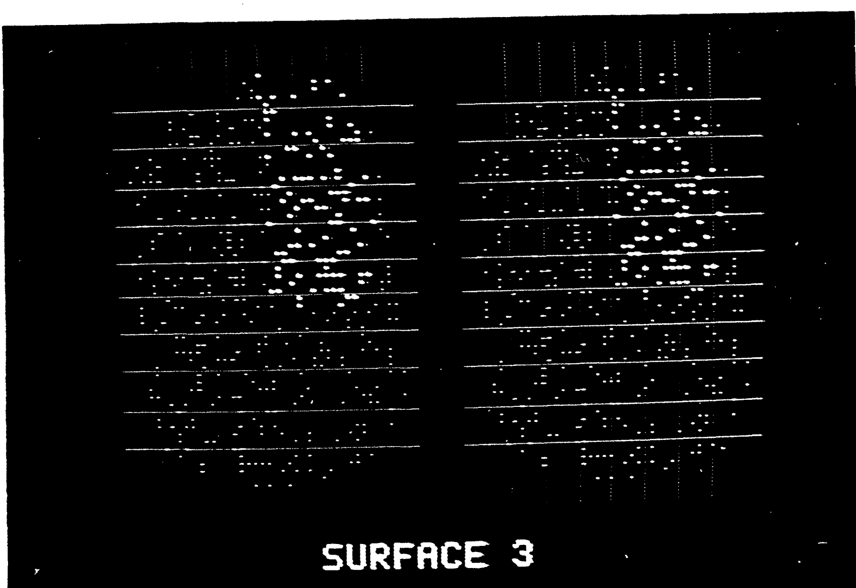


Mug / View 3 / Surface 1

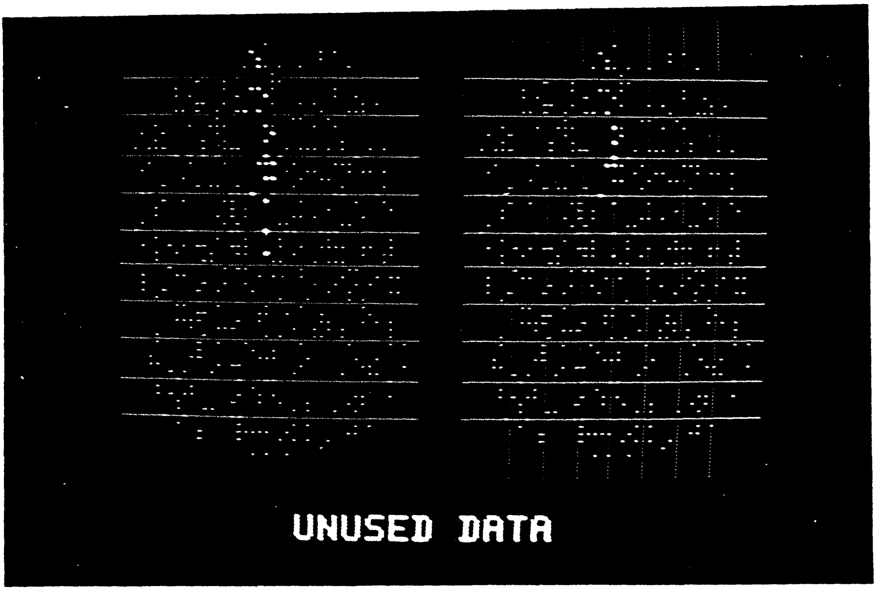


Mug / View 3 / Surface 2

Figure 6.3.8-16

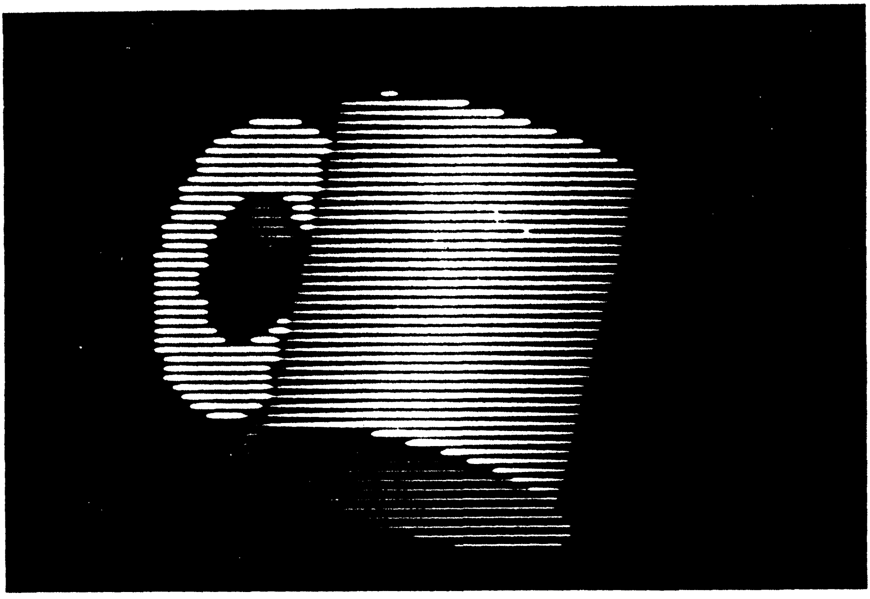


Mug / View 3 / Surface 3



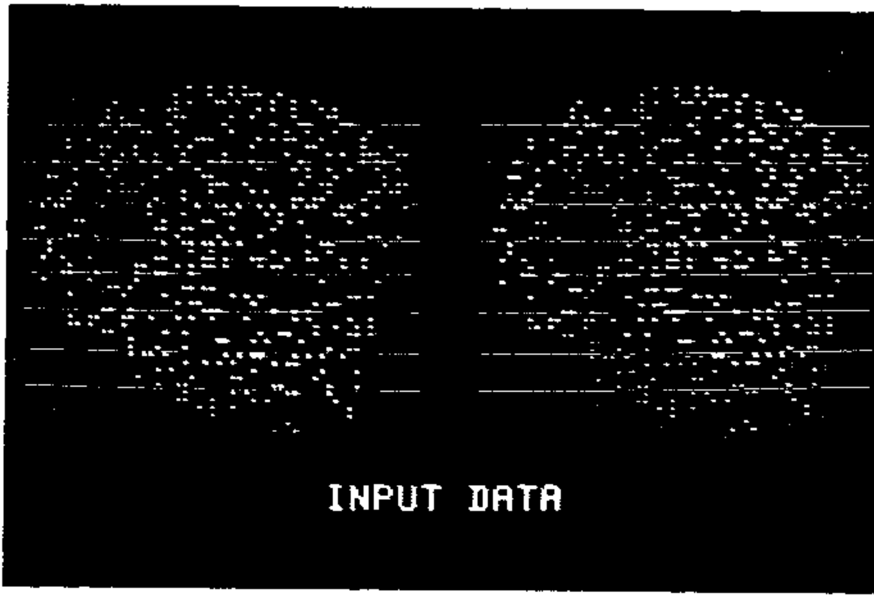
Mug / View 3 / Unused Data

Figure 6.3.8-18



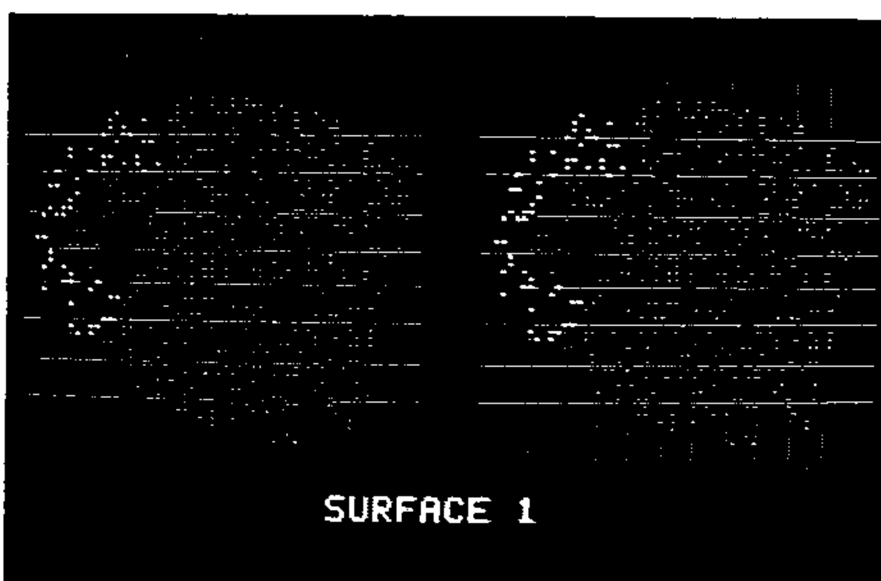
Mug / View 4 / Shaded Image

Figure 6.3.8-19



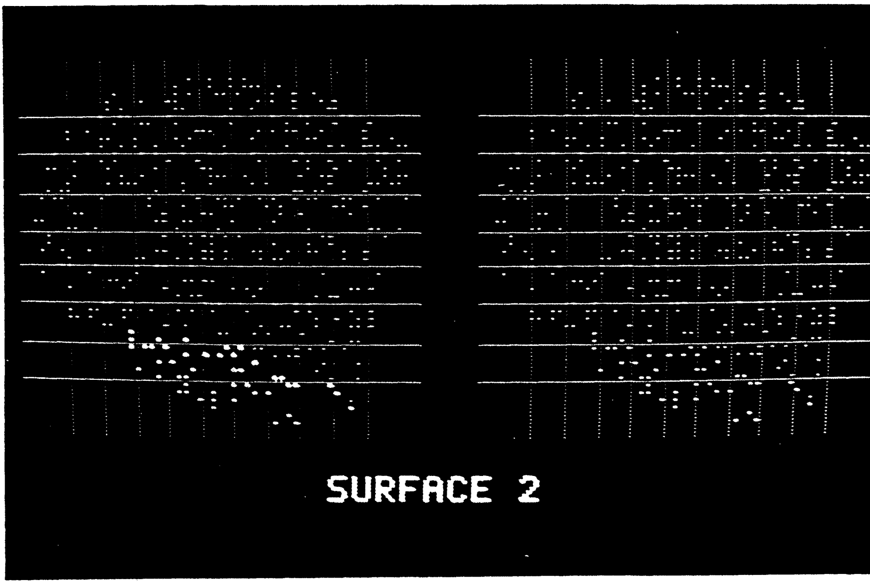
Mug / View 4 / Input Data

Figure 6,3.8-20



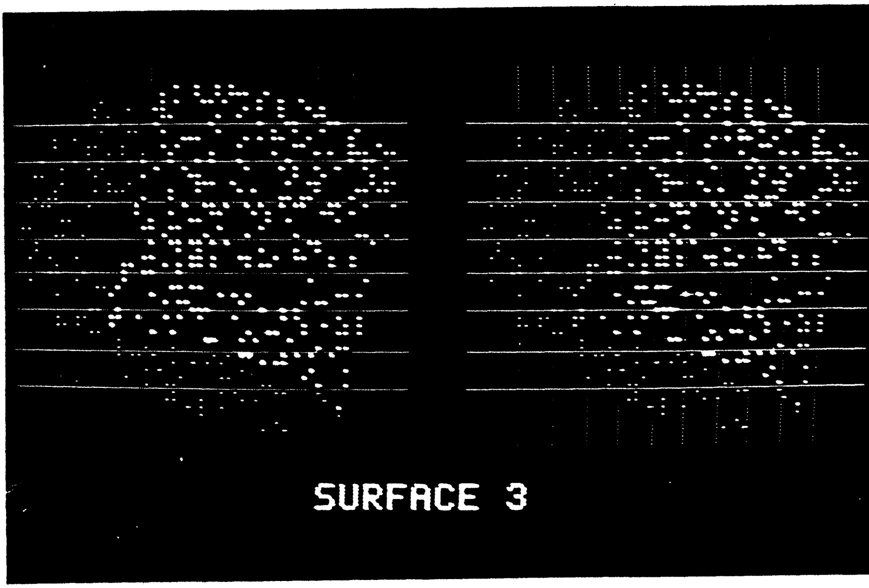
Mug / View 4 / Surface 1

Figure 6.3.8-21



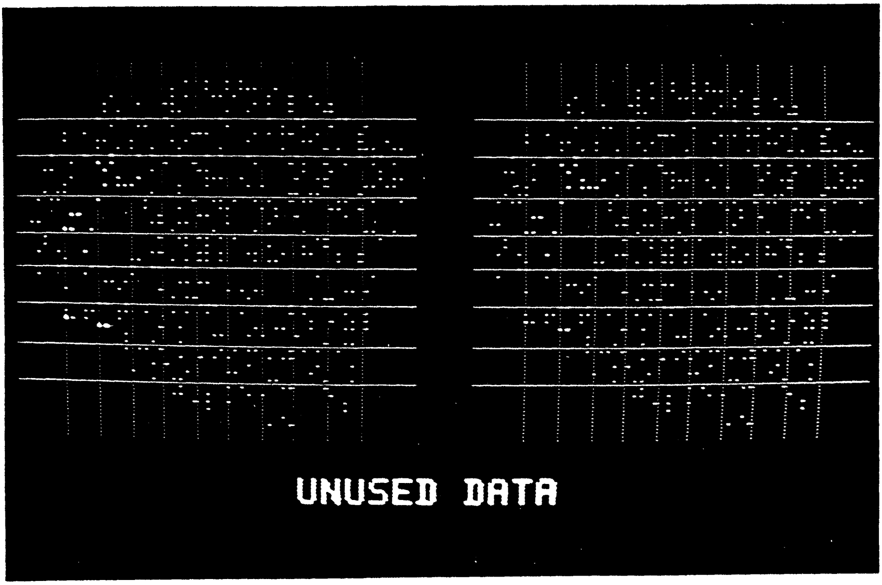
Mug / View 4 / Surface 2

Figure 6.3.8-22



Mug / View 4 / Surface 3

Figure 6.3.8-23

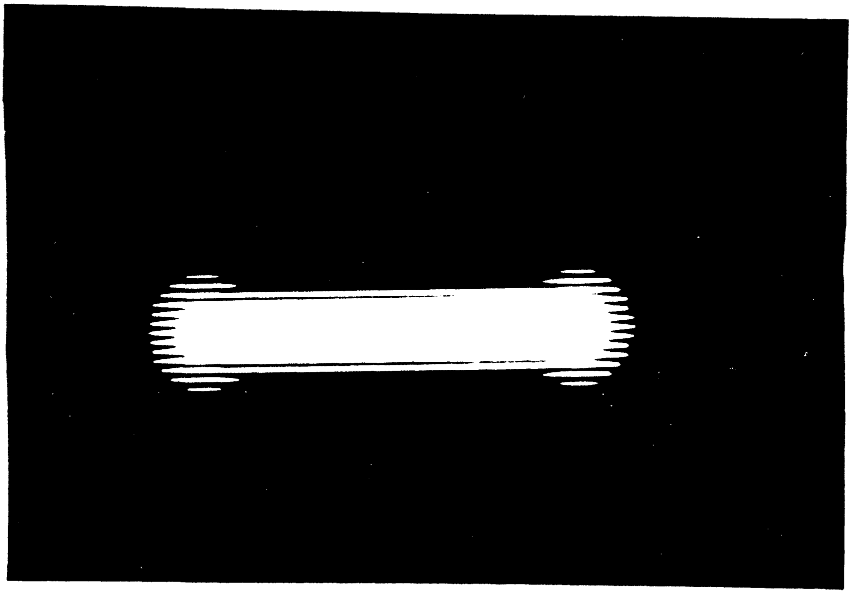


Mug / View 4 / Unused Data

Figure 6.3.8-24

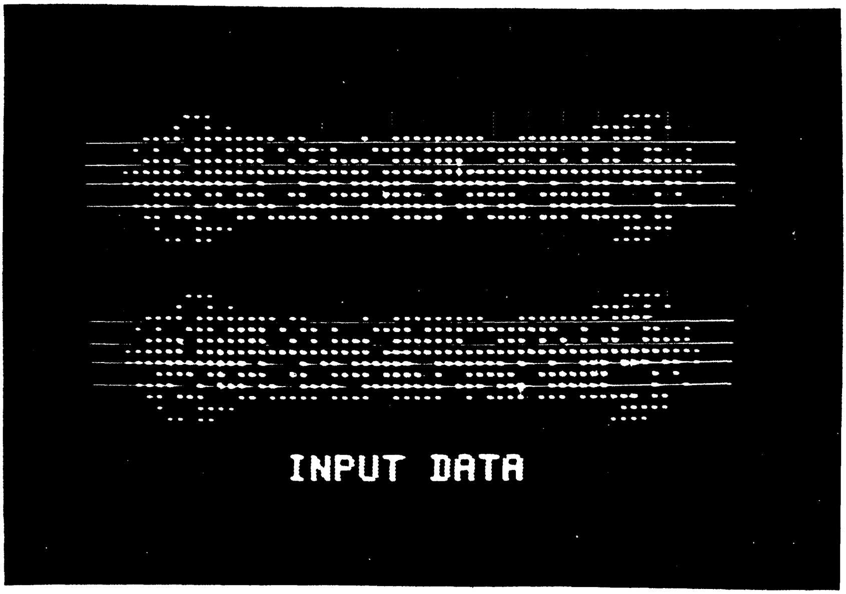
5.9 Telephone Handset -

The test object labelled "telephone handset[11] ii
nposed of a mouth piece and an ear piece connected by .
idle approximated with an elliptic cylinder. The moutl
i ear pieces are ellipsoids with single planar section:
noved to flatten an area. In views three and four, onl;
e of the planar sections is visible because of the viewin
rameters. The ability to describe a telephone was th
tivation for this work. The analyses of the four primar
ews were completed without difficulty. The integration o
e results of these local analyses produced an accurat
scription of the object. The final global descriptio
nsisted of two planar primitives, two ellipsoida
imitives and a cylindrical primitive.



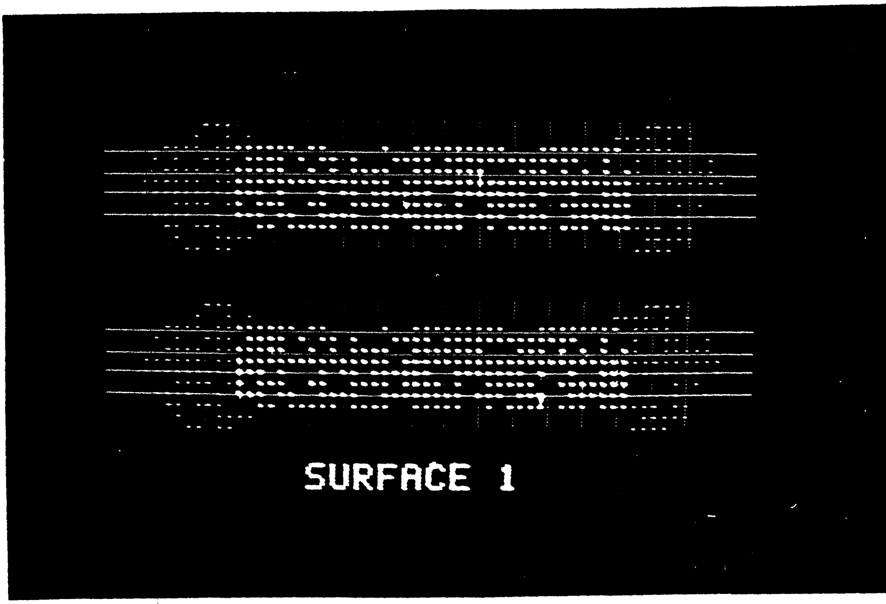
Telephone Handset / View 1 / Shaded Image

Figure 6.3.9-1



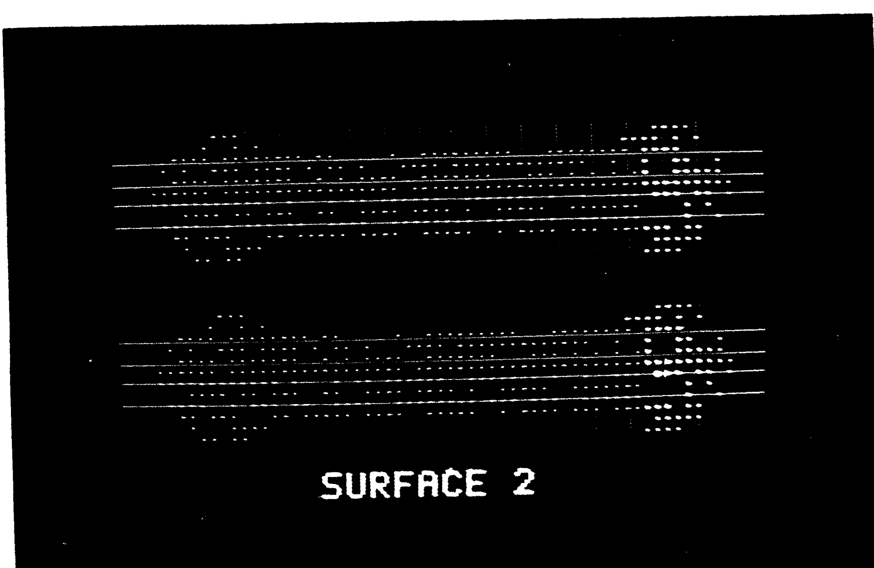
Telephone Handset / View 1 / Input Data

Figure 6.3.9-2



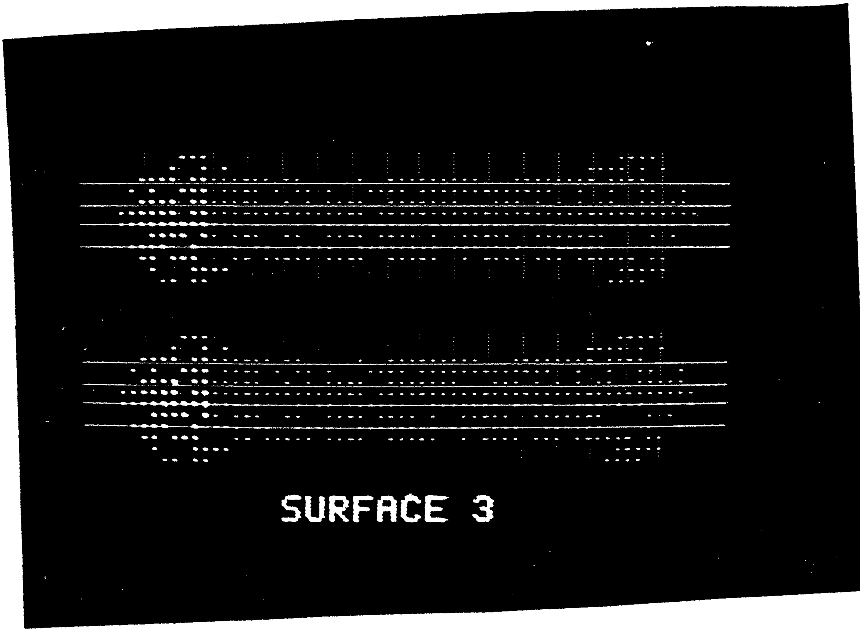
Telephone Handset / View 1 / Surface 1

Figure 6.3.9-3



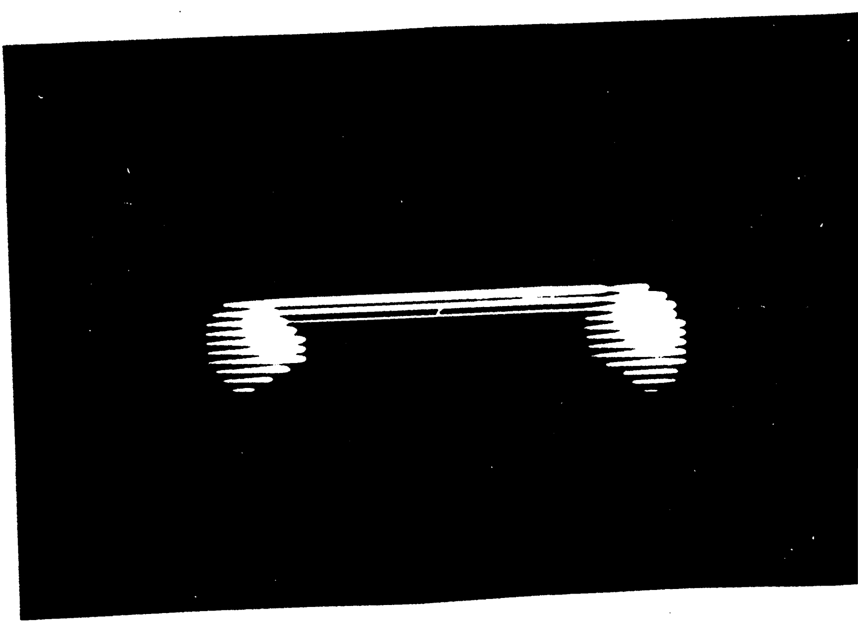
Telephone Handset / View 1 / Surface 2

Figure 6.3.9-4



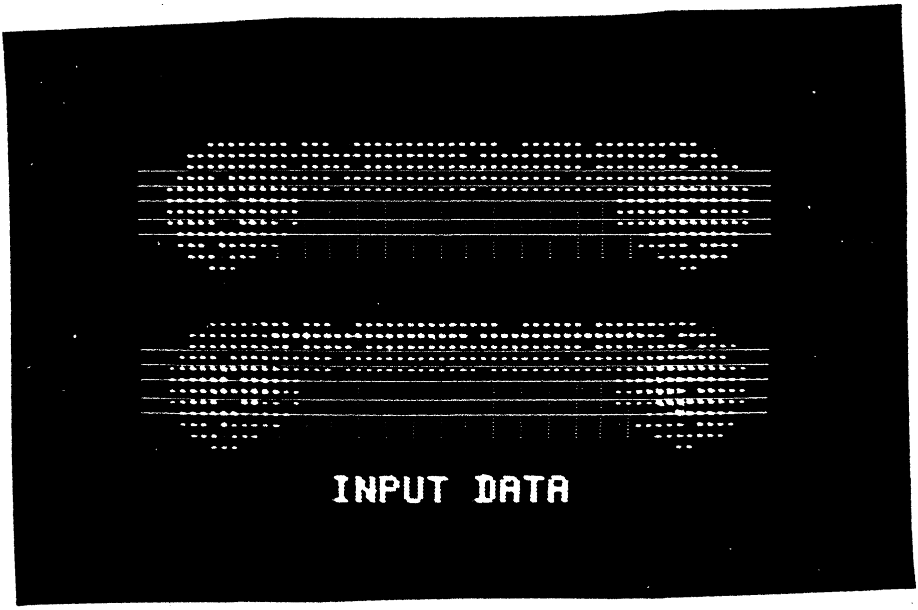
Telephone Handset / View 1 / Surface 3

Figure 6.3.9-5



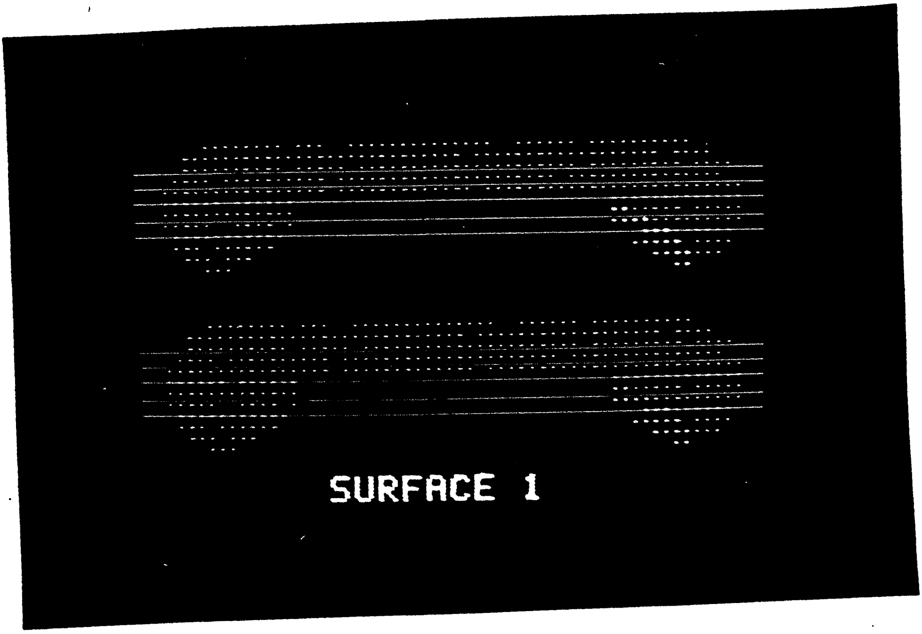
Telephone Handset / View 2 / Shaded Image

Figure 6.3.9-6



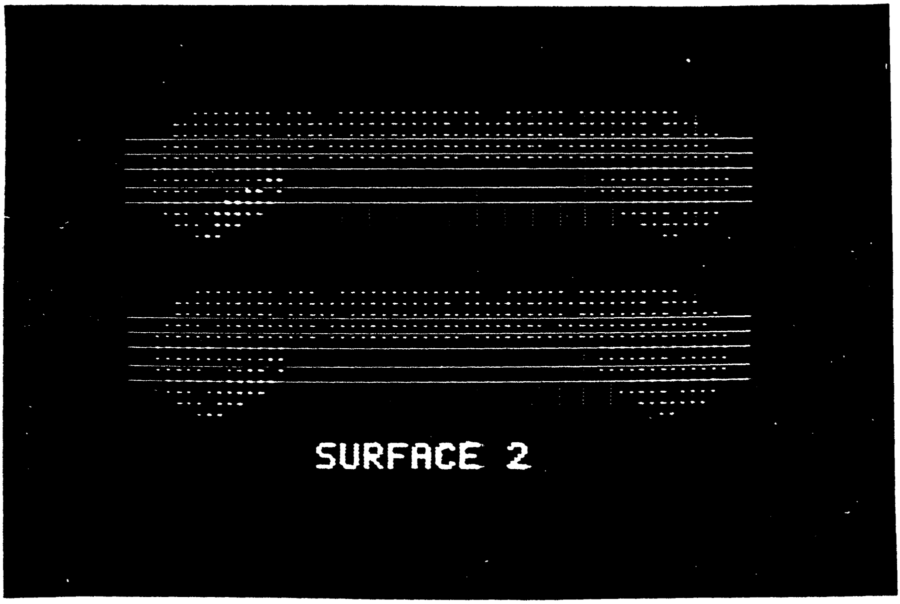
Telephone Handset / View 2 / Input Data

Figure 6.3.9-7



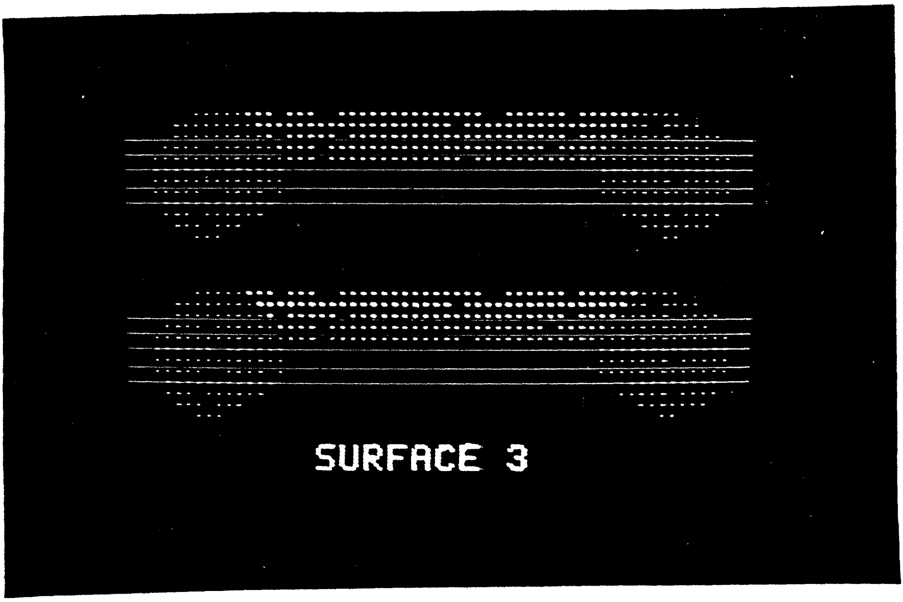
Telephone Handset / View 2 / Surface 1

Figure 6.3.9-8



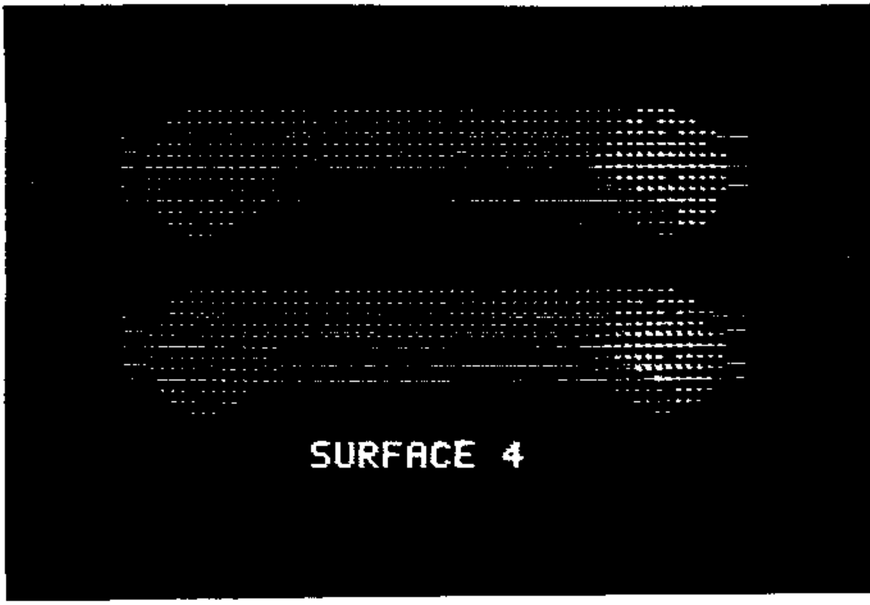
Telephone Handset / View 2 / Surface 2

Figure 6.3.9-9



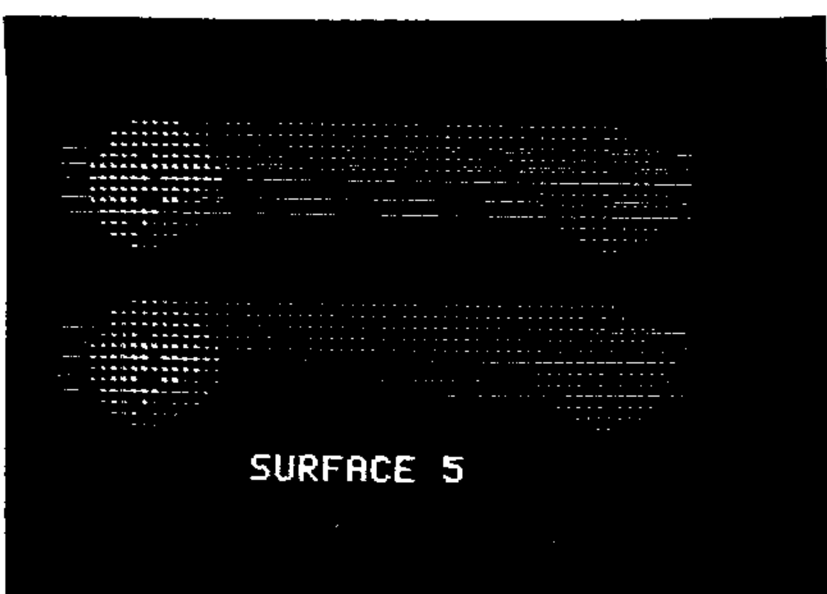
Telephone Handset / View 2 / Surface 3

Figure 6.3.9-10



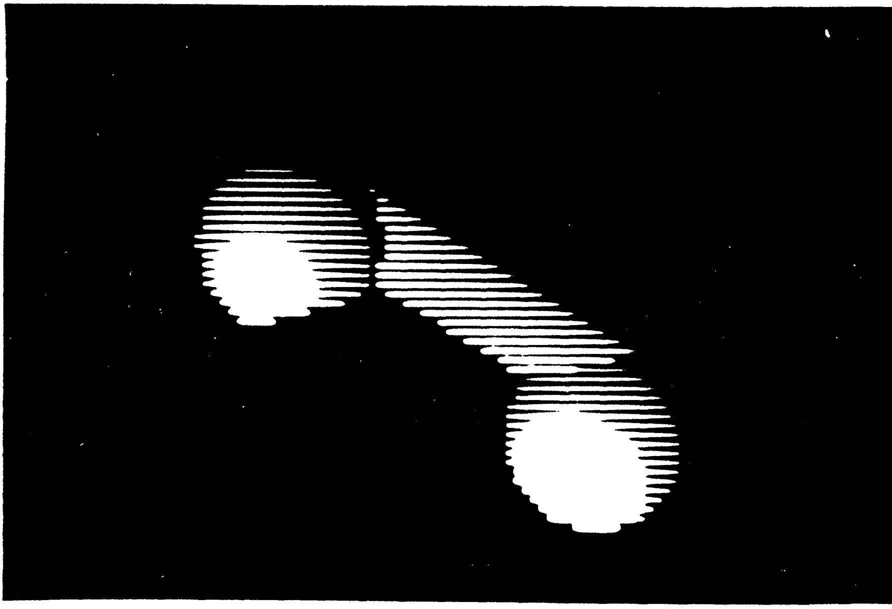
Telephone Handset / View 2 / Surface 4

Figure 6-3.9-11



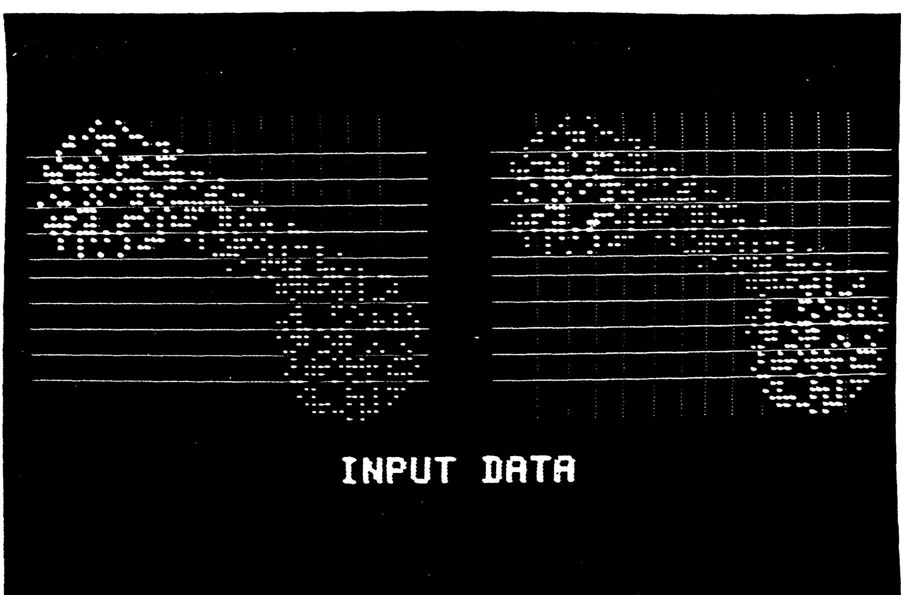
Telephone Handset / View 2 / Surface 5

Figure 6.3.9-12



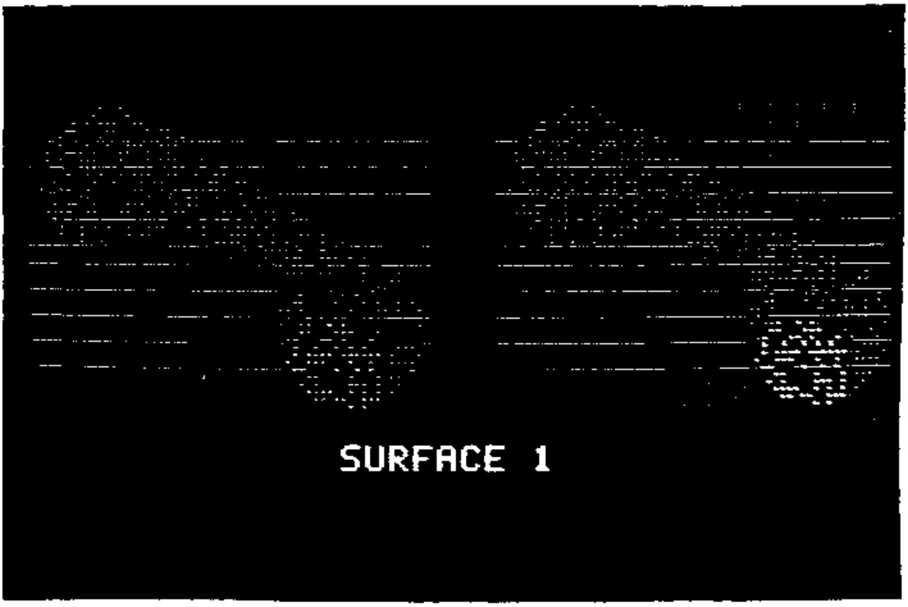
Telephone Handset / View 3 / Shaded Image

Figure 6.3.9-13



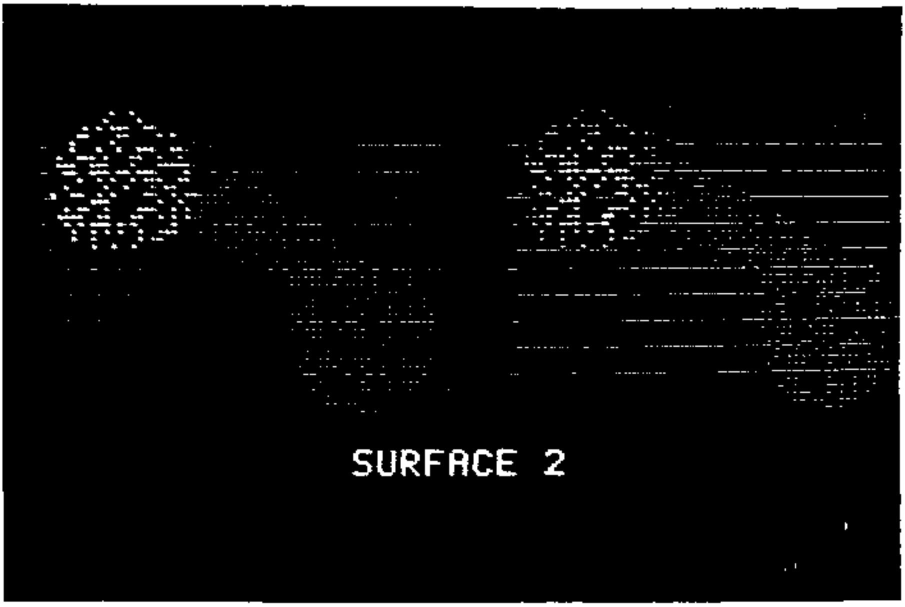
Telephone Handset / View 3 / Input Data

Figure 6.3.9-14



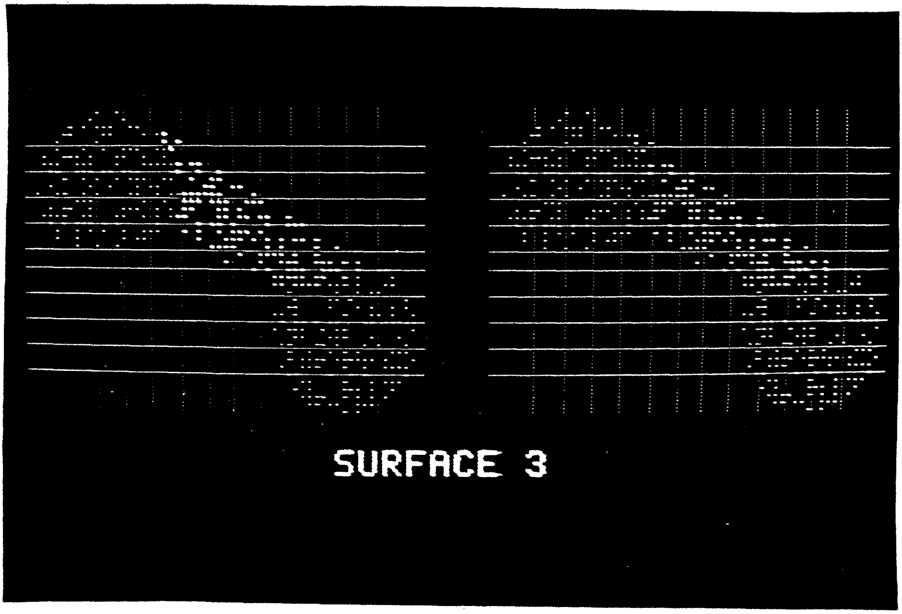
Telephone Handset / View 3 / Surface 1

Figure 6.3.9-15



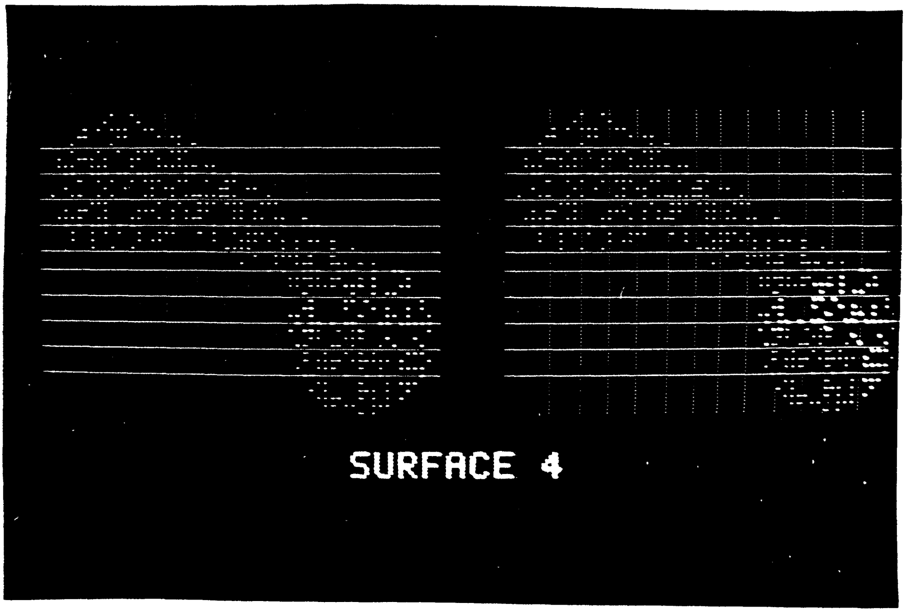
Telephone Handset / View 3 / Surface 2

Figure 6.3.9-16



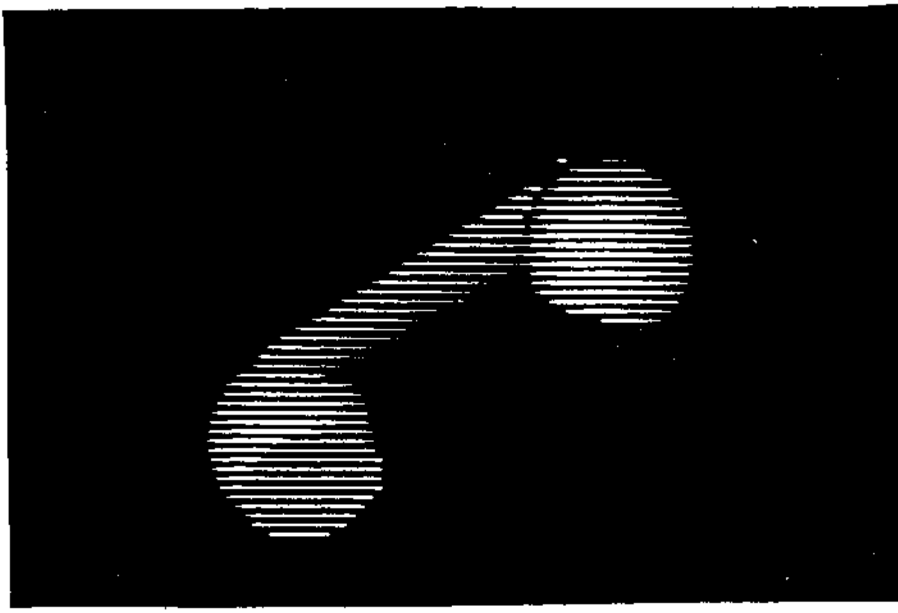
Telephone Handset / View 3 / Surface 3

Figure 6.3.9-17



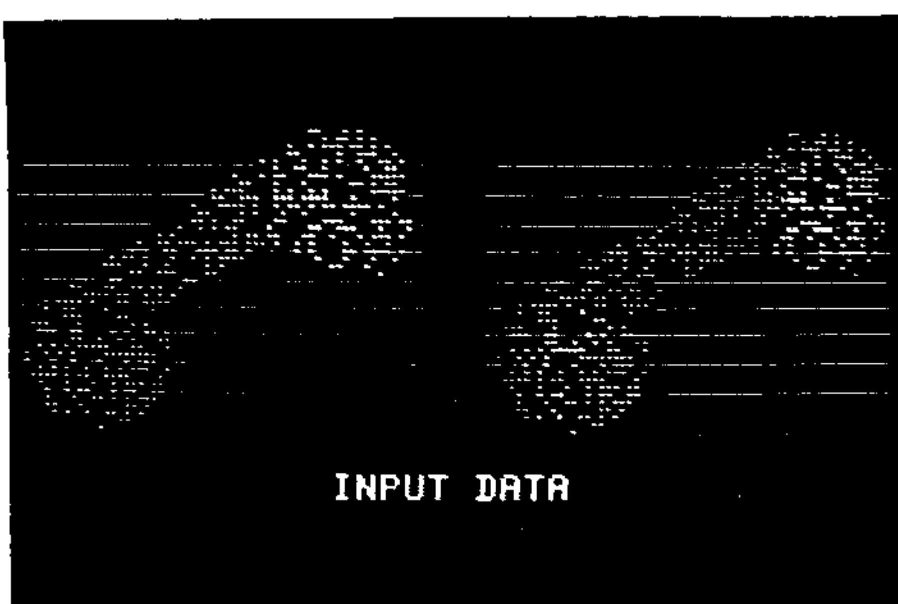
Telephone Handset / View 3 / Surface 4

Figure 6.3.9-18



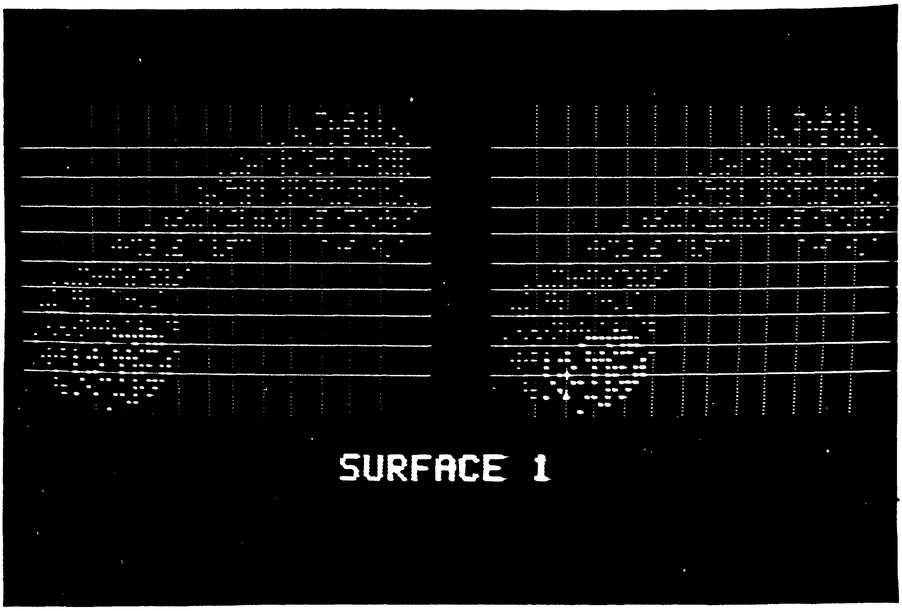
Telephone Handset / View 4 / Shaded Image

Figure 6.3.9-19



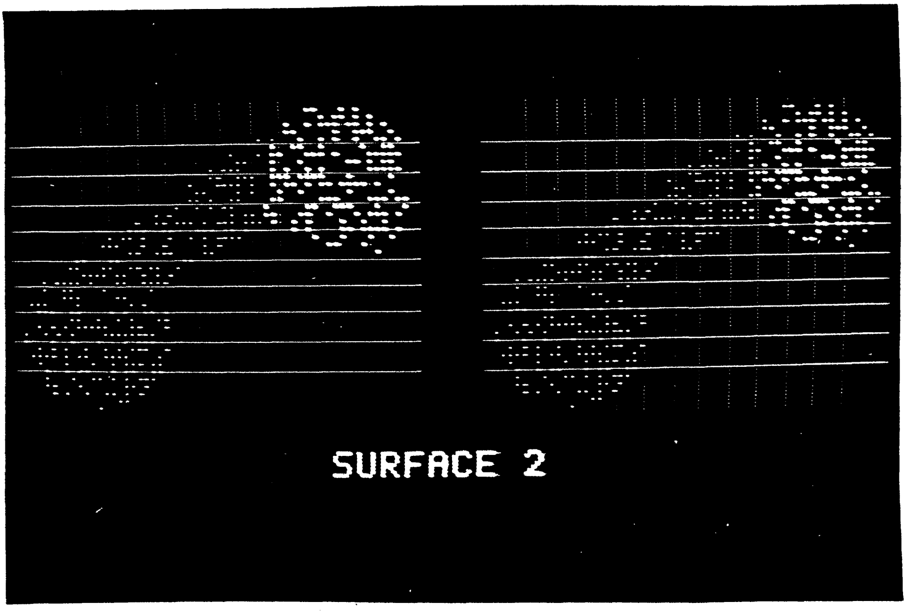
Telephone Handset / View 4 / Input Data

Figure 6.3.9-20



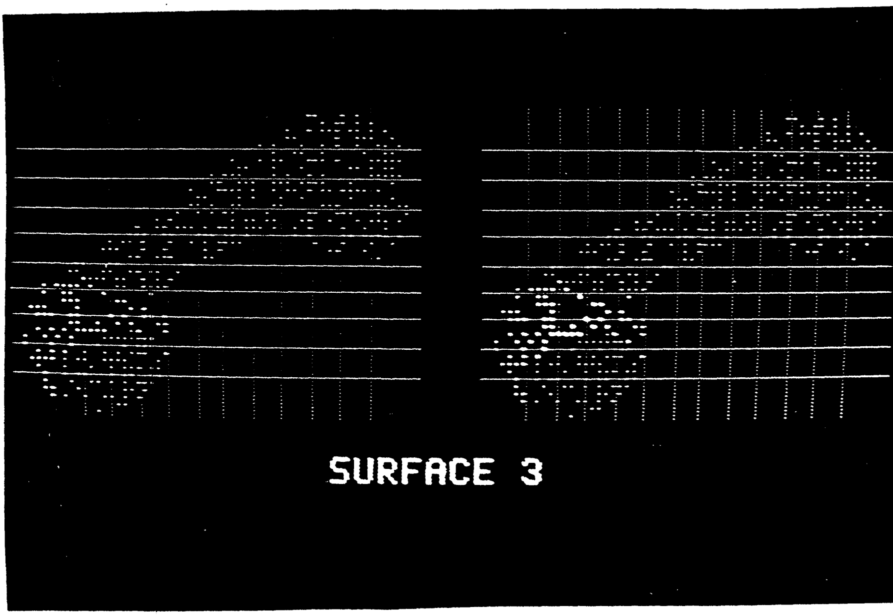
Telephone Handset / View 4 / Surface 1

Figure 6.3.9-21



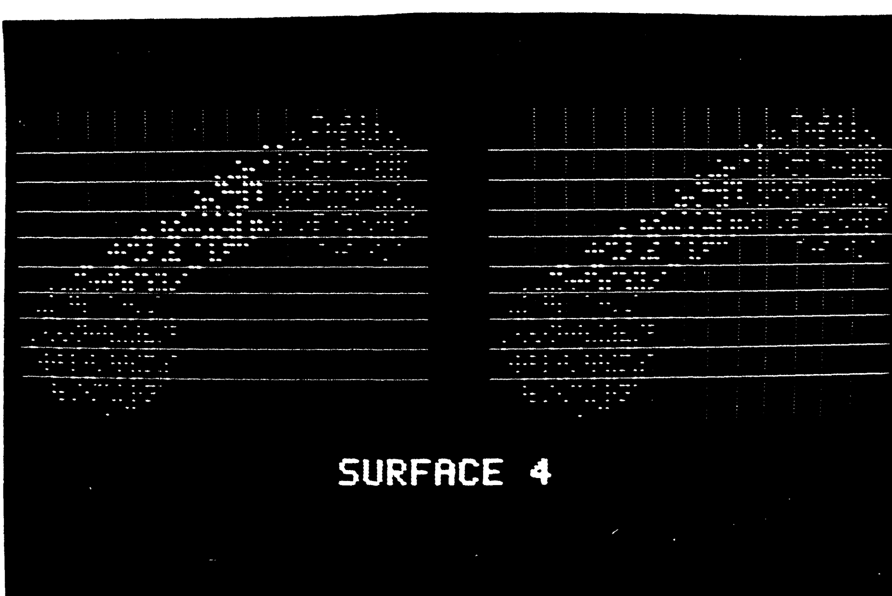
Telephone Handset / View 4 / Surface 2

Figure 6.3.9-22



Telephone Handset / View 4 / Surface 3

Figure 6.3.9-23



Telephone Handset / View 4 / Surface 4

Figure 6.3.9-24

CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORK

This chapter presents conclusions drawn fro experience gained in doing the work reported. S conclusions and suggestions about the implementati presented first. Conclusions about general iss representation are presented next. Finally, suggesti further study are presented.

7.1 Specific Conclusions

The analysis of the examples presented sho success of the use of the registered arrays which su input data. These arrays permit data to be organiz used effectively in a hierarchical manner. Thi increases the efficiency of computation. However, th for greater resolution is seen also. The res required is a function of the complexity of the viewed. The proposed model builder does a hiera analysis. It starts with a coarse resolution and whe detail is needed, it requests supplemental views of resolution but limited domain. To prevent repeated r for views of the same general area at greater and

^solution, it appears that the approximate four hundr<
Lta points and the eighty local cells be minimal. Usii
ro to five times as much information should improve tl
:tuation without an undue increase in computational cost.

The use of the average and standard deviation values 1
immarize observed properties is shown to be a useful meth<
) obtain reliable information in a noisy world. It is
)uble edged sword, however. The worse the input dal
lality or the greater the desired accuracy of the result!
le larger the amount of input data required. There ai
Lnite practical limits on the accuracy and amount <
iformation that can be collected. Ambitious applicatioi
Lways test the limits of the available technology
Dllect more and better information.

The identification of data points to be groupe
Dgether for representation by a primitive based on bo
patial and orientation information is supported by the te
esults. The implementation of the assumptions used
dentification is not the best, but it works for the objec
xamined. Specifically, the shape labelling process cou
e improved. Only qualitatively different shapes a
ifferentiated in the current implementation. As long
he underlying surface is, at most, quadric, no troub
ccurs. However, if the underlying surface is more compl
nd more than one surface primitive is required to model i

ne shape labelling process may not give adequate results hether to break the complex surface at places of high c ow curvature is unexplored in this work because the curren abelling scheme does not convey sufficient quantitati nformation about the local surface shape.

Various criteria for fitting surfaces were considere efore settling on the two used. One criterion used elated to spatial information, and the other criterion elated to orientation information. They are considered solation of each other. When no error in the data resent, the results are predictable. However, it ifficult to predict the effect of input data error on th itting of surfaces. In chapter five, the mix of spati nd orientation criteria used was shown explicitly. The s a dissimilarity in the units of measure of the t riteria, and an implicit equivalence was defined in an a oc fashion. Experiments using different weights we nconclusive as to the best mixture. The fact that t ombined criteria proved superior to just the spati riterion suggests that the spatial and orientation data a omplementary in nature. However, this idea seems to ontradicted by the fact that orientation information can pproximated from spatial information.

The identification of the same surface from differe
ews has been studied. The need to avoid classificati
hemes that use rigid, absolute criteria to determi
lentification is shown. An ad hoc similarity measure th
ses the quantitative surface coefficients has be
nplemented. The identification of the same surface fr
ifferent views works when there is little error in t
itted surfaces. However, the measure's performance in
oisy environment is difficult to predict in terms that a
eometrically intuitive. Another method is proposed th
akes a distinction between location and shape informatio
t is hoped that by explicit separation, the role of ea
ype of information can be clarified. However, the propos
ethod remains untested.

.2 General Conclusions

The use of multiple views, while not n
UNDERWOOD/COATES75], is unusual in the three-dimension
nalysis of scenes. In the past, use of multiple views h
verlooked the concept of closure. Only when the analys
s committed to obtaining an object description based
omplete information does closure become important. Just
itting the last piece of a jigsaw puzzle in place unit
ll the pieces into one picture, closure guarantees t
nformation needed to create a complete and consiste

object description is available. The analysis, knowing fact, can check the final description and insure that are no holes, like a missing edge, and discontinuities two surfaces not terminating cleanly at an Unfortunately, this idea is untested because the analyi edge graph information was not implemented.

The importance of using both spatial and orienl information in a representation is confirmed, representation that does not consider both type? information will have representational flaws that disqualify it from use in some applications. This wor! motivated initially to study the Gaussian image intermediate representation for use in buildii description of an object [SMITH79], [BAJCSY80]. Gaussian image ignores spatial information totally; ai a result, many objects are mapped to the same Gat description. Some £d[hoc method of augmenting the Gat image representation to compensate for the lack of s] information could be proposed. However, such a pr< would be like placing a small bandage over a gaping \ This representation was abandoned in favor of the regi? arrays that are capable of treating both spatia! orientation information in an integral f; [DANE/BAJCSY81].

The need for a primitive expressed in a canonical fo as been highlighted in the discussion of the measure imilarity. The ability to separate information defini hape from spatial information defining location is requir f results that have intuitive geometric interpretation a xpected. [HINT0N8i] cites evidence reported in t sychology literature that supports the idea that humans u "canonical, object-based" reference frame in the escription of three-dimensional objects. The canonic orm also serves to simplify the problem of recognition.

The use of a viewer-independent coordinate system f he object's description is a feature of the model builde on-essential, viewer-dependent information is n ncorporated in the description. In order to accompli his fact, the relationships between the various views a eeded to establish a common reference frame. Ideally, t inal object-centered coordinate system should permit high evel processing, such as finding symmetries, to be do asily and allow results to be expressed concisely.

What can be achieved by using the proposed mod uilder? A surface description of an object is construct rom which it is possible to estimate global properties su s volume, structural symmetries, and positions tability. The model can serve as an intermediate step he derivation of other types of representation from the r data. A global smoothing of raw data occurs as effect in the process of building the model. This sm has beneficial effects on data obtained f reconstruction based on the model. Such a reconst algorithm can be used as a source of information for to a graphics display or CAM system.

7.3 Future Work

During the implementation and testing of program use of artificial data proved to be invaluable for de and exposing weaknesses in the proposed algo However, before the ideas the programs seek to just be considered proven, additional tests must be run real data. Without this real test, the abilities programs to perform to specification cannot be tak granted. The use of both real and artificial data development process of programs is important and type of testing should be neglected.

There are two distinct areas where future work done. The first area is categorized as doing or work to build descriptions of objects in the real wor help the model builder function in a real world envir the suggestions presented previously should be imple The need to test the surface fitting technique implement a new measure of similarity for identif

rposes is especially important. It is suggested strongl
at future work dealing with three-dimensional data not b
tempted on a computer with a 32k address space. While i
not impossible, it does make implementation difficult.

The implementation of edges as the mathematica
tersection of primitives and the confirmation of th
istence of the edges is a major project. It is a wel
derstood problem with solutions suggested by other
EVIN76], [SHAPIRO/FREEMAN78]. Once completed, the loca
alysis can be expanded to generate edge graph information
e availability and use of this information woul
rengthen the integration step and permit th
plementation of the closure analysis to evaluate th
mpleteness of the global description. Beyond this work
ere are two rather large, uncharted regions to b
plored. The first is in the area of recognition. Give
object-centered model, how effectively can it be used i
cognition, graphics display, or CAD/CAM? The second is i
e area of strategies. What are the criteria for acquirin
re data? What are the criteria for analyzing the existin
ta more? What is the optimal mix to obtain a solution t
given problem?

This work has answered some questions representation, but it has revealed many new questio this respect, it is a success.

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