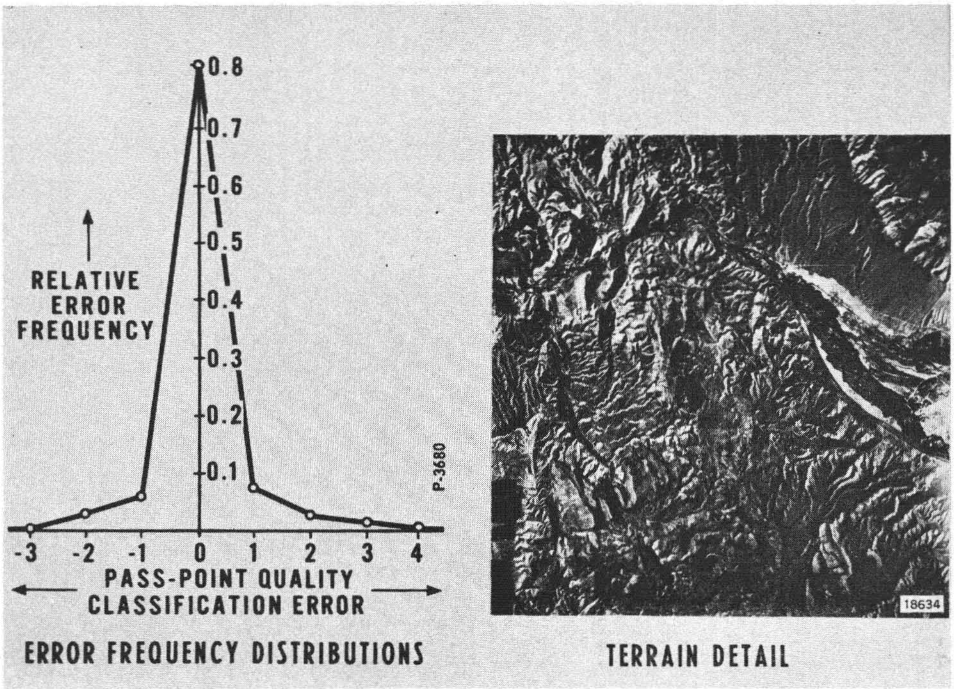


FRONTISPIECE. Example of pattern classification accuracy. (*See page* 839)

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# Automatic Pass-Point Selection

**Breadboard measurement and recording equipment provided data with the remainder of the trainable system being simulated on a computer.**

## INTRODUCTION

UNDER CONTRACT TO THE U. S. Air Force, Rome Air Development Center, Bendix Research Laboratories has developed trainable logic techniques for automatic pass-point selection. The selection techniques have been incorporated in the design of a system to evaluate and select pass-points for subsequent use in automatic point-transfer instruments. For each desired pass-point, the system searches a designated photograph area, selects the best pass-point in that area, and records the coordinates of that point along with a measure of its quality.

## SELECTION REQUIREMENTS

In the conventional process of pass-point selection and transfer, pass-points are selected, precisely located, and transferred by a human operator. The recent development of automatic equipment for locating and trans-

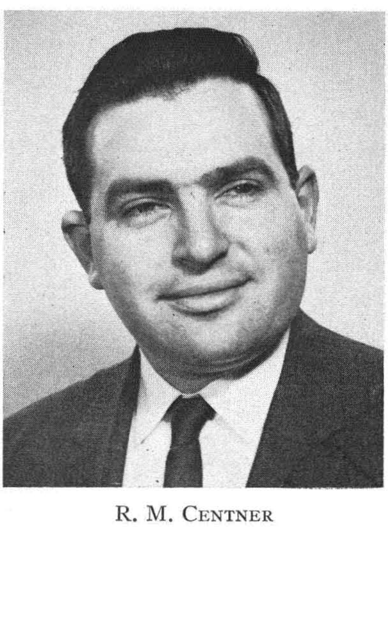
* Presented at the Annual Convention of the American Society of Photogrammetry in Washington, D. C., March 1966 under the title "A Trainable System for Automatically Selecting Photographic Pass-Points."

ferring points by means of electronic image correlation has produced the need for a specialized selection process for such equipment. This process differs considerably from conventional methods of pass-point selection. Several reasons for the differences may be noted. First, a human observer is able to focus his attention on a single point or detail in his field of view, whereas image correlation equipment scans and uses all of the detail in a small area. Second, a human observer is able to recognize and compensate for differences in perspective due to sharp relief, such as that due to buildings or trees. This ability is not available in state-of-the-art image correlation equipment, and it would be quite difficult to provide in future equipment. Finally, a human observer can recognize and either ignore or compensate for differences in image appearance due to daily or seasonal changes. Examples of such differences are shadows, reflections, and changes in foliation and agricultural patterns. Image-correlation devices see such differences as noise which lowers the accuracy of correlation.

Due to differences in the way in which a human observer and image correlation equipment match conjugate imagery, it is apparent that the selection of optimum imagery to be used for automatic transfer should include an analysis of the correlation properties of the imagery. The design of an automatic pass-point selector which performs such an analysis is the subject of this paper.

An ideal pass-point has properties which allow it to be accurately transferred to a variety of overlapping photographs. The overlapping photograph may differ from the photograph on which the pass-point was selected in scale, geometry, and exposure conditions. The differing exposure conditions may cause the appearance of the imagery to differ in the two photographs due to exposures at different times of day and at different times in the year. Automatic transfer of points between photographs which contain such differences requires that the automatic transfer instrument must have specific capabilities. To handle photographs with different scales, the transfer instrument must be capable of allowing the size of the areas scanned on the two photographs to differ by the ratio of the scale factors of the two photographs in order to match identical areas. The transfer of points between photographs with different geometry requires that the transfer instrument have the capability to independently shape and scale the two scan patterns. Differences in the appearance of the imagery in the two photographs which are caused by different exposure conditions cannot be compensated for by the automatic transfer instrument. Consequently, an ideal pass-point

ABSTRACT: *Under the sponsorship of Rome Air Development Center, Bendix Research Laboratories has developed experimental techniques for automatically selecting pass-points. The selected points are to be matched, or transferred, by means of image correlation techniques; hence the criteria for selection differ considerably from the criteria for points which would be transferred visually. The experimental techniques employ trainable, adaptive logic to evaluate pass-point quality on the basis of image parameters such as spatial frequency, contrast, correlation sensitivity, and terrain roughness. For each desired photograph area, the coordinates of the best pass-point are recorded, along with its quality weighting factor, for use in point-transfer operations or analytical adjustment procedures.*



R. M. CENTNER

must have characteristics which makes its appearance essentially invariant to differing exposure conditions.

To perform an accurate transfer of a pass-point using image correlation equipment, the image area which defines the pass-point must contain the following characteristics.

- High spatial-frequency components, which indicate that ample detail is present.
- A high value of cross-correlation, which indicates a high degree of similarity between the two photographic records.

The presence of these characteristics allows the correlation equipment to produce strong image alignment signals, thus permitting accurate measurement of the coordinates of conjugate images.

The fact that an area, instead of a point, is used in the image correlation process introduces the factors of terrain slope and roughness as potential error sources which would affect pass-point quality. It is possible to adapt the scanning process to terrain conditions by correcting for average terrain slope. However, these compensations may produce an accurate transfer of a given pass-point to only a portion of overlapping photographs containing the point. Thus, terrain slope should be considered in the selection of an optimum point for transfer to a wide variety of overlapping photographs.

From the preceding discussion, it is apparent that the principal characteristics which affect the quality of the image area to be used for transfer by image correlation equipment are as follows:

- Correlation properties of the imagery
- Average terrain slope
- Terrain roughness and curvature
- Image permanence, or the probability that the appearance of the imagery will not change with time.

An ideal pass-point will have good correlation properties, the terrain slope and terrain discontinuities will be small, and the image permanence will be high.

## Measurement Techniques

To developmeasures of the above characteristics, the automatic pass-point selector uses a stereo pair of photographs. Image quality is evaluated for one of the photographs, with the second photograph used only to obtain stereo information. The size of the area to be used as a pass-point is determined by the scale of the photograph in relationship to the scan size limitations of the automatic transfer device on which the points would be transferred. For small scale photography, a small area would be used, while a large area would be used for large scale photography.

The important correlation properties which are measured consist of the peak value of the cross-correlation function and a measure of the slope of the orthogonal-correlation function in the $X$ and $Y$ directions. These measurements determine the quality of the image match and the sensitivity of signals which control the positioning of the photographs. These measurements are exact for this particular stereo pair, and are therefore used as estimates of the average measurements for the variety of photographs which contain the same point.

The average terrain slope for the area scanned is obtained from measurements made of the scan shaping used to provide the best match. These measurements, combined with the stereo model position information, allow the average terrain slope of the area scanned to be computed.

A measure of the terrain roughness and curvature is obtained by making several relative elevation measurements around the center of the scan area. The variance of these measurements is used as a quality indicator of this characteristic.

A more difficult characteristic to measure is the image permanence, or the probability that the appearance of the imagery will not change with time. Measuring this characteristic is a pattern recognition and classification task. The techniques which have been developed to perform this task involve measuring the information content in the video signals obtained from the area scanned and computing the permanence from this information by means of trainable threshold logic techniques.

To design or train a pattern recognition computer to determine the pass-point quality of an image area, information on a large number of randomly selected potential pass-points was collected. The information collected for each potential pass-point included:

- Measurements of the correlation properties
- Measurement of the average terrain slope
- A measure of the terrain roughness and curvature
- Measurements of the image density statistics
- Measurements of the image spatial frequency statistics
- A measure of the modulation index of the scanned signal

These measurements were made on each of the potential pass-point areas, and the same area was given a permanence class by visual

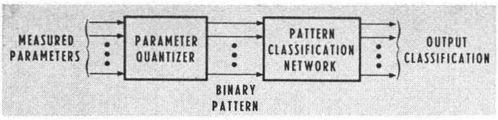



FIG. 1. Pattern recognition approach.

examination. Each area was classified as one of the following four classes: (1) cultural, (2) barren, (3) wooded, and (4) cultivated. The cultural class includes man-made objects which produce patterns containing straight lines and intersections of straight lines. This class of imagery was defined as having the highest permanence. Imagery classified as barren would have an intermediate permanence, and the wooded and cultivated classes were assigned low permanence factors.

The visually obtained permanence classification is combined with the measurements of the correlation properties, the measurement of the average terrain slope, and the measurement of the terrain roughness to produce an estimate of the pass-point quality, or figure-of-merit, of each point. The figure-of-merit classification network is designed to reproduce these quality values from the measurements. The following sections describe the design of this figure-of-merit computation.

## FIGURE-OF-MERIT COMPUTATION

A simplified block diagram of the figure-of-merit computation is shown in Figure 1. There are two main subsystems, the parameter quantizer and the pattern classification network. The parameter quantizer accepts image parameter data and encodes it into a binary pattern. In addition to enabling the subsequent data processing to be digital, parameter quantization serves as a form of filtering to eliminate redundant or extraneous data, and thereby simplifies the figure-of-merit computation. An adaptive threshold logic network is then used to classify the binary output pattern of the parameter quantizer into a pass-point figure-of-merit category.

The parameter quantizer accepts video and stereo parameters from the measurement system and converts the set of analog values into a 30-bit binary pattern; this pattern may be viewed as a coded "signature" of the area being scanned. The quantization technique is not a conventional analog-to-digital conversion; each parameter is quantized into one or more bits by determining threshold levels which are statistically optimum on the basis of maximum information transfer. Selection of the threshold levels is made by a digital computer analysis of parameter data for a large number of image points for which the pass-point quality (figure-of-merit) is known.

Conversion of the binary data pattern into a measure of pass-point quality is accomplished by the pattern classification subsystem. This subsystem uses a group of nonlinear threshold logic circuits to examine the pattern and assign it to one of eight classes ranging from the lowest to the highest pass-point quality. The nonlinear threshold logic, developed at Bendix Research Laboratories, constitutes a unique approach which overcomes certain difficulties existent in conventional (linear) threshold logic. As in the case of parameter quantization, design of the pattern classification subsystem is accomplished by digital computer analysis of a large quantity of experimental data.

The following paragraphs present more detailed information on the design of the parameter quantizer and pattern classifier subsystems. As indicated previously, design information is obtained from recorded parameter data for a large number of experimental image points. An independent analysis of each point is used to provide an estimate of the actual pass-point quality, and the system is designed, or "trained," to reproduce these measurements as closely as possible. If the experimental points represent a statistically significant sample, then the designed system will be generally applicable to any imagery which has similar statistical properties.

### PARAMETER SELECTION AND QUANTIZATION

Before designing the parameter quantization subsystem, it is necessary to analyze the measured parameters and eliminate those which are either redundant or have low relative significance. Two methods that have been used for parameter evaluation are correlation analysis and quantization analysis. Both of these methods can be implemented by digital computer processing of experimental data, and programs for this purpose have been written and successfully applied.

Correlation analysis entails the computation and analysis of a matrix of quantities known as correlation coefficients. These coefficients indicate the strength of the linear relationship between parameters. Parameters that are strongly correlated tend to be redundant; that is, they contribute essentially the same information. The significance of a parameter can be estimated by its correlation with the actual figure-of-merit values which are determined by independent analysis. The

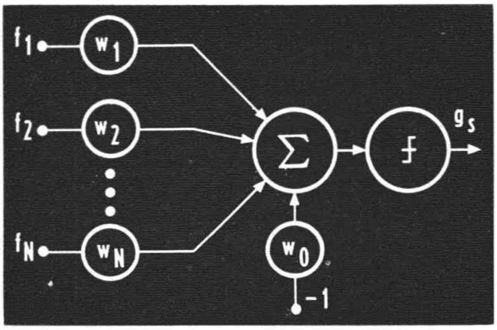



FIG. 2. Linear threshold logic circuit.

correlation analysis method thus enables an initially large set of potential parameters to be reduced to a smaller and more manageable set, while assuring that no important information is lost.

A further reduction in the number of measured parameters is effected by application of a computer program to determine optimum analog-to-digital conversion factors. This program performs the dual function of both evaluating parameters and designing the parameter quantizer.

The parameter quantizer is essentially a filter which extracts significant data from a set of analog-valued input parameters. The quantizer encodes the values of the various parameters according to statistically determined quantization levels. These quantization levels are the values at which the bits representing the parameter will undergo transitions. For example, in the quantization of a measured parameter $P_m$, the value of a given bit $f_n$ at the output of the quantizer is given by

$$f_n = +1 \quad \text{if} \quad P_m \geq \theta$$
$$f_n = -1 \quad \text{if} \quad P_m < \theta$$

where $\theta$ is a quantization level for the parameter $P_m$. The optimum set of quantization levels for a given set of measured parameters is one for which the output pattern contains a maximum of information indicative of the actual classification of the measured sample.

The computer design program uses a statistical analysis technique to calculate a measure of the figure-of-merit information contributed by each potential quantization level. By this means it is possible to obtain an ordered list of the specific quantization levels which contribute the most information. If, for example, it is desired to obtain a 30-bit pattern at the quantizer output, the 30 best quantization levels are simply selected from the ordered list. The list also provides a final selection of parameters, since it is only necessary to use the parameters which correspond to the 30 quantization levels.

In the pass-point selector design, over 50 parameters were recorded during initial experiments. The correlation analysis method was first used to reduce the set to 24 parameters. Application of the parameter quantizer design program indicated that the best 30 quantization levels could be obtained from 11 of these parameters, and these became the final set. Some of the final parameters may be encoded into four or five bits, and others into only one bit. The main point is that each parameter is encoded in a manner that will transmit the most useful information to the pattern classification subsystem.

## PATTERN CLASSIFICATION BY THRESHOLD LOGIC

To determine a pass-point figure-of-merit value from the binary pattern output of the quantizer, some type of pattern classification network is required. The term "threshold logic" defines a class of logic networks that are particularly well-suited to this problem. Such networks have the property of being "trainable," that is, the network can be externally adjusted to produce desired classifications without physical re-wiring. The network can therefore be trained to adapt to changes in problem conditions, as for example different types of photograph data. The following paragraphs contain a brief description of two approaches to threshold logic which have been considered for the figure-of-merit computation. These are designated as linear threshold logic and nonlinear threshold logic, respectively. For reasons given below, the nonlinear threshold logic approach was chosen for detailed investigation in the pass-point program.

In discussing linear and nonlinear threshold logic, it is convenient to deal with inputs that have values of "+1" or "−1", rather than the usual "1" or "0". In a linear threshold logic circuit, each input to the circuit is weighted, that is, multiplied by a quantity called a weight. If the analog sum of these weighted inputs is greater than or equal to a quantity called the threshold, the circuit produces a "+1" output. Otherwise, the circuit produces a "−1" output. Schematically, it is customary to represent a linear threshold logic circuit in the manner shown in Figure 2. In this figure, the weights are represented by the symbols, $w_1$, $w_2$, $\cdots$ $w_N$, and the threshold is represented by the symbol $w_0$. The inputs, for illustration purposes, are assumed to be the outputs of the parameter quantizer, $f_1, f_2, \cdots f_N$.

Previous studies of this type of logic have been directed towards the development of techniques for externally adjusting the circuit weight to realize a particular set of input/output relationships. Such techniques are known as training algorithms, and algorithms for single, linear, threshold logic circuits have been developed with some success. However, for large numbers of variables, a single linear circuit can correctly classify only a small percentage of the total possible number of logic functions. The only method of classifying more functions with the linear threshold logic approach is to combine several circuits in various networks. However, when several circuits are used, the training algorithm becomes much more complex. Thus, the linear threshold logic approach is severely handicapped in large-scale systems.

To overcome these disadvantages of linear threshold logic, a nonlinear logic technique has been developed. This approach appears to offer a significant improvement over linear threshold logic in the number of functions that can be classified, and particularly in ease of training. For these reasons, it has been applied in the pass-point selection program. The nonlinear threshold logic circuit differs from the linear form in the presence of an element known as a variable cross-multiplier stage. This stage is placed between the input variables and the weights, as shown in Figure 3. The outputs of the variable cross-multiplier stage, $B_1, B_2, \cdots B_Z$ are independent cross-products of certain combinations of the input variables. These cross-products are weighted, and the weighted sum of the cross-products determines the circuit output.

The training algorithm that has been developed for the cross-product approach includes a means for selecting the input variables in each cross-product, and also for selecting an appropriate weight for each cross-product. The algorithm is based upon the compilation of statistical parameters relating to the cross-correlation of each potential cross-product term with the desired network output. This data permits the selection of an optimum set of cross-product terms having the best correlation with the desired output classes, and it also provides information to determine the weight of each cross-product term.

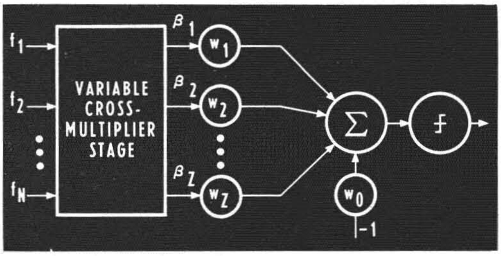



FIG. 3. Nonlinear threshold logic circuit.

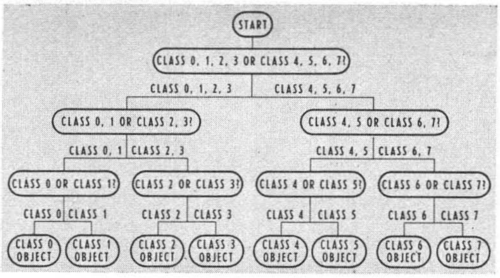



FIG. 4. Decision-tree classification procedure.

As indicated in Figures 2 and 3, a single threshold logic circuit provides a two-valued output decision of the "yes-no" type. In order to obtain more than two levels of figure-of-merit classification, a group of threshold logic circuits is connected in a decision-tree configuration. One type of simple decision tree for detecting eight levels of pass-point quality is shown in Figure 4. In practice, more complex trees are generally used to provide a degree of redundancy in the final decision. It should be noted that implementation of a decision tree does not require a large group of physically separate threshold logic circuits. A single time-shared circuit can be used repetitively, with weights and cross-product terms for each part of the decision tree stored in an external memory.

Results obtained from application of the nonlinear threshold logic and decision tree concepts to experimental pass-point data have been quite encouraging. The Frontispiece illustrates a typical error distribution for 160 test points obtained from a portion of mountainous terrain. The figure-of-merit was classified into one out of eight groups. Figure 5(a) shows that approximately 80 per cent of the points were classified correctly, that is, the classification network produced the same figure-of-merit class as the independent analysis of the point. Also, better than 95 per cent of the points were within one class of the correct value.

## SYSTEM DESIGN

A basic block diagram of an automatic pass-point selection system is shown in Figure 5. The inputs to the system are the master

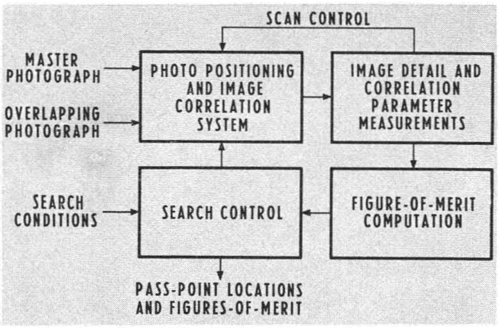



FIG. 5. Automatic pass-point selection system.

photograph, the overlapping photograph, and the search conditions. The search conditions include the boundaries of the area to search, the number of pass-points to select in the area, the minimum acceptable figure-of-merit class, and the size of the pass-point image area to be used. The output of the system consists of the photo coordinates of the selected pass-points and their computed figures-of-merit.

The overall control of the pass-point selection system is contained in the block labeled Search Control. Here a control program specifies the photograph coordinates of the points to be sampled within the boundaries of the search area. The control program conducts a coarse uniform sampling of the area, recording the location and figure-of-merit class for all points with a figure-of-merit above the minimum acceptable class. The coarse search is terminated when the entire area has been sampled or when the required number of pass-points are found which have a figure-of-merit class equal to or better than the minimum acceptable class. Upon completion of the coarse search, a fine search is conducted about each of the selected points to determine if a better pass-point exists in the immediate vicinity of each of the initially selected points.

The photo positioning and image correlation system performs the function of positioning the photographs to the point specified by the search control program so that the necessary measurements can be made in order to compute the figure-of-merit for that point.

The circuits which perform the function of measuring the parameters which are used by the figure-of-merit computer are included in the block labeled Image Detail and Correlation Parameter Measurements. The figure-of-

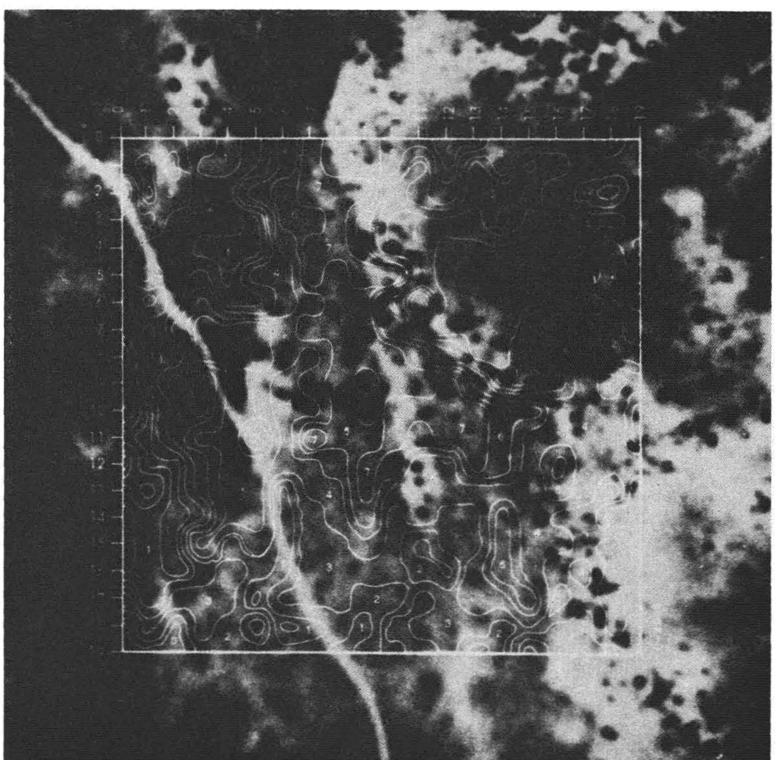


FIG. 6. Sample search area with overlay showing contours of pass-point figure-of-merit values.

merit class for each point is determined from the measurement by the figure-of-merit computer, which has been previously described.

Figure 6 shows a typical image area which was used to simulate search strategies. The contour lines superimposed over the imagery enclose areas with the same figure-of-merit class. The information which was used to draw these contours was obtained by making measurements at 400 uniformly spaced points in the area and computing figure-of-merit values for each point. The results of using a coarse-fine strategy in this area can be illustrated by an example. If a coarse search involving 25 uniformly spaced samples is made, four points having a figure-of-merit above 5 can be found. If fine searches are then made in the vicinity of each of these four points, three points can be found having a figure-of-merit of 7, which is the highest figure-of-merit class.

### Conclusion

Use of an automatic pass-point selector provides two features to improve the accuracy of subsequent triangulation and adjustment operations. First, it provides assurance that the best possible pass-points are used, and secondly, the figure-of-merit values can be used to determine weighting values for each point which is used in the adjustment calculations.

In the automatic pass-point selection development, image parameter data were collected on breadboard measurement and recording equipment, with the remainder of the system being simulated on a general-purpose digital computer. The results of the simulation have shown the feasibility of a fully automatic, on-line selection system. Such a system can be implemented either as an independent instrument or as an addition to an automatic point-transfer instrument.

The use of trainable logic techniques provides an ability for the system to improve its performance with time, based on feedback data on the success of subsequent operations with the selected pass-points. The trainable logic can also be easily adapted to utilize different selection criteria for different types of photography or for different end uses for the selected pass-points.

### Acknowledgment

A large number of people have contributed to the development of the automatic pass-point selection system. In particular, the authors wish to acknowledge the contributions of Messrs. Joseph Diello and Frank Scarano of Rome Air Development Center, and Messrs. V. C. Kamm, A. E. Whiteside, E. D. Hietanen, and D. C. Kowalski of Bendix Research Laboratories.

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## ERRATA

In the article Hallert, "Quality of Exterior Orientation," in the May 1966 issue:

In the fourth line from the bottom of page 476, the term $c$ should appear in place of $r$, and $s_c$ should be used in place of $s_r$ in all instances on pages 466 and 467.

The weight-and-correlation numbers shown in Table 1 refer to nine regularly located orientation points. The following expressions should be used:

$$Q_{by_2by_2} = (2/3) + (h^2/d^2) + (3h^4/4d^4)$$
$$Q_{by_2\omega_2} = (3h^2 + 2d^2h)/4d^4$$
$$Q_{bz_2bz_2} = h^2/2d^2$$
$$Q_{\omega_2\omega_2} = 3h^2/4d^4$$

but the other terms in the table are unchanged.

The first equation on page 470 should end:

$$\cdots)]^{1/2} = s_{\bar{\phi}_2}.$$

(*Continued on page 848*)