2 April 1963

MEMORANDUM FOR: Director, NPIC

FROM : Assistant for Plans and Development

SUBJECT : Report on PERCEPTRON [redacted] 25X1
25X1 [redacted] and COMPLEX [redacted] Concerning Automated 25X1
Image Recognition

1. Selected members of the Plans and Development Staff were present at briefings on the 19th and 22nd of March. The following paragraphs contain abstracts of these briefings, a summary, and recommendations for future action.

25X1 2. [redacted] presented a briefing from 0945
25X1 to 1200 on 19 March 1963 [redacted] Room 3B467. In addition to members of the P&D Staff, there were representatives from PID, TID, Air Force, Army and Navy Detachments, USNPIC, ONR, and Bu Weps. Security level was unclassified.

a. PERCEPTRON is a means of "automated recognition based on statistical separability in cognitive systems."

(1) It may be described as a "biological" computer system consisting of a sensory matrix coupled through a complex continuously variable weighting system to a general purpose digital computer, programmed in a fashion which simulates brain mechanisms. 25X1

(2) Its developmental history began in 1958 at [redacted]
25X1 [redacted] on the basis of concepts originated by [redacted] 25X1
Extensive research has been performed since that time in the following realms:

(a) Implementation and evaluation of the PERCEPTRON concept.

(b) Application of the PERCEPTRON to photo interpretation.

(c) Application of the PERCEPTRON to character recognition.

(d) Preprocessing of photo reconnaissance data.

This development program has been characterized by fundamental investigation. The process is deliberate, comprehensive and slow. This research is

GROUP 1
Excluded from automatic downgrading and declassification

the basic frame of reference for all development in this field. There is implication of a yet unreached stage in the development of the principle which must be attained before the majority of developmental effort can be directed toward application. The main effort of this program is now being directed toward "preprocessing" of the image. The processes of object detection, isolation and normalization are being investigated through systems other than PERCEPTRON, which is used solely for the recognition process.

25X1 3. [redacted] This briefing was held from 1400 to 1700, 22 March 1963,
25X1 at the [redacted] In addition to members of
the Plans and Development Staff, [redacted] of USNPIC and [redacted] of BuWeps 25X1
were present. Security level was unclassified.

a. CONFLEX I is said to be a "conditioned reflex Computer."

(1) It may be described as a "biological" computer system consisting of a sensory matrix, elements of which are systematically activated in a large number of different combinations, coupled to a special purpose digital computer programmed in a fashion which simulates brain mechanisms.

(2) Its developmental history began late in 1960 at [redacted] under an 25X1
Air Force study contract. The prototype CONFLEX I system was completed in November 1962. An impressive demonstration of learning and identifi-
25X1 cation of pictures of [redacted] personnel was presented. Related research has been performed in the following realms:

(a) Basic studies of biological response systems.

(b) Application of the CONFLEX system to character recognition.

(c) Application of the CONFLEX system to photographic image recognition.

(d) Prenormalization of photographic reconnaissance data.

This program is apparently a derivative of the original PERCEPTRON develop-
25X1 ment. [redacted] personnel have utilized these principles to design an ingenious, compact system which may have considerable application in the image recognition field. Their prenormalization system is based on slit scanning of a given image field at a large number of different attitudes and the consequent pattern of signals generated by such scans.

4. <u>SUMMARY</u>. The number and complexity of developments in this field indicate that the Plans and Development Staff must acquire more information before a complete program for development can be established. Implications of the observations made to date are as follows:

a. The PERCEPTRON-CONFLEX type of approach appears to show much more promise of eventual application to photo reconnaissance analysis than the pure digital scan systems such as AUTOMATAD.

25X1 b. [redacted] effort is a conservative, comprehensive,
fundamental research approach which is likely to be slow in yielding
directly applicable techniques or hardware. It does however, serve as a primary
reference with a broad base and a large amount of accomplished investigation.
By the same token it is likely to yield valuable results from continued research.

25X1 c. The [redacted] effort is representative of the relatively young research
facility. There is evidence of competent, highly motivated, dynamic development
being accomplished. It is possible that [redacted] and other organizations of this 25X1
type and caliber will produce the first practical devices for automated target
recognition and they may outstrip [redacted] in developing some special aspects of 25X1
more efficient electronic logic. In this regard it should be pointed out that
25X1 [redacted] has investigated a prenormalization system very similar to the one presently
25X1 under study at [redacted] It was eventually rejected due to the complex signal
caused by multiple images within a single field. The [redacted] approach appears 25X1
to overcome this limitation, but due to the limited knowledge acquired to date,
a full assessment cannot be made.

5. <u>RECOMMENDATIONS</u>. Immediate attention will be given to resolution of
the dilemma caused by the number of different endeavors being pursued in this
25X1 field. It appears that the [redacted] effort should definitely be supported for at
25X1 least one year at [redacted] level, and there is a strong possibility that parallel
development by a facility such as [redacted] should also be supported. However, 25X1
it is felt that further investigation is imperative before a decision can be
rendered on the latter aspect. In establishing priority for funding it is
25X1 important to note that the [redacted] program is currently being supported by the
25X1 Air Force whereas the [redacted] effort is to be terminated in June because the Navy
can no longer fund the program.

[redacted] 25X1

Assistant for Plans and Development

Encl 1

DESIGN OF A PHOTO INTERPRETATION AUTOMATON*

[redacted]

25X1

SUMMARY

The paper describes a system for automatic recognition of simple and complex objects in aerial photographs. Preliminary results from a general-purpose computer implementation of critical portions of the system are presented. Hope for achievement of a practical device is high because the basic pattern recognition capability required in the system is, to a great extent, based on the present state of the art.

INTRODUCTION

The extremely large volume of photographic material now being provided by reconaissance and surveillance systems, coupled with limited, but significant, successes in designing machinery to recognize patterns has caused serious consideration to be given to the automation of certain portions of the photo interpretation task. While there is little present likelihood of successfully designing machines to interpret aerial photographs in a complete sense, there is ample evidence to support the conjecture that simple objects, and even some complex objects, in aerial photographs might be isolated and classified automatically.

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[redacted]

25X1 [redacted]

Design of a Photo Interpretation Automation

Even if machinery, produced in the near future, can only perform a preliminary sorting to rapidly winnow the input volume and to reduce human boredom and fatigue on simple recognition tasks, the development of such machinery may well be justified.

The supporting evidence for the conjecture that simple objects can be identified in aerial photographs is based on work which has shown experimentally that present pattern-recognition machinery - indeed that which existed several years ago - can be applied to the recognition of silhouetted, stylized objects which are militarily interesting. Murray has reported just such a capability for a simple linear discriminator[1]. Since the information required to design more capable recognition machines is readily available, it might seem that there is no problem of real interest remaining to make a rudimentary photo-interpretation machine an accomplished fact. This, unfortunately, is not so. One of the most difficult problems is that which is referred to as the segmentation problem. The problem of pattern segmentation appears in almost all interesting pattern recognition problems, and is simply stated as the problem of determining where the pattern of interest begins and ends (as in speech recognition problems) or how one defines those precise regions or areas in a photo which constitute the patterns of interest. The problem exists whenever there is more than one simple object in the entire field of consideration of the pattern recognizer. The situation appears almost hopeless when one finds patterns of widely varying sizes, connected to one another (in fact or by shadow), enclosed within other patterns, or having only vaguely defined outlines.

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[1] See "PerceptronApplications in Photo Interpretation," A. E. Murray, Photogrammetric Engineering, September 1961.

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Design of a Photo Interpretation Automation

This paper constitutes a report on a system which has been conceived to solve some of these problems. It is being tested by general-purpose computer implementation. The system discussed represents one of several possible approaches to the problem and had its design focused towards the use of presently known capabilities in pattern recognizers. No special consideration has been given, at this time, to methods of implementing the device; however, the entire system can be built in at least one way.

SYSTEM PRINCIPLES

Figure 1 is the basic block diagram for the system. It has evolved from evaluation of possible approaches suggested by research conducted at [redacted] pattern recognition work of others, and techniques successfully used in other problems.

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As is evident from Figure 1, objects of interest have been categorized in two different ways. First, simple objects, such as buildings, aircraft, ships, and tanks have been distinguished from complexes, or complex objects. Second, simple objects have been categorized, according to their length-to-width ratios, as being either blobs (aircraft, storage tanks, buildings, runways) or ribbons (roads, rivers, railroad tracks). As shown, the detection of simple objects is accomplished separately for ribbons and for blobs. In the work reported here the blob channel - from the input end through the identification of a few complex objects - is receiving the major attention.

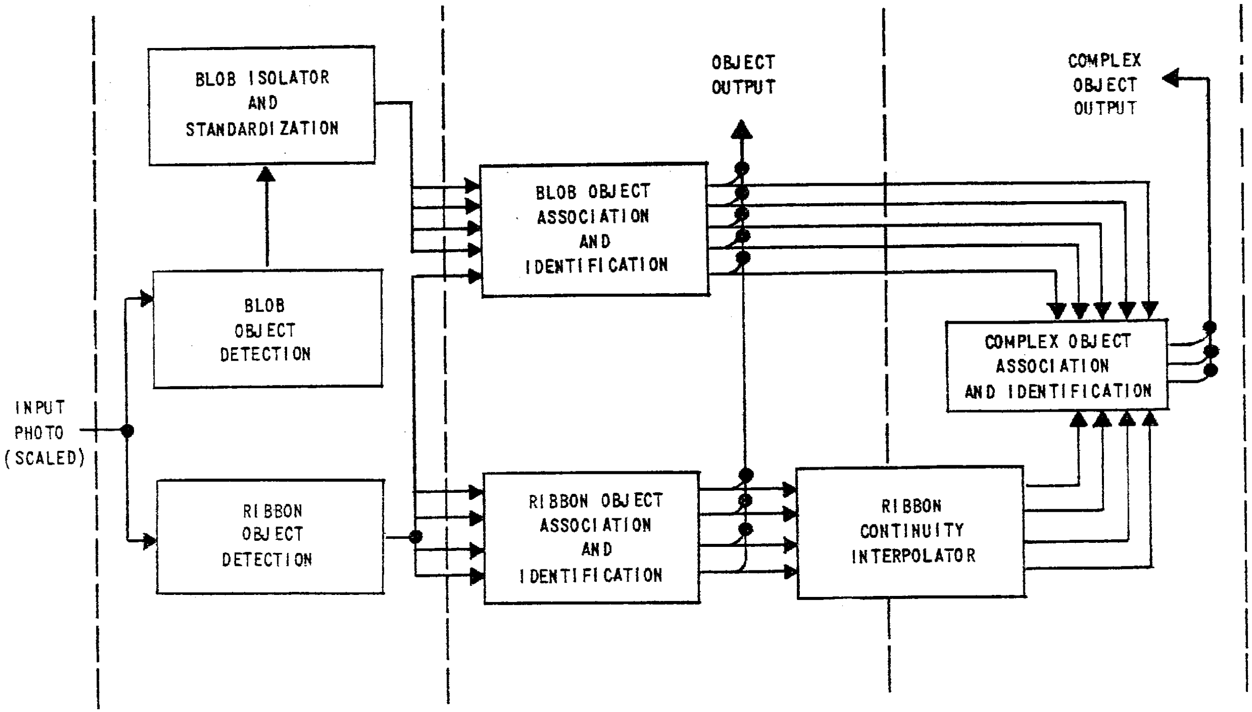

Figure I PHOTOINTERPRETATION SYSTEM BLOCK DIAGRAM

[redacted]

Design of a Photo Interpretation Automation

The preprocessing which is carried out in the first portion of the system solves several of the problems inherent in the use of a simple pattern-recognition device to aid in the photo interpretation problem. Briefly, objects are to be detected, isolated, and standardized so that they can be presented separately (not necessarily sequentially) for identification.

The function performed at the object identification level is that of identifying the blobs which have previously been detected, isolated, and standardized. The input material to this level or state consists of black-on-white objects. As has been previously indicated, existing devices are fundamentally capable of accomplishing the identification task.

At the complex object level, the location and identification information available from the simple object-level outputs is combined and appropriately weighted to identify objects at a higher level of complexity. An illustrative example is the combination of aircraft (simple objects) near a runway (another simple object) and a group of buildings (each a simple object) to determine the existence of an airfield.

In the following sections the basic steps in the preprocessing sequence will be described in more detail and some illustrations from current computer studies will be discussed. The most difficult part of the problem, by far, is that of detection.

[redacted]

Design of a Photo Interpretation Automation

OBJECT DETECTION

A study of sample aerial photography suggests three ways in which images of objects of interest differ from their backgrounds:

a.) points on objects may differ in intensity from the intensity characterizing the background.

b.) objects may be (perhaps incompletely) outlined by sharp edges, even though the interior of the image has the same characteristic intensity as the background.

c.) objects may differ from background only in texture, or two dimensional frequency content.

Examples of the first two kinds of objects are shown encircled in Figure 2. There seem to be many fewer examples of objects which differ from background solely by texture. This class of objects would be much larger if our definition of object were broader, including, for example, corn fields. Perhaps the most useful area in which spatial frequency content can be put into use is that of terrain classification. Terrain classification, as will be noted again later, can play a significant role in the final identification of our narrower class of objects.

For detection of objects in classes a) and b) above, we have been proceeding experimentally to determine the capabilities of simple, two-dimensional numerical filters, some nonlinear and some linear.

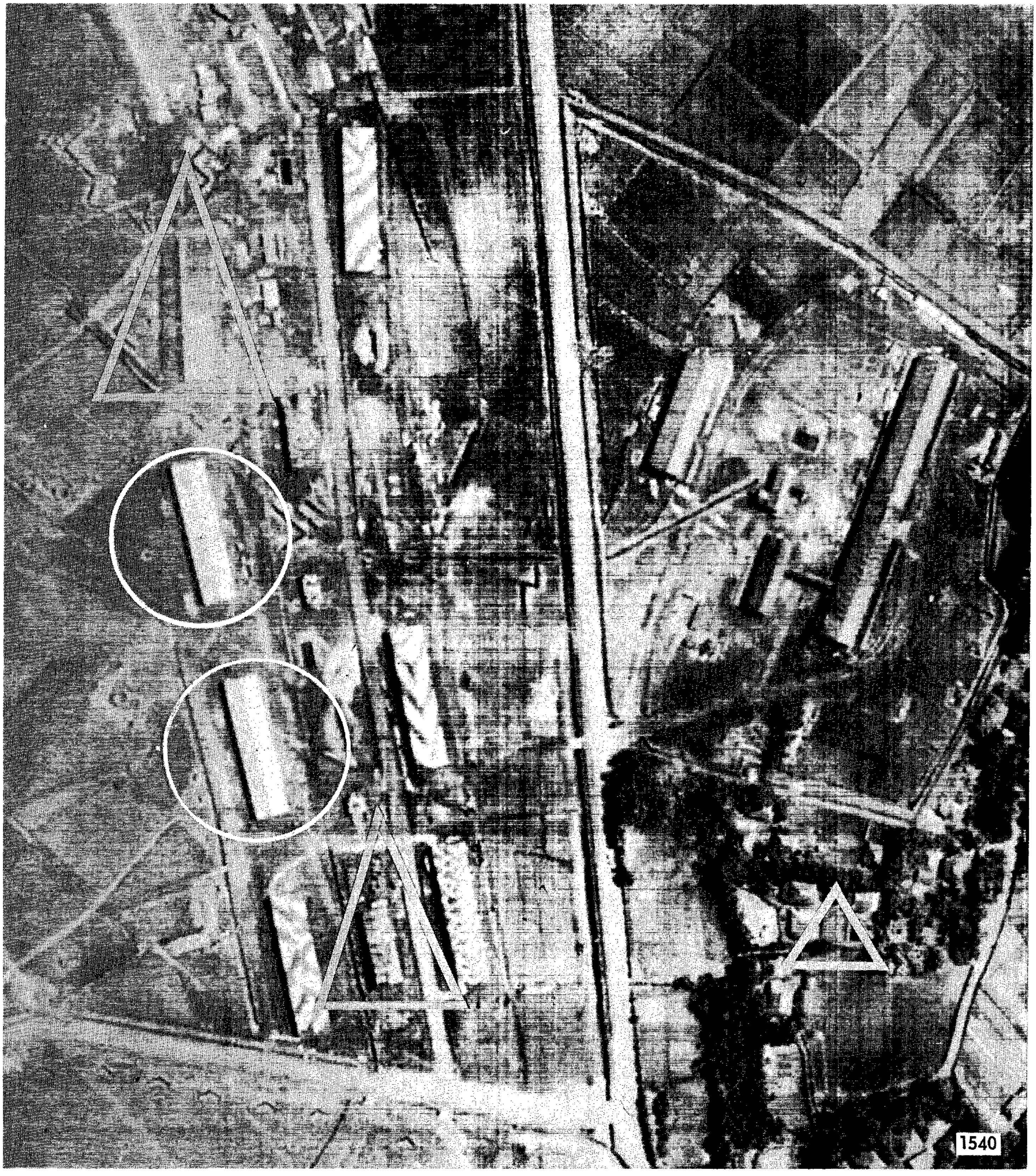

Figure 2 EXAMPLES OF OBJECTS DEFINED BY INTENSITY CONTRAST (O) AND BY EDGES (△)

[redacted]

Design of a Photo Interpretation Automation

For initial experimentation*, the object filters for discrimination based on intensity contrast (class a objects) were designed as shown in Figure 3. Square apertures ("picture frame" regions) were used to compute intensity information which was then compared with the intensity of the point at the center of the square, A, to determine if the central point differed sufficiently in intensity from its background to qualify as being a point on an object.

A computing method equivalent to the following was used. Each point in the input photograph was surrounded by a frame one point thick, and of width d (Figure 3). The mean, m, and standard deviation, σ, of the intensity of the points in the frame were then computed.

If

$$A > m + max\ (1,\ K\sigma)$$

or

$$A < m - max\ (1,\ K\sigma) \qquad (1)$$

the point was recorded as an object point. Several different frame sizes were used in order to detect objects of different sizes.

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* The experimental work reported was carried out using IBM-704 computer programs which were prepared to process photographic material. An input device was constructed to scan and quantize photographic information for input to the computer through the "real-time" package, and the computer printer was used to provide pictorial output.

A commercially available facsimile transmitter capable of 50 lines/inch resolution and a commercially available analog-digital samples and encoder form the basic input device package. In addition, the necessary isolating and synchronizing circuitry has been designed, and constructed to permit the output of the facsimile machine (through the encoder) to be read by the "real-time input package" on the 704 computer. Quantization and processing computer programs have been written and are in operation. These programs cause photographs to be sampled every 50th of an inch, quantized in sixteen intensity levels, and stored on magnetic tape. A relatively crude, interim-nature, output has been arranged by using combinations of symbols available in the computer printer. The available symbols allow representation of four different levels of intensity.

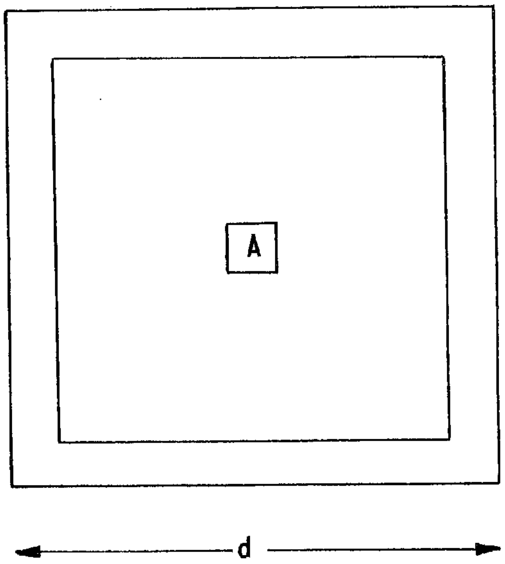

Figure 3 FILTER FOR DETECTION ON THE BASIS OF INTENSITY CONTRAST

Figure 4 ORIGINAL PHOTOGRAPH

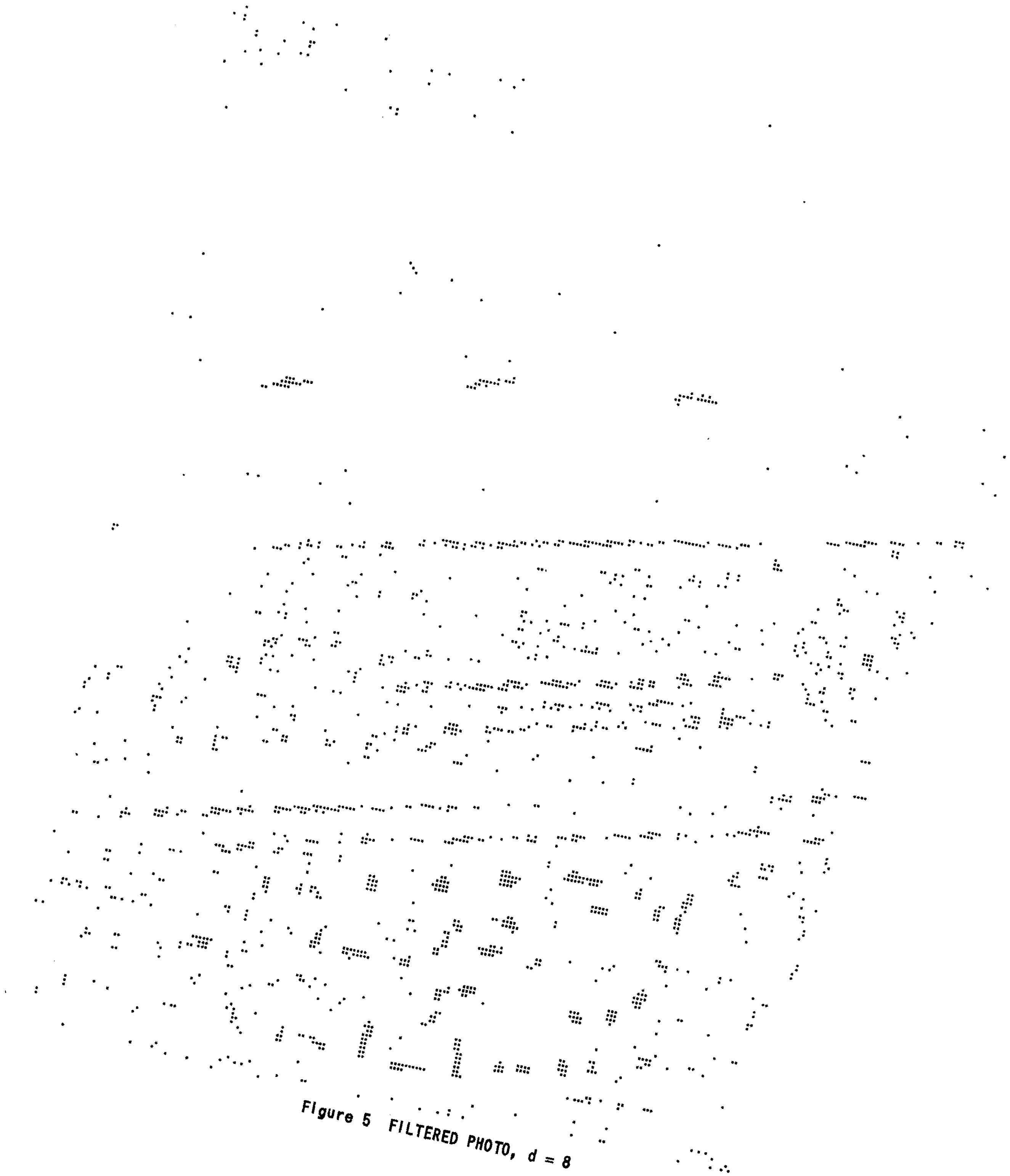

Figure 5 FILTERED PHOTO, d = 8

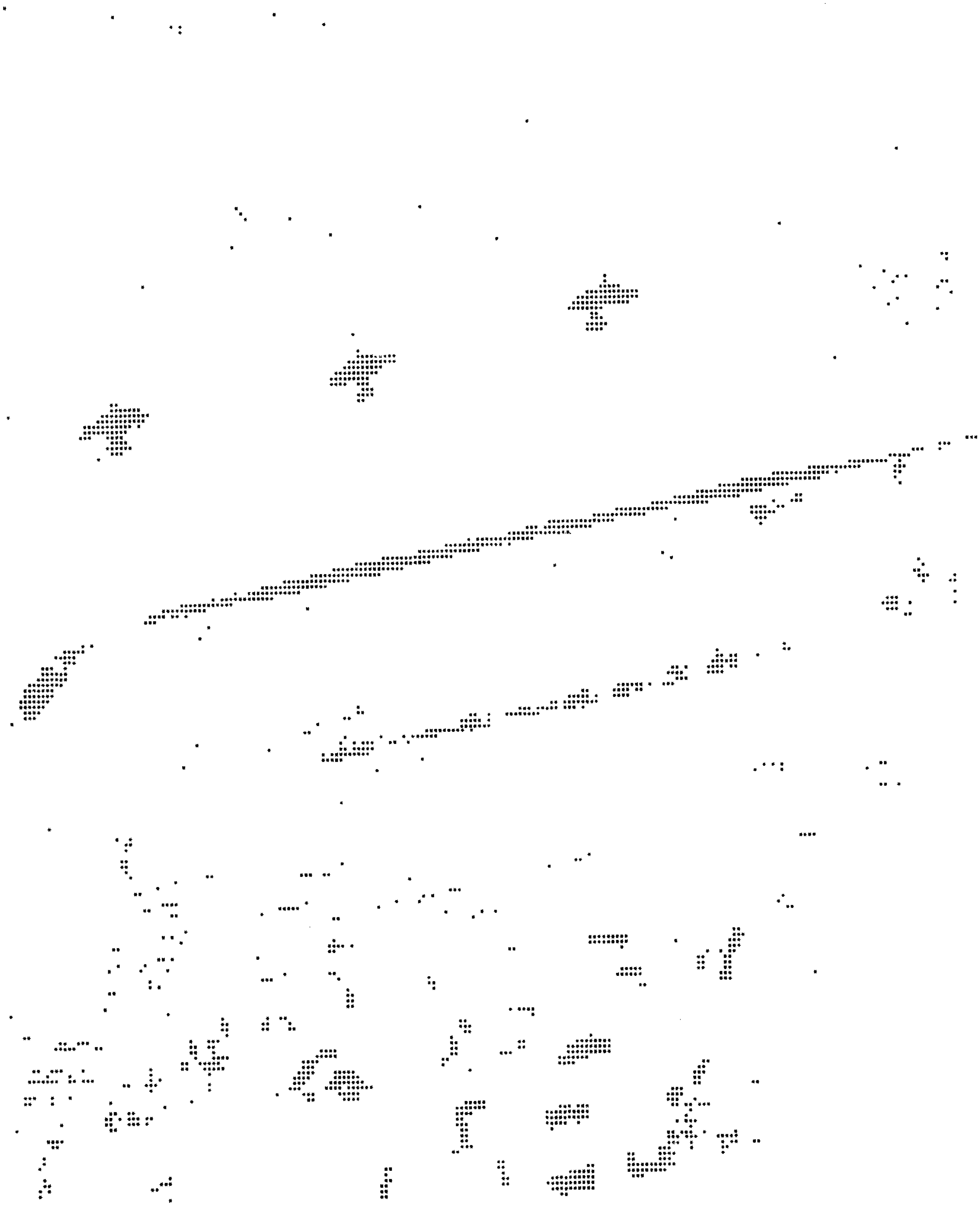

Figure 6 FILTERED PHOTO, d = 16

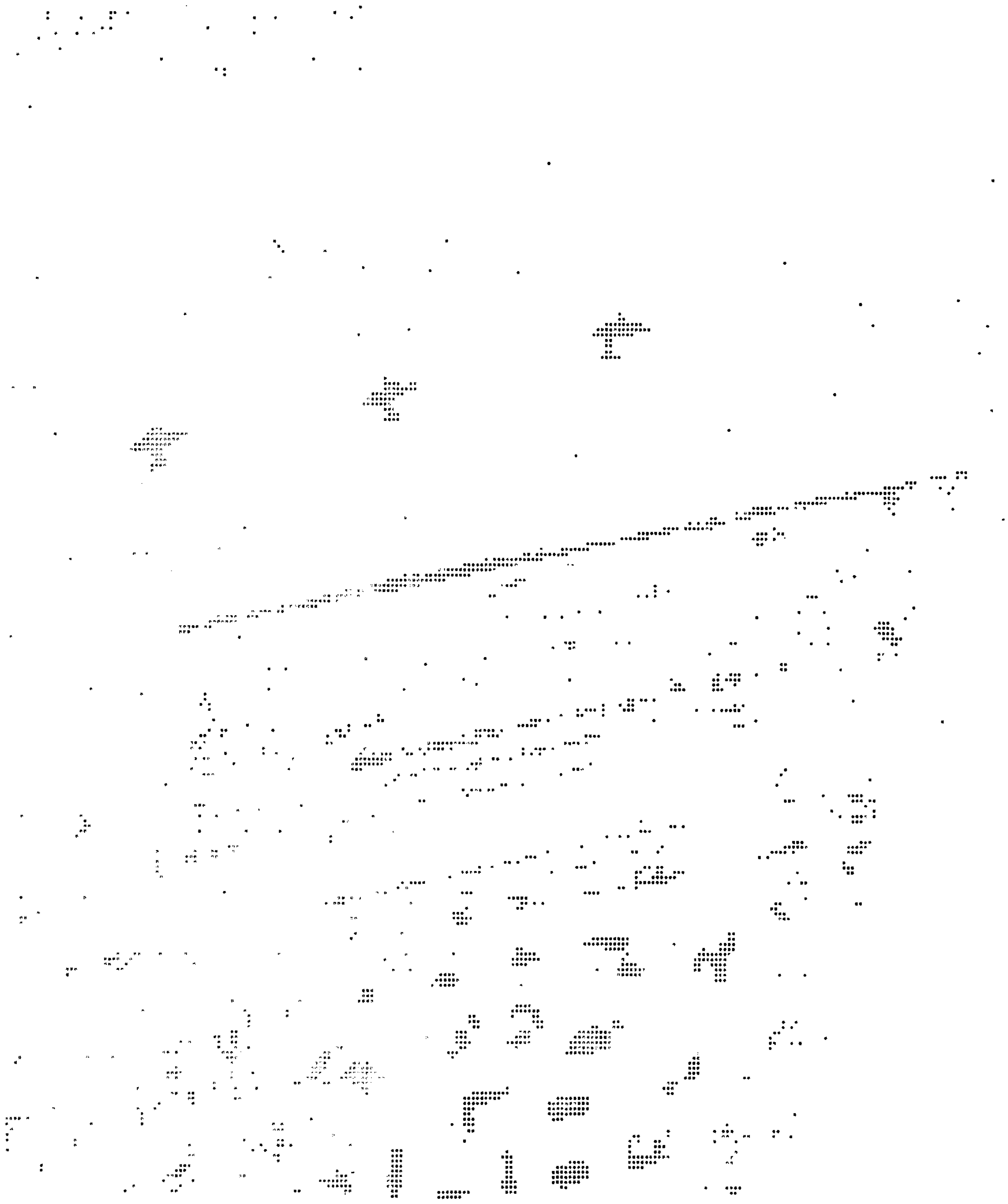

Figure 7 FILTERED PHOTO, d = 32

[redacted]

Figures 5, 6, and 7 indicate the results of applying three filters of the type described above to the photograph shown in Figure 4. The frame widths were 8, 16, and 32 points, and K of equation (1) was 2. The points which satisfied the inequalities of (1) were printed as asterisks.

The three figures illustrate that objects of different sizes are detected best (with least shape distortion) by filters of different size. This is especially noticeable for the building complex in the lower half of the photograph. In Figure 6 (d=16), the buildings are reproduced in perfect contrast about as well as can be expected considering the coarseness of the input information. In Figure 5, the buildings are broken up into segments, while in Figure 7, they tend to run together.

The seaplane launching ramp at left center is missing completely from Figures 5 and 6, while the filter which matches it well in size reproduces it in Figure 7.

It is important to note that the recognition logic used requires only that an object be detected by a single filter. Distorted versions which are detected by other filters will be rejected.

Simultaneously with experimentation in detecting objects using the object-point-intensity criteria, similar experiments are being carried out to detect objects by outlining them. There are three steps in this process; (1) object edges must be "detected", (2) gaps in the outlines of objects must be filled in, and (3) for compatibility with the first method of object detection in later system stages processing all detected objects, the outlined objects must have their interior space filled in to produce silhouettes.

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The basic operation in edge detection is, of course, differentiation. The earliest results were obtained by centering a numerical filter of the shape shown in Figure 8 about each image point.

	a	
c	A	d
	b	

Figure 8 BASIC FILTER FOR EDGE DETECTION

The values of intensity, $(d - c) = \Delta x$ and $(a - b) = \Delta y$ were determined and the sum of their magnitudes was taken as the gradient associated with the center point, A. A similar filter with nine elements is now being tested with superior results. This filter has the form shown in Figure 9.

a	b	c
d	e	f
g	h	i

Figure 9 IMPROVED FILTER FOR EDGE DETECTION

[redacted]

Now the difference in the x direction is taken to be

$$\Delta x = \left(\frac{c + f + i}{3}\right) - \left(\frac{a + d + g}{3}\right) \qquad (2)$$

and the difference in the y direction as

$$\Delta y = \left(\frac{a + b + c}{3}\right) - \left(\frac{g + h + i}{3}\right) \qquad (3)$$

Thus first differences are being used, as before, but a three-point average of intensity is used to establish the intensity on either side of the central point. The magnitude of the gradient associated with point e should, of course, be

$$\left|grad\right| = \sqrt{\Delta x^2 + \Delta y^2} \qquad (4)$$

The previous approximation to the true form $\sqrt{\Delta x^2 + \Delta y^2}$ has been improved over the simple sum of magnitudes in that we now use

$$\left|grad\right| = \left(\text{larger of } |\Delta x|, |\Delta y| + \frac{3}{8}(\text{smaller of } |\Delta x|, |\Delta y|)\right) \qquad (5)$$

If object detection by identification of edges is to be successful, one must plan on completely outlining objects of interest. In many cases, of course, there will be gaps in the outlines of objects as derived by edge detection. One procedure

[redacted]

currently being evaluated for this gap-filling job is described below. It accounts for the two factors which are most important in deciding whether to fill in a point of not; that is, such an action requires both proximity in intensity to the threshold value and proximity in space to at least one other super-threshold point.

After gradient computation, as described above, the complete image, made up of points computed by Eq. (5), is thresholded, eliminating low gradient points. The "influence matrix" shown below is then centered over every point in the thresholded gradient image (i.e. it is centered over high gradient points),

I_1	I_2	I_3
I_4	I_5	I_6
I_7	I_8	I_9

Figure 10 "INFLUENCE" MATRIX FOR GAP-FILLING

and the numbers I_1, I_2, I_3, ---- are added to the values in the prethresholded form of the gradient image. If any point covered by the influence matrix now exceeds the previously used threshold, that point is "filled in" as a high gradient or edge point.

It would, of course, be possible to train a recognition device to identify outlines of simple objects, but a much simpler system will result if outlined objects can be simply converted to solid objects similar to the silhouettes produced by the annular filter detectors. This can be accomplished very simply by forming the logical complement of the thresholded, edge-detected, binary picture and then operating on the complemented picture with the object isolator programs.

OBJECT ISOLATION

Originally computer routines which traced along the edges of silhouetted objects were planned for use in object isolation. This technique for isolation, however, does not solve the problem of how to extract the interior portion of the traced-out object from the background in any neat fashion. A different technique, 25X1 devised by [redacted] simultaneously traces through the interior of objects and records these elements in a frame for separate storage. At this stage, that is, after isolation, all images of objects are stored in binary form, in separate frames, and in their <u>original</u> size, orientation, and location within the frame.

OBJECT STANDARDIZATION

Standardization involves simply the translation of the binary image of the object so that its center of gravity coincides with the center of the frame and rotation of the image so that one of its principal axes of inertia is vertical. Recently, the programs being used in feasibility studies have been modified so as to provide scaling of all objects to the same maximum dimension.

OBJECT RECOGNITION

In the system being discussed, recognition of simple binary images, after detection, isolation, and standardization, will be accomplished by a linear discrimination device, i.e. by comparing the weighted sum of a set of property

[redacted]

values to a threshold. The weights used are determined by exhibiting a sequence of patterns whose classification is known and adjusting the weights when classification is incorrect, according to prescribed algorithms, until all patterns in the sequence are correctly classified. Thus, the device is "adaptive" and "learns." The properties may be thresholded sums of intensity at randomly selected points in the preprocessed image, or they may be more "objective" properties, that is they may be measured values of such determinable features of the pattern or image as maximum extent, area, or moments about principal axes. Certainly, use will be made of the size, area, and moment information derived during the standardization process.

The non-determinable properties mentioned earlier (thresholded sums of intensity at randomly selected points in the image) have the appeal of being very simple to derive and of being of demonstrated usefulness in classification problems. The ability of a system using such properties to generalize over pattern distortion and small translations has not yet been defined to our satisfaction. A recognition system using these non-determinable properties has been referred to by Rosenblatt as a simple perceptron. In our experimental work to date on this particular problem we have attacked the multiple class recognition problem by performing a set of dichotomizations. Some data on recognition capability have been gathered for synthesized patterns of the type to be produced by the preprocessor, but they are insufficient to make an explicit statement of capability at any reasonable confidence level.

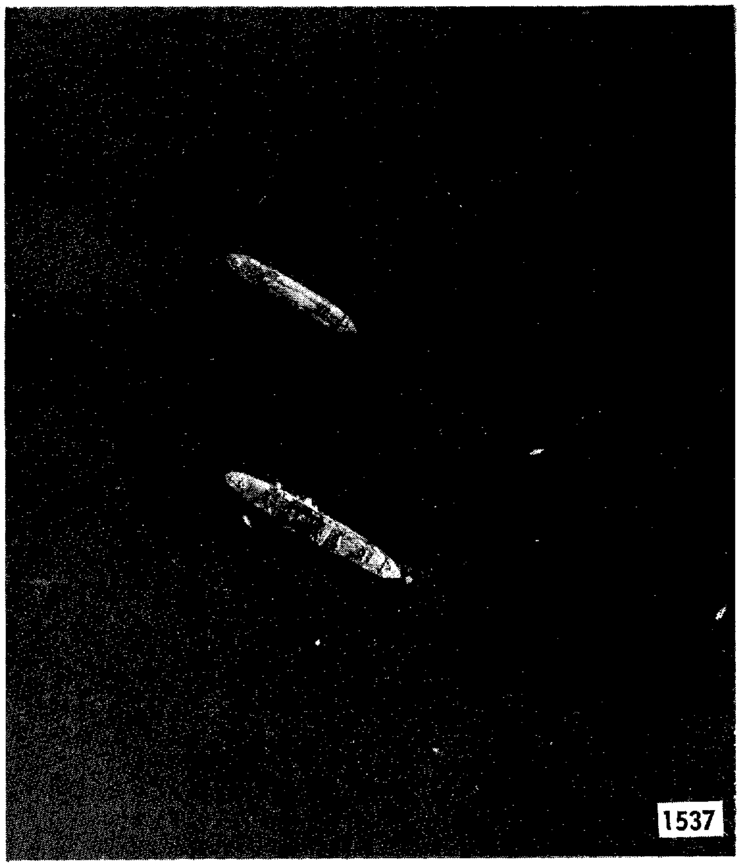

Figure 11 ORIGINAL PHOTOGRAPH

Figure 12 PROCESSED PHOTOGRAPH AFTER OBJECT DETECTION AND LOW-PASS FILTERING

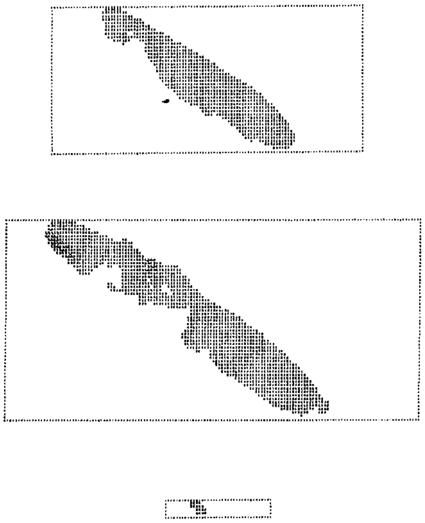

Figure 13 ISOLATED SILHOUETTES FROM PROCESSED PHOTOGRAPH

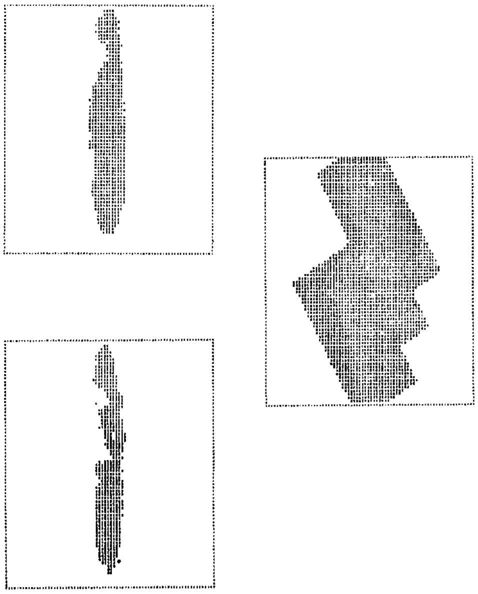

Figure 14 STANDARDIZED FORM OF ISOLATED SILHOUETTES

Two types of information are fairly readily available in the system and have apparent use in classification but have not yet been used. Thus, we could use the silhouetted image of an object to mask out all but that object in the original full gray scale image and then derive one or more object properties available in the original image. (For example, one might scan the interior of an object, to derive some measure of its interior complexity). This technique makes available recognition properties other than those based on shape. The second possibility is to use terrain classification information for the immediate background of an object to aid in the classification of that object. Certainly a final system might find such information useful.

ILLUSTRATIVE RESULTS

The entire sequence of preprocessing operations (including detection by intensity contrast, but not object detection using edges) is illustrated in Figures 11-14. These results were derived from experiments which use general-purpose digital computer programs to implement the entire sequence of operations. The first, Figure 11, shows the original aerial photo. It has been quantized spatially and fed into [redacted] IBM-704 computer through the facsimile input device. After processing by the intensity contrast filter, the binary photo of Figure 12 is produced. (The output is the 704 printer; an asterisk is printed in each 1/50" x 1/50" cell of the original photo which is a point on an object.) We found that some additional low pass filtering is very useful in making objects "hang" together, in filling in imperfections in silhouettes, and in reducing the number of small collections of points which appear but which are really not objects. After this

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[redacted]

filtering (a simple, low-pass, two-dimensional filter is used) and after eliminating collections of very few points, the binary photo was subjected to the isolation programs. This operation produced the frames shown in Figure 13. Each of these several frames from the silhouetted photo was then subjected to the rotation and translation programs and the corresponding frames of Figure 14 produced.

Now recall that standardization processing (1) fixes the center of gravity of a blob within the frame, (2) rotates it to align a major axis of inertia with the vertical in the frame, and (3) adjusts scale factor to roughly fill the frame. All information about how much translation, rotation, and scale change has of course been preserved for use in the recognition process (size is an input to simple target recognition, while location and orientation are inputs to target-complex recognition). Examining Figure 14 we find one odd looking building-shaped blob which must be explained. Referring back to Figure 13 we can locate the source of this standardized object, a small collection of points. Mentally treating each of these points as a square, rotating and enlarging the resulting shape shows that the standardization routine functioned properly. Scale change information would prevent recognition as a building.

CONCLUSIONS

In this paper approaches to the preprocessing portions of a photo interpretation automaton have been discussed. Clearly, some extremely important evaluative work remains:

1. Detection capability must be quantitatively defined. This first requires that some plausible criterion or criteria for this capability be defined.

[redacted]

2. Recognition capability must be quantitatively defined. Here there exists a body of evidence that recognition of silhouetted objects is within the recognition capability of current state-of-the-art systems. We are currently applying measures similar to probability of detection and false alarm rate to the definition of recognition capability for a property-list, linear discriminator type of system.
3. Implementation problems for a prototype system must be solved. Our IBM-704 work is for feasibility only. We have kept implementation problems in mind during the current system studies and have carefully avoided using system elements which are unduly complex. As an example, more complicated two-dimensional filters for object detection represent a very real temptation, yet we have exercised restraint and used only the simplest ones which we felt held any hope.

What has been achieved is a demonstration that a plausible system, combining current state-of-the-art pattern recognition capability and simple two-dimensional preprocessing operations, can be stated in specific terms and that it represents the very real and likely prospect of providing automated aid to photo interpreters.

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[redacted]

Illustrations to Accompany Presentation On

INVESTIGATION OF PERCEPTRON APPLICABILITY
TO
PHOTO-INTERPRETATION

(Project PICS)

Washington, D. C.

December 20, 1962

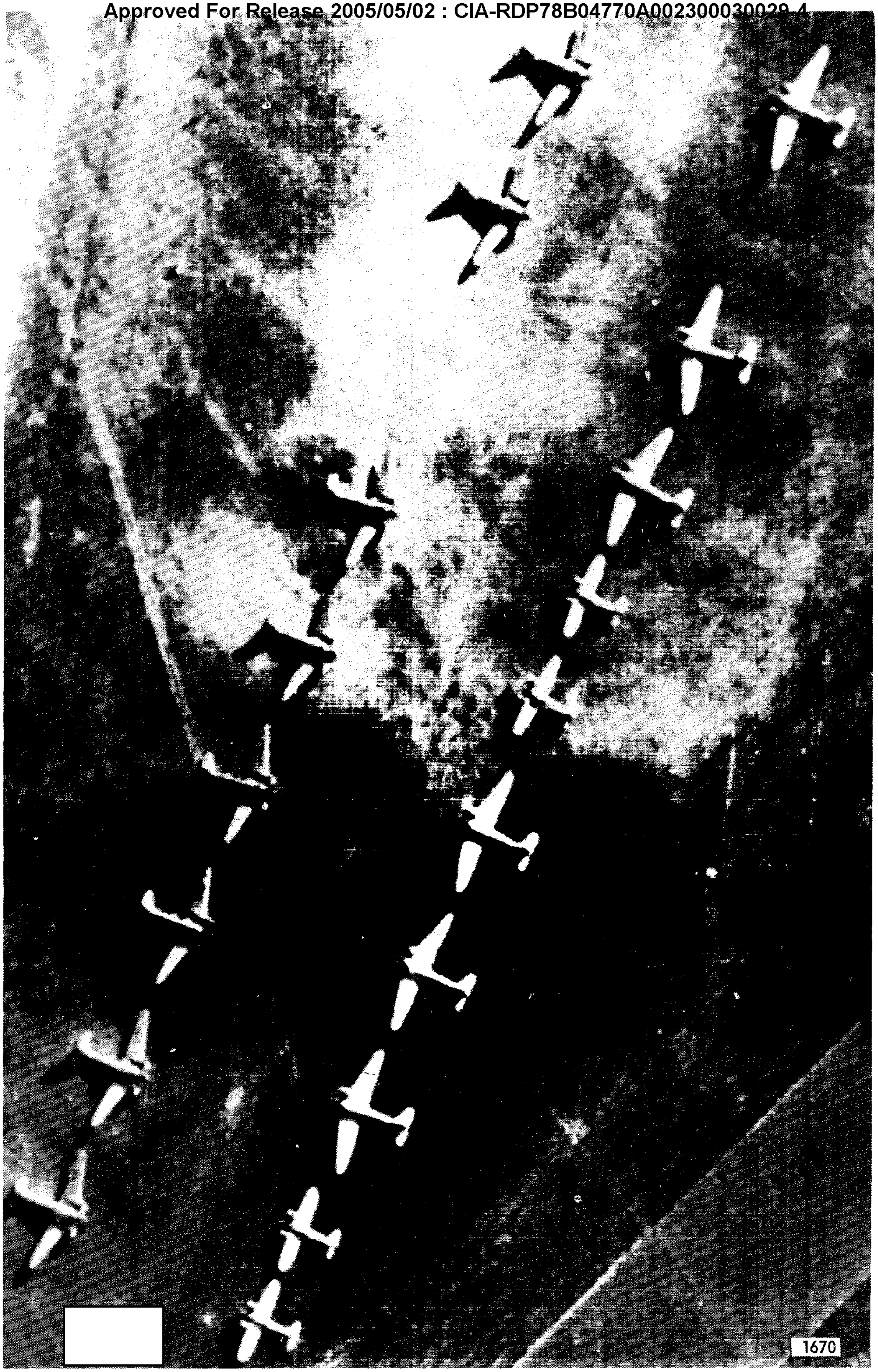

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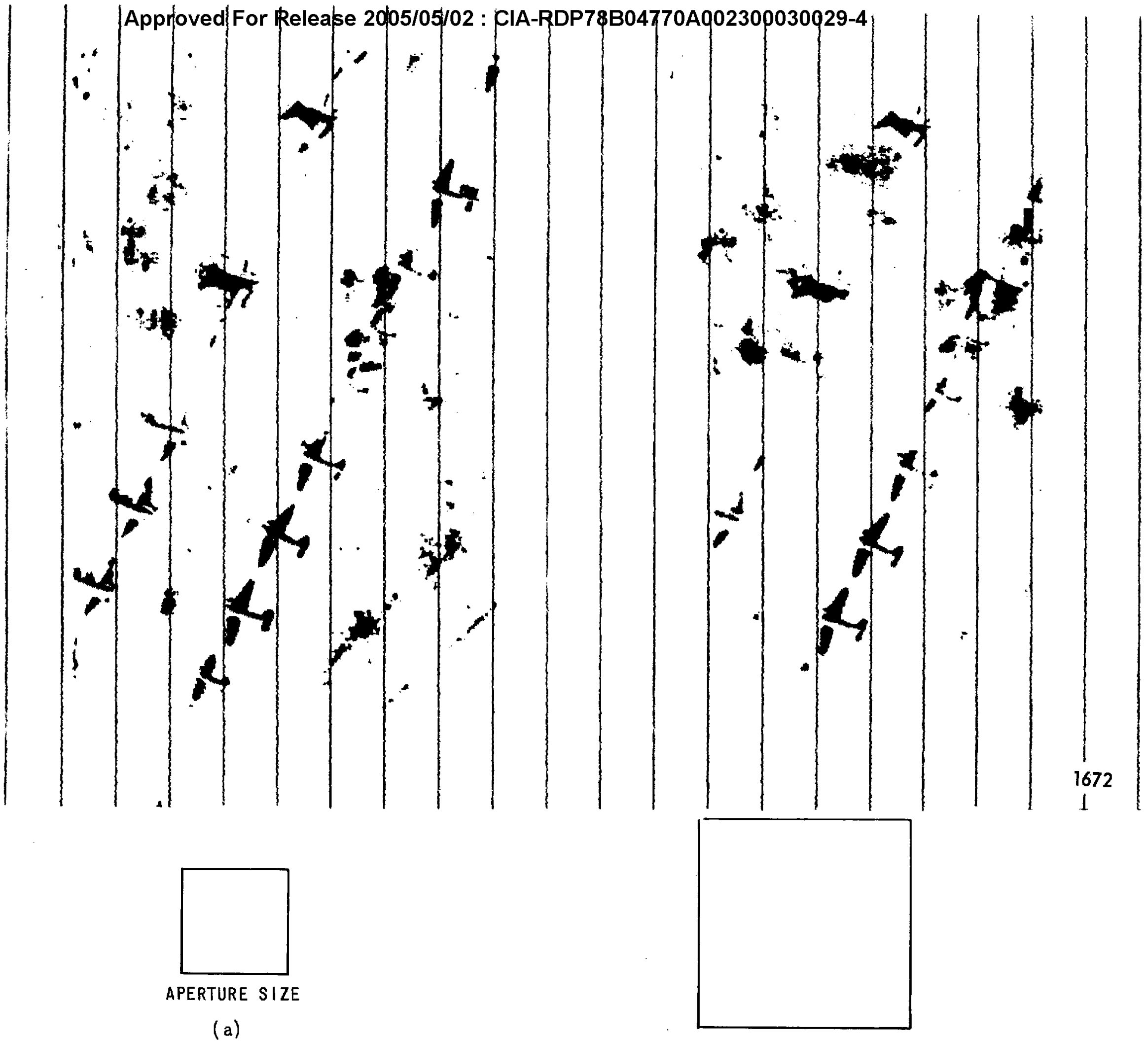
Figure 1 ORIGINAL PHOTOGRAPH

Figure 2 EDITED VERSION OF FIGURE 1



APERTURE SIZE

(a)

APERTURE SIZE

(b)

Figure 3 ANNULAR FILTER: OUTPUT FOR TWO APERTURE SIZES

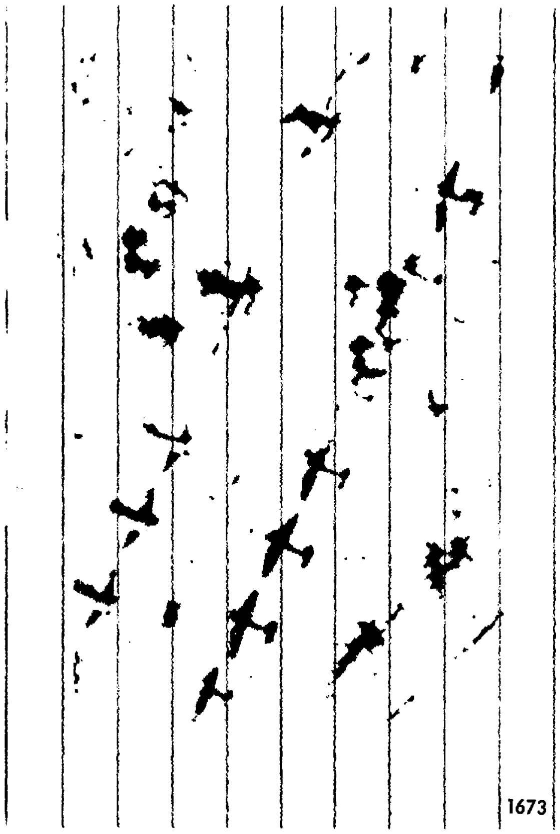


Figure 4 OUTPUT OF GAP FILLER APPLIED TO FIGURE 3(a)

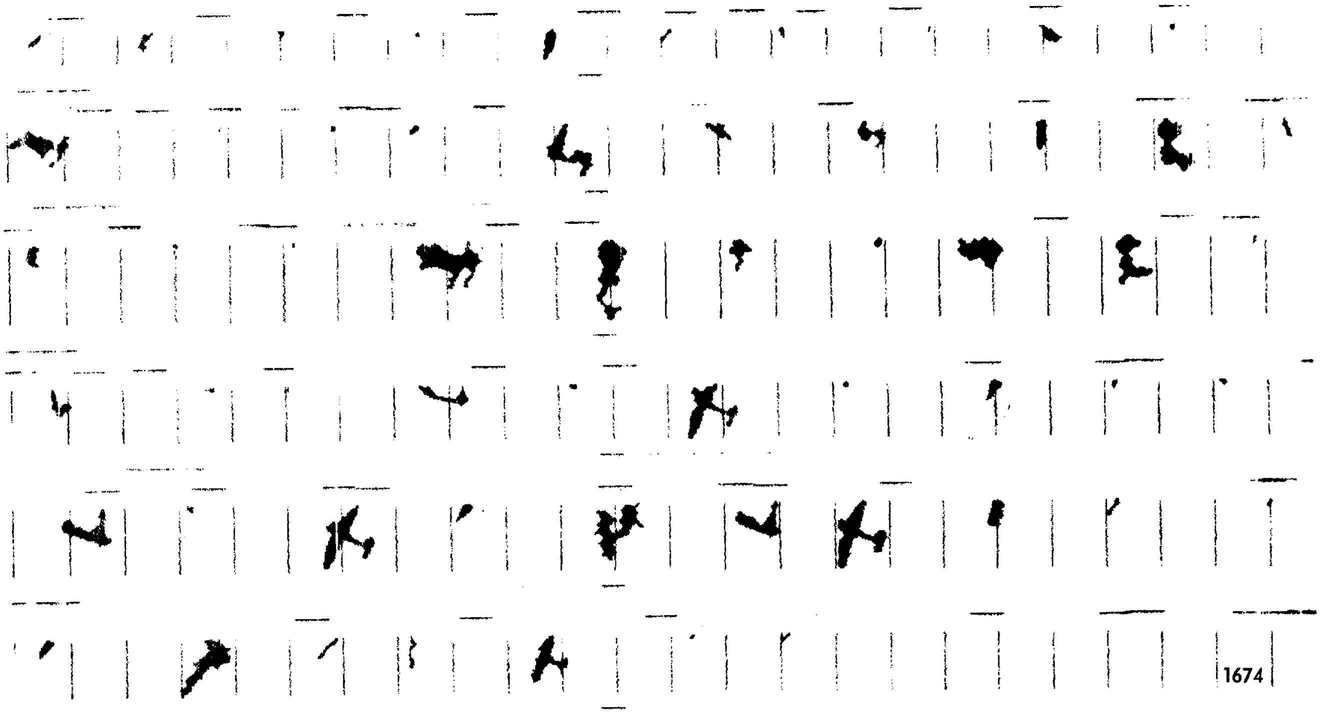


Figure 5 OUTPUT OF ISOLATOR APPLIED TO FIGURE 4

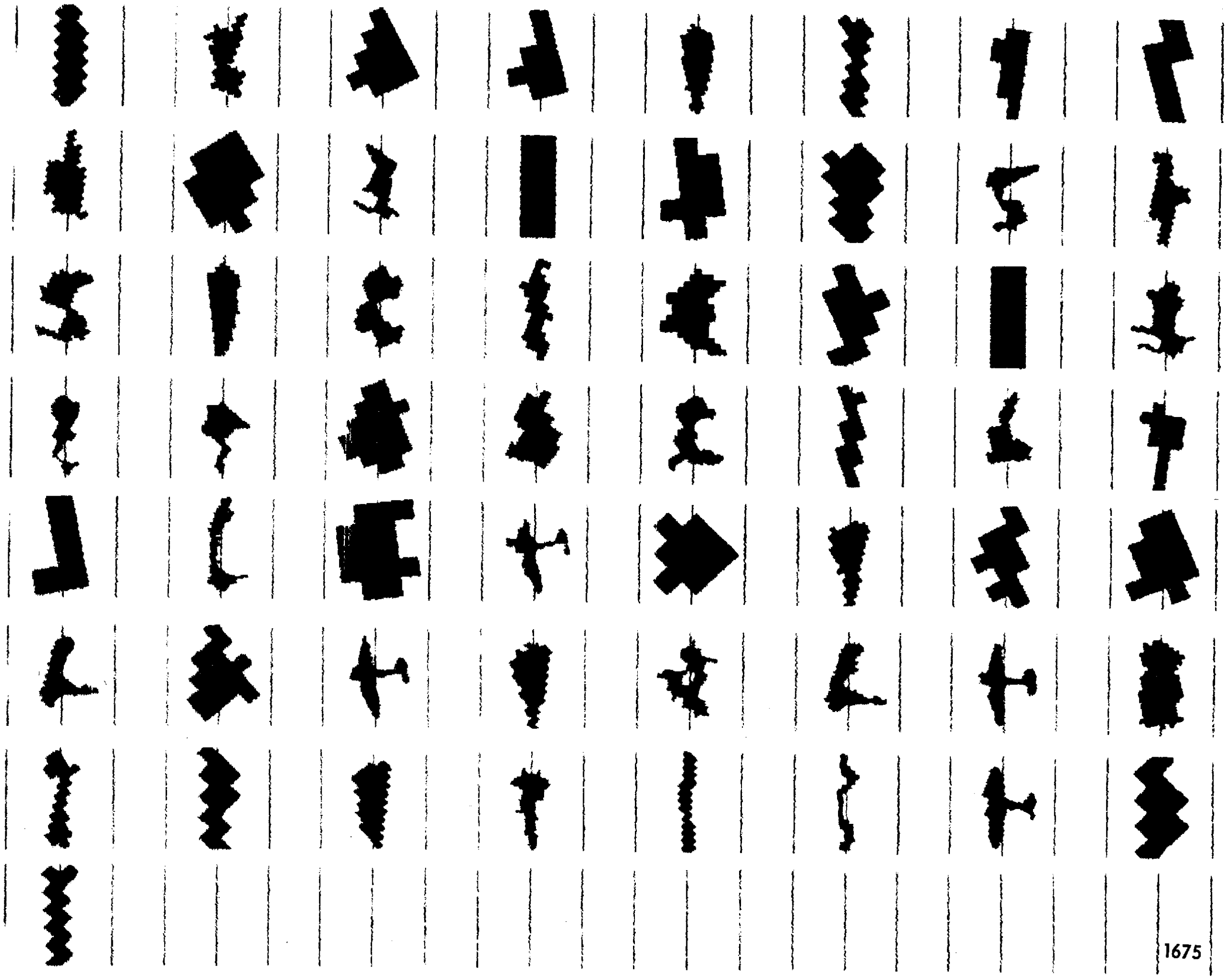
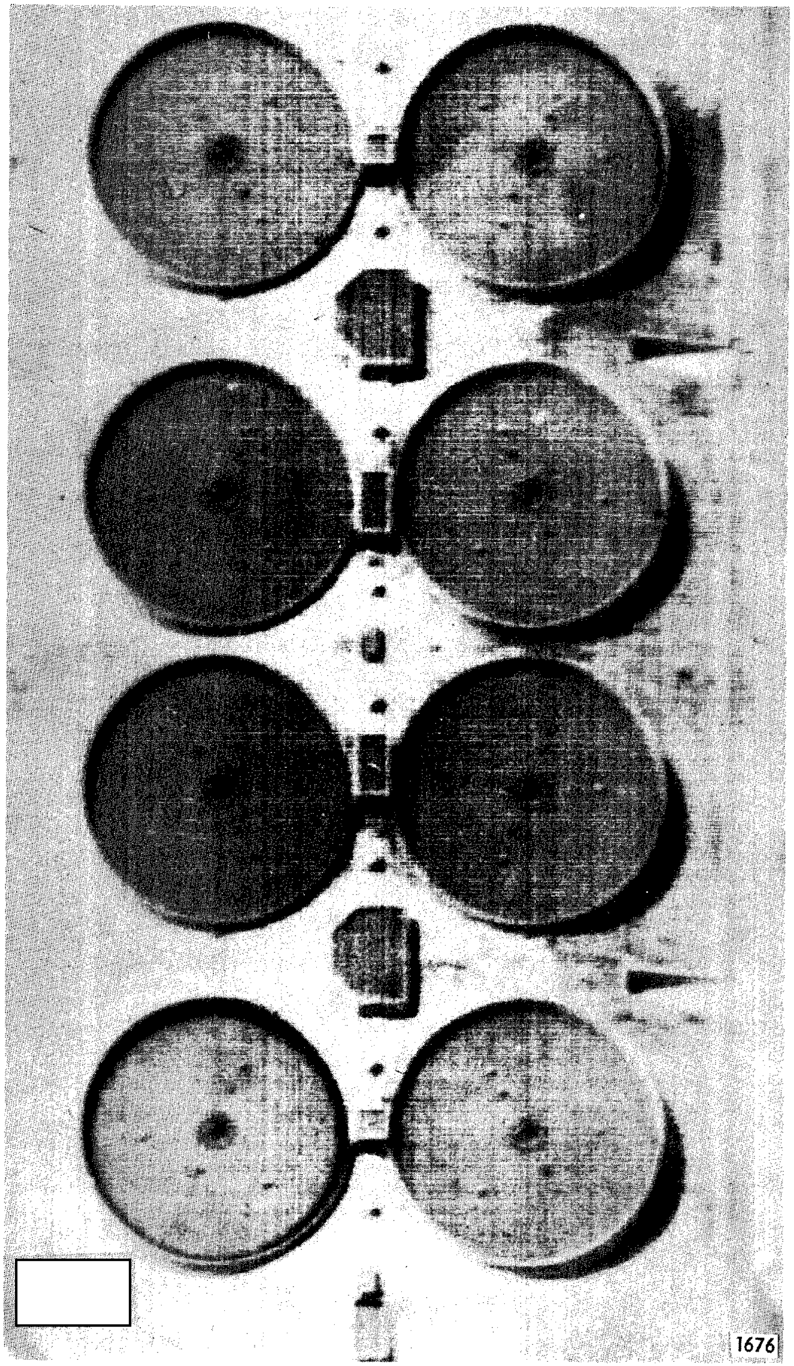


Figure 6 OUTPUT OF STANDARDIZER APPLIED TO FIGURE 5



25X1 [redacted]

Figure 7. ORIGINAL PHOTOGRAPH

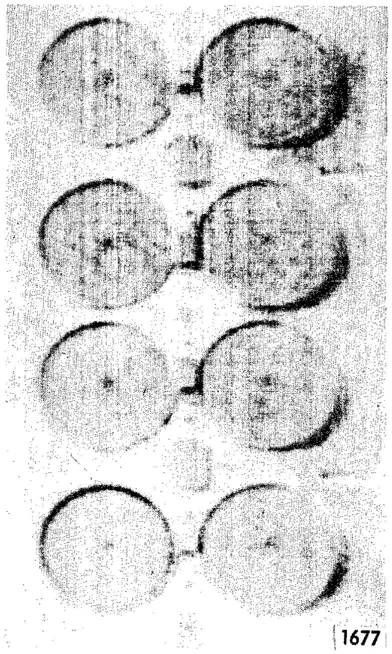
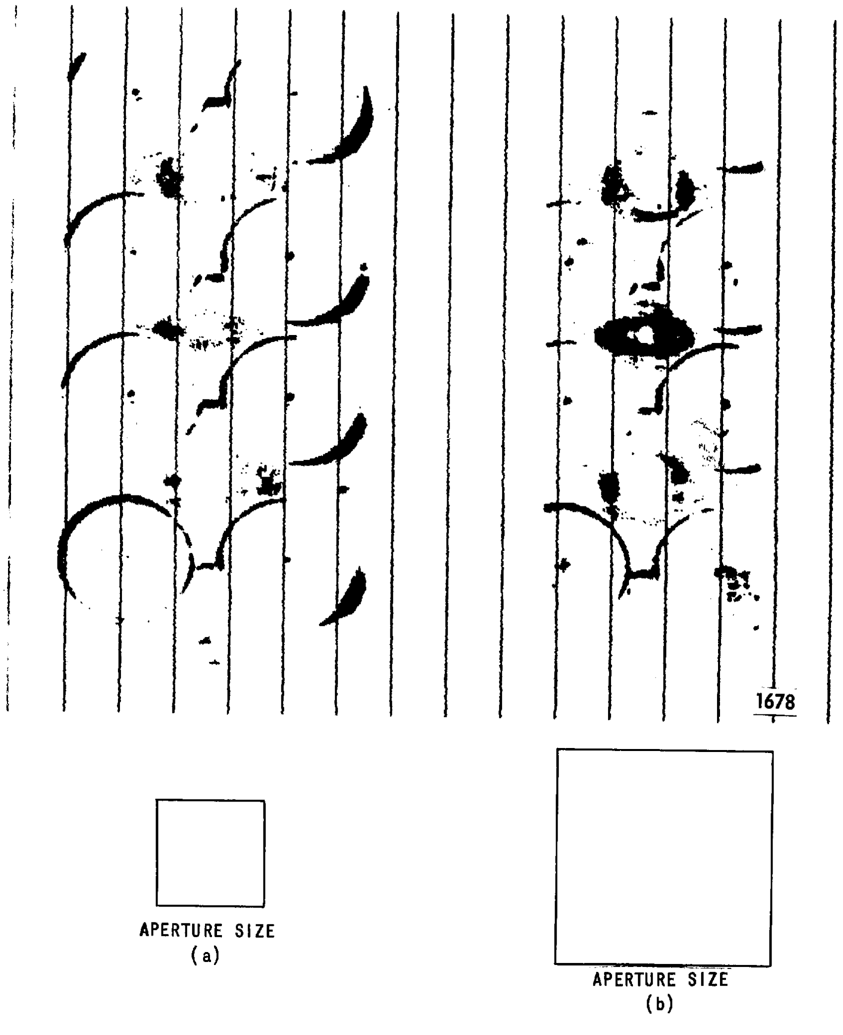


Figure 8 EDITED VERSION OF FIGURE 7



APERTURE SIZE
(a)

APERTURE SIZE
(b)

Figure 9 ANNULAR FILTER OUTPUT FOR TWO APERTURE SIZES

Figure 10(a) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 8

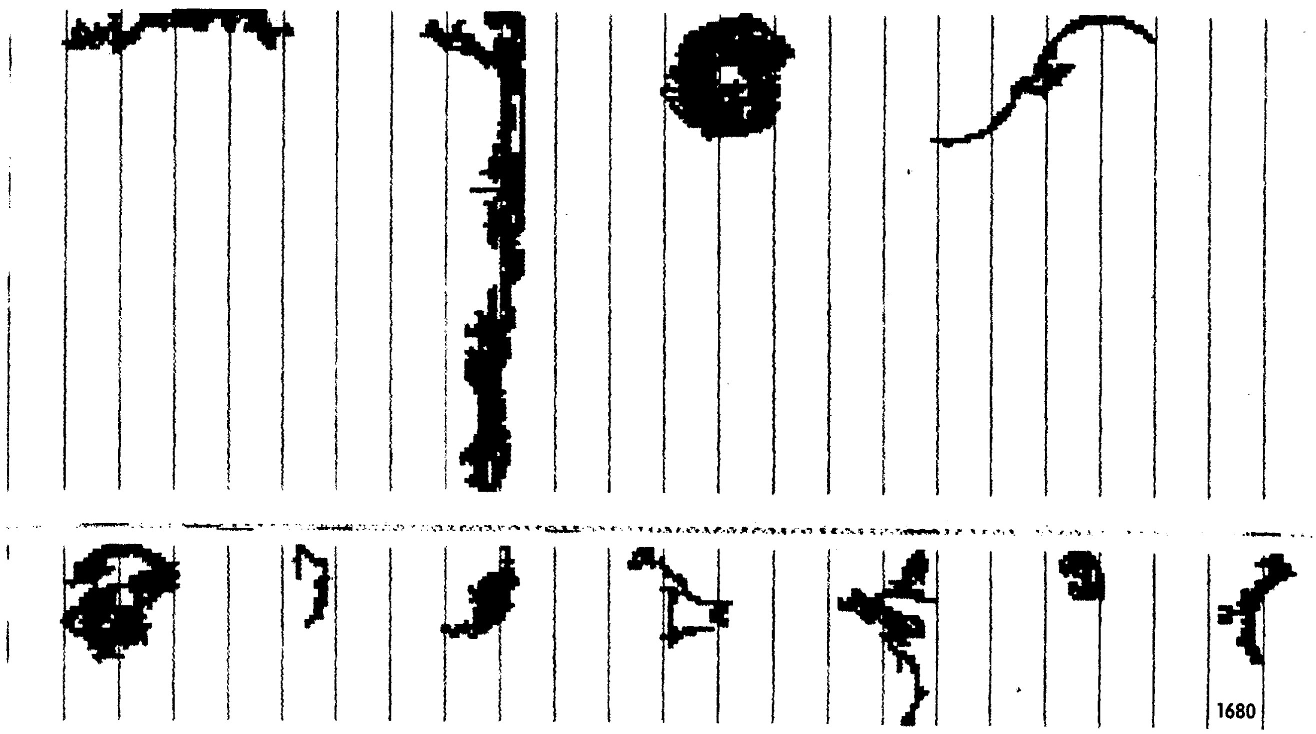


Figure 10(b) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 8

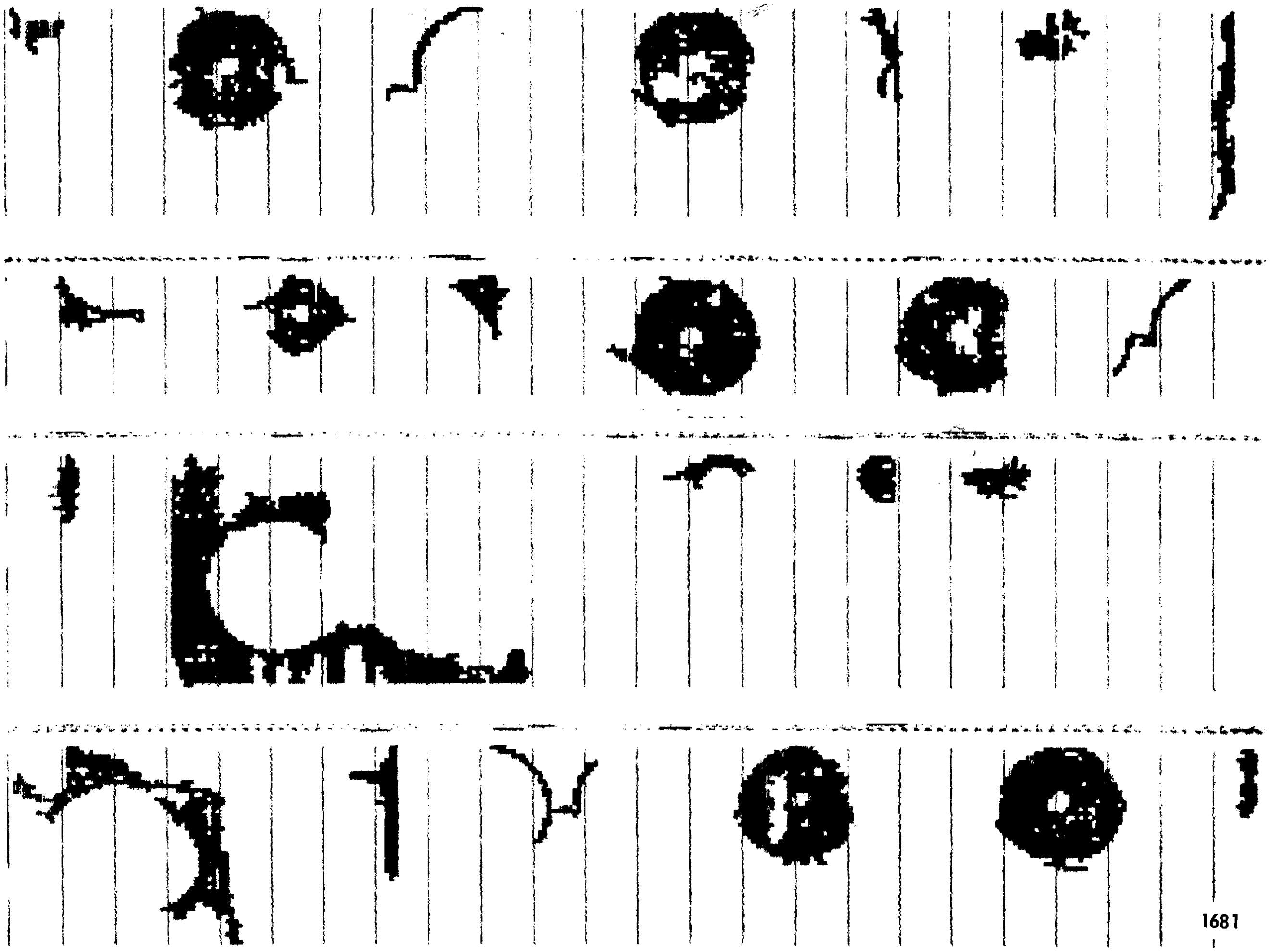


Figure 10(c) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 8

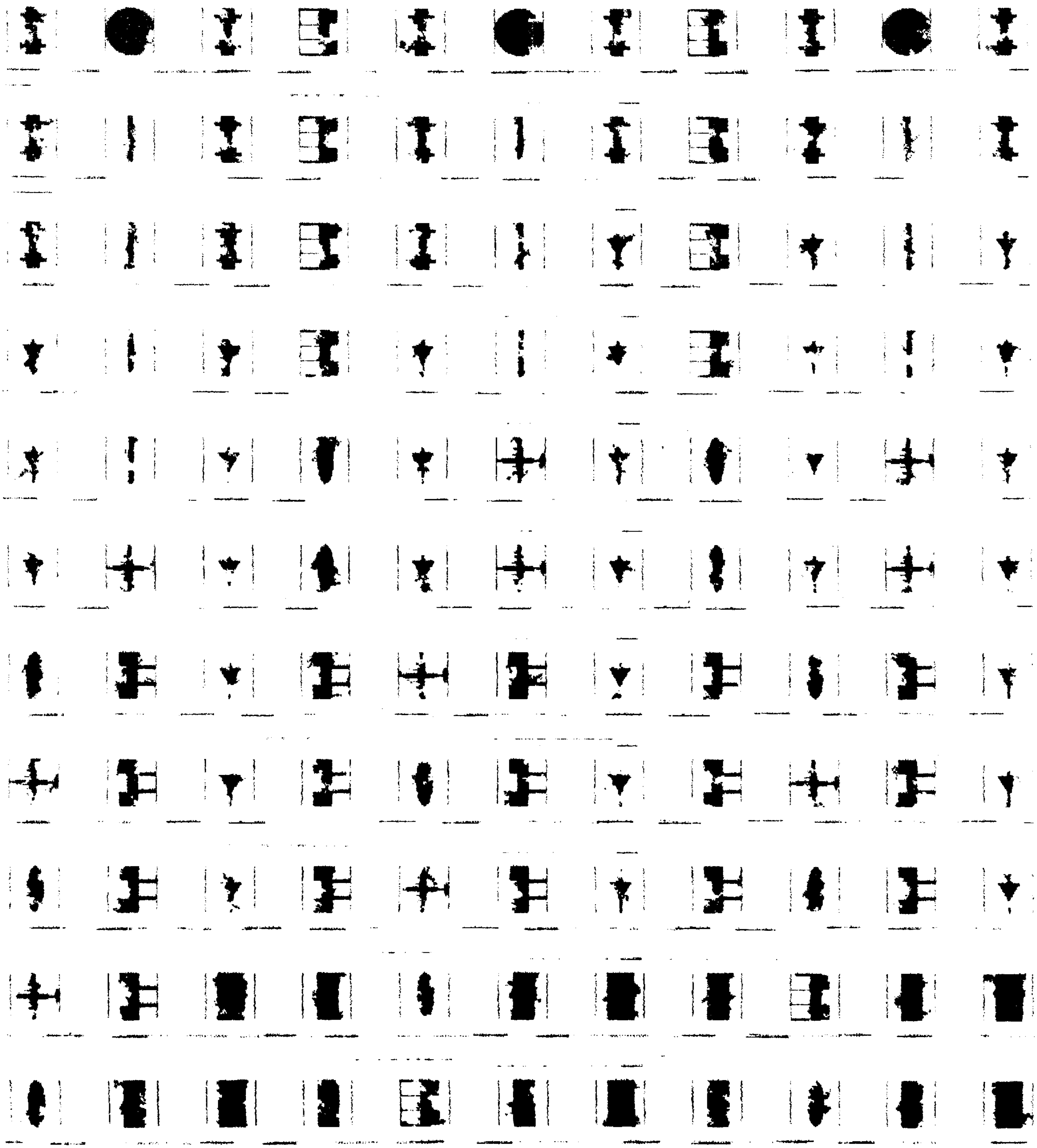


Figure 11 SAMPLE OF OBJECTS USED IN RECOGNITION EXPERIMENTS

1682

RESULTS OF RECOGNITION EXPERIMENT

Synthesized Objects

Correct Pattern Classification	Total Number	Number Correctly Classified	Number Incorrectly Classified	% Recognition
TU 104	60	60	0	100.0
IL 18	60	60	0	100.0
LA 60	60	60	0	100.0
F 102	60	60	0	100.0
SHIPS	60	59	1	98.3
BLDGS	90	86	4	95.5
TANKS	60	59	1	98.3
Object Total	450	444	6	98.7
Other	270	262	8	97.0

Object Detection Probability = .987

False Alarm Probability = .030

COMPLETE RECOGNITION RESULTS

	Recognized As								
Correct Classification ↓	TU 104	IL 18	LA 60	F 102	SHIPS	BLDGS	TANKS	OTHER	REJECTED
TU 104	60								
IL 18		60							
LA 60			60						
F 102				60					
SHIPS					59				1
BIDGS						86		4	
TANKS							59	1	
OTHER					2	6		262	

Encl 3

25 June 1962

PAPER PERCEPTRON

Notions of random connection generalization and learning have dominated discussions of the perceptron to the point of obscuring its basic principles of operation. Basically, the concept is simple; the mathematics describing its operation oftentimes appears complex and obscures the basic simplicity of the central ideas.

The purpose of this discussion is to explain the perceptron concept by showing how it works. A simple paper model (attached as a series of six pages to this discussion) is used as a means of demonstrating its classification function and illustrating the training process.

The perceptron can be divided into three basic sections - sensory, discriminatory, and response. Figure 1 shows a diagram of a simple perceptron. The sensors (or S-units) respond to stimuli from the machine's environment by producing a unit voltage or not, depending on the level of stimulus. The sensors, arrayed in an orderly pattern, are connected in a semi-random fashion to the discriminating layer (or A-units). Several sensor leads are connected to each A-unit in such a way as to produce a sum of stimuli from sets of sensor points. The model attached is a simplified paper representation of perceptrons which respond to light. Naturally, a perceptron of such small size cannot be expected to perform sophisticated tasks but two letter discrimination within a limited field is a suitable task for demonstration purposes.

In the model, S-A unit connections are represented by the clear squares in each of the ten separate A-unit masks (page two of the model). Every opening indicates a connection between that A-unit and a sensor point occupying that position in the sensor group.

The A-units serve to totalize the voltage input from all the sensors connected to them and present this sum to a thresholding device. Page one of the model shows the stimuli the machine is trained to classify. Properly trained, it should be able to recognize the difference between all "P's" and all "E's". Each letter is displayed in four positions to demonstrate the flexibility of the perceptron and its ability to cope with letters which do not maintain a single position. To see how the A-unit operates, we put the stimuli page under the A-unit page (page two of the model) so that the number of the stimulus appears in both the top and bottom pilot windows of the A-unit. Since the dots on the letters represent S-units stimulated, and the holes in the A-unit diagram represent S-A connections, it is apparent that a count of the dots visible through the squares represents the total voltage the A-unit receives. This total has been computed for each unit and stimulus, and the result has been entered in the upper matrix on page three of the model. Thus the matrix contains the sums of the input voltages at each A-unit, before thresholding, when the various stimuli are shown to the sensors.

The summation voltages are then thresholded to produce a "unit" voltage if the threshold is exceeded, a "zero" voltage in all other cases. In the model, $\theta = 3\frac{1}{2}$ was selected for the threshold. The lower matrix on sheet two of the model shows the output of each thresholding unit for each stimulus. In this matrix, each stimulus has its own unique binary number made up of the thresholded A-unit outputs taken in order. This suggests that there could be a way of training the perceptron to recognize the difference between the letters. It is apparent that the larger the number of S-units and A-units, the more patterns could be assigned a unique binary number and thus the greater the scope of the perceptron. Indeed, larger perceptrons have capabilities far beyond those indicated in this simple model.

We train the perceptron to recognize the letters by adjusting "weights" or voltage multipliers which connect the A-units to the response unit. Whenever the thresholder of any A-unit puts out a voltage, this voltage is multiplied by a weight which may give a positive or negative product, depending on its value. The response unit merely totals all the A-unit voltages and thresholds the sum. If the A-unit sum plus the threshold (10 units in the model) is equal to or greater than zero, the response unit puts out a positive unit of voltage. Negative sums elicit negative unit voltage outputs and "zero" sums, of course, give no output.

The machine is trained to distinguish between two letters, by adjusting the weights so that the response unit gives plus values for all letters of one type and minus values for all letters of the other type. Pages four and five of the model are a representation of this training process. Page four is a mask of the thresholded A-unit responses for each stimulus made from the information in the second matrix of sheet three. Each clear part in both the left and right hand columns of each stimulus mask indicates the A-unit which produced a plus "one" output. By placing the mask on page four of the model so that the stimulus number on the training cycle page appears in the pilot hole of the proper mask, the weight associated with each A-unit can be seen opposite the A-unit numbers. By totaling the weights and adding the threshold just as a physical machine would, the sum (Σ) which the response unit receives is obtained. If the sum is of the wrong sign, the weights involved must be changed. It has been shown that it is best to change the weights so the sum is as great in the proper direction as it was in the wrong direction. This change (Δ) is divided among the N weights involved and each is changed by ϵ . These new values are recorded in the second column of the mask and the new sum is listed opposite Σ_c . Starting with the weights all at zero, the machine is exposed to P_1 as the first stimulus in the training sequence to which it responds correctly. Using the stimulus E_1 and the same weights, the machine misclassifies and must be corrected by adjusting the weights using the procedure just described until a correct reading is obtained. As the sheet shows, the machine was exposed to all the stimuli in an orderly fashion until the perceptron correctly identified all the stimuli. On page five of the model, only the stimuli incorrectly classified during the training cycle are shown for the sake of brevity. The final column (labelled W_i) contains the final weights. Page six shows that the perceptron now correctly classifies the eight stimuli.

Now the tasks used for this demonstration are quite elementary. Extensions to more sophisticated tasks would demand a much larger perceptron, which would become unmanageable for paper computation. Thus, this exercise can only be thought of as an exposition of principles of operation.

JLH-1/rmm

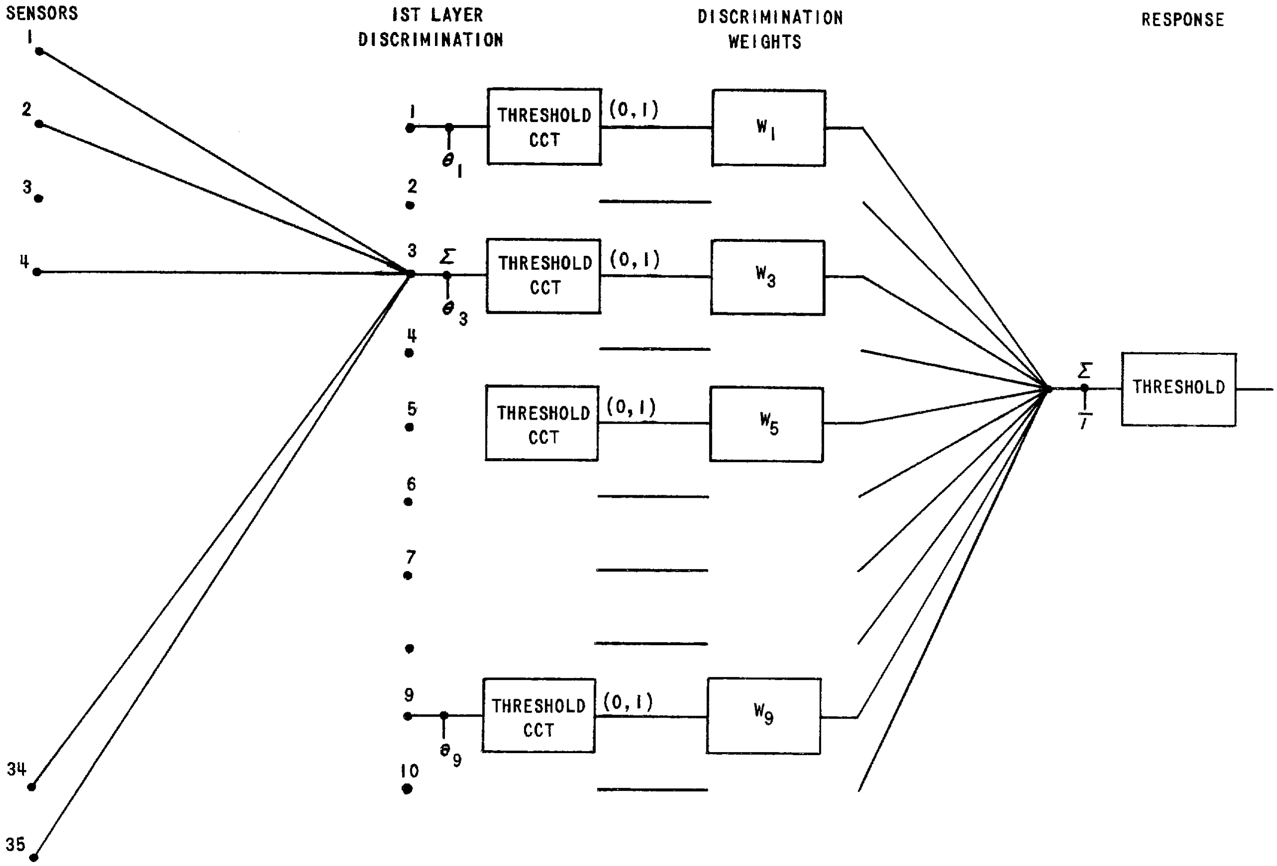
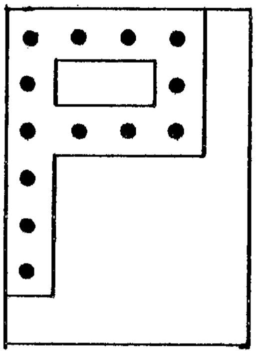


Figure 1 PATTERN RECOGNITION CONCEPTS

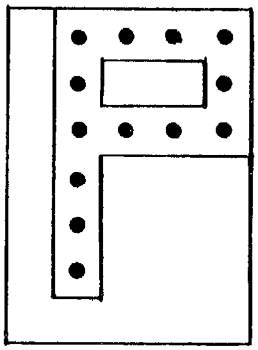
INPUT STIMULI

P_1



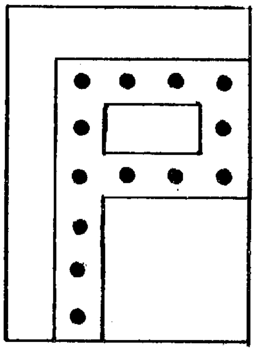
P_1

P_2



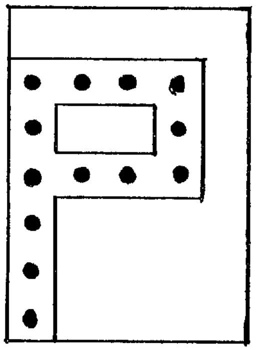
P_2

P_3



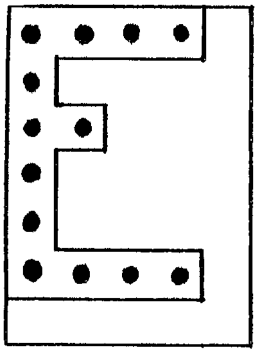
P_3

P_4



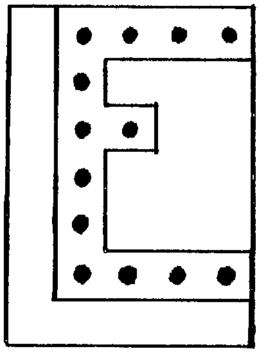
P_4

E_1



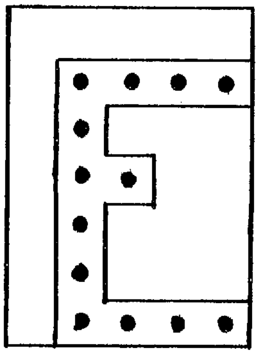
E_1

E_2



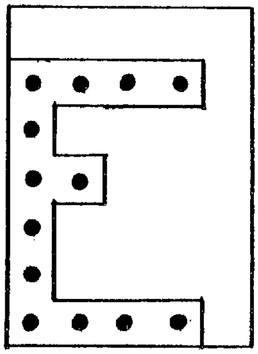
E_2

E_3



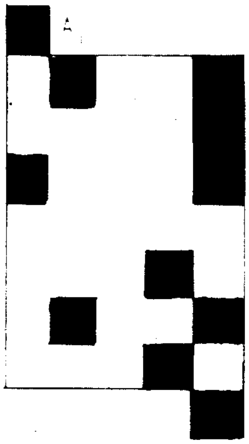
E_3

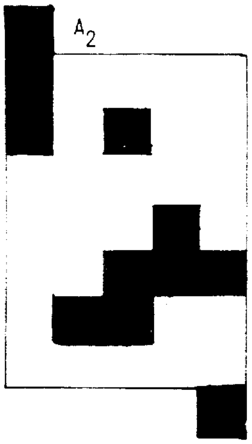
E_4

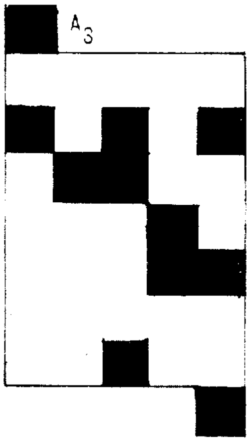


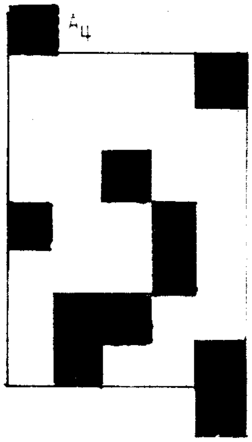
E_4

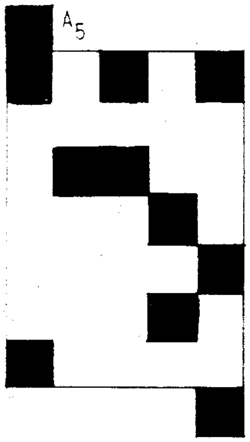
DISCRIMINATION UNITS

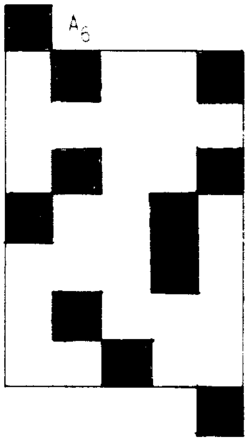

A_1

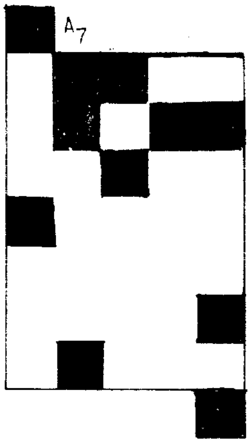

A_2

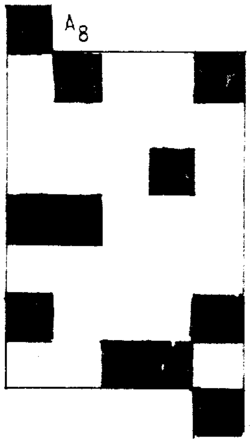

A_3

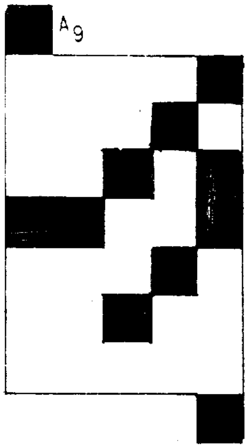

A_4

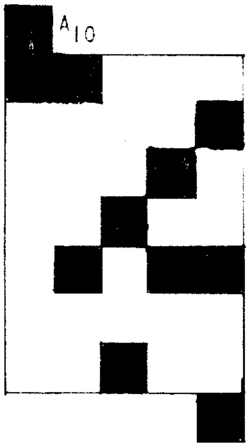

A_5


A_6


A_7


A_8


A_9


A_{10}

MATRICES

SUMMATION MATRIX

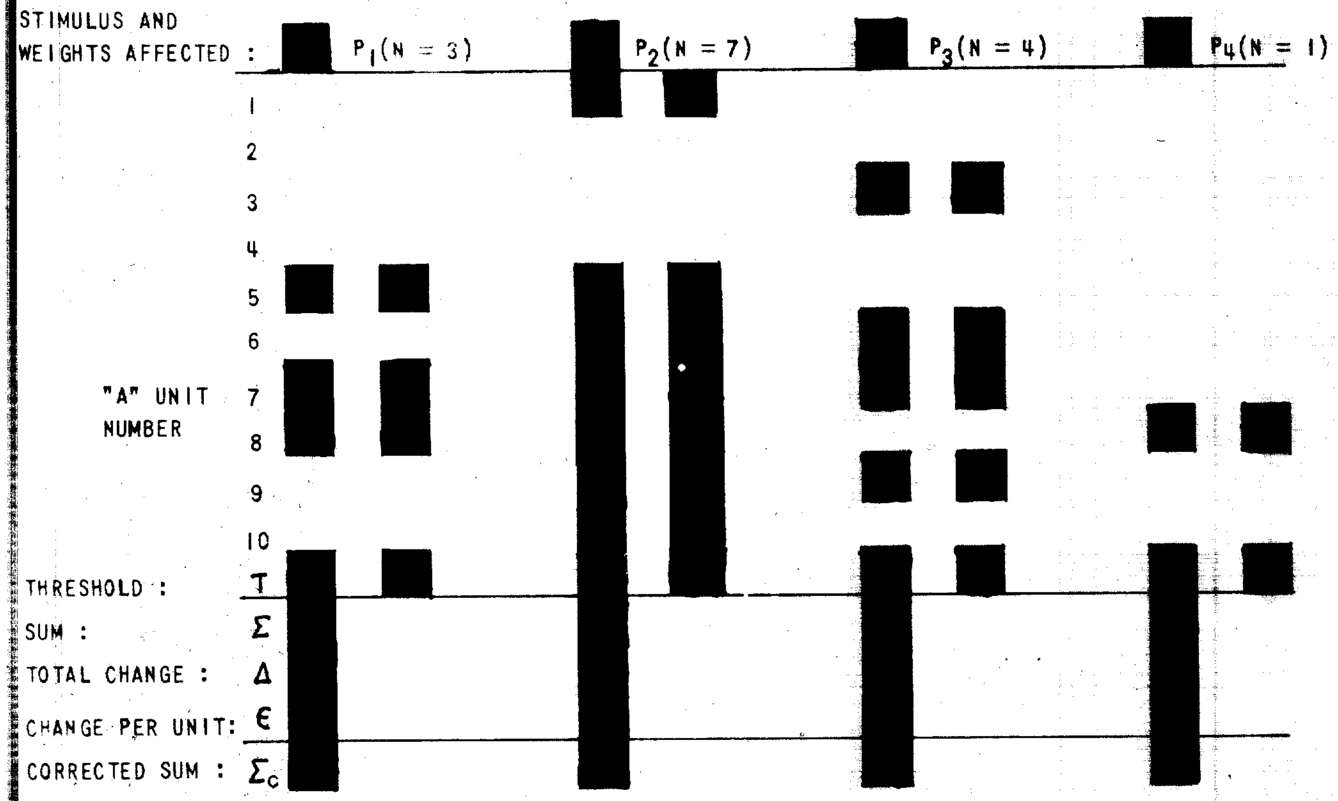
	STIMULUS IDENTIFICATION							
"A" UNIT NUMBER	P_1	P_2	P_3	P_4	E_1	E_2	E_3	E_4
1	2	5	3	1	3	4	3	2
2	2	1	3	3	4	2	2	2
3	3	3	4	3	2	2	4	3
4	2	3	3	2	3	4	3	2
5	4	4	2	2	4	5	1	1
6	3	5	4	2	4	4	3	2
7	5	5	4	3	3	5	4	4
8	4	4	1	4	3	4	3	5
9	3	4	4	3	2	4	2	3
10	3	4	3	2	2	2	4	1

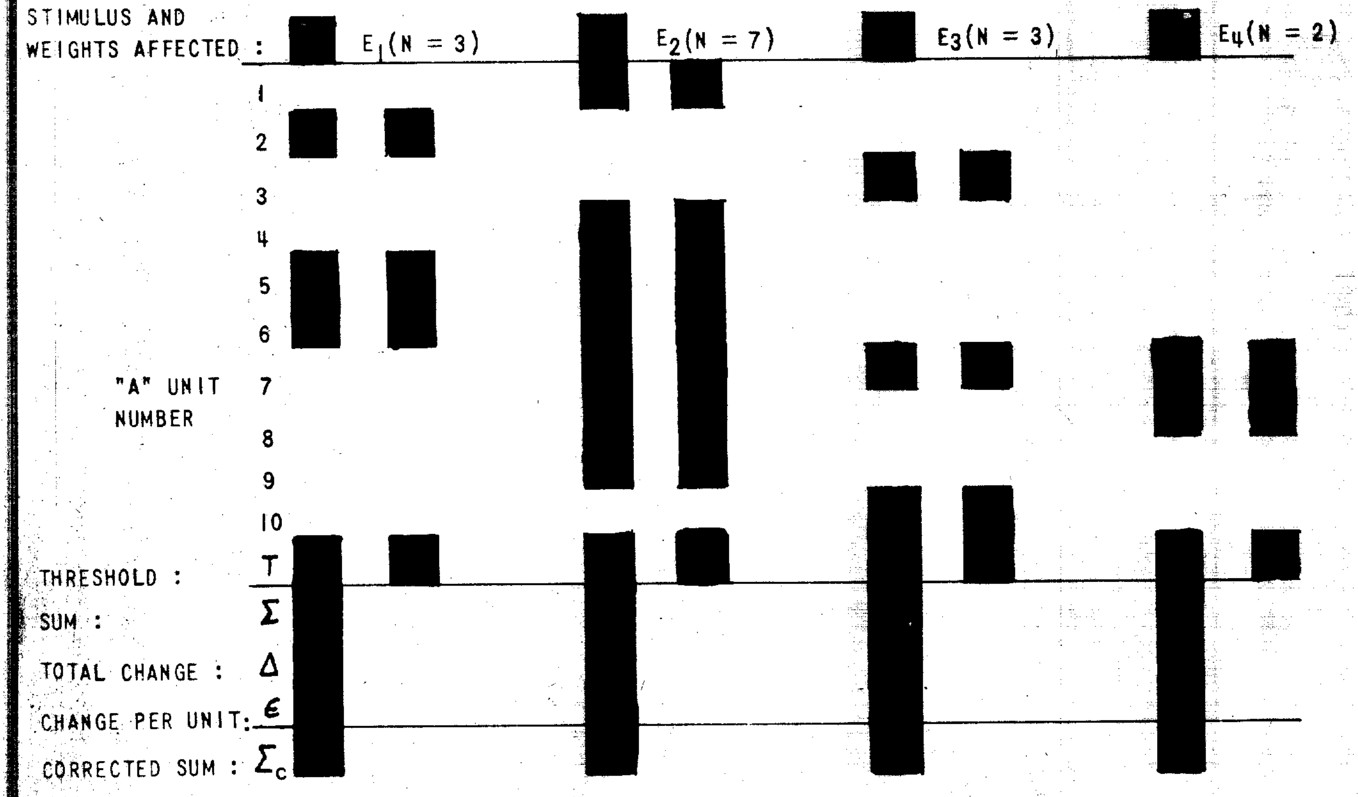
THRESHOLDED VECTOR MATRIX

	STIMULUS IDENTIFICATION							
"A" UNIT NUMBER	P_1	P_2	P_3	P_4	E_1	E_2	E_3	E_4
1	0	1	0	0	0	1	0	0
2	0	0	0	0	1	0	0	0
3	0	0	1	0	0	0	1	0
4	0	0	0	0	0	1	0	0
5	1	1	0	0	1	1	0	0
6	0	1	1	0	1	1	0	0
7	1	1	1	0	0	1	1	1
8	1	1	0	1	0	1	0	1
9	0	1	1	0	0	1	0	0
10	0	1	0	0	0	0	1	0

$\theta = 3\frac{1}{2}$

ACTIVITY VECTOR MASK





TRAINING CYCLES

$P \rightarrow \oplus$ $E \rightarrow \ominus$

STIMULUS IDENTIFICATION

"A" UNIT NUMBER	P_1	E_1	P_2	E_3	E_4	P_1	P_2	E_2	P_3	E_3	E_4	P_1	E_1
1	0	0	0	1	1	1	1	1	-1	-1	-1	-1	-1
2	0	0	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
3	0	0	0	0	-8	-8	-8	-8	-8	-2	-3	-3	-3
4	0	0	0	0	0	0	0	0	-2	-2	-2	-2	-2
5	0	0	-7	-6	-6	-6	1	1	-1	-1	-1	-1	7
6	0	0	-7	-6	-6	-6	-6	-6	-8	-2	-2	-2	-2
7	0	0	0	1	-7	-11	-4	-3	-5	1	0	-12	-4
8	0	0	0	1	1	-3	4	4	2	2	2	-10	-2
9	0	0	0	1	1	1	1	1	-1	5	5	5	5
10	0	0	0	1	-7	-7	-7	-7	-7	-7	-8	-8	-8
	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	-4	12	4	-10	0	8	-12	2	12	-13	
		-20	8	-24	-8	20	1	-16	24	-4	-24	26	
		-7	1	-8	-4	7	(1)	-2	6	-1	-12	8	
	10	-11	3	-12	-4	11	1	-6	12	-1	-12	11	

	E_1	P_2	E_2	P_3	E_4	P_1	P_2	E_2	P_3	P_2	E_3	E_4	P_2	W_1
1	-1	-1	0	-2	-2	-2	-2	1	-2	-2	-1	-1	-1	-1
2	-7	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12
3	-3	-3	-3	-3	-2	-2	-2	-2	-2	-2	-2	-3	-3	-3
4	-2	-2	-2	-4	-4	-4	-4	-4	-7	-7	-7	-7	-7	-7
5	7	2	3	1	1	1	2	5	2	2	3	3	3	4
6	-2	-7	-6	-8	-7	-7	-7	-4	-7	-6	-5	-5	-5	-4
7	-4	-4	-3	-5	-4	-7	-6	-3	-6	-6	-5	-5	-6	-6
8	-2	-2	-1	-3	-3	-6	-5	-2	-5	-5	-4	-4	-5	-5
9	5	5	6	4	5	5	5	8	5	5	6	6	6	6
10	-8	-8	-7	-7	-7	-7	-7	-4	-4	-4	-3	-3	-3	-3
T	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Σ	8	-5	7	-2	3	-2	-10	11	0	-6	0	1	-1	
Δ	-16	10	-14	4	-6	4	20	-22	1	12	-1	-2	2	
ϵ	-5	1	-2	1	-3	1	3	-3	(1)	1	(-1)	-1	(1)	
Σ_c	-7	2	-7	2	-3	1	11	-10	1	1	-1	-1	1	

TRAINED PERCEPTRON RESPONSES

P → ⊕ E → ⊖

STIMULUS IDENTIFICATION

		P_1	P_2	P_3	P_4	E_1	E_2	E_3	E_4
	1	-1	-1	-1	-1	-1	-1	-1	-1
	2	-12	-12	-12	-12	-12	-12	-12	-12
	3	-3	-3	-3	-3	-3	-3	-3	-3
	4	-7	-7	-7	-7	-7	-7	-7	-7
	5	4	4	4	4	4	4	4	4
"A" UNIT NUMBER	6	-4	-4	-4	-4	-4	-4	-4	-4
	7	-6	-6	-6	-6	-6	-6	-6	-6
	8	-5	-5	-5	-5	-5	-5	-5	-5
	9	6	6	6	6	6	6	6	6
	10	-3	-3	-3	-3	-3	-3	-3	-3
	τ	10	10	10	10	10	10	10	10
	Σ	3	1	3	5	-2	-3	-2	-1

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INPUT / OUTPUT EQUIPMENT FOR RESEARCH APPLICATIONS

25X1

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INPUT/OUTPUT EQUIPMENT FOR RESEARCH APPLICATIONS

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Cornell Aeronautical Laboratory, Inc.

ABSTRACT

The purpose of this paper is to review the input/output requirements for computers used in research activities, to establish a cohesive philosophy encompassing foreseeable requirements, and to illustrate that philosophy with case histories of equipment designed and constructed at Cornell Aeronautical Laboratory for its own research purposes. Research problems arising in the areas of photointerpretation, pattern recognition, speech analysis and radar signal analysis are described with examples of specific solutions of these problems in terms of input/output equipment. This paper, in addition, demonstrates that access to a special input/output system will permit for the solving of research problems, a radically different approach which is not ordinarily evident at the outset of an investigation.

INTRODUCTION

Over the past decade, computers have penetrated and served almost every facet of scientific research including research on information processing systems themselves. Accompanying this penetration has been an intensified requirement for input-output systems satisfying special needs not met by standard available equipment. In the very recent past, movements towards satisfying these requirements are in evidence, but the overall pattern has not been completely established.

The purpose of this paper is to review the input-output requirements for computers used in research activities, to establish a cohesive philosophy encompassing foreseeable requirements, and to illustrate that philosophy with case histories of equipment designed and constructed at Cornell Aeronautical Laboratory for its own research purposes. In the course of the discussion, we will describe research problems areas imposing special requirements and to present specific approaches to the solution of these problems in terms of input-output equipment. In many cases, we have found that access to a special input-output system permitted a radically different approach to a research problem and opened research vistas not clearly appreciated before the revised approach was taken.

In retrospect, it is possible to observe major trends in the use of computers which have imposed progressively more exacting requirements on input-output facilities for general-purpose digital computers. These trends are roughly delineated by Table I. At the outset, computers were used chiefly in scientific computation. Characteristically, this imposed minimal demands on input-output equipment in terms of the quantity of data to be inserted into the machine. Card and punched tape inputs were entirely adequate and printer/plotter output largely satisfied display requirements.

Table I

EVOLUTION OF COMPUTER USE AND INPUT/OUTPUT REQUIREMENTS

APPLICATION	I/O CHARACTERISTICS
SCIENTIFIC COMPUTATION	LIMITED I/O DATA
INFORMATION PROCESSING SYSTEMS	STEREOTYPED DATA OFTEN HIGH VOLUME DATA OFTEN REAL-TIME I/O
INFORMATION PROCESSING RESEARCH	
(1) BY SIMULATION (ARTIFICIAL INPUTS)	LIMITED I/O DATA
(2) BY IMPLEMENTATION (REAL INPUTS)	INCREASING AMOUNTS OF I/O DATA UNUSUAL INPUTS SUCH AS PHOTOS, SPEECH, ETC. ENCOUNTERED
(3) BY REAL-TIME EXPERIMENTS	EXTENSIVE DATA TRANSFER I/O COORDINATION WITH COMPUTATION AS WELL AS EXTERNAL SYSTEMS PRINCIPLE PROBLEM
MASS DATA REDUCTION	EXTENSIVE INPUT DATA BUFFER STORAGE REQUIREMENT

Use of computers in information systems such as SAGE, MISSILE MASTER, and NTDS imposed new requirements and raised two issues which significantly affected attitudes toward input-output systems: (1) the use of computers in a real-time environment, (2) the need for massive, sophisticated information processing research to make the system work at all. Issues of noisy inputs and nonlinear processes forced much of this research into the general purpose computer. The input-output needs for computers used in information systems, however, tended to be stereotyped, special-purpose, and therefore not of interest in a discussion of research requirements.

At first, research on information systems problems was confined to analytic studies and simulation of the problem using artificially generated inputs. More recently, pattern recognition research as well as some signal processing research have entailed problems for which artificial inputs cannot be readily generated. Thus, special-purpose input systems for pictorial and other forms of information have become needed. Consequently, we see information processing research imposing demands on computer input systems which cannot be met with conventional card or perforated tape inputs.

At the same time that research on information systems became important, scientists dealing with experimental research problems began to seek in computers, a way out of the cumbersome, time-consuming, and costly data reduction problems which their experimental procedures were imposing upon them. Requirements for the processing of large masses of data then proliferated, and solutions to input-output problems imposed by this movement have become imperative. Generally, the data to be transferred into the computer are time-varying functions in several parameters and, by and large, some sort of a buffer store is required between the experiment and the computer.

Since some of the most interesting input-output problems imposed by today's research activities are entailed in the last two of the areas cited, information processing research and mass data reduction, we will concentrate on these areas as a means to focus this paper.

INFORMATION PROCESSING RESEARCH

The two major areas of information processing research which currently impose the most significant input-output requirements are shown in Table II. It is clear from the research topics delineated in these figures that the salient feature of each problem which imposes an unusual input-output requirement stems from the fact that the input to the system under study cannot be readily characterized analytically. Research in other areas such as radar track-while-scan research could readily proceed through the mechanism of artifically generated inputs. Confidence in the validity of these artificial inputs, while not perfect, is high enough to justify use of the research results for most design purposes. On the other hand, characterizing either an aerial photograph or the essentials of the spoken word analytically is virtually impossible except for early exploration studies. Thus, research in these areas utilizing general-purpose computers is dependent upon input-output equipment suitable for the task.

Table II

INFORMATION PROCESSING RESEARCH

PATTERN RECOGNITION	SIGNAL PROCESSING	DATA PROCESSING
ALPHA-NUMERIC CHARACTER RECOGNITION	COMMUNICATIONS CODING	INTERFEROGRAM ANALYSIS
HAND PRINTED CHARACTER RECOGNITION	SPEECH BANDWIDTH COMPRESSION	PARTICLE SIZING AND COUNTING
HANDWRITTEN CHARACTER RECOGNITION	PHOTO BANDWIDTH COMPRESSION	CELL COUNTING
FINGERPRINT IDENTIFICATION	ELECTROCARDIOGRAM INTERPRETATION	BACTERIA COUNTING
X RAY INTERPRETATION	ELECTROENCEPHALOGRAM INTERPRETATION	AEROSOL INVESTIGATION
SPEECH RECOGNITION		GEOLOGICAL MICRO-ASSAYING
RECOGNITION OF SUBMARINE SOUNDS		
DECOY DESCRIMINATION		
AUTO-CRASH SOUNDS RESEARCH		

Further contemplation of the research problems demanding special input equipment convinces one that a pictorial input system capable of accepting monotone, opaque or transparency, material and transferring to store, four to five bit quantizations of the gray scale level for a spatial square matrix of 10^5 to 10^7 elements would satisfy a very large percentage of the problems involving two-dimensional patterns.

Figure 1 shows the major blocks of a Photo Input System designed and put in operation at the Laboratory for use on its research programs.* The facsimile transmitter is a standard commercial unit designed to accept flat copy 8-3/8" wide. The scanning rate is 6 lines per second, corresponding to a feed rate of 3.6 inches per minute. The system is synchronized by incorporating a pulse generator into the facsimile transmitter. This consists of an inductive pickup associated with a 180-tooth gear driven by the mechanical scanning system at five times the line scanning speed. The resultant "clock" frequency is thus 5.4 Kc with 900 pulses per line locked to the scan motion. The clock frequency after shaping is used as a trigger to control the conversion time of the analog-to-digital converter. The converter receives a continuous analog signal from the facsimile scanner by way of the photomultiplier, cathode follower and gamma correction amplifier. (The latter restores the compression introduced in photographic reproduction processes.) At each trigger pulse, the instantaneous analog signal is converted to a four-bit binary number in 22 microseconds and appears on the four output lines of the converter. The converter also furnishes an end-of-conversion pulse 0.5 microsecond after conversion. This pulse is used after shaping, to control the "read" time of the computer via the "MQ" line.

The circuitry shown in the block diagram as the input buffer section accepts the digital information from the analog-to-digital converter on the four lines and modifies the levels corresponding to "0" or "1" to make them compatible with the computer. The gate associated with each level changer is under control of the "read select" line from the computer. The gate is either open, permitting information transfer, or closed, clamping the cathode follower to "0" level. The "read select" line also controls the copy feed motion via the cathode follower and relay in the control section.

The photo input system is controlled completely by the digital computer as if it were a standard item of peripheral equipment, such as a tape reader. A computer program developed by the Laboratory makes use of copy content to control registration of copy area. A black bar, four inches long by one-fourth inch wide, is placed at the top of the copy 0.4 inch above the desired first line of the area to be read. The bar may be printed as part of the photograph or may be applied as a strip of black tape. To perform a reading operation then, the facsimile transmitter is energized, starting the scanning system. The prepared copy is inserted until engaged by the pinch roller using the roller hand wheel. The computer program is read into the computer in the normal manner. When the program step selects the real-time input, the read select line is energized, opening the gates in the input buffer and starting the copy feed motor. The computer program starts a search routine looking at the digital information presented to the I/0 bus. This program step continues until the black bar is intercepted. The next step allows the copy to advance 0.4 inch, then initiates a second search routine to locate the pedestal (black level interval at end of each scan line). Location of the pedestal starts a counting routine that counts the number of MQ pulses received as the scan line advances from left to right. Upon reaching the desired magnitude (100 counts per inch), the computer transfers the digital number presented to the I/0 bus into core storage. Each sample thereafter is transferred until a total MQ count of 900 is reached. Counting continues until the desired magnitude is again reached on the next scan line (without digital number transfer). Establishment of the count again starts the digital number transfer to core storage and the cycle is repeated until a predetermined total number of MQ pulses has been reached, terminating the read-in program.

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*This development was sponsored jointly by Geography Branch, Office of Naval Research and Photographic Management Division, Bureau of Naval Weapons.

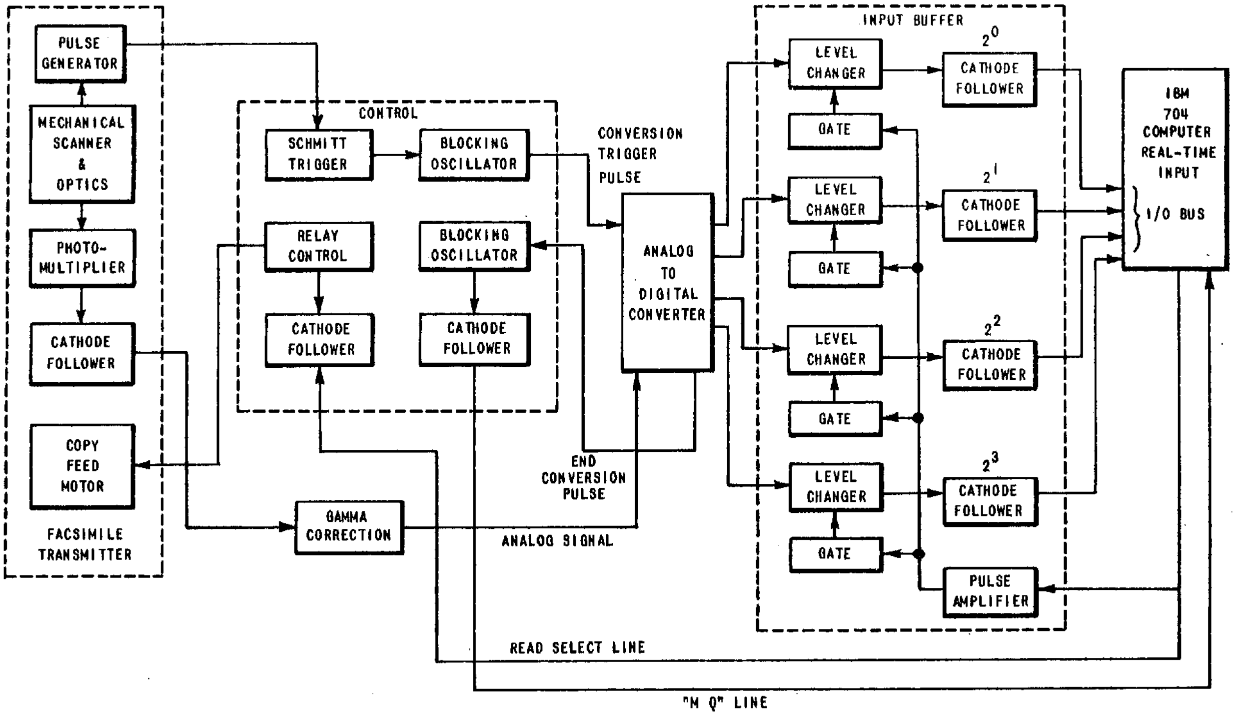

Figure 1 BLOCK DIAGRAM OF PHOTO INPUT SYSTEM

Thus it may be seen that the recorded area of copy is controlled vertically by the location of the black bar and the total magnitude of the MQ count. Horizontal location is controlled by the MQ count along the scan line. In the actual program, a packing routine is used to conserve core storage by consolidating nine four-bit samples into one standard thirty-six bit computer word. Flexibility of this control method should be apparent.

Figure 2 shows the physical arrangement of the major components. The gamma correction amplifier appears at the top of the rack. Directly below is located the modified facsimile transmitter. Below the transmitter is the control and input buffer circuitry, while the analog-to-digital converter and associated power supply are located at the bottom of the rack. Primary power for the control and input buffer chassis is supplied from the 704 computer. Figure 3 shows the details of the pulse generator.

Access to a photo input system enables a research worker to investigate two-dimensional filtering, processing, and decision making methods without costly breadboarding of proposed systems. Photographic inputs are inserted with full usable gray scale for numerical processing. Figure 4 shows an aerial photograph of which the left half was read into the computer, and printed out in four levels of gray scale using different letter symbols for each gray level. Figure 5 shows a numerical printout of alpha-numeric pictorial material which was read into the computer by the photo input system and printed out using each of the ten numerals and four letters of the alphabet to represent each of the available 16 levels of gray.

The nature of processing research which is accommodated by such a photo input system illustrated by Figure 6 which shows an original photograph (6a) and three different types of numerical operations performed on the photo after read-in to the computer. From the full gray scale record, two-dimensional filters were used to produce the binary image (6b). Although it is not immediately apparent from the illustration, one of the two filters was a sophisticated variable, dual threshold filter. The other was a simple low pass filter. The objects in the (6b) binary image were then isolated one from the other to make the separate binary images (6c). A scissors program was used to produce this result. Finally each image was normalized by measuring c.g.'s, angle between horizontal and major axis of inertia, rotating each image through that angle, and re-sizing the images to a common vertical dimension.

These examples afford only a glimpse of the research potentialities of such an input system. Naturally a matching photo output system is a useful adjunct to the photo input system described.

Speech recognition and bandwidth compression constitute the remaining major area of research for which special purpose inputs may be of value.

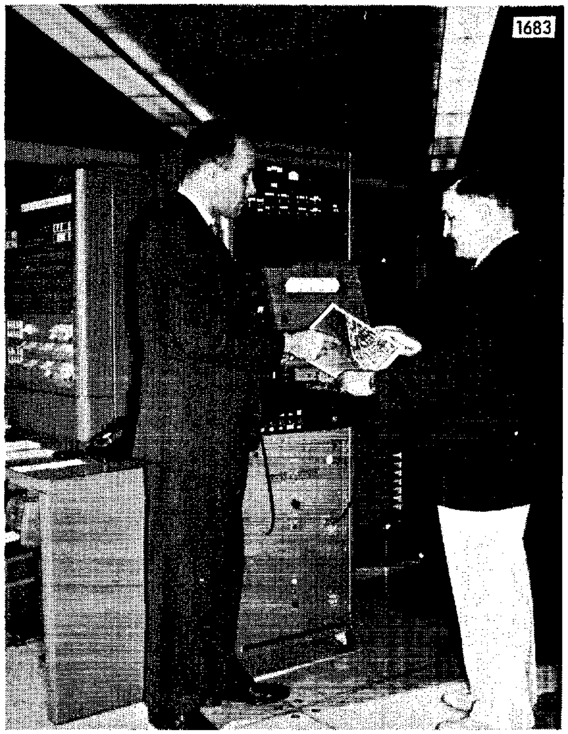

Figure 2 EXTERNAL VIEW - PHOTO INPUT SYSTEM

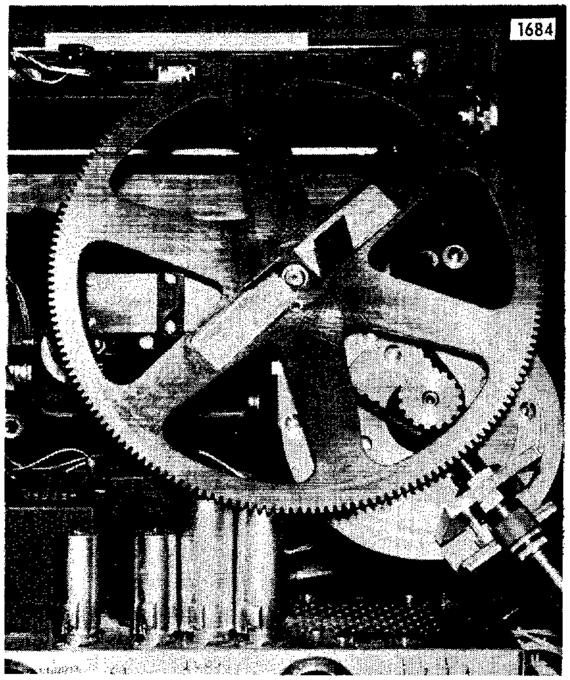

Figure 3 DETAIL OF PULSE GENERATOR

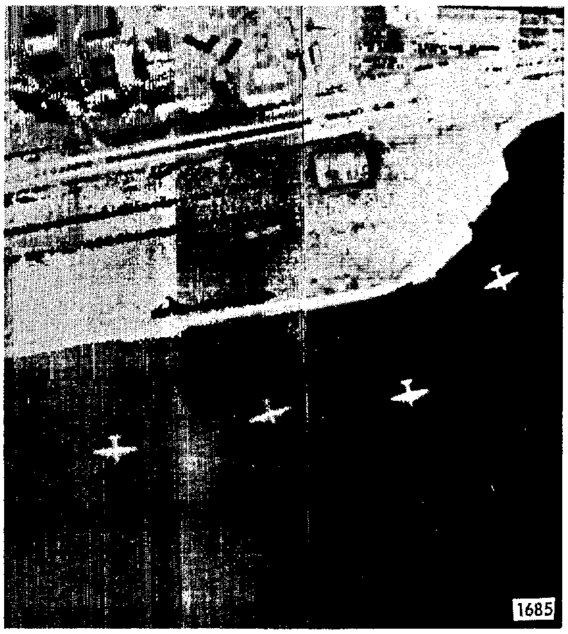

Figure 4 ILLUSTRATION OF DIGITALLY STORED PHOTOGRAPHIC INFORMATION

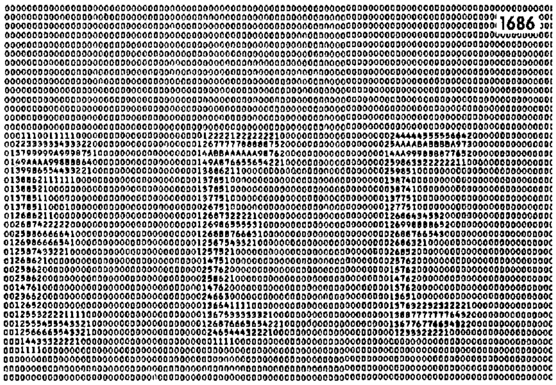

Figure 5 NUMERICAL PRINT-OUT OF PHOTOGRAPHIC DATA

Figure 6a ORIGINAL PHOTOGRAPH

Figure 6b PROCESSED PHOTOGRAPH AFTER OBJECT DETECTION AND LOW-PASS FILTERING

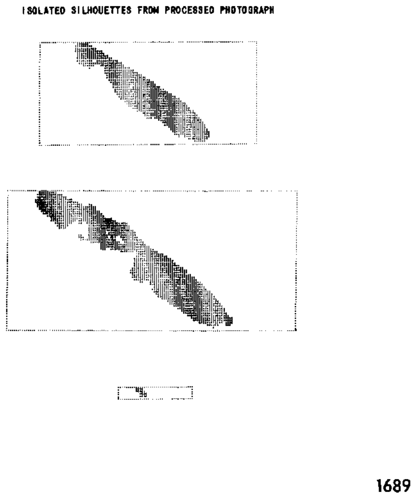

Figure 6c ISOLATED SILHOUETTES FROM PROCESSED PHOTOGRAPH

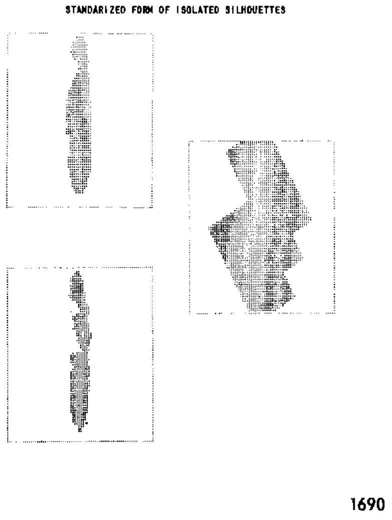

Figure 6d STANDARDIZED FORM OF ISOLATED SILHOUETTES

Actually the approach one uses for this type of research is as much a matter of preference and background as necessity of or even advantage. Laboratories staffed with experimentally oriented personnel, well versed in filter and active circuit design, may not observe any advantage in the flexibility afforded by general purpose computers. Nevertheless, we cannot ignore the fact that very flexible filter programs for general purpose machines can be prepared and almost any experimental operation which can be performed on a speech record could be as readily performed within a general purpose computer.

An input system for speech research purposes could be limited in performance to cover only the frequency bands known to be needed for recognition of spoken words by humans, but to so limit the system might undesirably inhibit research. Thus the system described here, in use at the Cornell Aeronautical Laboratory, covers a sampling rate up to 27000/second and employs much of the same circuitry developed for the photo input system. In regard to Figure 7 one can see that the input buffer section is similar except that the full eleven bit capacity of the A/D converter is used, thus affording 1/2% least count for the system. The control unit accomplishes the same functions as in the photo input system with added circuitry to provide one additional control line to the computer in the form of an end of record signal. Both of these features enhance the flexibility of the system by allowing complete control by computer program. For example, the computer program can specify the number of bits desired in a particular application to match the accuracy of the analog data presented. The end of record pulse serves the function of segmenting the data in convenient blocks for subsequent manipulation within the computer.

Performance of this system is intimately related to the processing program desired for the data reduction. The converter has a conversion rate of 44,000 samples/second, but when applied to an IBM 704 computer using fixed program logic and no word packing, a resulting read-in rate of 27,777 samples/second is obtained. Adding dynamic program logic reduces the input rate to 16,667 samples/second. As a consequence of finite core storage and inadequate time for transfer to tape during a run, lengths of coherent records are limited unless word packing is employed. Packing the 11-bit information in the 36-bit word length in order to extend run length further reduces the input data rate to approximately 6,000 samples/second.

One of the first applications of this equipment was in connection with the investigation of radar video. Here the objective was to improve experimental measurements by long term integration. The video signal was recorded on a suitable magnetic recorder together with a trigger pulse and range marker pulses on separate tracks. The

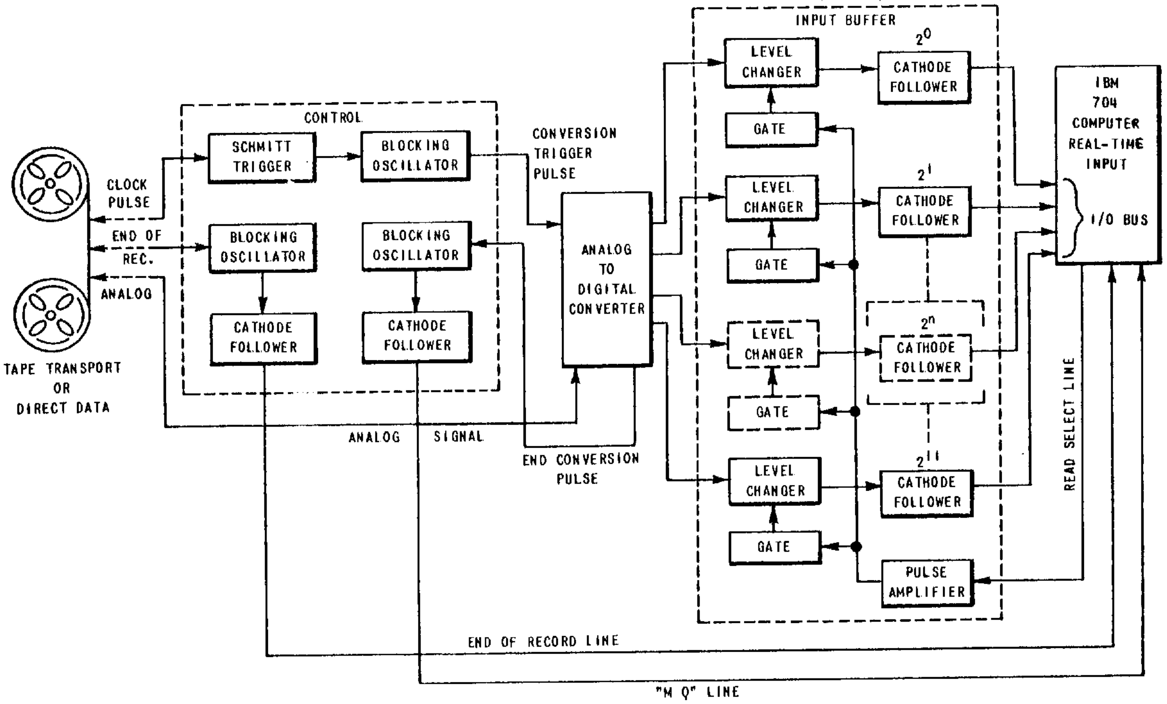

Figure 7 BLOCK DIAGRAM OF GENERAL PURPOSE ANALOG INPUT

signal then was played back at reduced speed and fed to the input of the general purpose input system. The trigger pulse served as the end of file input while the range marker pulses served as clock pulses.

From the specifications on the system, it is clearly compatible with speech recognition and bandwidth compression requirements.

Thus, we see the outlines of approaches to the solutions to broad areas of information processing research. This equipment has been found not only to facilitate the special research for which it was designed, automatic photointerpretation, and radar information studies, but also to have a broader application to research problems of the two generic classes listed at the outset.

MASS DATA REDUCTION

Wind tunnels have provided one of the earliest forces toward mass data reduction by digital computers. Digital recording systems have been employed in the Cornell Aeronautical Laboratory's variable density tunnel since its inception in the 1942-45 era. A large number of parameters are measured very accurately; equations governing data reduction are complex; and timely results for examination in the course of a sequence of runs is of great economic advantage. Although on the surface these factors might suggest an on-line operation with direct electrical connection of the sensors into the computer, the Cornell Aeronautical Laboratory found the use of punched card buffer store to be satisfactory and more economical. The notion of having experiments funneling data into the real-time bus of a computer for processing and display of instant results at the experimental site has a certain appeal to the showman in us, but can rarely be justified. Most input-output systems for mass data reduction will incorporate some form of buffer storage.

Choice of buffer stores is part of the input-output design problem. Experience with strip chart recorders - the principal buffer store during the past two decades - predicts that computer input systems will be required to provide compatible buffer stores over a frequency spectrum of at least 0 to 5000 cycles per channel, with channel capacities ranging from two to ten.

Experience at the Cornell Aeronautical Laboratory with research problems ranging from aircraft control problems to measurement of three-dimensional radar cross-section profiles, has demonstrated a clear, high-volume research requirement for a digital buffer store to handle an information rate of up to 200 bits per second. The basic system, using punched perforated tape, is sufficiently flexible to permit selection of the number of channels and dynamic range to be employed. Clearly, given a basic information rate, trade-off among (1) numbers of channels, (2) maximum frequency to be recorded, and (3) dynamic range required, are governed by the relation

$$R = \frac{1}{2} \sum_{j=1}^{n} f_j \log_2 \frac{M_j}{L_j}$$

where R = information rate in bits per second
n = number of channels
f_j = maximum frequency of jth channel in cycles per second
M_j = maximum level of jth channel
L_j = required least count of jth channel

This relation presumes, of course, a substantially noise-free system. Naturally one is faced with a compromise in deciding how much flexibility to provide in order to take maximum advantage of this relationship over a broad range of possible experimental requirements. We would not want to suggest that the system to be described (ANDIT) is an optimum compromise; in fact, second generation models have tended toward less flexibility.

ANDIT equipment (Figure 8) affords a buffer store with an information rate capability of approximately 200 bits per second. This compares with direct galvanometer recorders (14 bits/second per channel) and electronically-driven galvanometer recorders (700 bits/second per channel). Experience with strip chart recorders would suggest that two additional buffer stores capabilities, one with information rates in the region of 1,000 bits/second per channel, and the other with rates around 50,000 bits/second per channel would have utility for experimental research investigations. Naturally if one can accommodate both rates in a single economical system, that approach would be superior.

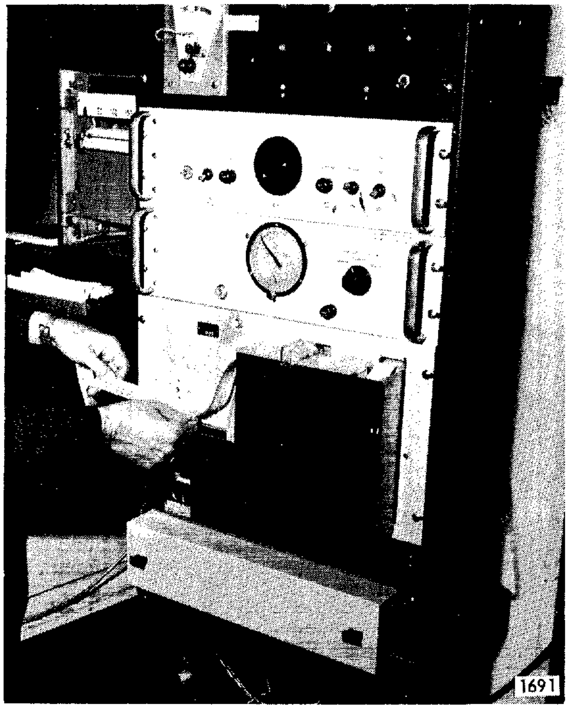

Figure 8 DIGITAL RECORDING EQUIPMENT

The ANDIT equipment characterizes an approach to buffer storage in which analog to digital conversion occurs prior to making the permanent record. This feature exhibits the advantage that channel multiplexing and therefore flexible employment of the available information rate is facilitated, but has the disadvantage for higher information rates that it places a more expensive piece of equipment at each experiment, thus raising the cost of mass data reduction to each experiment.

Another approach, that of using analog buffer stores, is characterized for precision records by magnetic tape instrumentation recorders. This approach has been explored commercially and instruments are available covering information rates up to approximately 200,000 bits/second per channel. These systems are more expensive than the strip charts which they would replace, but the added capital investment is more than offset by the elimination of costly manual conversion. When analog buffer stores are used, it is necessary to accompany those stores with a suitable analog-to-digital conversion facility at the general purpose computer. An example of such a system roughly compatible with requirements for analog buffer stores has already been discussed in connection with speech research interests. Clearly flexible record-playback speeds are desirable to match the conversion system effectively.

The issue of allowable record length impinges on both the buffer store and on design of analog-to-digital converter systems feeding directly into a main frame. Characteristically, as the information rate increases for a buffer store, the allowable coherent record length decreases. In the course of conversion, analog-to-digital, for injection into the computer, a similar limitation is encountered. Whenever the information rate is sufficiently great that transfer to tape is not possible in the course of data breaks, the core storage of the computer eventually is exceeded and conversion must be discontinued until transfer to tape can be effected. Naturally, this operation produces data discontinuities unless techniques are employed to ensure coherence from one record to the next. So far, the Laboratory has not in its research encountered this problem to the extent that special techniques needed to be created.

Analog-to-digital converter systems for use in mass data reduction do not constitute an unusually sophisticated design problem. Converters with speeds acceptable for this service are available and can usually be adapted for coupling to the real-time input bus of a general purpose machine. The system described under speech recognition input systems is characteristic of such a device.

High speed printers and x-y plotters are obviously still effective output systems for research purposes. In this discussion, we are interested only in new approaches to display of data which may afford solutions to some of the more recent research problems being undertaken, and will not touch on advances in printer speed or plotter facility per se.

For example, this Laboratory has constructed for its research purposes an output system which permits plotting the time-varying results of computer reduced data on a high-speed photographic-trace oscillograph, and this kind of a facility is characteristic of the special-purpose output systems we are interested in discussing in this paper.

At present, we have partially completed the design of a photographic output system for use in conjunction with the photographic input system already described. Such a capability is important if one is attempting to design two-dimensional spatial filters. Thus, the research worker is able to assess easily the results of a filtering operation on a given piece of input material.

We expect, however, that this output system may have broader application than to studies in automatic photointerpretation and pattern recognition. For example, it affords the interesting opportunity to read-out computed curve plots in conjunction with a graphical format which was read into the machine through the photographic input. Thus, for example, a research worker could insert a log-log or polar or other graphical record format into the machine, complete with titles, ordinates, and perhaps even the symbols to be used by plotting each of several curves, and having stored this format on tape, and generated the curve points with a computational program, read-out the composite result of both these processes through the photo output system. He is thus able to produce a complete graphical picture of the desired results. Such a picture would be entirely suitable for reproduction in reports or slides, and thus would facilitate a more economic reporting process. The potential for presenting numerical information in three dimensions, X, Y and density, should find increased application to report and documentation efforts. Imaginative employment of this technique of compositing graphical data derived from philosophically different sources may very well lead to some unusual research techniques, unforeseen at present.

CONCLUSIONS

Evidence points to a well-established requirement for pictorial input-output systems for modern research in pattern recognition, signal processing, and data reduction. Means for entering computers with time-varying data up to 20 kc for speech recognition and related research is an additional requirement. Such a system may at the same time serve the purposes for mass reduction of data gathered by analog buffer stores in the 1,000 bit/second and above classes. Perforated-paper-tape buffer-store input systems afford an economical input medium responsive to experimental needs which formerly were handled by ink-pen trace strip charts. This same perforated tape format can, if designed for sufficient flexibility, invade an area of recording formerly handled by electronically driven galvanometer recorders. The principal merit of the perforated tape system is low cost equipment at the experiment site, ease of editing data before entry to the computer, and a reasonable degree of facility for injection of the data into the general purpose computer. Moves toward higher and higher perforated paper tape recording speeds may entirely satisfy the needs currently being handled by electronically driven galvanometer strip charts. However, systems (possibly analog instrumentation recorders) making available information rates in excess of 60,000 bits/second per channel will be required for specialized experiments unless analog-to-digital conversion coupled with digital buffer stores of sufficient information rates can compete economically. If the latter becomes feasible, compatible format magnetic tape records would be a desirable feature.

Photo Input/Output systems offer a potential for information compositing (curve-on-chart) as yet unexplored.

ACKNOWLEDGEMENTS

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TWO-DIMENSIONAL SPATIAL FILTERING AND COMPUTERS

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ABSTRACT

Processing of two-dimensional signals has important applications, for example, in photographic image analysis, but when the weighting function of a two-dimensional linear filter extends over a large area, e.g., smoothing filters, digital realization via a two-dimensional convolution is prohibitively time consuming, and analog realization is extremely difficult. The principal purpose of this paper is to show how a broad and useful class of two-dimensional filtering operations can have notably shortened execution time in the digital case, and be put into a particularly convenient form for electrical filtering. The procedure includes a reduction of dimension from two to one; transformation of two-sided (weighting function extends into both past and future) operations into one-sided (physically realizable) operations; and finally, for the digital case, the transformation of a direct many-term convolution expression into a compact recursive form ideally suited for digital computation. An important class of smoothing filters, with weighting functions approximately Gaussian, is derived and used for illustration. The result is a several-order-of-magnitude reduction in time for digital two-dimensional filters, and some interesting results applicable to one-dimensional zero-phase-shift filters.

I. INTRODUCTION

Analog or digital processing of two-dimensional signals has many important applications, notably in photographic image analysis for military or commercial purposes. Much of this type of processing is special purpose, tailored to the physically significant details within an image. But there are certain basic operations (e.g. high and low-pass filtering) that are extensions of corresponding one-dimensional operations, and which have a similar range of usefulness.

Because in two-dimensional processing by digital means, or by means of electrical filters, storage and processing time requirements are much greater[1] than for one dimension, there is a genuine need for nontrivial methods to alleviate time and storage problems. This need is greatest when each computed point in the output image is affected by values from a relatively large area of the original or input image. Such filters, called area filters, are exemplified by many smoothing operations; they form the principal topic of this paper. In contrast to the area filter is the local filter, in which the value of an output image point depends only upon a small neighborhood of the corresponding input image point.

II. THE DIRECT CONVOLUTION APPROACH

The direct approach to realization of an arbitrary filter operating on a two-dimensional input is explicit convolution of the impulse response of the filter with the input. In the digital case this takes the form:

$$y_{m,n} = \sum_{i=-I}^{I} \sum_{j=-J}^{J} h_{ij}\, x_{m-i,\, n-j} \quad , \qquad (1)$$

where subscripts on y (output) and x (input) give the digitized coordinates of the image point, and h_{ij} is the discrete two-dimensional impulse response or weighting function.

In the case of a local filter the number of terms in this expression is small, and the method

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[1] An exception is the optical filter, not considered in this paper.

is practical and often useful. For example, Kovasznay and Joseph (Ref. 1) describe an interesting analog equivalent to (1) used for outline enhancement. David (Ref. 2) reports a digital application of linear and nonlinear local operations for noise reduction.

In the case of an area filter, the large number of terms (121, for example, if $I = J = 5$) required for each output point makes this approach impractical.

III. THE SIMPLIFICATION STEPS

Equation (1) of the direct method is the starting point for a number of drastic simplifications. The goal is a set of one-dimensional filters, of simple recursive form for digital computation, and of physically realizable form for analog use. The simplification steps are:

(a) Restriction of the weighting function h_{ij} or $h(t_1, t_2)$ to a product form $f_i g_j$ or $f(t_1) g(t_2)$; this special form allows the two-dimensional problem to be decomposed into two one-dimensional problems.

(b) Transformation of the one-dimension filtering operation, which has an impulse response extending into both positive and negative time values, with two filtering operations of the "physically realizable" form, in which output depends upon the "past" (impulse response vanishes for negative argument).

(c) In the digital case, conversion of the one-dimensional filter into a recursive form so that only very few terms appear in the computation of an output value, even though the effective memory extends far into the past.

These items are discussed in the following four sections.

IV. REDUCTION OF DIMENSIONALITY

The first major simplification of (1) is the reduction in dimensionality from two to one, by restricting (with some loss of generality) the weighting function of two variables to be of product form

$$h_{ij} = f_i g_j \text{ (discrete) or}$$
$$h(t_1, t_2) = f(t_1)\, g(t_2) \quad \text{(continuous)}$$

Then the complete double summation of (1) may be replaced by two sets of calculations, each only having a single sum; omitting details, and again writing only the digital equations, we have:

$$\hat{y}_{m,r} = \sum_i f_i \, x_{m-i,r} \qquad (2)$$

$$y_{m,n} = \sum_r g_r \, \hat{y}_{m,n-r} \qquad (3)$$

Here, $\hat{y}_{m,r}$ is an intermediate result, computed from the x's, then regarded as input variable for final computation of the desired $y_{m,n}$ values. The first computation (2) is (for any fixed r) an ordinary one-dimensional filter, operating on one horizontal[2] line of the image; the parameter r identifies which line. Similarly, the second computation (3) is, for any fixed m, an ordinary one-dimensional filter, operating on a vertical line[2] of the y image; the parameter m identifies which vertical line.

To illustrate the general effect in terms of saving computing time, suppose that a 100 x 100 grid of picture intensity values is to be filtered, and assume that the weighting function of (1) extends 10 terms in each of the possible directions ($I = J = 10$). With edge effects ignored, the application of (1) directly would require 21 x 21 = 441 operations (an operation consisting of a multiplication and addition) for each processed point, for a total number of 4,410,000 operations. The corresponding double application of one-dimensional filters, according to (2) and (3), would require 21 + 21 = 42 operations per processed point, for a total number of 420,000 operations -- less than 1/10 as many.

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[2] We arbitrarily identify horizontal lines with fixed second subscript, varying first subscript, and vertical lines with contrary conditions, in analogy with the continuous form $x(t_1, t_2)$, where the first variable normally gives the abscissa value and the second gives the ordinate value.

V. SIMPLIFICATION OF THE ONE-DIMENSIONAL FILTERS

The following approach towards simplifying the one-dimensional filters of (2) and (3) gives results definitely useful in originally one-dimensional filtering problems, as well as in the present context as intermediate aids for two-dimensional filtering.

It is convenient to drop the redundant double subscript, and begin with the generic form (open-loop, double-sided) form that is implied by (2), (3) and the preceding discussion:

$$y_n = \sum_{k=-K}^{K} h_k x_{n-k} \qquad \text{(discrete)}$$
$$y(t) = \int_{-\infty}^{+\infty} h(\tau)\, x(t-\tau)\, d\tau \qquad \text{(continuous)}, \qquad (4)$$

and it is convenient to regard a subscript as a time value (e.g., y_n is the value of y at the quantized time value n).

Equation (4) could be used in its existing form for digital computation. But for the case where the number of terms is large, there is a more efficient method most conveniently derived by orienting our terminology towards the continuous-time situation, so that we can simultaneously develop a method suited to electrical filtering and of a form that can be converted to an efficient recursive digital filter.

Write $h(\tau) = h_+(\tau) + h_-(\tau)$, where h_+ vanishes for negative time, and h_- vanishes for positive time. The h_+ part could be the impulse response of a realizable filter, assumed to have rational transfer function $F_1(s)$ with its poles in the left half plane. The h_- part may be achieved with a realizable filter by reversing the time variable, for example, by storing the input on magnetic tape, then playing the tape backwards. A reversed-time signal passed through a realizable filter with transfer function $F_2(s)$, gives a result that is formally equivalent (in the sense of a bilateral Laplace transform) to passing the original forward-time signal through a filter with transfer function $F_2(-s)$. Thus we may speak of filters with poles in the right half plane, with the understanding that they refer to a physically realizable filter driven by a time-reversed version of an input signal.

Thus, if the original picture is processed with filter having transfer function $F_1(s)$, then the original picture is filtered independently with filter having transfer function $F_2(-s)$ (actually accomplished by running the input signal backwards through a filter with transfer function $F_2(s)$), and the results are added, the resultant impulse response will be desired $h_+ + h_-$, and the total effective transfer function will be

$$G(s) = F_1(s) + F_2(-s)$$

The rational functions $F_1(s)$ and $F_2(-s)$ may be combined into a single multiplicative expression, of the form

$$G(s) = G_1(s)\, G_2(s)$$

where G_1 contains all of the poles in the left half plane and G_2 contains all of the poles in the right half plane. Thus, we have a cascade form: rather than filter the original picture twice and add results, as in the previous paragraph, one could filter the original picture with G_1 , then filter that result with G_2 . In the digital case, the latter has the advantage of eliminating the need for duplicate storage space, by means which, if not obvious, are simple. For analog filtering the cascade form is more convenient and avoids various practical synchronization difficulties.

VI. DIGITAL ONE-SIDED RECURSION FILTERS

An open-loop one-sided digital filter has the form

$$y_n = h_0 x_n + h_1 x_{n-1} + h_2 x_{n-2} + \cdots,$$

the expression possibly being infinite in extent. "Open-loop" refers to the fact that y is expressed only in terms of x's (inputs); "one-sided" refers to the fact that only present (time n) and past values of input are used to determine output. For example, the one-sided open-loop digital filter corresponding to an exponential impulse response (simple RC lag filter) is

$$y_n = x_n + \alpha x_{n-1} + \alpha^2 x_{n-2} + \alpha^3 x_{n-3} + \cdots. \qquad (5)$$

If, as in this example, the number of terms is infinite, then digital computation can be performed only by approximating with a finite number of terms. But if α in the expression above is fairly close to unity, (e.g., 0.99), it is possible that several hundreds of terms would be required for satisfactory approximation.

A one-sided feedback digital filter equivalent to (5) has the form

$$y_n = \alpha y_{n-1} + x_n \qquad (6)$$

where α is the same one as in (5). This form is of course particularly suited to digital computation, since it contains only two terms. "Feedback filter" here refers to the fact that output depends explicitly on prior output, as well as the x input; this type of filter is also commonly called a recursive (or recursion) filter.

VII. RECURSION FORMULAS FROM TRANSFER FUNCTIONS

The general problem of converting a transfer function (such as our $F_1(s)$, if additive form is used, or $G_1(s)$ if cascade form is used) into a digital recursion relationship is easily solved by means of a method presented at the 1961 NEC (Ref. 3, 4), which is described here only in necessarily very sketchy form. In the expression for a transfer function $G(s)$, make the substitution $s \rightarrow \frac{2}{T}\,\frac{1-z}{1+z}$, clear of extraneous fractional forms and normalize numerator and denominator into the following form:

$$G \rightarrow \frac{a_0 + a_1 z + a_2 z^2 + \cdots + a_m z^m}{1 + b_1 z + b_2 z^2 + \cdots + b_r z^r} \qquad (7)$$

(z can be interpreted as the delay operator, with Laplace transform e^{-sT}).

Then the recursion formula becomes

$$\begin{aligned} y_n = {} & a_0 x_n + a_1 x_{n-1} + \cdots + a_m x_{n-m} \\ & - b_1 y_{n-1} - b_2 y_{n-2} - \cdots - b_r y_{n-r} \, . \end{aligned} \qquad (8)$$

The quantity T is a time scaling parameter; in this application, it relates the time variable of the Laplace transform to the separation between adjacent sample values.

To illustrate, we use a transfer function that will later be used to illustrate another aspect of the two-dimensional filtering problem;

$$G(s) = \frac{2\sqrt{3}}{s^2 + 3s + 2}$$

The impulse response has time constants of the order of one second in real time. Suppose we desire that over one of these time constants there would be 10 picture elements (in a rough sense, the memory covers ten picture elements, if memory is taken to be a nominal time constant). Then $T = 0.1$. Use of the substitution described above gives for the final recursion formula:

$$y_n = 0.00849\,(x_n + 2x_{n-1} + x_{n-2}) + 1.951\,y_{n-1} - 0.9106\,y_{n-2}$$

VIII. ILLUSTRATIVE EXAMPLE

In many two-dimensional filtering applications, it is desired to have an impulse response that is circularly symmetrical. The purpose of this section is to show how one class of such impulse responses can be approximately realized with the multiple application of one-dimensional filters as described above.

Circular symmetry requires that the filter impulse response h be a function of $t_1^2 + t_2^2$. Thus the one-dimensional filter $g(t)$ which is to be applied in each direction must be chosen such that

$$\begin{aligned} & h(t_1, t_2) = g(t_1^2)\,g(t_2^2) \\ & \text{with } g(t_1^2)\,g(t_2^2) = g(t_1^2 + t_2^2) \, . \end{aligned} \qquad (9)$$

A solution of this functional equation is

$$g(t) = e^{-t^2} \qquad (10)$$

In accordance with the previously prescribed procedure, we now attempt to find a one-sided, one-dimensional filter whose impulse response is

$$\begin{aligned} f(t) &= e^{-t^2} & t > 0 \\ &= 0 & t < 0 \end{aligned} \qquad (11)$$

There is no filter whose Laplace transform is a rational function of s which has the impulse response (11). However, there is a class of filters with transfer functions rational in s, and with impulse responses approximately (11) in the vicinity of $t = 0$. These can be found by expanding (11) in a Taylor series about the origin, transforming the result, and equating the coefficient to the large s expansion of a rational function. Thus, for

$$f(t) = 1 - t^2 + \frac{t^4}{2} - \frac{t^6}{6} + \cdots \text{ as } t \to 0 \qquad (12)$$

we want

$$F(s) \sim \frac{1}{s} - \frac{2}{s^3} + \frac{12}{s^5} - \frac{120}{s^7} + \cdots \text{ as } s \to \infty \qquad (13)$$

The first few of a family of approximations to (13) are:

$$F_3(s) = \frac{s + a}{s^2 + as + 2}$$

$$F_5(s) = \frac{s^2 + as + 4}{s^3 + as^2 + 6s + 2a}$$

$$F_7(s) = \frac{s^3 + as^2 + 10s + 4a}{s^4 + as^3 + 12s^2 + 6as + 12}$$

Here $F_n(s)$ is an approximation to (13) good through terms in s^{-n}. All of the transfer functions are stable for any positive value of the parameter a. A numerical example of the two-dimensional filter related to $F_3(s)$ with $a = 3$ has been worked out. The results are presented as contours of constant impulse response in Fig. 1. Note that in the vicinity of the origin the contours are approximately circular, as predicted. Two cross sections of the "impulse mountain" are shown in Fig. 2.

The example above can be continued to display explicitly the transfer function to be used for each separate filtering operation. The one-sided one-dimensional transfer function is

$$F(s) = \frac{s + 3}{s^2 + 3s + 2} \qquad (14)$$

The two-sided one-dimensional transfer function is then (in summation form)

$$\frac{s + 3}{s^2 + 3s + 2} + \frac{-s + 3}{s^2 - 3s + 2} .$$

We can combine the terms to obtain

$$\frac{12}{(s^2 + 3s + 2)(s^2 - 3s + 2)} = \frac{\sqrt{12}}{s^2 + 3s + 2} \cdot \frac{\sqrt{12}}{s^2 - 3s + 2} .$$

It can thus be seen that the required transfer function to produce the two-dimensional impulse response of Fig. 1 is $\frac{\sqrt{12}}{s^2 + 3s + 2}$. This transfer function is used for four cascaded filtering operations: positive t_1 direction, negative t_1 direction, positive t_2 direction, negative t_2 direction.

Examination of the two-sided transfer function shows that this filter has a high frequency attenuation of 24 db per octave and no phase shift at any frequency.

IX. CONCLUSION

When a two-dimensional image is to be processed with a filter for which the response at an output point depends upon a large region of the input image, the methods of this paper find their principal utility. When the methods are applicable, there is a potential for decreasing execution time by several orders of magnitude in the digital case, or for putting the processing steps into a form suited for physically realizable filters in the analog case.

These simplifications are achieved by (a) restricting the two-dimensional impulse response to the product of two one-dimensional impulse responses -- a loss of generality that is satisfactory in many practical applications if one judiciously chooses the proper one-dimensional functions -- and (b) simplifying the one-dimensional operations so that recursive filters may be used in digital computation, and ordinary electrical filters may be used in the analog case. One of the important features is the time-reversal step, accomplished by routine programming (digital) or by using a reversible storage medium such as a tape recorder (analog). The time reversal permits impulse responses which are nonrealizable in the ordinary sense. In particular symmetrical impulse responses become possible.

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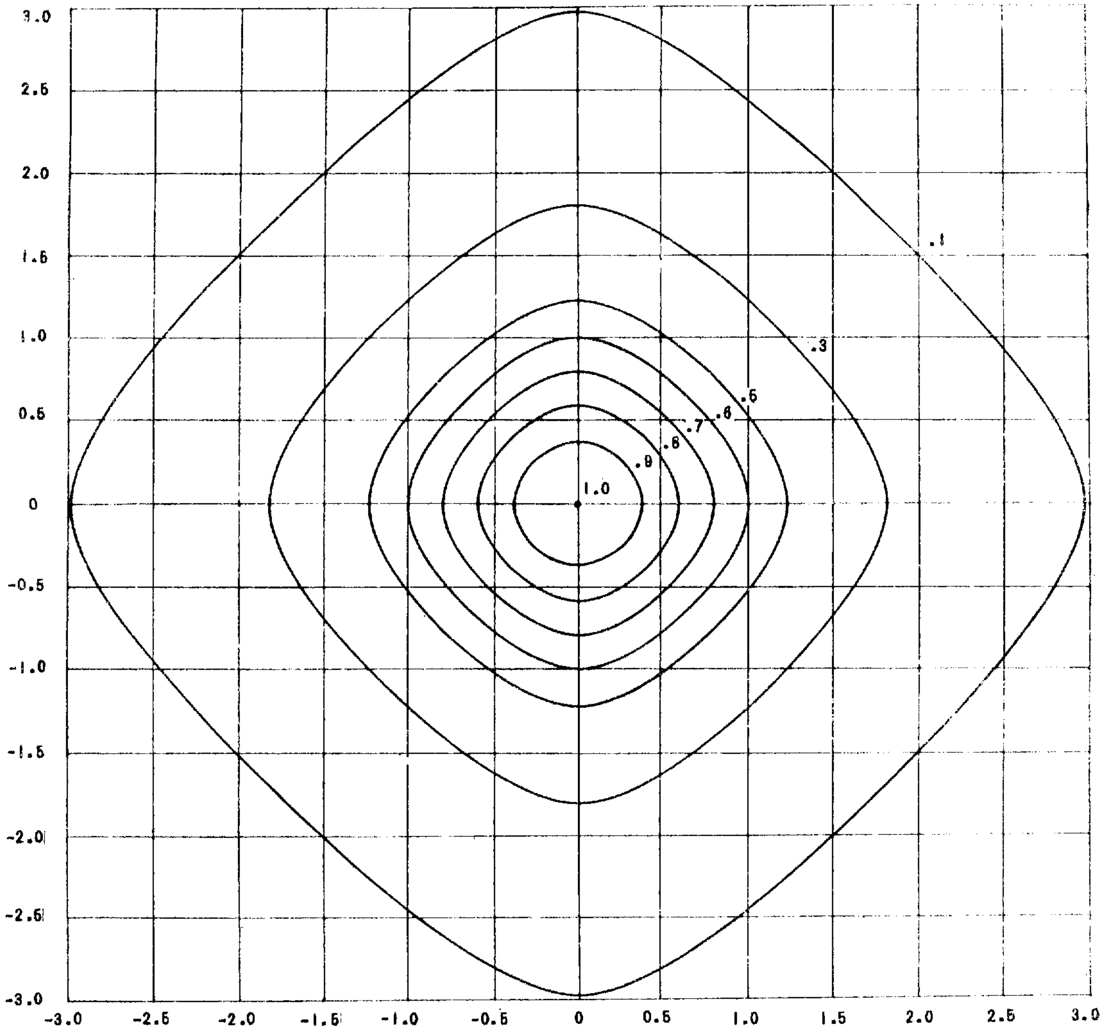

Figure 1 CONTOURS OF CONSTANT IMPULSE RESPONSE FOR THIRD ORDER APPROXIMATION TO GAUSSIAN FILTER

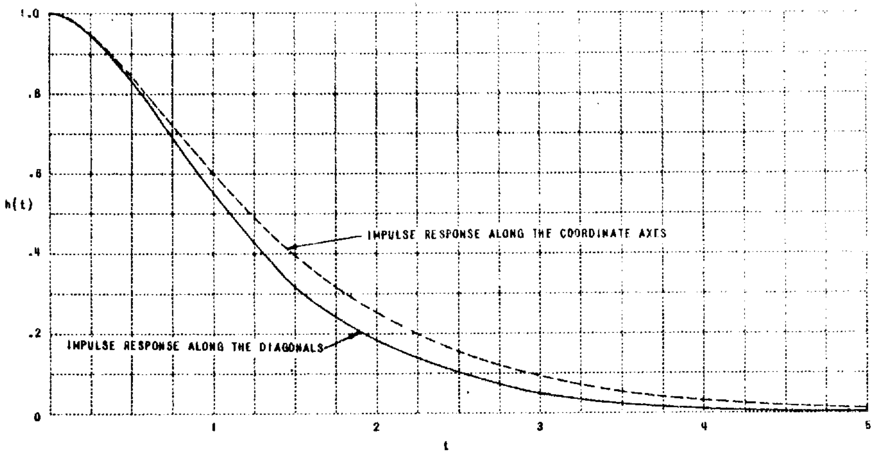

Figure 2 IMPULSE RESPONSE ALONG THE AXES AND DIAGONALS FOR THE SAME FILTER AS FIGURE 1

SYNTHESIS OF AN OPTIMAL SET OF RADAR TRACK-WHILE-SCAN SMOOTHING EQUATIONS

BY

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Synthesis of an Optimal Set of Radar Track-While-Scan Smoothing Equations[*]

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Summary—**Performance measures are described which realistically reflect both noise-reduction and maneuver-following capability of a radar track-while-scan (TWS) system. Illustrations are given which compare various smoothing equations on the basis of this performance measure. Finally, a set of position-and-velocity tracking equations is synthesized by a calculus-of-variations technique.**

The synthesized set is optimum for both position and velocity tracking within the given performance sense, in the class of all fixed parameter, linear tracking equations. The resulting optimally synthesized set characterizes the commonly termed "α-β" tracker, with the important proviso that

$$\beta = \alpha^2/(2-\alpha).$$

I. Introduction

In RADAR track-while-scan (TWS) systems (or digital pulse-to-pulse range or angle trackers) raw digitized position estimates must be processed to give 1) a smoothed present-position output; 2) a smoothed present-velocity output; and 3) a one-unit ahead predicted position for track-correlation or bin selection. If a system is designed well for outputs 1) and 2), good estimates for output 3) will be obtained.

In the design of these "sampled-data" trackers, one must compromise between the conflicting requirements of good noise-smoothing (heavy filtering, sluggish system, long time constant, or narrow bandwidth) and of good maneuver-following or transient capability (light filtering, fast system, short time constant, or wide bandwidth). Some compromise is always required. However, the smoothing equations should be constructed so as to give the "best" compromise. Once the form of equations or system topology is established, there should be only *one parameter* left free for the compromise. Further, for every value of that parameter, noise smoothing should be the maximum for a given transient capability, and vice-versa. It is asserted that some present-day systems do not satisfy this important requirement. This paper details the synthesis of equations satisfying this requirement. The equations are *a priori* freely selected from the entire class of fixed linear combinations of the past of the input.

II. Definitions and Nomenclature

For

x_n = raw input sampled-data position sequence, (1a)

$\bar{x}_n$ = system smoothed-position output sequence (1b)

is given by

$$\bar{x}_n = g_x(0)x_n + g_x(1)x_{n-1} + g_x(2)x_{n-2} + \cdots$$
$$= \sum_{k=0}^{\infty} g_x(k)x_{n-k} \qquad \text{(a convolution)} \tag{1c}$$

where

$g_x(k)$ = the position-to-position weighting sequence, or unit-impulse (Kronecker delta input) *response* of the system. (1d)

Alternatively, sampled-data systems can be characterized by a recursive or difference equation such as

$$\bar{x}_n = \gamma_1\bar{x}_{n-1} + \gamma_2\bar{x}_{n-2} + \cdots \gamma_N\bar{x}_{n-N} + \delta_0x_n + \delta_1x_{n-1} + \cdots \delta_Mx_{n-M}. \tag{2}$$

When such a recursive equation terminates, *i.e.*, $\gamma_k = 0$ for $k \geq N+1$, the equation is termed Nth order. One will then require at least N storage locations in a digital computer, or at least N delay lines in a recirculating delay-line digital system. It is important to note that for $N \geq 0$ the $g_x(k)$ sequence will usually not terminate.

The system smoothed-velocity output sequence $\bar{\dot{x}}_n$ can be given by

$$\bar{\dot{x}}_n = \sum_{k=0}^{\infty} g_{\dot{x}}(k)x_{n-k} \tag{3a}$$

where

$g_{\dot{x}}(k)$ = the input position to output velocity weighting sequence or unit-impulse response. (3b)

A difference equation for the velocity output could also be written. One can also combine the difference equations for position and velocity into a set of difference equations. For example, the common [2] "α-β" or "g-h" ($g=\alpha$ and $h=\beta$) equations become

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$$\bar{x}_n = x_{pn} + \alpha(x_n - x_{pn}) \tag{4a}$$

$$\bar{\dot{x}}_n = \bar{\dot{x}}_{n-1} + \frac{\beta}{T}(x_n - x_{pn}) \tag{4b}$$

$$x_{p_{n+1}} = \bar{x}_n + T\bar{\dot{x}}_n \tag{4c}$$

where

T = sampling period and
$x_{p_{n+1}}$ = predicted position at $n+1$ time index.

The set (4) is second order, as can be seen by writing them in terms of only one output variable.

In Z transform [3] one can characterize a sampled-data tracker by a multiplicative operation

$$\bar{X}(Z) = G_x(Z)X(Z) \tag{5}$$

and

$$\bar{\dot{X}}(Z) = G_{\dot{x}}(Z)X(Z) \tag{6}$$

where $Z = \epsilon^{j\omega T}$ is a forward time shift and the transforms for signals are given, for example, by

$$\bar{X}(Z) = \sum_{n=0}^{\infty} \bar{x}_n Z^{-n} \tag{7}$$

and for the system, for example, by

$$G_x(Z) = \sum_{n=0}^{\infty} g_x(n) Z^{-n}. \tag{8}$$

The inversion is given, for example, by

$$g_x(n) = \frac{1}{2\pi j} \oint_{\Gamma} G_x(Z) Z^{n-1} dZ. \tag{9}$$

The indicated contour of integration, Γ, is the unit-radius circle in the Z plane.

III. PERFORMANCE MEASURES

In order to assess properly the two attributes of noise reduction and transient performance, two measures are introduced; in every case their effects will be considered simultaneously.

For *noise smoothing*, the performance measures will be, for constant input variance, the variance reduction ratios

$$K_x(0) = \frac{\text{steady-state variance in position output}}{\text{variance in raw position input}}$$

$$K_{\dot{x}}(0) = \frac{\text{steady-state variance in velocity output}}{\text{variance in raw position input}}.$$

The notation $K_x(0)$ and $K_{\dot{x}}(0)$ is used to coincide with the definitions of $K_x(n)$ and $K_{\dot{x}}(n)$ the input-normalized autocorrelation sequences of the position and velocity outputs. $K_x(0)$ and $K_{\dot{x}}(0)$ are calculated (for uncorrelated scan-to-scan input noise) from the corresponding unit-impulse responses $g_x(n)$ and $g_{\dot{x}}(n)$ by the formulas[1]

$$K_x(0) = \sum_{n=0}^{\infty} g_x^2(n) \tag{10a}$$

$$K_{\dot{x}}(0) = \sum_{n=0}^{\infty} g_{\dot{x}}^2(n). \tag{10b}$$

For *transient* (maneuver-following) performance, the demerit figures will be [referring to (1)]

$$D_x^2 = \sum_{n=0}^{\infty} [(\text{unit-increment ramp}) - (\text{position ramp response})]^2$$
$$= \sum_{n=0}^{\infty} \left[n - \sum_{j=0}^{n} g_x(j)(n-j) \right]^2 \tag{11}$$

and

$$D_{\dot{x}}^2 = \sum_{n=0}^{\infty} [(\text{velocity of unit-increment ramp}) - (\text{velocity ramp response})]^2$$
$$= \sum_{n=0}^{\infty} \left[1 - \sum_{j=0}^{n} g_{\dot{x}}(j)(n-j) \right]^2. \tag{12}$$

Ramp-type test inputs of component position are selected because they are realistic for radar TWS operation on airplanes (sudden heading changes) and are also realistic for any sampled-data tracking start-up transients.

Meanwhile, consider the evaluation of arbitrary tracking systems on these performance bases. See Fig. 1. Here arbitrary tracking systems are compared. One seeks to design a system which is "close" to the origin. However, for Tracker A, as parameter p is increased so as to decrease D_x^2, $K_x(0)$ increases. Tracker B is clearly better than Tracker A in Region I; Tracker A is clearly superior in Region II. The optimum tracker by definition has a single-parameter locus where the

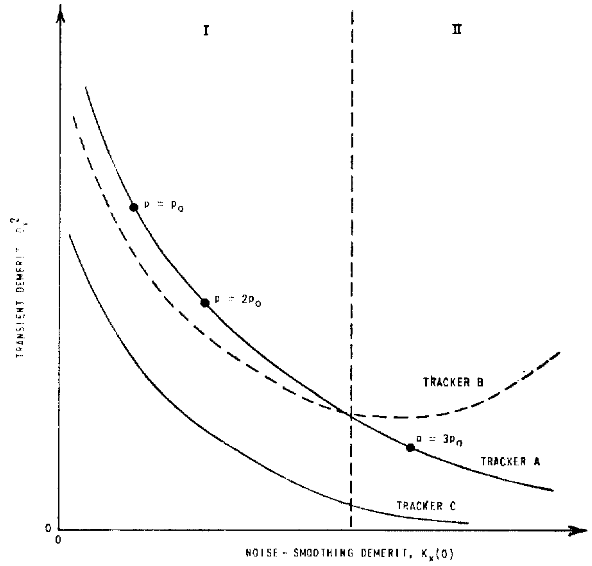

Fig. 1—Arbitrary system position performance.

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[1] See Appendix I.

ray from the origin is shortest everywhere. Such a tracker is illustrated by Tracker C on Fig. 1.

The equations derived in the next section will be optimal for position and velocity tracking simultaneously.

Some concrete examples are now given.

Example 1:

For the α-β tracker as listed in Section I, if one calculates the impulse response and thence the performance measures, he obtains Table I. Some parameter pairs (α, β) will be poor compromises. The pairs $(\alpha, \alpha^2/2-\alpha)$ were shown analytically to form the optimal locus for the (α, β) tracker in position *and* velocity. This analysis is performed by 1) assuming $K(0)$ a constant, then $dK=0$; 2) the value of α (or β) that minimizes D corresponding to the constant value of K is found by equating $dD/d\alpha$ to zero; and 3) solving $dK=0$ and $dD/d\alpha=0$ for β in terms of α. These loci are plotted on Fig. 2a and 2b.

TABLE I

PERFORMANCE MEASURES FOR THE α-β TRACKER

	Position Output	Velocity Output
Variance Reduction Ratio	$K_x(0)=\frac{2\alpha^2+\beta(2-3\alpha)}{\alpha[4-\beta-2\alpha]}$	$K_{\dot{x}}(0)=\frac{1}{T^2}\cdot\frac{2\beta^2}{\alpha[4-2\alpha-\beta]}$
Transient Performance	$D_{\dot{x}}^2=\frac{(2-\alpha)(1-\alpha)^2}{\alpha\beta[4-\beta-2\alpha]}$	$D^2=\frac{1}{T^2}\cdot\frac{\alpha^2(2-\alpha)+2\beta(1-\alpha)}{\alpha\beta[4-2\alpha-\beta]}$

Example 2:

A first-order (one pole, two zeros) tracker is given by

$$\overline{x_{n+1}} = c_0\bar{x}_n + c_1x_n + c_2x_{n-1} + c_3x_{n-2}. \tag{13}$$

For the conditions

$$c_0 + c_1 + c_2 + c_3 = 1 \text{ (unit dc gain)}$$

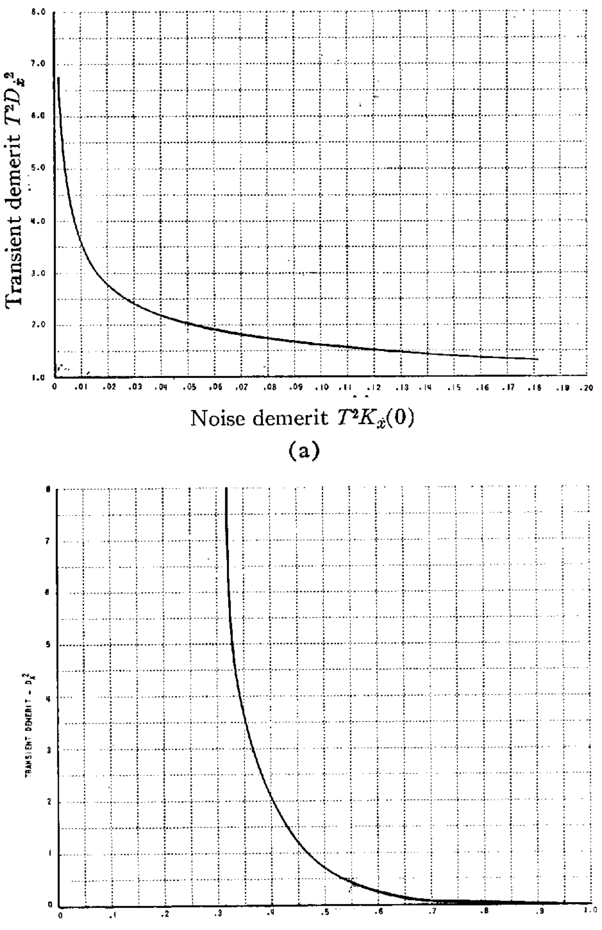
$$c_2 = 3 - 2c_0 - 2c_3 \text{ (zero steady-state ramp-following error)}$$

one has the measures

$$K_x(0)=\frac{13-15c_0+4c_0^2-2c_1(8-7c_0+c_0^2)+2c_1^2(3-c_0)}{1+c_0} \tag{14}$$

$$D_x^2=1+\frac{(2-c_1)^2}{1-c_0^2}\,. \tag{15}$$

These measures are plotted parametrically on Fig. 3. This tracker shows up everywhere worse than the optimal $(\beta=\alpha^2/2-\alpha)$ $\alpha-\beta$ tracker.[2]



(a)

(b)

Fig. 2—(a) Tracker velocity performance. (b) Tracker position performance.

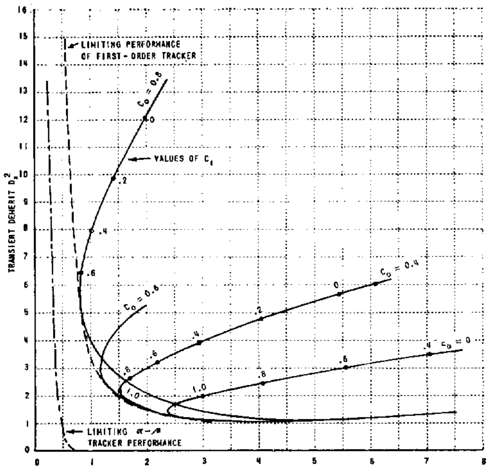


Fig. 3—First-order tracker position performance.

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[2] This judgment will be lessened in magnitude, but not reversed, if the first-order tracker used present input and present output.

IV. SYNTHESIS BY CALCULUS OF VARIATIONS

Suppose now that one wishes to find the optimal set of tracking equations. That is, it is desired to select perfectly freely the impulse responses $g_x(n)$ and $g_{\dot{x}}(n)$ so as to minimize D_x^2 for a given $K_x(0)$ and vice versa, and so as to minimize $D_{\dot{x}}^2$ for a given $K_{\dot{x}}(0)$ and vice versa.

Taking the velocity case for an example, one wishes to minimize

$$J = K_{\dot{x}}(0) + \lambda D_{\dot{x}}^2 \tag{16}$$

where λ is the Lagrangian multiplier (and the final single parameter).

Letting $r(n)$ be the optimal unit-increment ramp response, one has the double-difference identity[3]

$$g_{\dot{x}}(n) = r(n+1) - 2r(n) + r(n-1). \tag{17}$$

Then

$$J = \sum_{n=0}^{\infty} [\{r(n+1) - 2r(n) + r(n-1)\}^2 + \lambda\{1 - r(n)\}^2]. \tag{18}$$

Let the optimal $r(n)$ be perturbed by

$$r(n) \to r(n) + \epsilon h(n).$$

The number ϵ is a constant scalar; $h(n)$ is an arbitrary variation, but realizable in the sense that $h(n) = 0$ for $n \leq 0$. Then forming the equation

$$\left.\frac{\partial J[r(n) + \epsilon h(n)]}{\partial \epsilon}\right|_{\epsilon=0} = 0$$

gives

$$\sum_{n=0}^{\infty} \{[r(n+1) - 2r(n) + r(n-1)][h(n+1) - 2h(n) + h(n-1)] + \lambda[1 + r(n)][-h(n)]\} = 0. \tag{19}$$

Recordering the indices appropriately, and recalling that

$$\begin{aligned} r(n) &= 0 \qquad n \leq 0 \\ h(n) &= 0 \qquad n \leq 0, \end{aligned} \tag{20}$$

one obtains

$$\sum_{n=0}^{\infty} h(n)\{[r(n+2) - 4r(n+1) + 6r(n) - 4r(n-1) + r(n-2)] - \lambda[1 - r(n)]\} = 0. \tag{21}$$

Now since the left-hand side of (21) is zero for an arbitrary $h(n)$, one obtains the Euler equation

$$r(n+2) - 4r(n+1) + 6r(n) - 4r(n-1) + r(n-2) - \lambda[1 - r(n)] = 0. \tag{22}$$

Note that (22) holds only for $n > 0$ since the fact that $h(n) = 0$, $n \leq 0$ (realizability) insures the validity of (21) for $n \leq 0$. Now consider the function $f(n)$:

$$f(n) = r(n+2) - 4r(n+1) + 6r(n) - 4r(n-1) + r(n-2) - \lambda[1 - r(n)]. \tag{23}$$

The Z transform of $f(n)$ has poles only *outside or on* the unit circle (contour Γ) since $f(n) = 0$, $n > 0$. Taking the Z transform, one has

$$\begin{aligned} F(Z) &= \left[Z^2 - 4Z + 6 - \frac{4}{Z} + \frac{1}{Z^2}\right] R(Z) + \lambda R(Z) - \lambda \frac{Z}{Z-1} \\ &= \frac{(Z-1)^4 + \lambda Z^2}{Z^2} R(Z) - \frac{\lambda Z}{Z-1}. \end{aligned} \tag{24}$$

Since $f(n)$ for $n \to \infty$ tends to a constant (ramp response for velocity filter) $F(Z)$ has an isolated pole on Γ at $Z = 1$: therefore the function

$$Z^2(Z-1)F(Z) = (Z-1)[(Z-1)^4 + \lambda Z^2]R(Z) - \lambda Z^3 \tag{25}$$

has no poles inside or on Γ. But from (17) one has that the optimum impulse response Z transform

$$G_{\dot{x}}(Z) = \frac{(Z-1)^2}{Z} R(Z). \tag{26}$$

Hence (25) becomes

$$Z(Z-1)F(Z) = \frac{[(Z-1)^4 + \lambda Z^2]}{(Z-1)} G_{\dot{x}}(Z) - \lambda Z^2. \tag{27}$$

Note from (27) that $G_{\dot{x}}(0) = 0$, and also that $G_{\dot{x}}(1) = 0$ since the left-hand side of (27) has no poles on Γ.

Finally note from (27) that since the left-hand side has no poles inside or on Γ, that any realizable poles (on or inside Γ) of $G(Z)$ must *match* the zeros of the quartic

$$(Z-1)^4 + \lambda Z^2 = 0. \tag{28}$$

Now (28) has two pairs of roots

$$\begin{aligned} Z_{1,2} &= \frac{2 \pm j\lambda - \sqrt{-\lambda^2 \pm 4j\lambda}}{2} \quad \text{poles inside } \Gamma \\ Z_{3,4} &= \frac{2 \pm j\lambda + \sqrt{-\lambda^2 \pm 4j\lambda}}{2} \quad \text{poles outside } \Gamma. \end{aligned} \tag{29}$$

Thus

$$\begin{aligned} |Z_1| &= |Z_2| \leq 1 \\ |Z_3| &= |Z_4| \geq 1 \end{aligned}$$

for all $\lambda \geq 0$.

---

[3] See Appendix II.

Since $G(z)$ can then only possess two poles inside or on Γ, Z_1 and Z_2, it must be of the form

$$G_{\dot{x}}(Z) = \frac{\text{numerator}}{(Z - Z_1)(Z - Z_2)} \cdot \tag{30}$$

Since $G(0)=0$, one has that

$$G_{\dot{x}}(Z) = \frac{Z[\text{factor}]}{(Z - Z_1)(Z - Z_2)} \cdot \tag{31}$$

Since the unit-step response must decay to zero (or see 27), $G(1)=0$, and one has that

$$G_{\dot{x}}(Z) = \frac{AZ(Z - 1)}{(Z - Z_1)(Z - Z_2)} \cdot \tag{32}$$

The numerator must be of order two if present output velocities are to depend upon input values up to and including the present. Finally, one requires that

$$A = (1 - Z_1)(1 - Z_2) \tag{33}$$

in order that the steady-state response to a unit-increment ramp input be unity. Hence the optimum velocity tracker has the Z transform (allowing for sample time-interval T)

$$G_{\dot{x}}(Z) = \frac{1}{T}(1 - Z_1)(1 - Z_2)\frac{Z(Z - 1)}{(Z - Z_1)(Z - Z_2)} \cdot \tag{34}$$

In precisely similar fashion, one can establish the optimum position tracker Z transform

$$G_x(Z) = \frac{Z[(1 - Z_1Z_2)Z + (2Z_1Z_2 - Z_1 - Z_2)]}{(Z - Z_1)(Z - Z_2)} \cdot \tag{35}$$

Finally, if one finds the Z transforms for the $\alpha-\beta$ tracker of Section I, he gets

$$G_{\dot{x}}(Z) = \frac{\beta Z(Z - 1)}{Z^2 - (2 - \alpha - \beta)Z + (1 - \alpha)} \tag{36a}$$

and

$$G_x(Z) = \frac{Z[\alpha Z + (\beta - \alpha)]}{Z^2 - (2 - \alpha - \beta)Z + (1 - \alpha)} \cdot \tag{36b}$$

Note that the pole-zero structures of the optimum tracker and the $\alpha-\beta$ tracker are identical. Finally, the poles are made to match. The loci of poles for the optimal tracker (see 29) as λ is varied will be identical with the loci for the $\alpha-\beta$ tracker

$$Z_{1,2} = \frac{2 - \alpha - \beta \pm j\sqrt{4\beta - (\alpha - \beta)^2}}{2}, \tag{37}$$

if and only if $\beta=\alpha^2/(2-\alpha)$. (This is proved by setting (37) equal to the inside-Γ equation of (29) and eliminating λ.)

In conclusion, it has been proved that not only reducing the (α, β) parameter pair to $(\alpha, \alpha^2/2-\alpha)$ optimizes the α-β tracker, but also that this tracker is optimum over the entire class of all fixed-parameter linear sampled-data operators. The optimal TWS smoothing equation set is then:

$$\bar{x}_n = x_{pn} + \alpha(x_n - x_{pn}) \tag{38a}$$

$$\bar{\dot{x}}_n = \bar{\dot{x}}_{n-1} + \frac{\alpha^2}{(2 - \alpha)T}(x_n - x_{pn}) \tag{38b}$$

$$x_{pn+1} = \bar{x}_n + T\bar{\dot{x}}_n. \tag{38c}$$

This set is optimal for every value of the single parameter α.

V. Interpretations of the Result

The optimal set of TWS equations has been derived to be the "α-β tracker" with the proviso that $\beta=\alpha^2/2-\alpha$. This relationship ensures a certain degree of damping in the dynamical system; for all α, the system is slightly under-damped. Causing the α-β tracker to be critically damped ($\alpha=2\sqrt{\beta}-\beta\alpha$) will not degrade the performance significantly—only a few per cent larger rms noise output for fixed transient performance.

The method used here to derive the optimal set bears a resemblance to the Wiener-Hopf solution for optimal noise-filtering; the basic difference is in a constraint to fixed transient error. The calculus-of-variations approach and the pole-location solution to the Euler equation are similar. A pleasant aspect of this solution is that input S/N information is not required for the system synthesis.

The method used here can be extended to transient performance with regard to an nth power input test signal. If one were to use a quadratic test signal instead of a ramp, a third-order system would result; instead of solving the quartic

$$(Z - 1)^4 + \lambda Z^2 = 0$$

for the two inside-Γ pole locations, one solves the sextic

$$(Z - 1)^6 - \lambda Z^3 = 0$$

for the three inside-Γ pole locations (one real and two conjugate poles).

Finally, the result of this analysis indicates that optimal tracking can be performed with but a second-order recursion (say only three storage locations in a digital computer) and a minimum of arithmetic. There is no need for a search among obscure predictor-corrector schemes that might "better" performance.

This analysis does not specify the optimum value of the single remaining parameter α; this would be impossible. The choice of $\beta=\alpha^2/2-\alpha$ is essentially one of damping factor, which can be optimized. The remaining choice of α is one of bandwidth. Selection of an α value must depend upon the system application, where the *relative* importance of $K(0)$ and D^2 can be ascertained. For example, if the tracker is to be used for interceptor control, and other things being equal, collision-course vectoring would require a smaller α than pursuit vectoring.

CONCLUSIONS

Within the limits of the performance measures applied here, it is concluded that:

1) The optimal α-β tracker is obtained when $\beta=\alpha^2/2-\alpha$.
2) The optimal α-β tracker is the optimal linear fixed-parameter tracker.
3) For adaptive tracking [5] (variable time-constant) it is highly recommended that one construct an α-β tracker with $\beta=\alpha^2/2-\alpha$, and vary α with observed high-frequency power fluctuations of the error signal x_n-x_{pn}.

APPENDIX I

VARIANCE REDUCTION RATIO

For the entire class of linear trackers characterized by (1) or (3), the input f_k and output c_k are related by the convolution

$$c_k = \sum_{j=0}^{k} g(j)f(k-j).$$

Since the operation is linear, the output variance can be calculated by considering only the noise component of the input. Thus the normalized output autocorrelation becomes

$$\begin{aligned} K(n) &= \frac{E[c(k)c(k+n)]}{\sigma_f^2} \\ &= \frac{1}{\sigma_f^2}\sum_{j=0}^{k}\sum_{i=0}^{k+n} g_j g_i E[f(k-j)f(k+n-i)]. \end{aligned}$$

If the input noise sequence f_k has zero mean, is linearly independent scan-to-scan, has constant variance σ_f^2,

$$\begin{aligned} E[f(k-j)f(k+n-i)] &= \sigma_f^2 \qquad \text{when } i=j+n \\ &= 0 \qquad \text{when } i\neq j+n. \end{aligned}$$

Hence in the steady state,

$$K(n) = \sum_{j=0}^{\infty} g(j)g(j+n)$$

and

$$K(0) = \sum_{j=0}^{\infty} g^2(j).$$

APPENDIX II

RELATIONSHIP BETWEEN RAMP RESPONSE AND IMPULSE RESPONSE

For impulse response $g_{\dot{x}}(k)$, the ramp-response $r(n)$ is determined from the ramp input n by (3) in the form

$$r(n) = \sum_{k=0}^{n} g_{\dot{x}}(k)[n-k].$$

Consider the difference (delayed step response)

$$\begin{aligned} r(n) - r(n-1) \\ &= \sum_{k=0}^{n} g_{\dot{x}}(k)[n-k] - \sum_{k=0}^{n-1} g_{\dot{x}}(k)[n-1-k] \\ &= \sum_{k=0}^{n-1} g_{\dot{x}}(k)[n-k] + 0 - \sum_{k=0}^{n-1} g_{\dot{x}}(k)[n-1-k] \\ &= \sum_{k=0}^{n-1} g_{\dot{x}}(k). \end{aligned}$$

Similarly the double difference

$$\begin{aligned} [r(n+1) - r(n)] - [r(n) - r(n-1)] \\ &= r(n+1) - 2r(n) + r(n-1) \end{aligned}$$

becomes the impulse-response:

$$\begin{aligned} r(n+1) - 2r(n) + r(n-1) \\ &= \sum_{k=0}^{n+1} g_{\dot{x}}(k)[n+1-k] - 2\sum_{k=0}^{n} g_{\dot{x}}(k)[n-k] \\ &\quad + \sum_{k=0}^{n-1} g_{\dot{x}}(k)[n-1-k] \\ &= \sum_{k=0}^{n} g_{\dot{x}}(k)[n+1-k] - 2\sum_{k=0}^{n-1} g_{\dot{x}}(k)[n-k] \\ &\quad + \sum_{k=0}^{n-2} g_{\dot{x}}(k)[n-1-k] \\ &= \sum_{k=0}^{n-2} g_{\dot{x}}(k)[n+1-k-2n+2k+n-1-k] \\ &\quad + g_{\dot{x}}(n)[1] + g_{\dot{x}}(n-1)[2] - 2g_{\dot{x}}(n-1)[1] + 0 \\ &= 0 + g_{\dot{x}}(n). \end{aligned}$$

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APPLICATION OF PERCEPTRONS TO PHOTOINTERPRETATION

SUMMARY REPORT
REPORT NUMBER VE-1446-G-3
CONTRACT [redacted]
AUGUST 1963

25X1

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[redacted]

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INTRODUCTION

This paper summarizes the accomplishments of three phases of a continuing research program at the [redacted] that is directed towards 25X1 the development of techniques for automatic recognition of features in photographs. This research, which has been sponsored by the Geography Branch of the Office of Naval Research, places strong emphasis on the pre-processing of original imagery in order to require only a present state-of-the-art capability in automatic pattern 25X1 recognition. [redacted] efforts to date have generally confirmed the validity of the system philosophy being pursued, and have evaluated a number of techniques for accomplishing the various steps (object detection, object isolation, object standardization, and object recognition) in the automatic system. Volume quantities of actual photographic material have been processed within a general purpose digital computer for detection, isolation, and standardization. Excellent object recognition results have been obtained with a simple perceptron, using quite badly distorted synthesized object material.

Phase I: Objectives and Accomplishments

Research to investigate the feasibility of the application of perceptrons to automatic photo interpretation at [redacted] began in April 25X1 of 1960. This first phase of the program, which extended to November 1960, had as its principal objective a basic determination of feasibility of using perceptrons to automate the photo interpretation task. It was recognized that there was little likelihood of an early device to interpret photography in any complete sense, but there was considerably evidence to support the conjecture that simple objects, and even some complex objects, in aerial photographs might be isolated and classified automatically. Even if machinery produced in the near future could only perform rapidly a preliminary sorting to insure earlier attention to the most promising material, the development of such machinery might well be justified. In the Phase I program, there were two major accomplishments:

1. The Mark I perceptron (an early hardware model built at [redacted] was 25X1 used to demonstrate the capability of simple perceptrons to recognize militarily interesting target shapes. This work was reported in project reports as well as in the technical press ("Perceptron

Applications in Photo Interpretation," A.E. Murray, Photogrammetric Engineering, September 1961) and in the semi-technical press (Aviation Week, April 24, 1961).

2. A Mark II perceptron was designed. This machine was based on the use of magnetic drum and would have provided a capability for implementing a variety of simple and complex perceptrons. The Mark II machine was not constructed.

Phase II: Objectives and Accomplishments

Phase II work began in approximately April of 1961, and was - at an early stage - oriented toward the idea of implementing perceptron recognition systems within a general purpose digital computer for feasibility studies. This move would provide flexibility so that a variety of systems or system components could be tested. Use of the general purpose computer in this role called for the construction of a photo input capability, and providing this input system was one Phase II objective.

Perhaps the most significant objective of Phase II was one not specifically emphasized in the proposal for that work, but one whose important role quickly became apparent - the need to determine an overall system with which to work in developing a perceptron based photo interpretation device. While it is conceptually possible to simply present aerial photos, in essentially their raw form, to a very large perceptron for training and, later, for object recognition, it was obvious at this stage that such a direct approach would require prohibitively large perceptrons and similarly long training procedures. Thus, a major objective of Phase II became the development of a system which did not require such large machinery and great amount of training but which capitalized on the well-demonstrated pattern recognition ability in perceptrons of modest size.

Phase II was thus partly characterized by important evolutions in objectives. It was, even more importantly, characterized b very significant accomplishments. These accomplishments will be summarized a little later on, but the manner in which the objectives were pursued and fulfilled is important enough to warrant some detailed development at this point.

System Philosophy and Block Diagram

Of the many system philosophies considered during the early parts of the Phase II program, that one shown in Figure 1 seemed simultaneously to capitalize best on current pattern recognition capability and to meet the immediate and final project objectives in a realistic fashion. The two principal operations are called pre-processing and object recognition. An immediate and natural consequence of the selection of this system as a framework with which to work was that much of the Phase II effort was concentrated on the pre-processing operations, simply because these were the ones which no one knew how to accomplish.

Pre-processing Operations

Detection, isolation, and standardization are the three major pre-processing operations. They are illustrated as sequentially performed on the same simple photo in Figure 2.

Detection should produce a black-on-white version of the original photo in which ideally all objects of interest appear as black objects on a white background. In this binary or black-on-white image, the spatial relations of the original photo are maintained and the size and shape of the objects detected should not be changed. (In Figure 2, there is some size change, but this is simply a minor error in preparing the illustration). The detection processes (we have investigated several) must differentiate between objects and their background relying on:

a. difference in contrast (or reflection coefficient) between objects and their backgrounds,

b. textual differences between objects and their backgrounds, or

c. the existence of edges outlining objects.

It is particularly important to note that the detection is occurring before any attempt at object recognition is made, thus detection process cannot rely on knowledge of object shape; it must be shape independent but shape preserving. The detection process is the most difficult part of the pre-processing. It will certainly detect, with the result that they will be presented for recognition and must be rejected, many non-objects or objects of no interest.

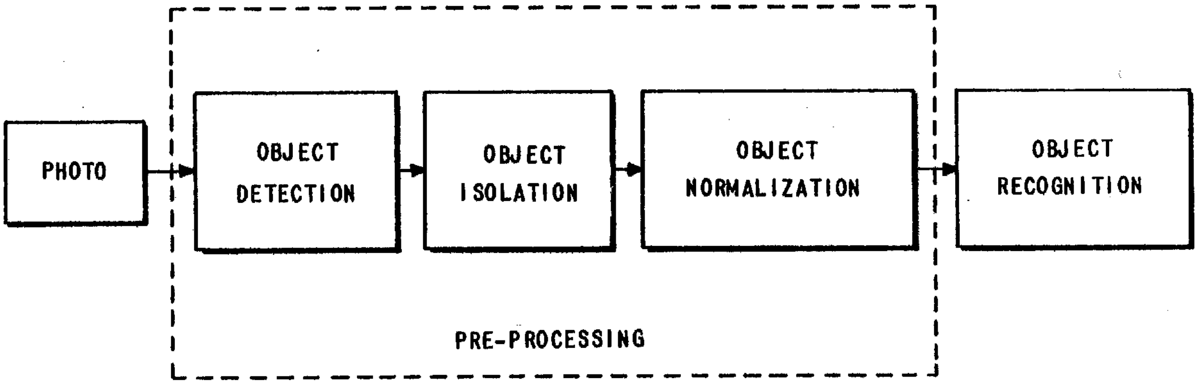


Figure SYSTEM BLOCK DIAGRAM

Isolation has the objective of placing each detected object of significant size in a separate frame. Step 3 of Figure 2 illustrates this process. The isolation process is straightforward in concept, as well as in programming for computer feasibility studies, but its hardware implementation is not. The isolation procedure must successfully isolate objects within objects, and it must avoid breaking-up images of objects.

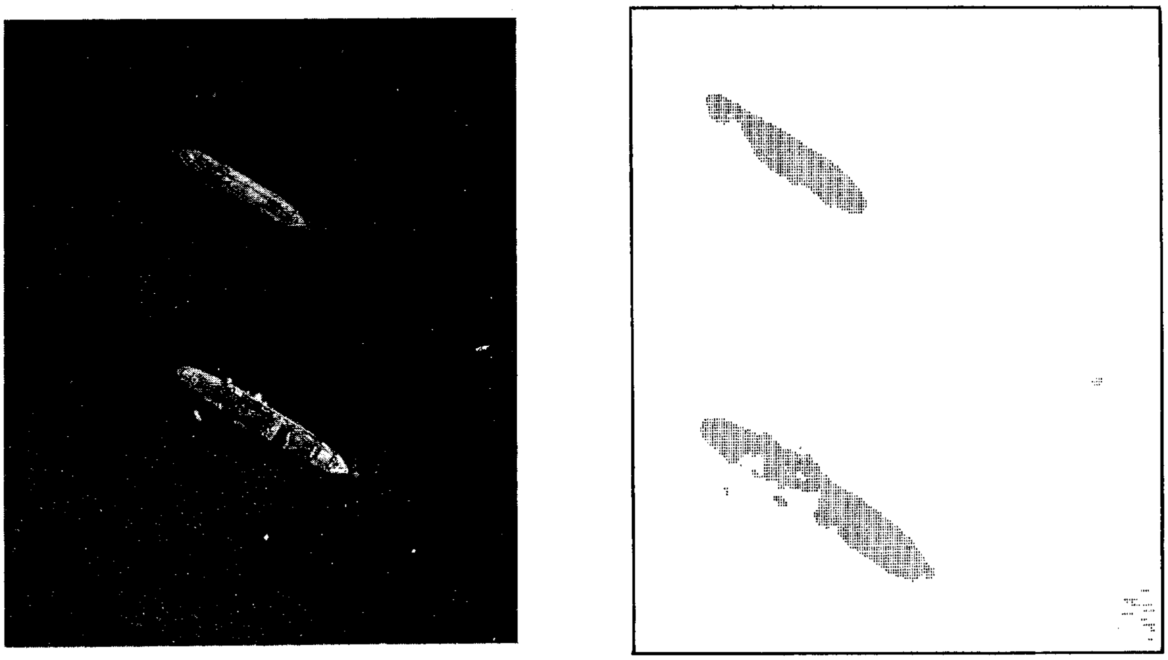
Standardization involves simply the translation of the binary image of each object so that its center of gravity coincides with the center of its frame and rotation of the image so that one of its principal axes of inertia is vertical within its frame. The programs being used in feasibility studies also scale all objects to the same maximum dimension.

Object Recognition

In the system being discussed, recognition of simple binary images, after detection, isolation, and standardization, will be accomplished by a linear discrimination device, i.e. by comparing the weighted sum of a set of property values to a threshold. The simple perceptron, which can accomplish the operation of deriving the properties from the input pattern, weighting them and comparing them to a threshold for a recognition decision is shown in Figure 3. The S, or sensor, layer accepts the image, thresholds it, and transmits a binary representation to the A, or association, units through connections which are diagrammatically shown in the figure for two A-units. These connections are -1, 0, or +1. In a sense, every A-unit is connected to every S-unit, but, since a 0 weight connection is an open circuit, the number of actual connections is less than the total number of S-units.

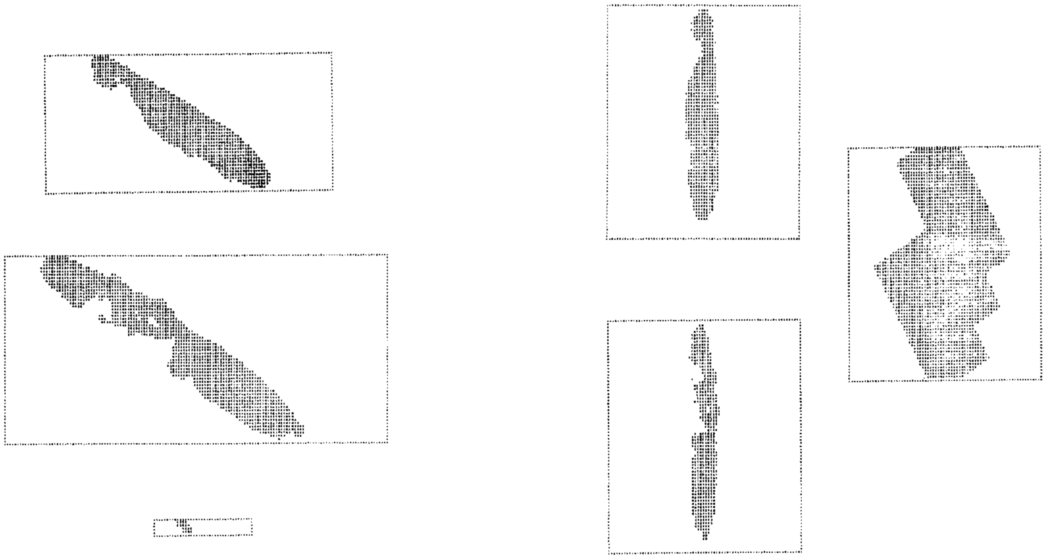
The information received by an A-unit from all S-units to which it is connected is added together linearly and the sum is thresholded to produce a binary output, which is either 1 or 0. All A-units are connected to the R, or response, unit through a set of variable weights, W_i. Thus, a binary output X_i from A-unit A_i is received at a given response unit as $X_i W_i$ and the total signal received at any given response unit it .

The simple perceptron is an adaptable or trained device, and is used in object recognition as follows. During the training procedure, a set of patterns representative of those which the machine is to recognize is used. The individual members



ORIGINAL PHOTOGRAPH 3335

PROCESSED PHOTOGRAPH AFTER OBJECT DETECTION AND LOW-PASS FILTERING



ISOLATED SILHOUETTES FROM PROCESSED PHOTOGRAPH

STANDARDIZED FORM OF ISOLATED SILHOUETTES

Figure 2 PRE-PROCESSING OPERATIONS

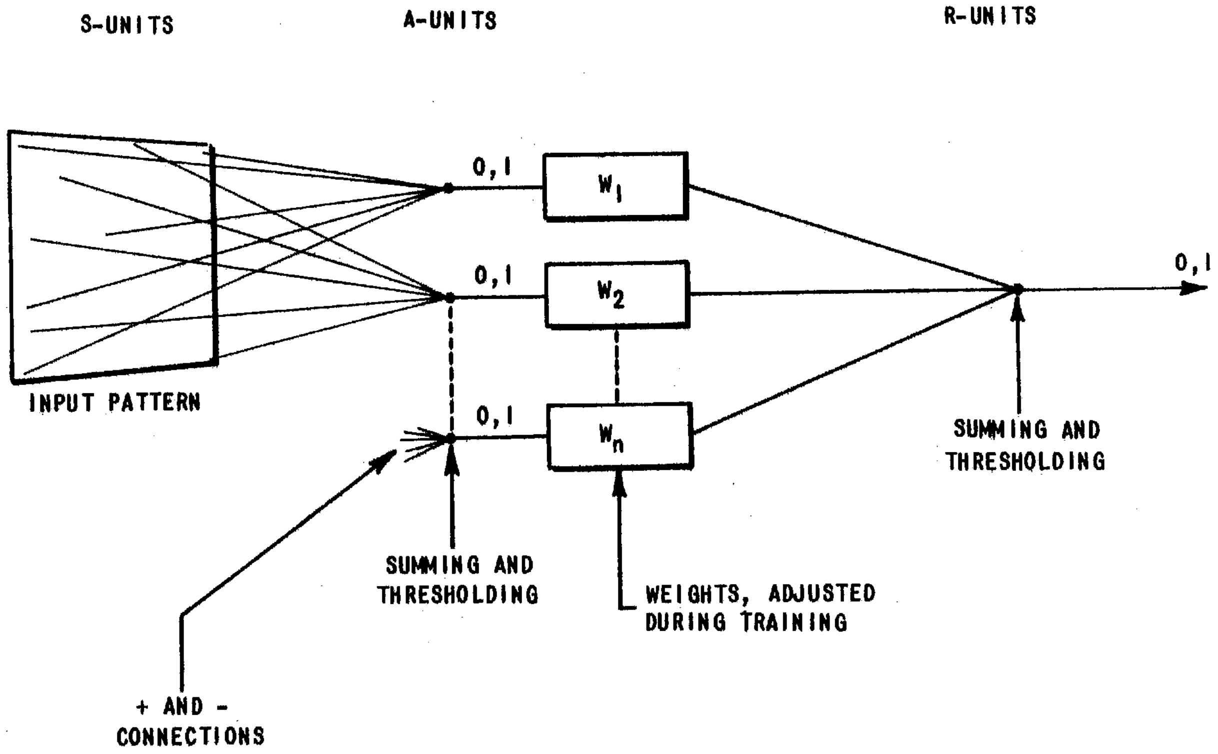


Figure 3 SIMPLE PERCEPTRON

in this training set are impressed in the input space and the R-unit response, (a 0 or 1) is observed. With only one R-unit the patterns can be divided into only two classes, and all the patterns in the training set must be pre-classified as class 0 or class 1 patterns prior to training. Now if the R-unit response is correct, i. e. coincides with the pre-classification, the next pattern is selected and the R-unit response is observed. When during the process of sequentially using all the training patterns, a correct response occurs, no action is taken. When an incorrect response occurs all the weights, W_i , between the A-units and the R-units are changed by an amount prescribed by a training algorithm or rule. The entire sequence of training patterns is repeatedly used in this fashion until all patterns in the training set are correctly classified. The machine is then in a trained state as far as recognition of these two types of patterns is concerned. It is now usable, and one of the first things usually done is to test its ability to generalize, that is to recognize patterns of the same representative class as those in the training set, but not identical to the training patterns. In discussing Phase III work, the numerical specifications of a simple perceptron used in recognition experiments and a summary of results will be given.

Photo Input Facility

The photo input facility developed during Phase II is shown diagrammatically in Figure 4. The facsimile scanner is a commercially available unit. Other basic components are the analog-digital converter and control and synchronizing circuitry. Basic characteristics of the device are:

a. it has a sixteen level gray scale,

b. it can sample photo material every 1/100 of an inch along scan lines 1/100 inch apart, and

c. the time required to insert a 5 inch square photo into the IBM 704 computer through the scanner is about 1-1/2 minutes.

Summary of Phase II Accomplishments

Several of the Phase II accomplishments have been already described in some detail. Furthermore, an adequate background has now been supplied to permit a meaningful statement of the major program results as of April 1962.

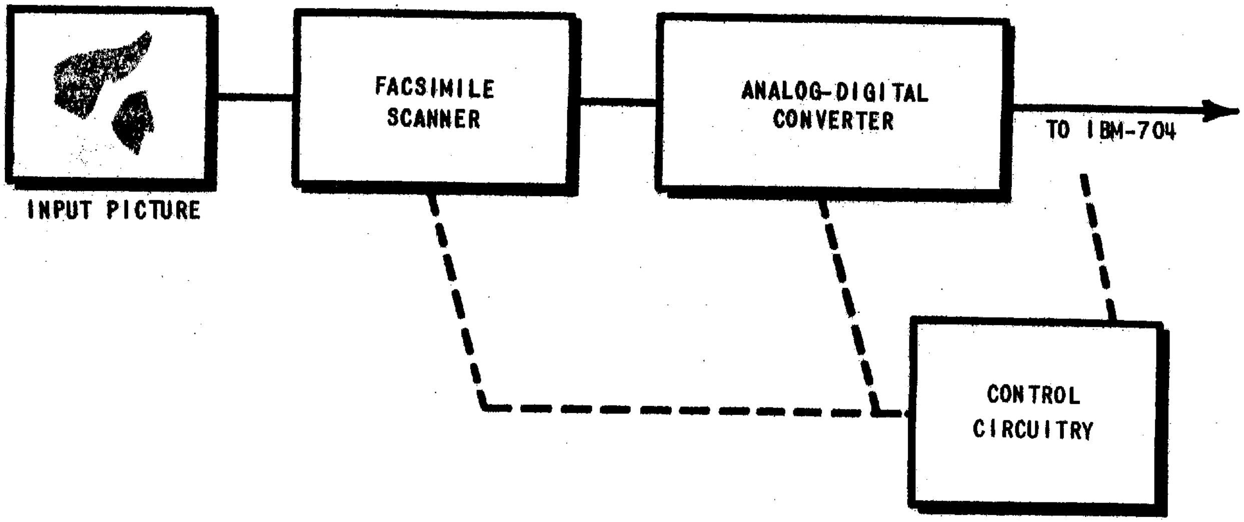


Figure 4 PHOTO INPUT FACILITY

These are:

1. An over-all system diagram was developed which recognized the importance of pre-processing of imagery prior to the object recognition function.
2. Techniques for the detection, isolation, and standardization operations were established. (These will be illustrated in discussing Phase III work.)
3. Digital computer programs implementing the detection, isolation, and standardization operations were developed and put into use.
4. Partial evaluation of the pre-processing techniques was provided.
5. Computer programs for implementing perceptron object recognizers were developed and put into operation.
6. A 100 line per inch, 16 gray level photo input system was designed, built, and put into operation.

Phase III: Objectives and Accomplishments

The Phase III (April 1962 - December 1962) program objectives developed directly from the problems uncovered and successes achieved in the Phase II program. Thus, while the detection procedures developed in Phase II research worked well for relatively high contrast objects in regions of low object density, they had shortcomings in low contrast, high object density situations. Other pre-processing problems were satisfactorily solved in Phase II, insofar as computer feasibility studies, so that reasonable further objectives were to determine specific requirements of the object recognizer, and demonstrate, on the IBM 704, a simple, but complete version of the entire system. To summarize, in Phase III [redacted] was 25X1 to:

1. Complete determination of the feasibility of the pre-processing techniques that were proposed and partially evaluated in Phase II.
2. Develop techniques for detecting low contrast objects in high object density photography.

3. Establish the requirements of a perceptron-like device to recognize objects of military interest which are detected by pre-processing system.
4. Demonstrate, using the programs implemented on the IBM-704, a complete, but simple automatic photo interpretation device which can identify five or more simple object categories.

Pre-processing Techniques

Chart 1 summarizes the most useful of the many techniques which we have tried for the object detection process. (It also shows the devices or techniques to be used to fulfill the functions of removing variability from patterns and for object recognition in the simplest system). In two of the detection techniques the Kolmogorov-Smirnov (hereafter, K-S) test and the simple uniformity test, object separation or isolation is performed as part of the detection process. In using the annular filters for object detection, a separate isolation operation is required.

Pre-processing Using the Annular Filters

The annular object filters, which discriminate on the basis of intensity contrast, are designed as shown in Figure 5. Square apertures ("picture frame" regions) are used to compute intensity information which is then compared with the intensity of the point at the center of the square, A, to determine if the central point differs sufficiently in intensity from its background to qualify as being a point on an object.

A computing method equivalent to the following is used. Each point in the spatially quantized photograph is surrounded by a frame one point thick, and of width d (Figure 5). The mean, m, and standard deviation, σ, of the intensity of the points in the frame are then computed.

If $A > m + \max(1, K\sigma)$

or $A < m - \max(1, K\sigma)$

where K = a constant,

the point was recorded as an object point. Several different frame sizes were used in order to detect objects of different sizes. In actual operation the point

FUNCTION	TECHNIQUE		
OBJECT DETECTION	ANNULAR FILTER PLUS GAP FILLER	KOLMOGOROV-SMIRNOV TEST	SIMPLE UNIFORMITY TEST
OBJECT SEPARATION	ISOLATOR		
VARIABILITY REMOVAL	STANDARDIZER		
OBJECT RECOGNITION	PERCEPTRON		

Chart I SYSTEM FUNCTION AND TECHNIQUES

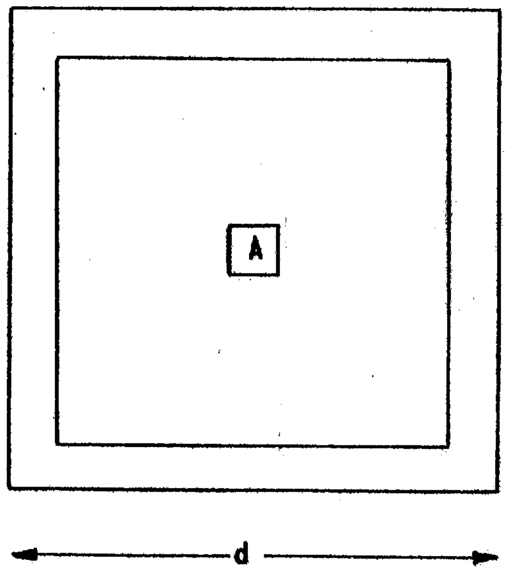


Figure 5 FILTER FOR DETECTION ON THE BASIS OF INTENSITY CONTRAST

labeled A effectively scans the entire photo in a scan pattern similar to that used for television, with the picture frame moving along with point A. In Figure 6, a synthesized photo having both light gray and darker gray background areas with aircraft in each is used to illustrate how the filter operates in different situations. In the upper part of the illustration, point A is an exceptional (object) point when it falls on either the bright fuselage or darker wing of the aircraft, even though the picture frame intersects the aircraft elsewhere. In the lower right part of the illustration the aircraft is bright and contained entirely within the frame; again point A is an object point. With either type of background-but only background-lying under the filter, point A will not be an object point. The annular filters have the following significant features:

1. They do a good job of detecting such objects as aircraft when the aircraft differ from their backgrounds by more than one level in intensity.
2. The <u>same filter</u> can detect light objects on darker backgrounds or darker objects on light backgrounds. They can successfully handle bright-winged aircraft which have dark fuselages.
3. The detection process is largely shape independent but shape preserving.

Figure 7 - 12 illustrate the pre-processing operations when using the annular filters for detection. Figure 7 is a part of one of the photos acquired for project use from PICS. It shows numerous aircraft on different types of background and illustrates various problems of detection. This photo was read into the IBM-704 computer through the photo input device and read out, to observe effects of the input operations, on the photo output system which [redacted] completed during Phase 25X1 III of the project activity. Figure 8 shows the reproduced output photo. It evidences some distortion due to limitations on the resolution of the input device and also some loss of gray scale range. Figure 8 is included so that the reader is not misled as to what the processes internal to the computer have available to work with. Figure 9 shows the result of using two different size annular filters for detection processing of the photo of Figure 8. It should be quickly pointed out

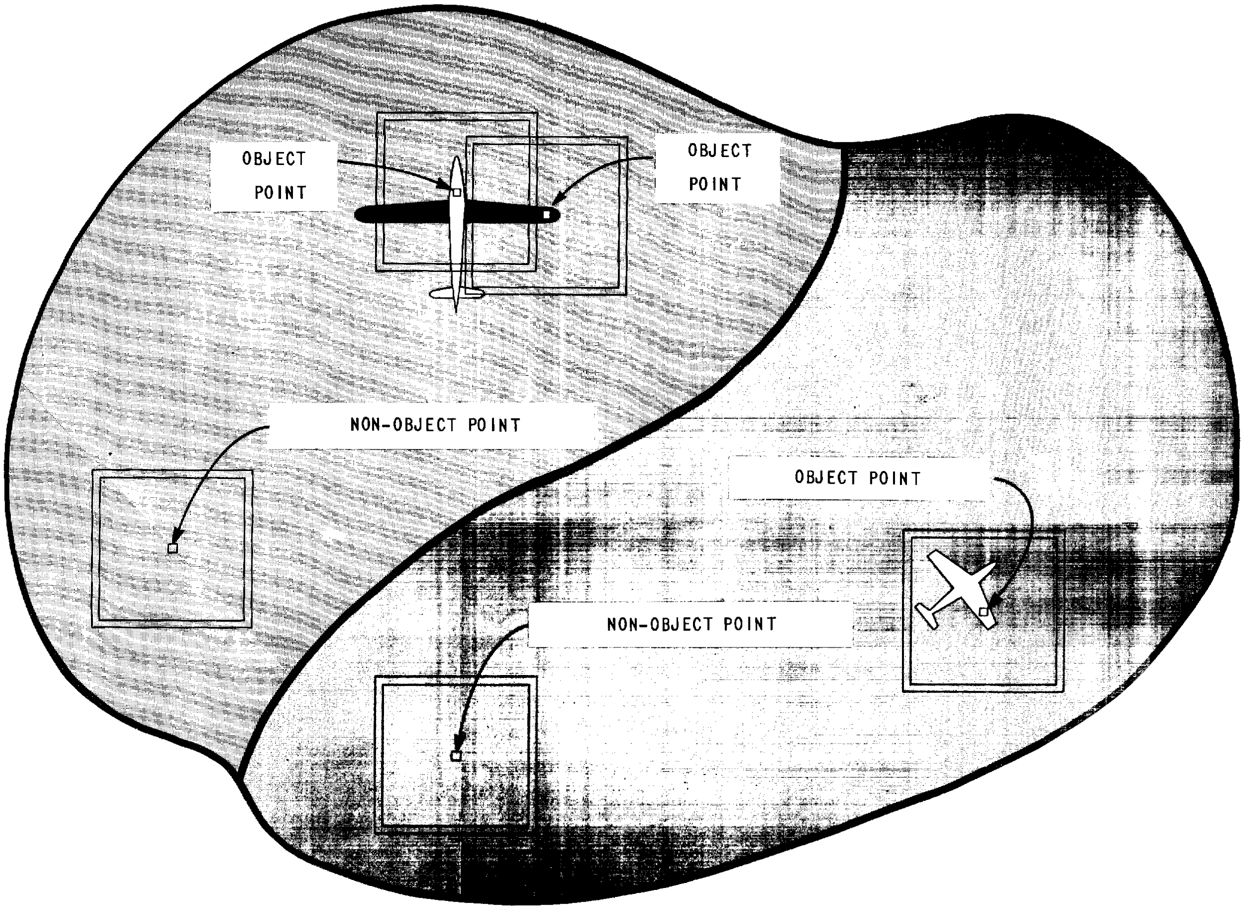
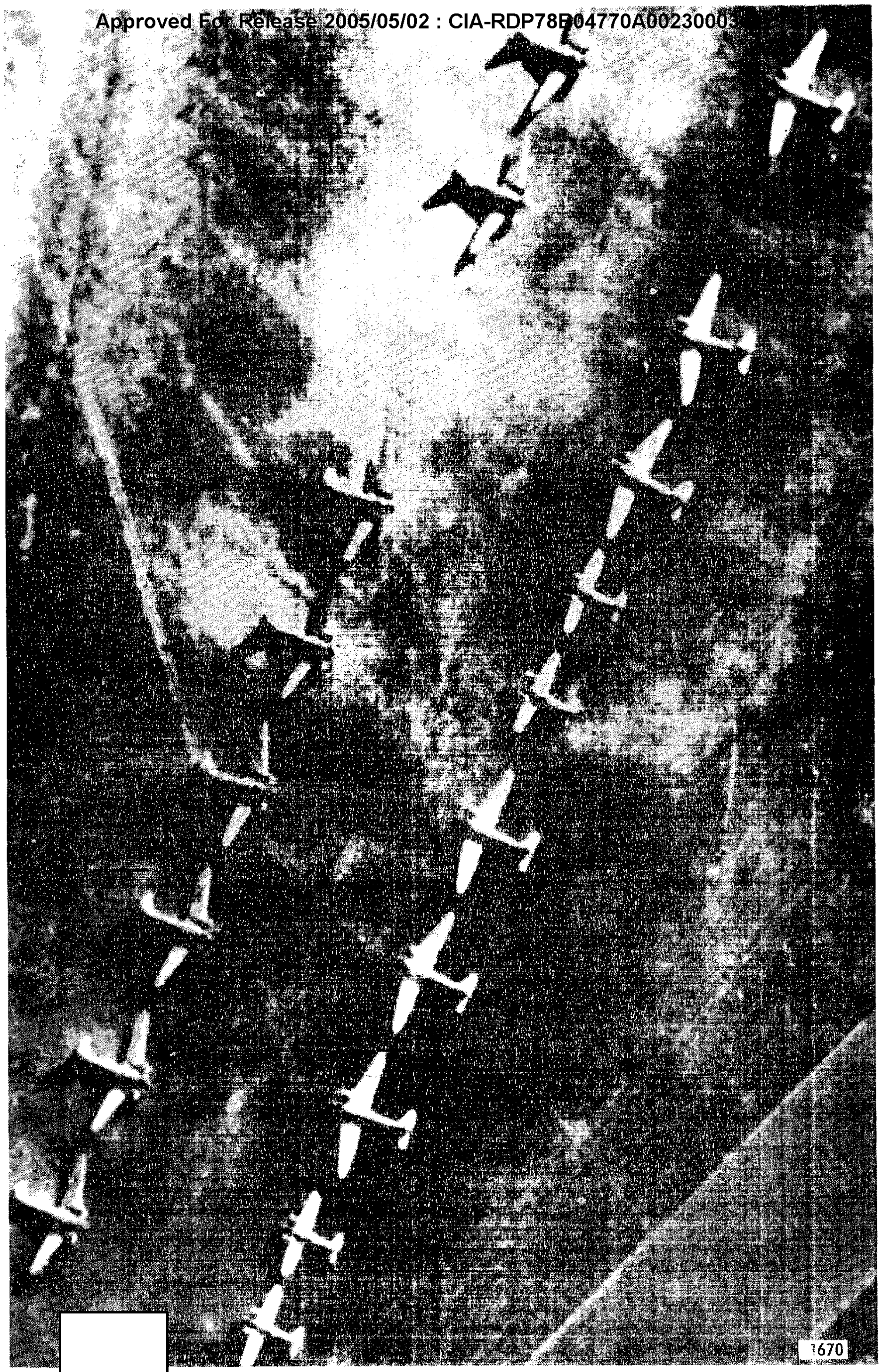


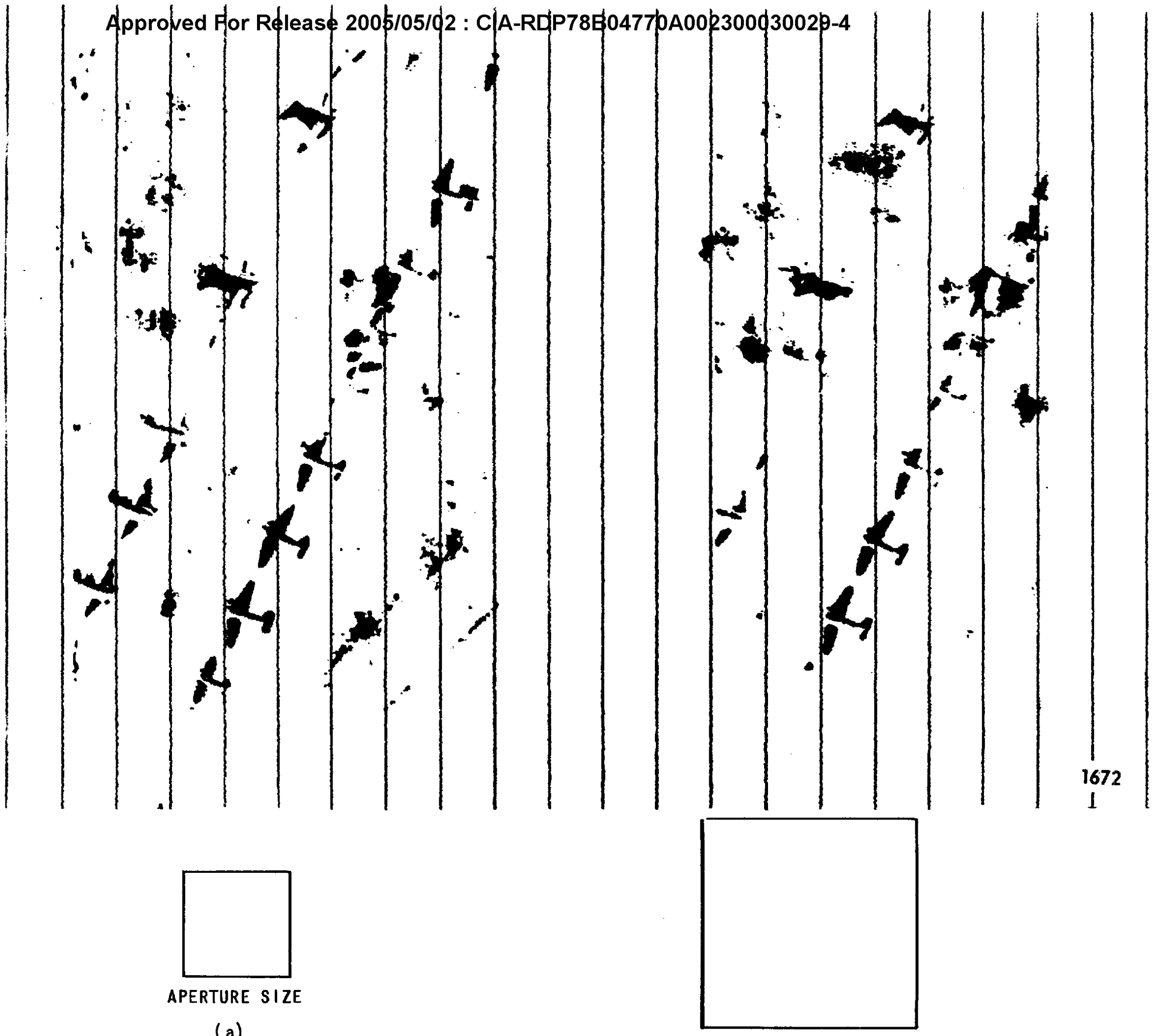
Figure 6 ANNULAR FILTER OPERATION



25X1 [redacted]

Figure 7 ORIGINAL PHOTOGRAPH

Figure 8 EDITED VERSION OF FIGURE 7



APERTURE SIZE

(a)

APERTURE SIZE

(b)

Figure 9 [illegible] TWO APERTURE SIZES

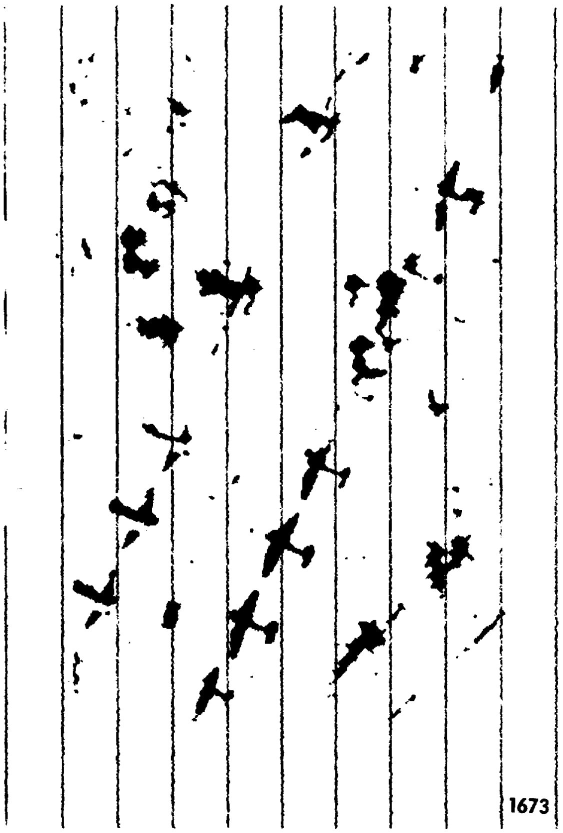


Figure 10 OUTPUT OF GAP FILLER APPLIED TO FIGURE 9(a)

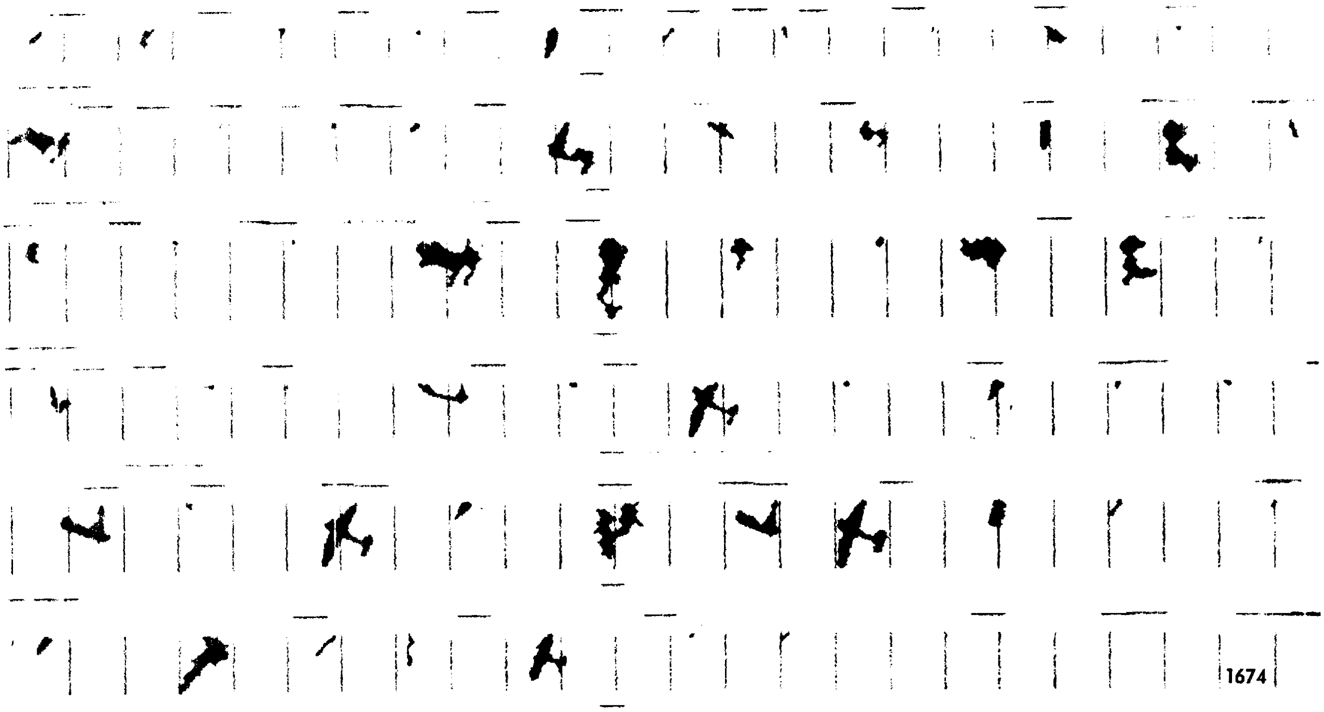


Figure 11 OUTPUT OF ISOLATOR APPLIED TO FIGURE 10

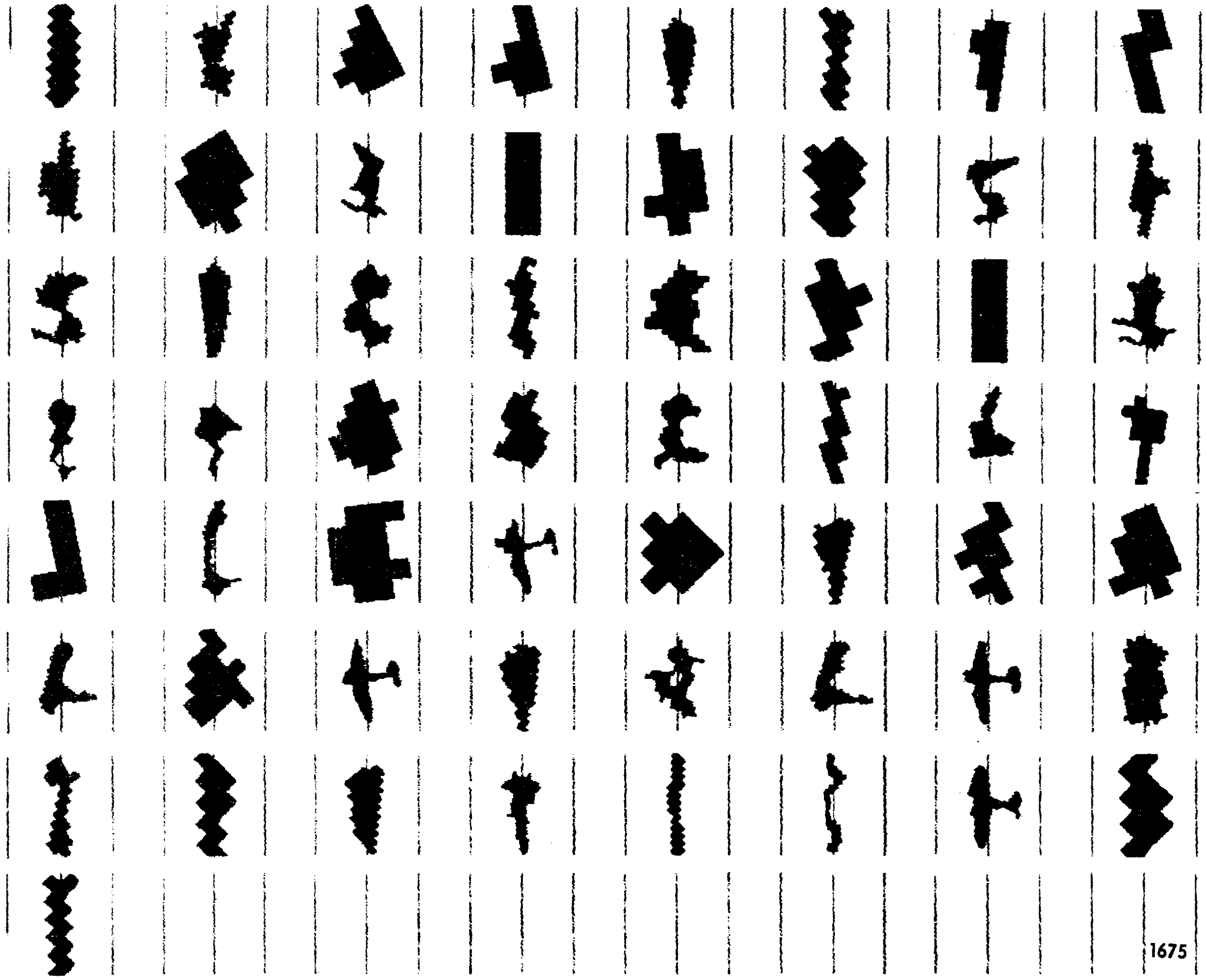


Figure 12 OUTPUT OF STANDARDIZER APPLIED TO FIGURE 11

that in this detection procedure the filters have no ability to detect any object which is within approximately one aperture size of any edge of the original photo. Thus, many of the aircraft in Figure 8 cannot be detected by the present version of this process and the absence of detected objects near photo edges should not be charged against the detection process. In a prototype system, the edge effect problem can be handled either by providing sufficient frame-to-frame overlap or by mathematically modifying the filtering process near photo edges. This is not a central problem for feasibility studies. Figure 9 shows a considerable capability at aircraft shape detection and also illustrates some common problems. In some cases there is simply a failure to detect aircraft shape, in others one or more aircraft wings are detached due to fuselage shadows.

A solution to this detached wing problem is illustrated in Figure 10 where a nonlinear two-dimensional numerical filter has been applied to Figure 9a. This filter has a capability for joining associated object pieces without seriously distorting object shape, something which cannog be achieved with linear filters and, thus, normal optical processing techniques. Reattachment of wings and tail pieces is important to prevent their appearing as separate objects after isolation. Figure 11 shows the isolated objects produced from the detected frame of Figure 10. Those aircraft shapes which are successfully detected are clearly isolated but the pieces of the shape or outline which are not attached to the main portion are, of course, placed in separate frames. Where there are serious effects of this type, such as an entire wing missing, the object recognition device must either be trained to recognize the distorted shapes or they will probably be rejected as non-objects. Figure 12 shows the output of the standardizer applied to the individual objects of Figure 11. The aircraft shapes which appear are distinctly different from the non-object shapes appearing at this point and there should be no serious difficulty in successfully recognizing the detected aircraft appearing in Figure 12.

The illustrations of Figures 7 - 12 clearly show a significant and useful capability for detecting aircraft. The processes are obviously not perfect and there are refinements to the detection procedures which can be developed to further improve this already useful capability. Although this discussion has been concerned with aircraft, shape information has not been used to aid detection in any way and the procedures are not at all restricted to aircraft.

Pre-processing Using the K-S Detection Test

The annular filter detection procedure described immediately above does not work very satisfactorily on material such as that shown in Figure 14, which is characterized b the interiors of objects occupying a high percentage of the frame and the relatively low contrast between the objects and their backgrounds. Figure 12 is the original version of the photo and it indicates somewhat higher contrast, but again it must be remembered that the computer works with something much more like Figure 14.

The K-S detection test and the closely related simple uniformity test were developed to attempt to overcome the deficiency of the annular filters in situations such as that described above. Operation of the K-S test is illustrated in Figure 15, which shows, in its upper portion, a gray tank on a darker gray background. The K-S test uses a three element by three element cell of nine elements in detecting objects. It is based on one of a broad category of techniques called non-parametric statistical tests, of which the K-S test is a specific one utilizing the cumulative probability distribution of intensity within the nine element cells. In the upper half of the figure it has been assumed that the detection process has already started and that, in fact, the three nine element cells lying within the tank interior and drawn in solid lines are already determined to be part of the object. Two different cells are also shown in dashed lines. The K-S test proceeds by concsidering such nine element cells adjacent to the already-detected object portion testing whether or not these adjacent cells belong to the object in the sense that, they have the same cumulative probability distribution in intensity as the already-detected part of the object. In the illustration of Figure 15 one of the cells dotted-in is within the object and the other is not. The K-S test explores the interior of the object, defining the boundaries, and thus the interior, as it proceeds. It thus accomplishes the isolation process along with detection. This qualitative description of the K-S test ignores the problem of getting started within an object which was solved in our computer programs. The K-S test has the following interesting features:

1. It provides successful detection for low contrast objects in high object density regions.
2. It degrades resolution in the sense that it answers the question "does a nine element cell belong to the object", rather than "does a single element cell belong to the object"?

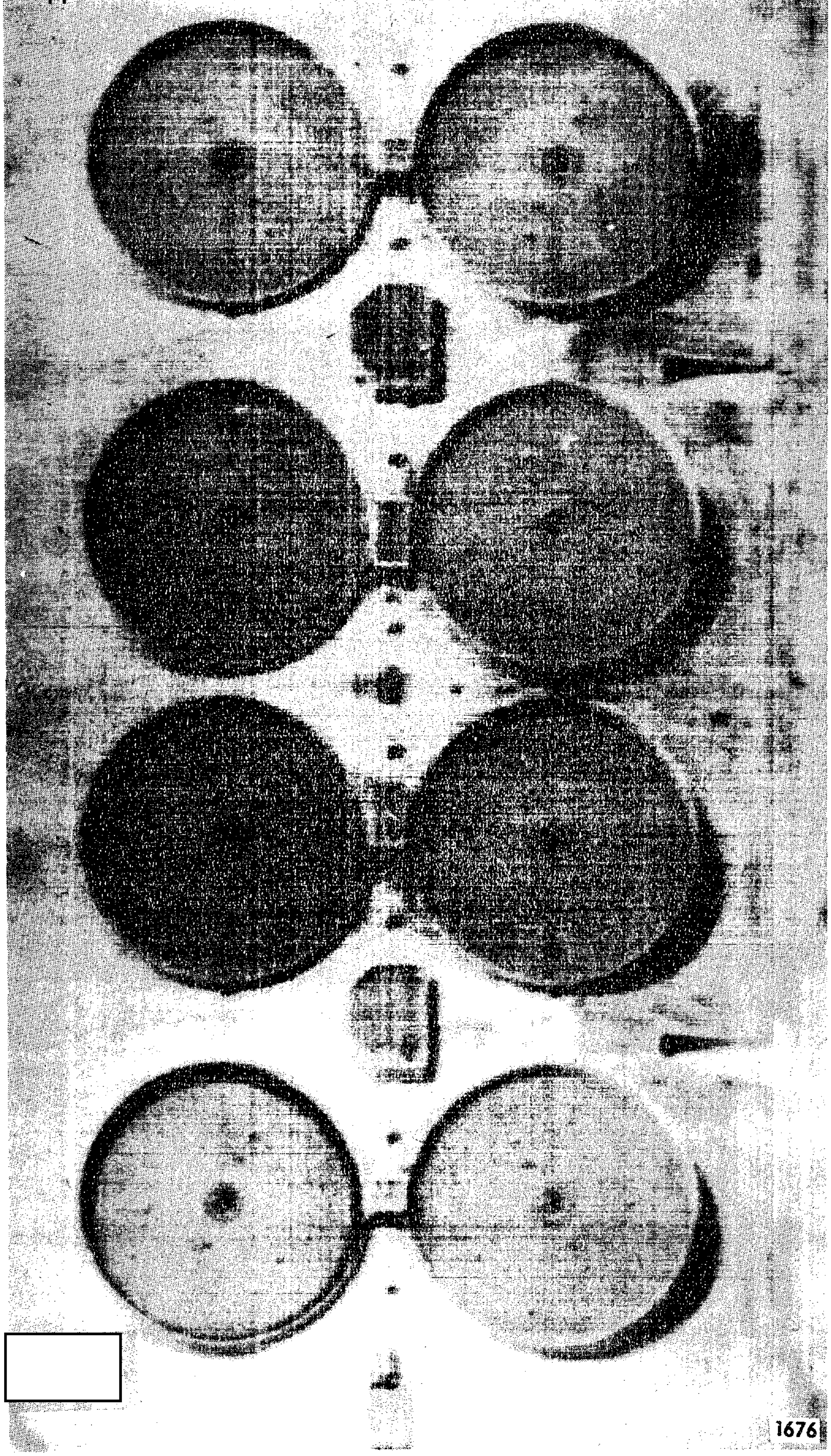


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Figure 13 ORIGINAL PHOTOGRAPH

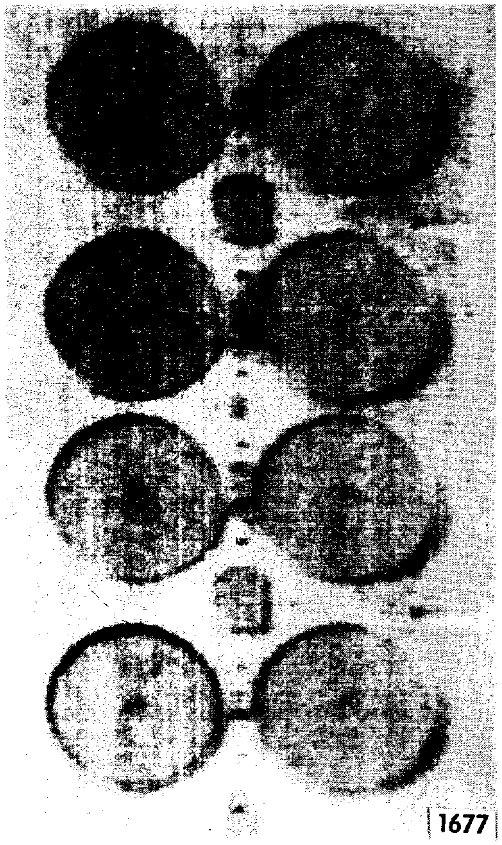
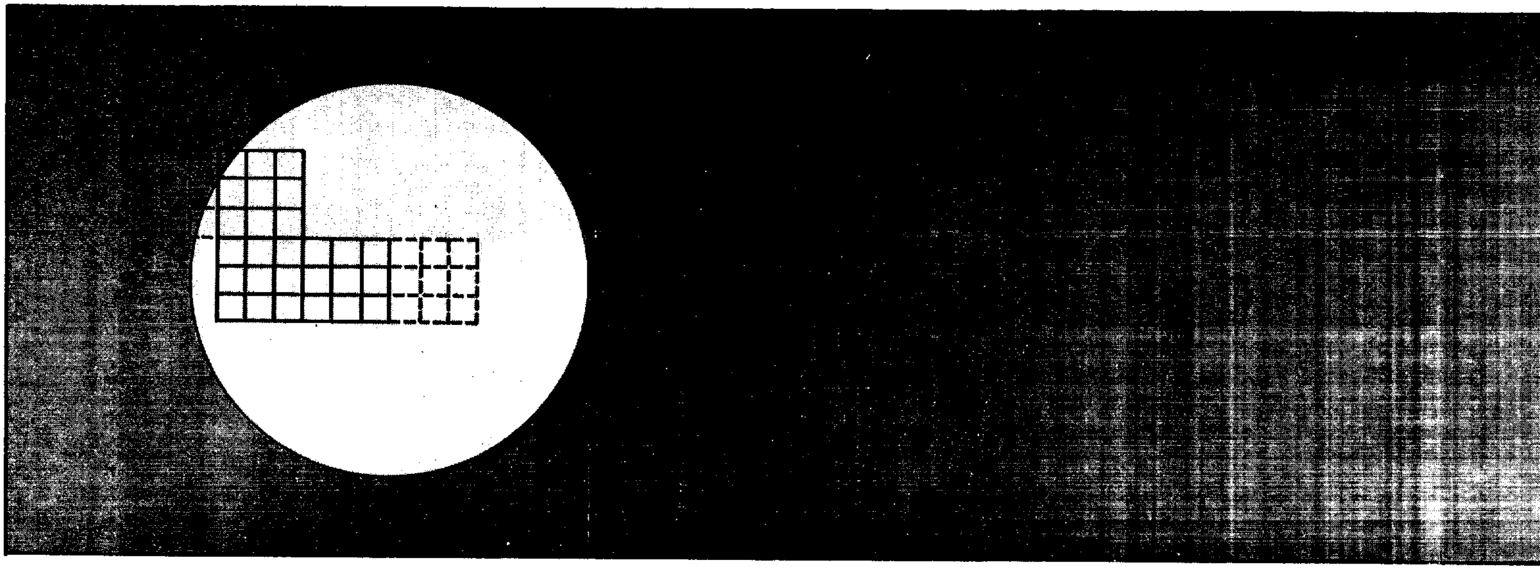
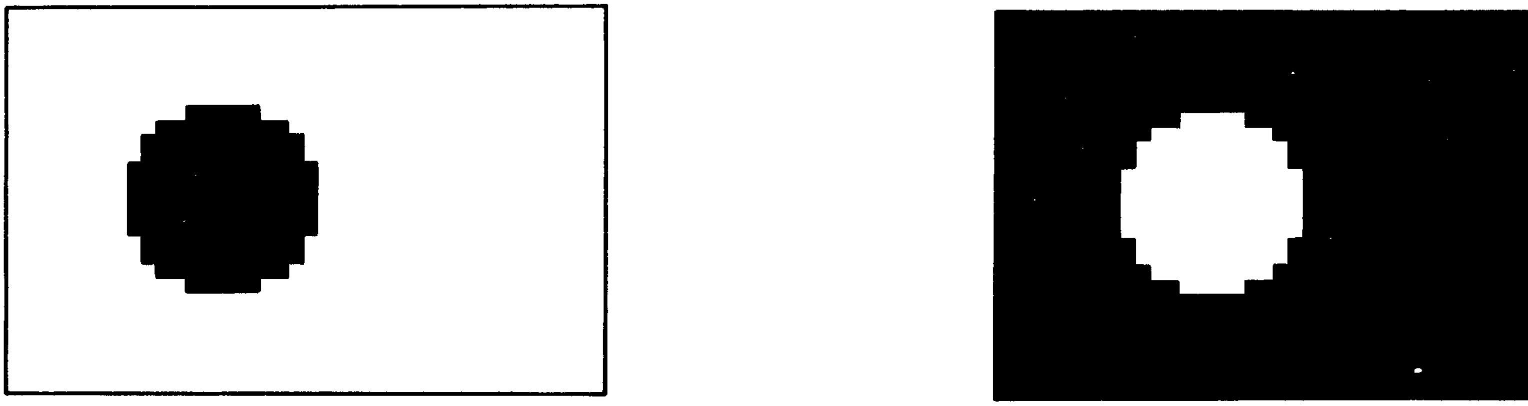


Figure 14 EDITED VERSION OF FIGURE 13

DETECTION AND ISOLATION USING K-S TWO SAMPLE TEST



RESULTS (HALF SIZE) OF K-S PROCEDURE OPERATING ON PICTURE ABOVE



OBJECT 1

OBJECT 2

Figure 15 KOLMOGOROV - SMIRNOV DETECTION TEST

3. It produces not only objects but consistent parts of the background as non-objects at its output. This is illustrated in the lower half of Figure 15, showing (at half scale) object (1), which is the storage tank we seek to detect, and the background as object (2). We are not particularly interested in the background and it must be rejected by the object recognizer.

The K-S test and the simple uniformity test are similar in basic operation, although the latter uses cells of only one element and a simpler test for membership of cells in the group comprising an object.

Figure 16, parts a, b, and c, illustrates the output of the K-S test produced by applying it to the photo of Figure 14. All eight storage tanks are detected and isolated, with what we feel is sufficiently low shape distortion to ensure proper recognition.

Object Recognition Capability

The Phase III activity would not permit the use of actually pre-processed material in parametrically studying and designing the object recognizer. As an alternate, having the purpose of providing a convincing demonstration of recognition capability at a minimum cost, recognition tests were run using synthesized objects. In this experiment a perceptron-like recognition device having the capability of separating multiple classes was used. As Figure 17 indicates, distorted stimuli were generated in a 36 x 36 matrix or input array and 500 A-unit type weights were provided to separate each of the seven classes of objects of interest from each other class. The illustration of Figure 17 shows only the set of weights and the output signal for discriminating aircraft from non-aircraft, but actually specific classification of four different types of aircraft as well as of ships, circular storage tanks, and rectangular buildings was demanded.

In training and testing the system for object recognition, non-distorted patterns of the object classes and of the non-object class were distorted using a random walk technique to produce patterns similar to those appearing at the output of the pre-processor. Figure 18 illustrates 121 of the 720 objects used in training the

Figure 16(a) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 14

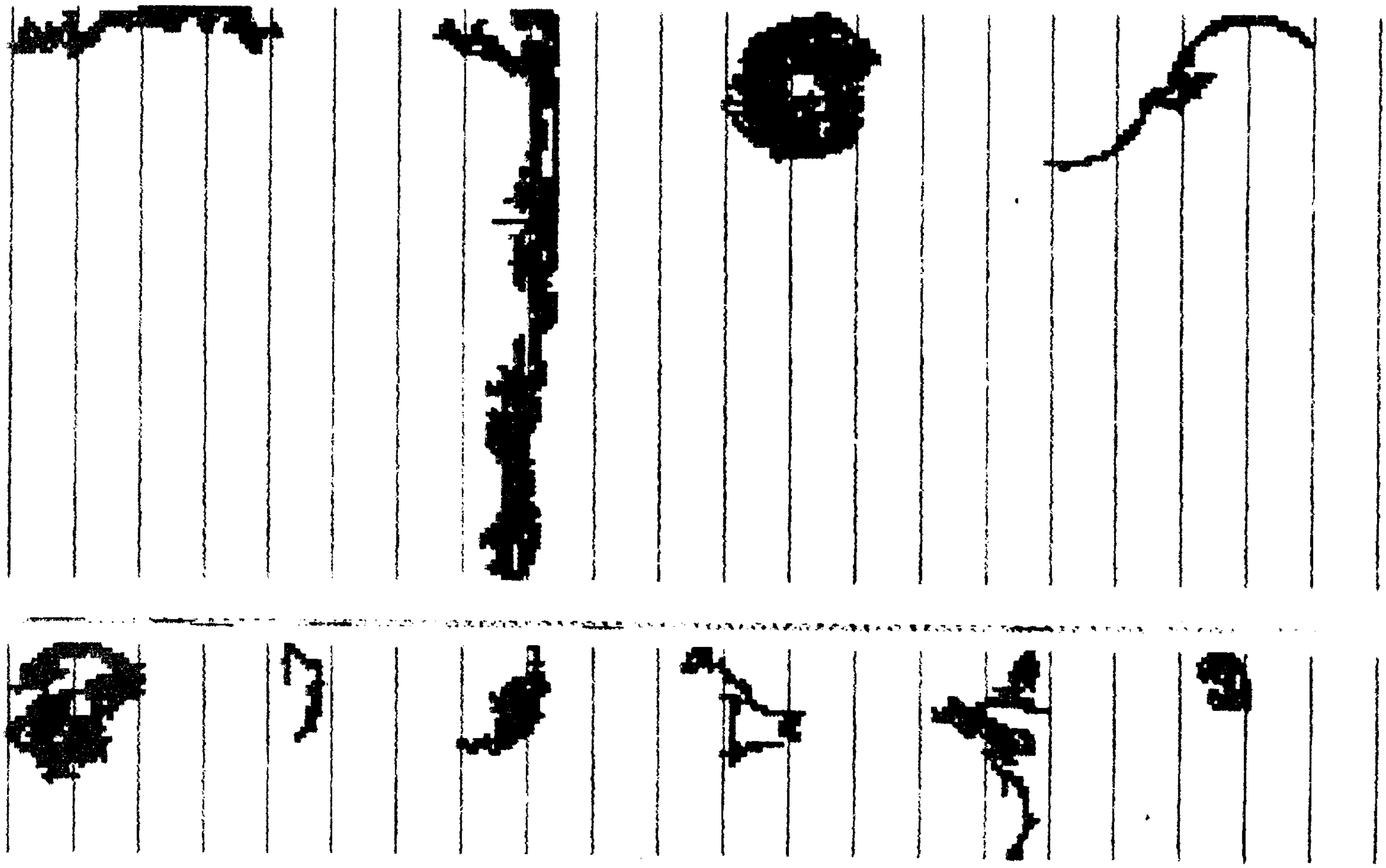


Figure 16(b) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 14

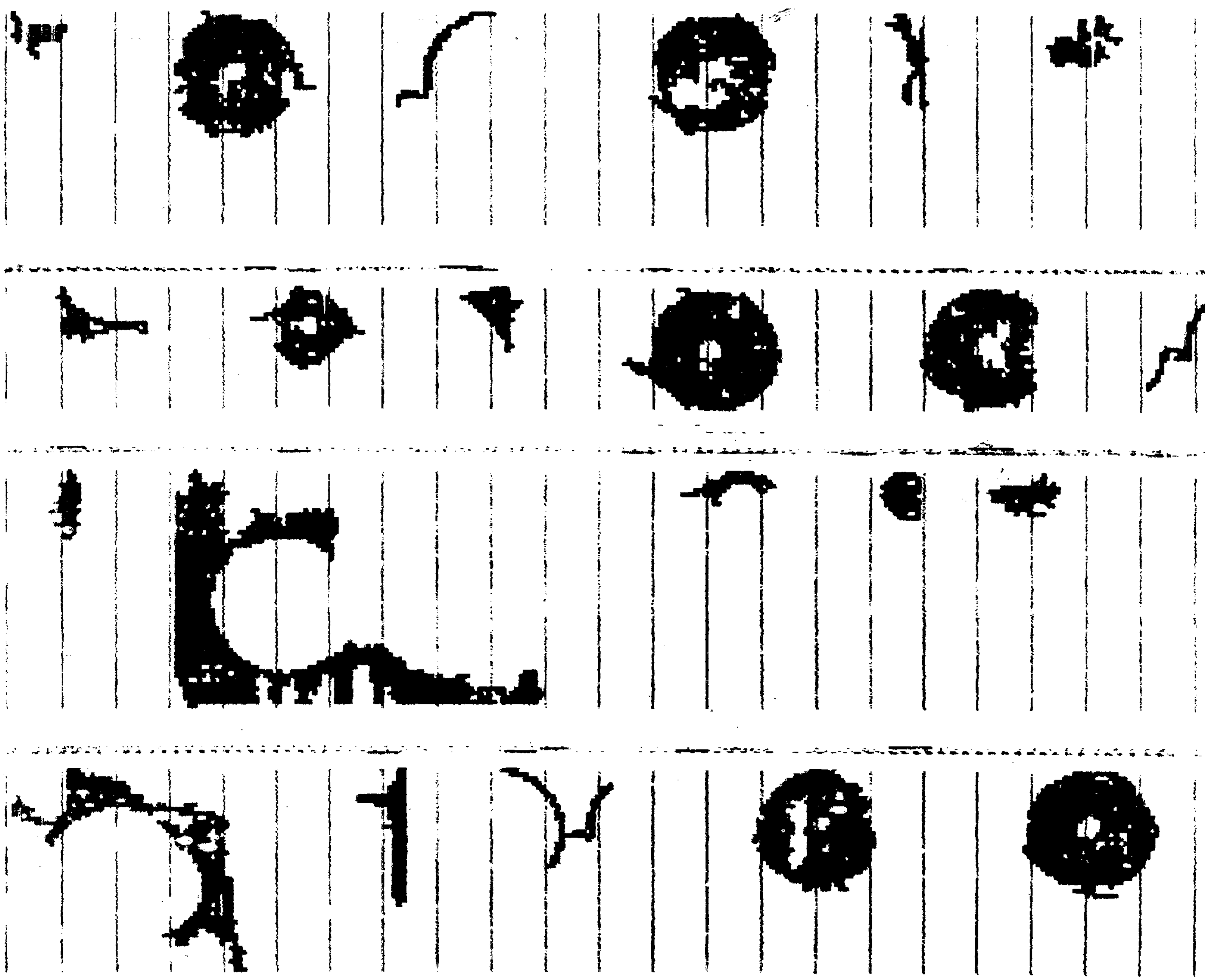


Figure 16(c) OUTPUT OF KOLMOGROV-SMIRNOV FILTER APPLIED TO FIGURE 14

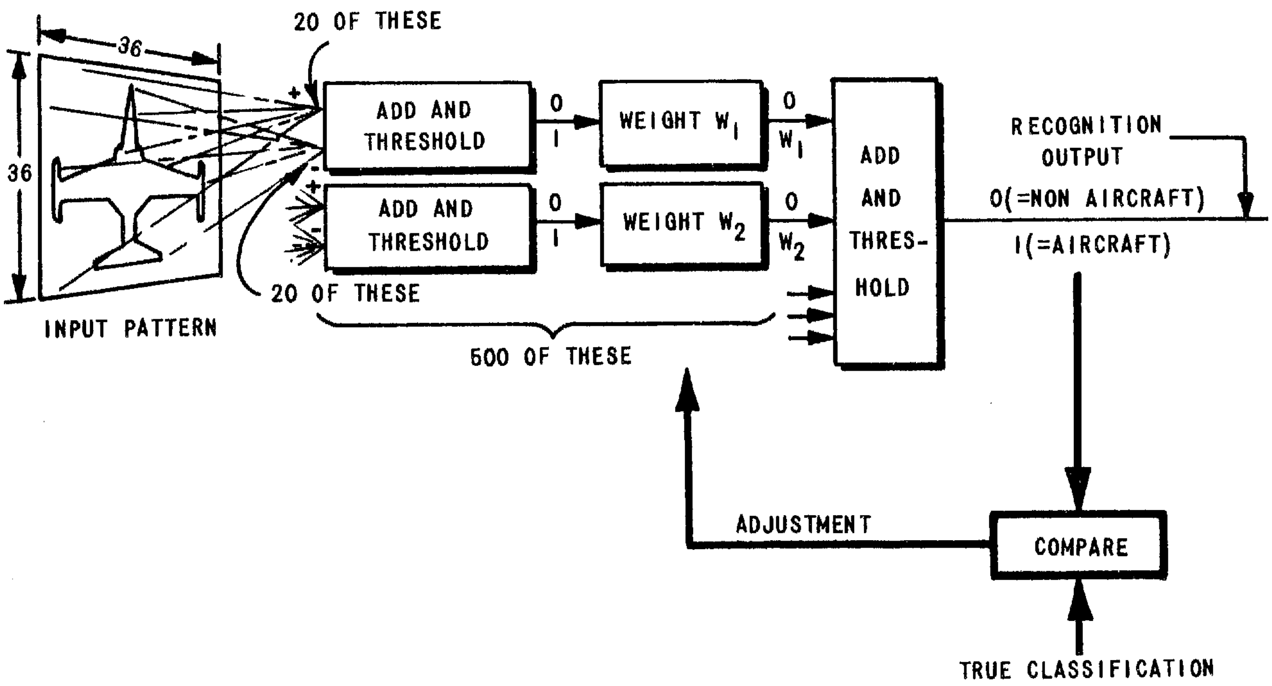


Figure 17 PERCEPTRON CONFIGURATION FOR RECOGNITION EXPERIMENTS

system. It contains some of each of the classes (TU-104's, IL-18's, LA-60's, F-102's, ships, storage tanks, and rectangular buildings) as well as the abstract shapes, ellipses of moderate eccentricity, and very long narrow rectangles comprising the non-object category.

A similar set of 720 patterns was used for testing the trained object recognizer. The results of this recognition test are shown in Table 2, where they are presented in a number of different ways. The lowest individual performance figure was the 95.5% correct recognition capability for identifying rectangular buildings. For all other object categories, the recognition rate was in excess of 98%. The over-all object detection probability figure is 98.7% and the false alarm rate in these experiments was 3%. Comparison of Figure 18 to Figure 12 provides some convincing evidence that the object recognizer will be able to handle the actual material produced by the pre-processor. The recognition rate and the false alarm rate will, we expect, be worse when actual material is used. In addition, of course, these are figures for recognition alone and are not to be confused with the over-all results for the system which are certainly of interest.

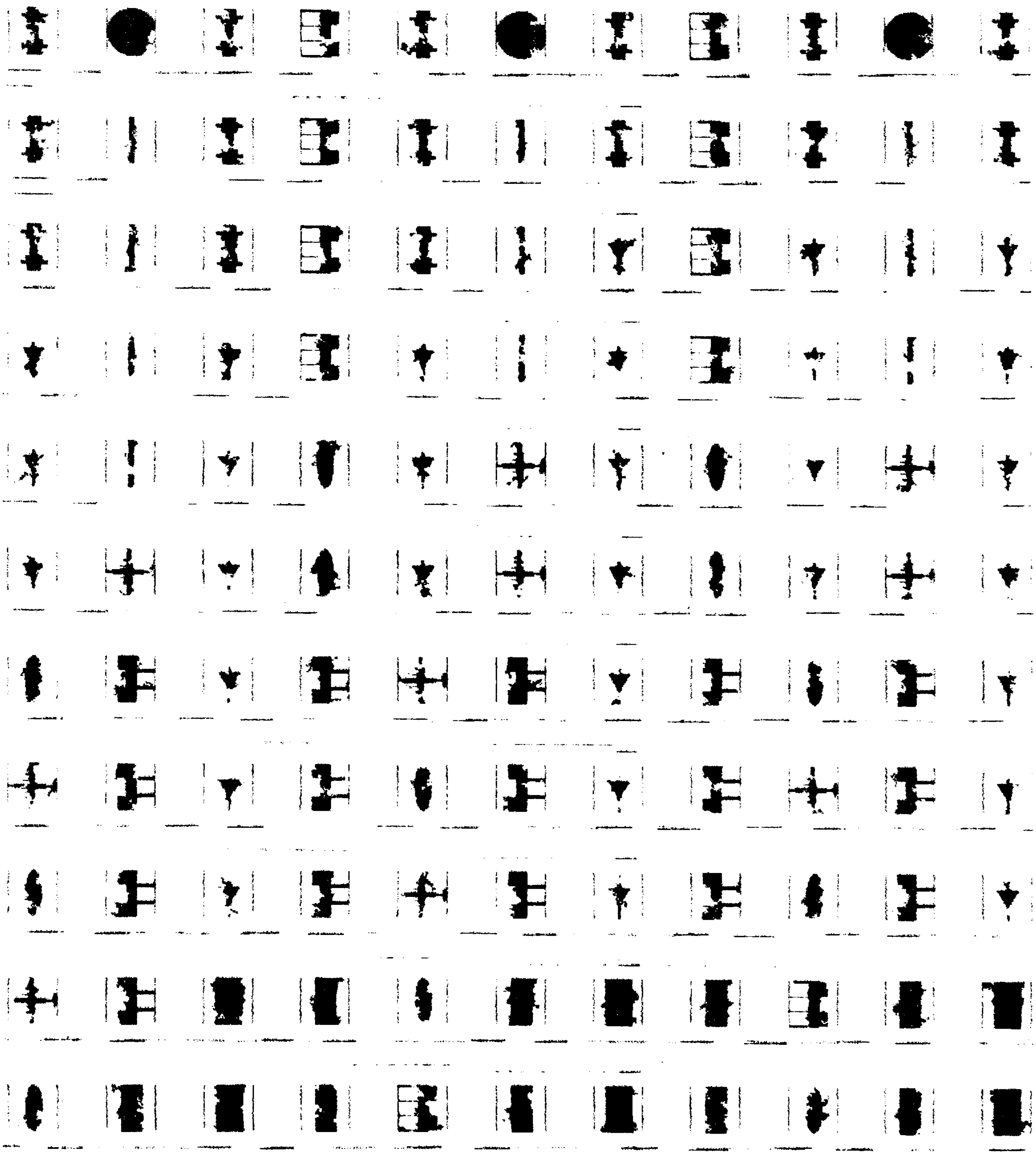


Figure 18 SAMPLE OF OBJECTS USED IN RECOGNITION EXPERIMENTS

Nevertheless, the results of the recognition experiments using synthesized objects provide a convincing demonstration of the ability of a simple perceptron to recognize quite badly distorted objects with a very high correct recognition rate.

Summary of Phase III Accomplishments

The major technical accomplishments of Phase III are as follows:

1. An improved photo input facility has been developed. The Phase III effort in this area consisted of packaging the input facility more conveniently, radically improving its signal to noise ratio, and providing nonlinear compensation, if desired.
2. The photo output facility has been developed and put into extensive use on the project.
3. Statistical hypothesis testing techniques have been developed and evaluated for the detection and isolation processes (this includes the work on the K-S and simple uniformity tests).
4. Nonlinear filtering techniques for gap-filling have been developed.
5. A large number of photographs have been prepared and processed through the detection and isolation steps of the pre-processing part of the system. A smaller number of photographs have been carried through the standardization process.
6. The capability of a 500 A-unit perceptron to recognize distorted, militarily interesting objects with a very high degree of correct recognition has been established by experiments designed so that there is high statistical confidence in the results.

Summary of Current Capability

The following paragraph briefly recounts the capability existing as the result of research on all three phases of the program.

A useful system philosophy and block diagram have been developed. Two successful procedures for detection have been developed and evaluated. One, the annular filter, works well in regions of low object density and low contrast. The isolation and standardization operations are being accomplished routinely in our computer feasibility studies. Recognition experiments with noisy synthesized patterns have been very successful.

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