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The Binford-Horn LINE-FINDER *

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ABSTRACT

This paper briefly describes the processing performed in the course of producing a line drawing from an image obtained through an image dissector camera. The edge-marking phase uses a non-linear parallel line-follower. Complicated statistical measures are not used. The line and vertex generating phases use a number of heuristics to guide the transition from edge-fragments to cleaned-up line-drawing. Higher-level understanding of the blocks-world is not used. Sample line-drawings produced by the program are included.

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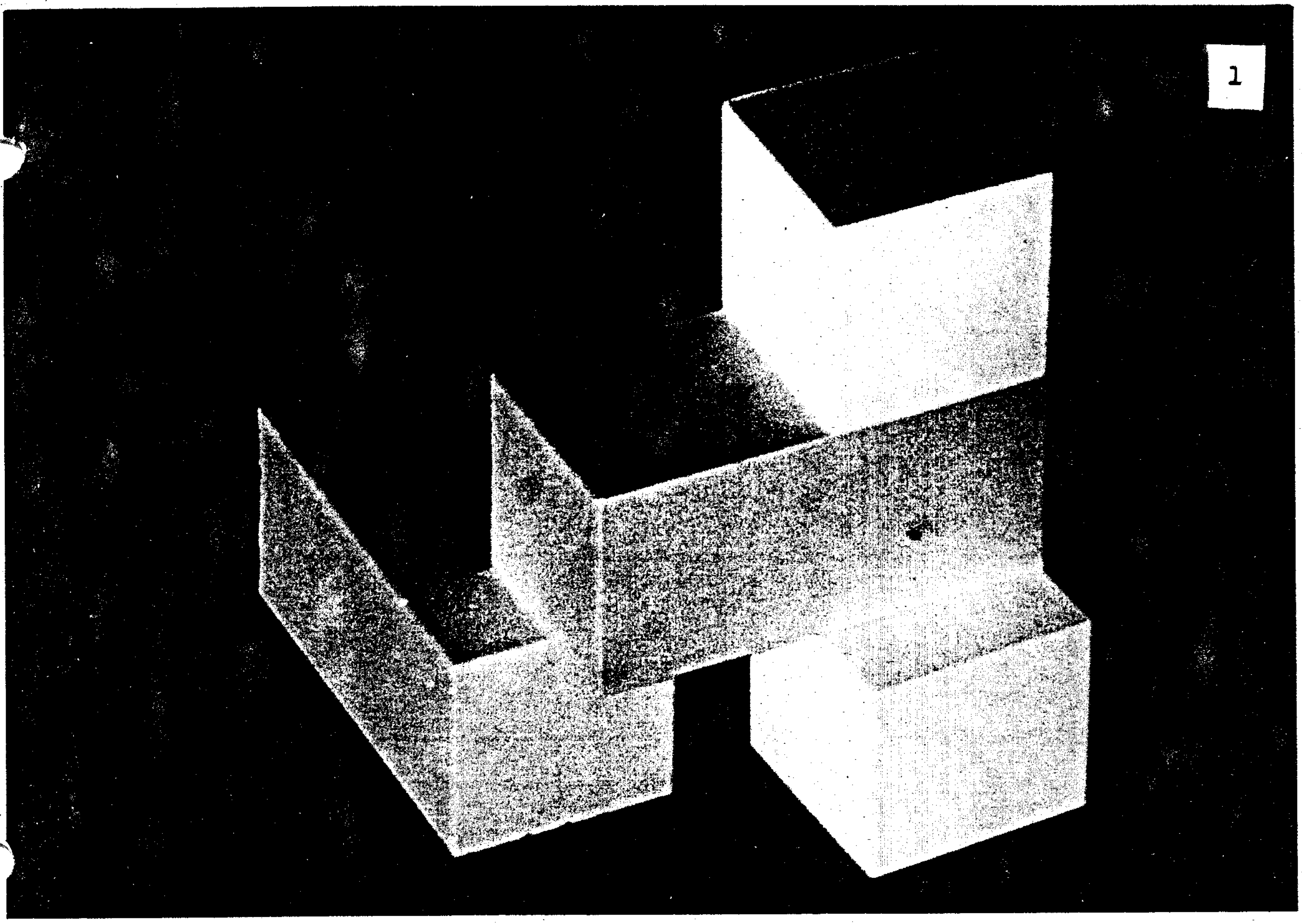
* This is a revised version of Vision Flash 16 (July 1971).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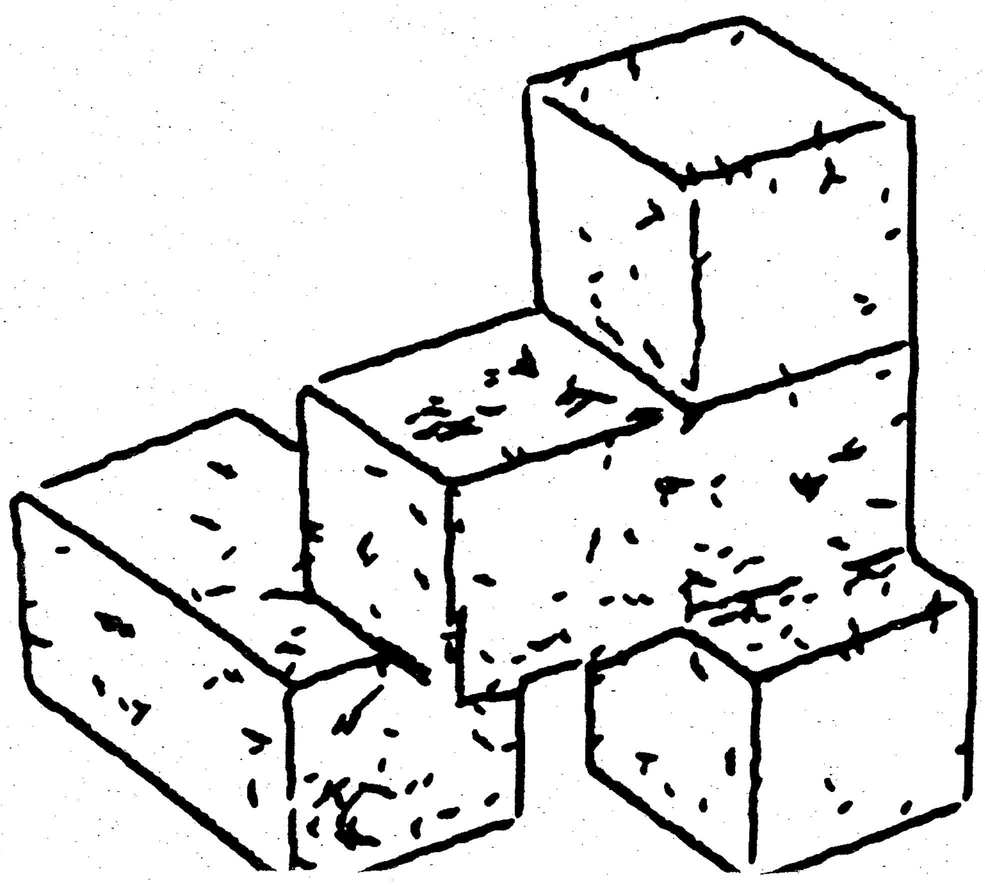
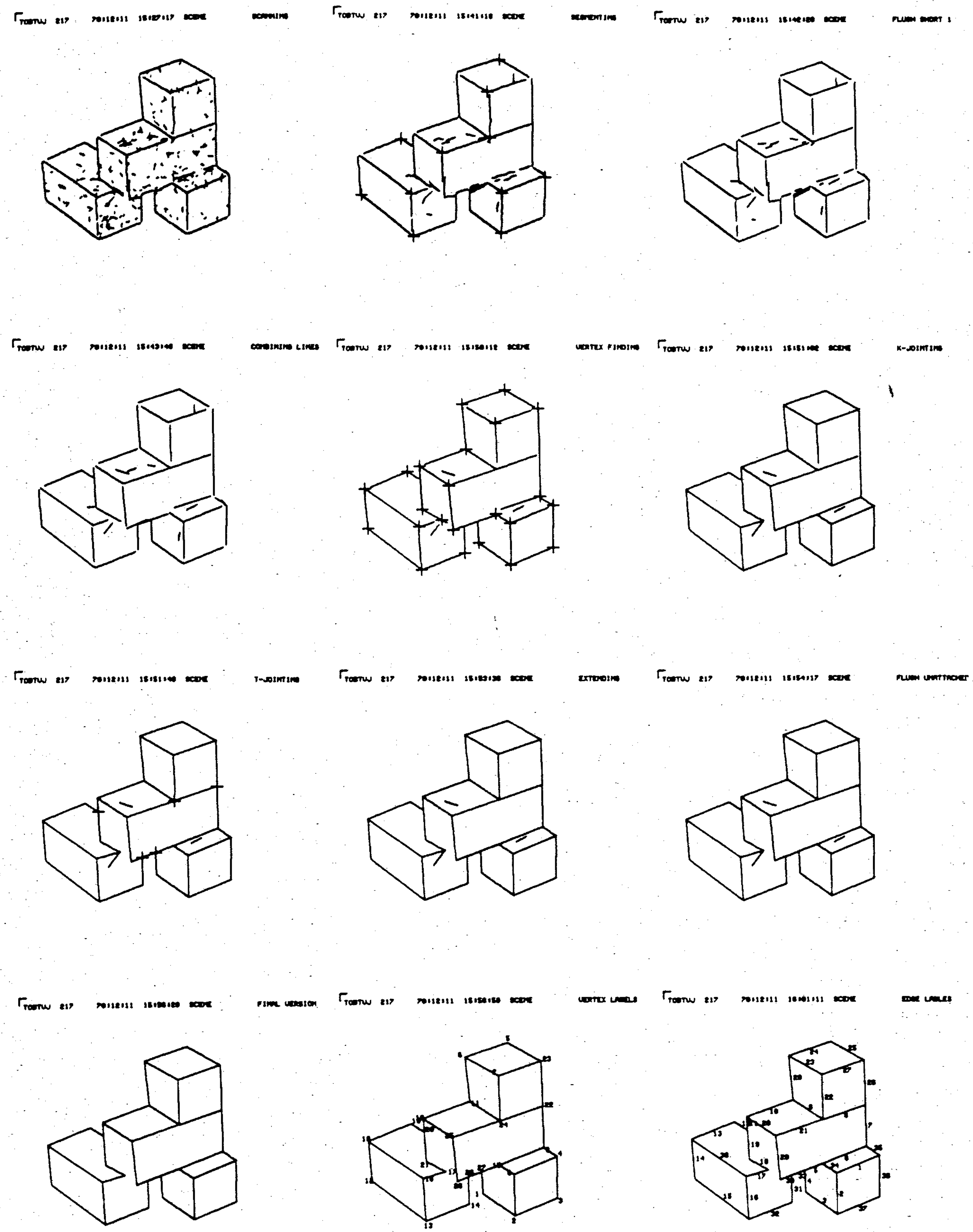
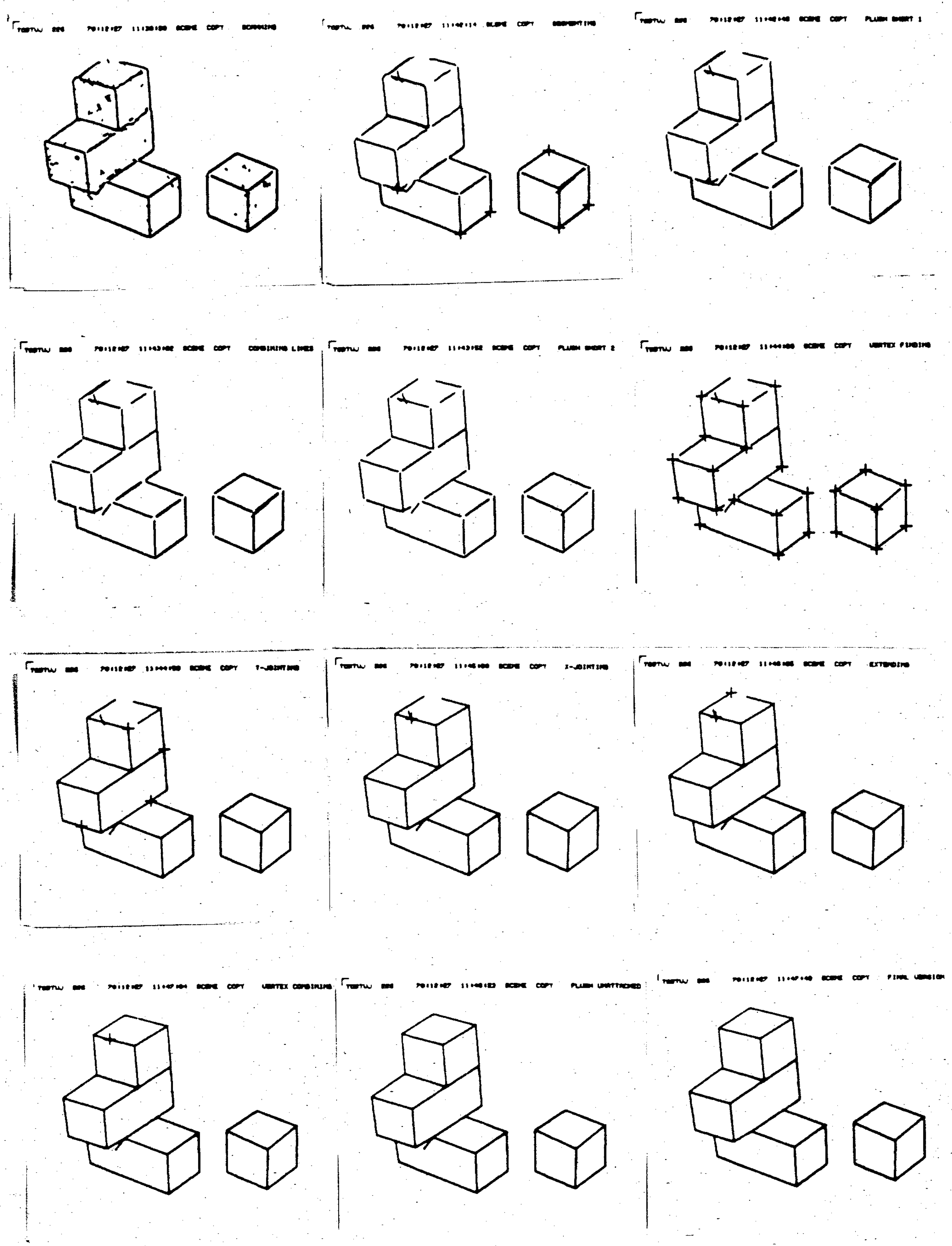



SCENE SCANNING
SCENE SEGMENTING
SCENE FLUSH SHORT 1
SCENE COMBINING LINES
SCENE VERTEX FINDING
SCENE K-JOINTING
SCENE T-JOINTING
SCENE EXTENDING
SCENE FLUSH UNATTACHED
SCENE FINAL VERSION
SCENE VERTEX LABELS
SCENE EDGE LABELS



1. THE LINE-FINDER.

Programs able to produce line-drawings from images of single convex polyhedra have existed for several years. It was thought that it should be easy to generalize the methods used to deal with more complex blocks-world scenes involving obscuration, shadows and mutual illumination. Only recently, however, has it become possible to reliably produce line-drawings of images of sets of polyhedra. There are two main problems. Firstly, images of sets of polyhedra are not as simple as one might expect. Secondly, current scene-analysis programs demand a complete line-drawing with well-defined vertices.

One might reasonably conjecture that the image of a set of polyhedra ought to consist of polygonal areas of more or less uniform intensity. These areas should be separated by step-like transitions in intensity at the lines corresponding to the projections of the edges of the objects. This is not the case because of mutual illumination, shadowing, scattering of light, surface smudges, translucency and a number of defects in the imaging device [Horn 1969]. Usually in fact, the variation in intensity within one region (corresponding to a face or the visible portion of a face of an object) is often larger than the difference between the intensity of adjacent regions. Furthermore, only the most obvious edges (such as those separating the scene from the back-ground) are associated with anything like a step-like transition in intensity. Many transitions are instead roof-shaped or flat except for a small peak right on the edge [Herskovits & Binford 1970].

The most obvious image degrading effect introduced by the sensing device is noise. In our case this amounted to about 1 to 2% of the signal magnitude [Horn 1969]. There is little point trying to improve on this, since the surface visual noise is not much smaller even for clean, evenly painted polyhedra. One of many other device defects is internal scattering, which reduces the contrast between adjacent regions by almost a factor of two and produces annoying gradients within regions [Horn 1972].

2. CLASSIFICATION OF LINE-FINDERS.

Line-finders can be classified according to whether they are region-oriented or edge-oriented. Region-oriented line-finders attempt to find regions of more or less homogeneous intensity. The areas not conglomerated in this fashion are then thinned out and lines are fitted to them. Edge-oriented line-finders avoid the problems of inhomogeneous regions and the blending together of adjacent regions. They instead determine likely edge-points and link these up into edge-fragments. The fragments are later combined into lines.

Line-finders can also be classified according to whether or not the filter function (also called the local predicate) applied to the image is linear. If visual noise were spatially independent, a case could be made for an optimal linear predicate. This however is not the case, since smudges, for example, have a distinctly non-random spatial distribution. Non-linear methods, while more complex, have a clear advantage on real images.

Line-finders can be further classified according to whether they use a fixed raster scan or a search pattern which follows lines. The first method is convenient from the point of view of reading intensity values asynchronously ahead of time and also for program simplicity. In some cases the imaging device forces the use of a raster scan, particularly if it is an integrating device. Line-followers on the other hand can be made to be more sensitive and accurate at the price of program complexity.

3. EDGE-MARKING.

Input is obtained from a random-access image-dissector camera or a picture stored as a disk-file. The edge-marker is a non-linear parallel line-follower. That is, several lines are followed simultaneously, while the image is being scanned in a raster-like fashion, thus combining the good features of raster-scan with those of line-following. The separation between scan-lines is larger than the spacing of image points sampled along a line. Three scan-lines are considered at any one time. The intensities are correlated with the three most common intensity transitions, namely the step, the roof and the peak. If any correlated value exceeds a threshold (adjusted according to the known signal-to-noise ratio), a check is made for a local maximum.

Once a likely edge-point (also called feature-point or inhomogeneous point) is discovered, a subroutine checks to see if it could be the continuation of a line already being followed. The test involves a check on proximity and angle as well as such attributes as type, direction and size of intensity transition. If the edge-point cannot form the continuation of an existing line, yet is strong and not too close to any other line, it will be used as the starting point of a new line. This new line will also be followed on subsequent scans.

A line that cannot be continued in this manner is retained only if its length exceeds some minimum. One pass over the scene consisting of successive horizontal lines picks up all edges within about fifty degrees of vertical. A second pass consisting of vertical lines does the same for edges within about fifty degrees of horizontal. For a typical scene about a million intensity values are read from the image, and the whole process takes a few minutes.

We end up with a number of lists of tentative edge-points. Some of these lists will represent more than one edge (an L-joint for example), while some edges will be represented by more than one list (a fragmented edge for example). These lists will often not include points very close to vertices, except at L-joints. This is because lines are prevented from encroaching too closely on each other by the nature of the correlation process and some of the tests described. Each list of tentative edge-points has associated with it a number of attributes such as type, direction and size of the intensity transition and how sure the program is that the edge-fragments are not merely due to noise.

Up to this stage not very many heuristics have to be invoked and consequently the possibility of corrupting the data is small. Numerous line-finders have been developed to this stage, few however produce as clean a set of tentative edge-points as T. Binford's program. Very few line-finders have proceeded beyond this level to actually create the kind of useful cleaned-up line-drawing required by current higher-level scene-analysis programs. In part this is often due to inadequate edge-marking, but more often it is because unexpected difficulties are met when dealing with what at first sight seems a simple process: forcing the data into the form of a line-drawing with well-defined vertices.

4. GENERATING LINES.

Since some lists may contain feature points of more than one edge, the lists have to be segmented. This is done recursively at the point of maximum distance from the line connecting the end-points of the list of edge-points. Segmentation proceeds until the remaining edge-points fall within a tolerance band. Re-segmentation is used to cope with portions that are parallel to the line joining the end-points. Once segmented, least-squares lines are fitted to the lists [Horn 1972] (The partial results of this fit continue to be part of the data associated with the line, to allow combining lines later without loss of accuracy).

We next have to combine partial lines corresponding to the same edge. Overlapping lines are the first to be considered in this process. A number of tests are applied to avoid combining unrelated lines. These tests include checks on proximity, relative orientation, perpendicular distance of the end-points from the potential combined line and so on. Lines more or less co-linear are combined in a similar manner provided the gap between them is relatively small. Any short lines remaining at this stage are discarded.

The line-drawing is fairly recognizable at this stage, lacking only vertices. The lines have been distorted very little in this process, unless unrelated lines happened to be combined despite the stringent tests. The less conservative and more difficult part is yet to come. The data at this stage is quite compact already and might profitably be handed to a program with some understanding of blocks-world scenes instead of the somewhat arbitrary heuristic program described next.

5. GENERATING VERTICES.

Some of the vertices are clearly indicated by the close convergence of lines. A first estimate of the location of such a vertex is made by considering the center of gravity of the end-points of the lines (if there are only two lines, their intersection is used instead). A search is then made for all lines which end near this point and whose extension would pass very close to it. The vertex is finally declared at the point of least-squares perpendicular distance from these lines [Horn 1972]. The appropriate lines are then connected to the vertex.

Next, the program tries to establish T-joints. That is, it searches for lines that have an end-point close to another line and checks if it would we reasonable to extend the line to form a new vertex. A K-joint is similarly made where a vertex is close to a line. Finally, crossing lines give rise to X-joints. Numerous heuristics inform this process; for example, lines already connected at one end are treated preferentially to those still free at both ends. All vertices have now been found and an attempt is made to extend unattached lines to nearby vertices. The extension must be short and pass very close to the vertex to be accepted. Following this, vertices which are close together are conglomerated. Any lines not properly attached at this stage are discarded. The progress of these steps in the processing can be slowed down and viewed on a display, before the final product is disgorged in a convenient LISP-readable format.

The heuristics, which developed empirically, depend on certain tolerances which are initially calculated in terms of the line-scan interval, the known resolution of the imaging device, and the signal-to-noise ratio. These factors could be "tuned" to improve performance and accuracy, but this is probably not worth the effort (the time would be better spent on designing new ways of directing the vertex creation phase). A large portion of this assembly language program is concerned with debugging, displaying and performing the required list-processing. The data-base is maintained in two forms: As assertions about lines (and what vertices they connect to) and as assertions about vertices (and what lines impinge on them). These two forms are kept consistent by demons invoked when assertions are added, removed or changed in either data-base.

The line and vertex generating phases of the program frequently need to settle questions of proximity for both points and lines. A set of four superimposed rectangular grids covering the image is used as a set of buckets for this purpose. This method is sometimes referred to as multi-entry coding [Horn 1972]. Each point is entered into four buckets, and each line will appear in many. This makes for high speed, despite the need for a number of iterative applications of various heuristics to the whole data-structure.

6. PERFORMANCE.

An idea about how to produce line-drawings from images is of little use until it has been demonstrated by a working program. The program discussed here has processed over a hundred scenes and produces excellent line-drawings of simple blocks-world scenes. In more complicated cases, a number of shortcomings can be observed. The simplest and easiest to deal with is the absence or incompleteness of some of the lines, usually due to a lack of contrast between adjacent faces of an object. At times extra lines are introduced by shadows, smudges and noise. There is a trade-off between these two effects, and since present scene-analysis programs can handle missing lines better than extra lines, the threshold is set to favour the former.

Occasionally a section of a line-drawing will be garbled, usually due to the combination of two unrelated vertices. This causes some distortion of the lines and may make the line-drawing locally uninterpretable. This last effect in particular is a function of the amount of detail and can be avoided by using a finer resolution at the cost of an increase in scan and computation time. This of course is only possible if the imaging device has sufficient resolution.

7. COMMENTS ON THIS APPROACH.

Some of the ways in which images of sets of polyhedra differ from our intuitive model of equal intensity polygonal areas have important implications in other areas. Mutual illumination for example will prove to be a problem when one is developing a program that exhibits color constancy. Further, it should be noted that some of the edges missed by this program will also be missed by line-verifiers: when following lines one can afford to be quite sensitive. Fortunately the better line-proposers are very conservative and hardly ever propose a line were there shouldn't be one. One could perhaps accept their proposals without attempting verification.

The only features that can be reliably determined from a corrupted image are those with significant spatial extension. Without such extension we cannot apply the integrative processes necessary to collect evidence for the existence of the feature. Vertices for this reason are perhaps not primitive elements of an image, but exist only as the intersection of lines. Letting the line-drawing program establish vertices introduces inaccuracies, because it may join unrelated lines.

8. HOW TO DO BETTER.

This program has no idea what a reasonable line-drawing should look like when it represents an image of polyhedra. Instead it is very general and will find arbitrary line-drawings. Observing the particular way in which things sometimes go wrong, one quickly comes to the conclusion that higher-level understanding of the scene being analysed could greatly improve the line and vertex creating phase of this program. As things stand now this understanding comes only after the line-finder has done its work. It would be hard to embed this kind of knowledge into such a large assembly language program. At the same time trying to implement the "low-level" routines in a higher level language would cause great inefficiencies.

9. HISTORICAL NOTE.

The line-finder described here consists of an edge-marker due to T. Binford and a line-drawer due to B.K.P. Horn. It was used as part of the system of vision and manipulation programs developed for the copy-demo by P.H. Winston, E. Freuder and B.K.P. Horn in the fall of 1970 [Winston 1971 & 1972]. It is also the "hierarchical" program referred to by Shirai [Shirai 1973].

10. REFERENCES.

Herskovits A. and Binford T. (1970) "On Boundary Detection" A.I.Memo 183 (Cambridge, Mass.: A.I.Lab, M.I.T.)

Horn B.K.P. (1969) "The Image Dissector 'Eyes'" A.I.Memo 178 (Cambridge, Mass.: A.I. Lab, M.I.T.)

Horn B.K.P. (1972) "VISMEM: A bag of 'robotics' formulae" Vision Flash 34 (Cambridge, Mass.: A.I. Lab, M.I.T.)

Shirai Y. (1973) "A Context Sensitive Line Finder for Recognition of Polyhedra" Artificial Intelligence, Vol 4, No 2.

Winston P.H. (1971, 1972) Vision Flashes 7, 8, 9, 15 and 30 (Cambridge, Mass.: A.I. Lab, M.I.T.)

Winston P.H. (1972) "The M.I.T. Robot", Machine Intelligence 7 (Edinburgh: Edinburgh University Press)