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The Design of Advanced Digital Image Processing Systems

There is an increase in the use of digital computers to process images. Much more complex image transformations can be performed with this method than with analog methods.

INTRODUCTION

DURING THE PAST few years digital computers have increasingly been used to manipulate images. [1,2,3,4,5] The present article reviews the nature of these rapidly evolving digital systems. Image processing applications have special requirements which they impose on the designer of such systems and these are also considered.[6] This article is introductory in nature and the information contained herein is addressed to the user rather than the designer of digital image processing systems.

ABSTRACT: *Digital computers are being used to an increasing degree to process images. The principal stimulus for this application of computers is their ability to perform much more complex image transformations than have been possible in the past when using analog methods. Digital input/output equipment is being improved to achieve higher speeds and to provide increased spatial and gray-scale quantization consistent with photogrammetric requirements. Special-purpose microprogrammable image processors are being developed which are more than two orders of magnitude faster than today's general-purpose computers. The ability to produce cost effective solutions has only been partially demonstrated, but significant progress is being made today for applications involving large volumes of imagery. Because digital computers are capable of automatically extracting new kinds of information and of performing imagery transformations never before possible, prior economic considerations based on analog methods are in many cases no longer valid.*

As shown in Figure 1 there are basically three design forcing functions. The first of these is the rate at which digitized imagery data must flow through the system. This is determined by the nature of the digital encoding of the scene. The second is the complexity of the image transformation itself and the third is the nature of the output required by the user. The equipment fulfilling each of these three requirements is in a somewhat different state of technological evolution. Furthermore, one needs to differentiate between on-line and off-line operation when evaluating various system configurations.

If we step back in time and examine image processing from an historical point of view, we see that we are dealing with an old and highly developed technology which is intermixed with a good deal of analog art. Photography is almost 150 years old and during this period the design of optical systems and the development of photo-chemical processing techniques for the recording of imagery information has progressed continuously. Exacting requirements from the fields of astronomy and cartography have led the way in stimulating the development of advanced analog systems. Techniques have been continuously refined to measure the geometrical

FIG. 1. Factors which influence the design of digital image processing systems.

and gray-scale properties of the information stored on the photographic film. Systems involving precision lead screws and microdensitometers have been at the leading edge of this technology. The product of these efforts has been the science of photogrammetry.

Whereas analog methods have proven capable of *recording* information on a photographic film they have always left something to be desired in the field of *controlling* the generation of new imags. For example, in creating mosaic images using classical techniques the edge lapping problem has never been adequately solved. The implication of this experience is that more degrees of freedom are needed, mathematically speaking, in the geometric restitution process. In particular, correlation techniques are needed to perform the edge matching to a much higher degree of accuracy than has hitherto been possible. These complex map warp transformations must be accomplished at a level of accuracy comparable to resolution of the imagery itself. From the point of view of densitometry, the analog process of generating new images with a modified mean density and contrast leaves even more to be desired and it is still extremely difficult to introduce controlled nonlinear gray-scale transformations. The precision control of geometric and radiometric transformations represent areas where digital technology has much to offer.

In a complex field such as the one under consideration, one needs to be somewhat cautious in making generalizations concerning the relative merits of analog and digital techniques. When one considers accuracy, there is little doubt that classical analog techniques for the measurement and generation of film images are still superior. Improved digital encoding and display equipment is needed to handle the large amount of information contained on a high resolution photographic film. This is not the case, however, in the area of image manipulation where digital techniques are already superior to analog methods. This proves to be the case, in part, because the digital methods are superior in their ability to perform complex transformations. Analog image processing methods, *such as optical Fourier transforms*, are superior to digital techniques when it comes to speed. This does not include the time necessary for film development, which is commonly needed for both analog and digital methods. When electro-mechanical control systems are required as a part of analog equipment, generally this equipment is slower than a purely digital system performing the same transformation. Speed thus depends on the exact application and in some cases analog methods are faster and in others digital techniques are superior.

Finally, in the area of information extraction, digital techniques come strongly to the fore.[8] Since they can be made almost completely automatic it is not necessary to employ dozens of skilled workers at the tedious process of manually measuring various image features. Not only can the digital techniques automatically provide statistical summaries but they can create new images containing the original information in conspicuously modified form. With this powerful capability an image analyst, such as an agronomist or a geologist or a meteorologist or even a radiologist, can devote his effort to the more complex and challenging pattern recognition and interpretation problem.

USER REQUIREMENTS

In the United States approximately 25 billion frames of imagery are created each year. Approximately 15% of this quantity is related to industrial, scientific and medical applications. Depending on just how effective digital image processing techniques prove to be in extracting information, it is estimated that 5% to 20% of the industrial, scientific and medical images will be processed digitally within ten years. This admittedly is only an estimate but, regardless of the exact numbers, the potential is very large being roughly *400 million frames per year under these assumptions*.

It is obvious that this very large digital image processing market will not develop without cost effective solutions. But the cost per computation, for general-purpose computing (adjusted for inflation) has dropped by a factor of almost ten in the last ten years and is continuing to drop. Considering the problem of digital image processing, by employing special-purpose microprogrammable computing systems which are designed to achieve a high efficiency when processing imagery, very substantial further reductions in the per frame processing cost are achievable. For systems involving large volumes of imagery and dedicated special-purpose processors, a gain in cost effectiveness of almost one-hundred now appears possible. Regardless of the exact projection used, the enormous user potential coupled with the increasing efficiency of digital systems is creating a very rapidly growing market.

Who will the users of the next generation digital image processing systems be? What kind of applications can be expected to develop most rapidly? What are the user's needs? Because of the large amount of image applicational research which is now underway, answers to these questions are beginning to emerge.

Today the DOD interest in military surveillance and reconnaissance and the NASA-ERTS interest in the remote sensing problem represent the largest areas of application. Within five years medical applications will be very nearly comparable in size. A few years later, industrial applications will become significant. Tables 1 and 2 represent an attempt to list some of these applications.[8-13] These are classified according to the value of the ratio of scene size to image size, and are called Macro-Scale, Meso-Scale and Micro-Scale. A fourth category is called Non-Pictorial Source Data.

The Macro-Scale applications are those in which an earth directed sensor is carried on board an aircraft or a satellite. The Meso-Scale applications are those in which the ratio of the size of the image to the size of the object ranges from about 1:1000 to 1:1. These include ordinary close up photography and most industrial and medical applications. The Micro-Scale applications are those in which the object is smaller than the image such as the images produced using the techniques of photomicrography. The Non-Pictorial Source Data represent cases in which the values in a matrix contain underlying patterns of visual interest, even though they are not derived in any way from actual images.

Digital image processing systems for these applications all have in common the problem of manipulating a large matrix of gray-scale values. Primary interest for the digital designer centers on the size of the matrix, which typically ranges from 300 × 300 to 30,000 × 30,000 picture cells. That these images differ in spatial quantization by 10,000:1 is significant to the designer of such systems because digital memory cost may be a significant fraction of the total system cost. The gray-scale word length is typically eight bits in length, thus permitting 256 gray levels to be encoded. Variations in gray-scale word length of a few bits one way or another have a relatively minor effect on the system cost.

The functions which are performed by the digital processor can be classified in the manner shown in Table 3. This subdivision is based on numbers of images which must be correlated to complete the task in question. When a single image is processed by itself the transformations shown in the left hand column are commonly employed. When pairs of images are driven into geometric and gray-scale registration functions of the type shown in the middle column are employed. When more than two images must be processed to extract the desired information the applications shown in the right hand column apply. Often equipment which is designed to

TABLE 1. DIGITAL IMAGE ANALYSIS: MACRO-SCALE APPLICATIONS

APPLICATION	PRIMARY USER
AGRICULTURE • CROP EVALUATION • DISEASE PROPAGATION	FEDERAL AND STATE GOVERNMENT
ASTRONOMY • POSITIONAL ASTRONOMY • PHOTOMETRIC ASTRONOMY • BALLISTIC STREAK CAMERAS	UNIVERSITIES
ENVIRONMENT • THERMAL/CHEMICAL POLUTION OF WATER OR ATMOSPHERE	LOCAL GOVERNMENT
GEOLOGY • MINERAL RESOURCES EVALUATION • GEOLOGICAL FORMATIONS • CARTOGRAPHIC RENDITIONS	FEDERAL AND STATE GOVERNMENT/INDUSTRY
MAPPING • UPDATING • TOPOGRAPHIC • SUPERPOSITION OF PHOTOGRAPHY AND MAPS	FEDERAL GOVERNMENT/INDUSTRY
METEOROLOGY • CLOUD PATTERNS	FEDERAL GOVERNMENT
NAVIGATION • ALTIMETER MAPS • RADAR MAPS	FEDERAL GOVERNMENT
OCEANOGRAPHY • OCEAN FLOOR STUDIES	FEDERAL GOVERNMENT/UNIVERSITIES
PETROLEUM • GEOLOGICAL FORMATIONS • SEISMIC RECORDS	INDUSTRY
RECONNAISSANCE • PHOTOGRAMMETRY • STEREO RECONSTRUCTIONS • CHANGE DETECTION • MICRO STEREO • TARGET RECOGNITION	FEDERAL GOVERNMENT
SEDIMENTOLOGY • EROSION AND RIVER SEDIMENTS	FEDERAL GOVERNMENT
SPACE EXPLORATION • SURFACE FEATURES OF EXTRA TERRESTRIAL PLANETS	FEDERAL GOVERNMENT
URBAN PROBLEMS • TRAFFIC FLOW PATTERNS • RESIDENTIAL AND INDUSTRIAL GROWTH PATTERNS • NEW CONSTRUCTION (FOR TAX PURPOSES) • LAND USE ANALYSIS	STATE AND LOCAL GOVERNMENT

TABLE 2 DIGITAL IMAGE ANALYSIS: MESO-SCALE APPLICATIONS

APPLICATION	PRIMARY USER
BIOMEDICAL • X-RAY PHOTOGRAPHS	UNIVERSITIES/MEDICAL PROFESSION
PHYSICS • BUBBLE CHAMBERS • DIFFRACTION PATTERNS	UNIVERSITIES/ATOMIC ENERGY COMMISSION
ENGINEERING • STRESS PATTERNS • HYDRONAMICS • CHANGE, IN HIGH SPEED PHOTOGRAPHY • EVALUATION OF INTEGRATED CIRCUIT FABRICATION	INDUSTRIAL RESEARCH
LAW ENFORCEMENT • FINGERPRINTS • FACIAL IDENTIFICATION	FEDERAL AND LOCAL GOVERNMENTS
PUBLISHING • NEWSPAPERS • MAGAZINES • ADVERTISING	PRINTING INDUSTRY

TABLE 2B. DIGITAL IMAGE ANALYSIS: MICRO-SCALE APPLICATIONS

APPLICATION	PRIMARY USER
BIOMEDICAL • MICROTOME SECTIONS • CANCER CELL GROWTH • BLOOD CELL STUDIES • CELL STRUCTURE	UNIVERSITIES/ BIOMEDICAL
PHYSICS • CRYSTALLINE STRUCTURE AND GROWTH • PARTICLE STATISTICS	UNIVERSITIES/INDUSTRY
BIOCHEMISTRY • ORGANIC GROWTH	UNIVERSITIES/INDUSTRY

TABLE 2C. DIGITAL IMAGE ANALYSIS: NON-PICTORIAL SOURCE DATA

APPLICATION	PRIMARY USER
ECONOMICS • CONSUMER BUYING PATTERNS • INPUT/OUTPUT ANALYSIS	FEDERAL GOVERNMENT/INDUSTRY
MATHEMATICS • MATRIX ALGEBRA	UNIVERSITIES/INDUSTRY/GOVERNMENT
COMMUNICATIONS • STATISTICAL PATTERNS OF COMMUNICATIONS ACTIVITY	INDUSTRY
AGRICULTURE • CROP YIELD STATISTICS • RAINFALL STATISTICS	DEPARTMENT OF AGRICULTURE

TABLE 3. IMAGE PROCESSING FUNCTIONS

SINGLE IMAGES	DOUBLE IMAGES	MULTIPLE IMAGES
• GEOMETRICAL RESTITUTION • CONTRAST ADJUSTMENT • SPATIAL FREQUENCY FILTERING • GRADIENT IMAGE GENERATION • DEBLURRING • FEATURE EXTRACTION • GRAY SCALE FILTERING • SHADOW ENHANCEMENT • GLINT SUPPRESSION	• CHANGE DETECTION • TOPOGRAPHIC CONTOURING • IMAGE CORRELATION • ORTHO IMAGES • FEATURE ORIENTED PROCESSING • PHOTO-EQUALIZATION • SPATIAL MATCHING • IMAGE REPEATABILITY	• DYNAMIC PROCESS MODELING • FALSE COLOR IMAGES • COMPOSITE DATA BASE • MULTIPLE CHANGE ANALYSIS • 3D CORRELATION AND RECONSTRUCTION • GENERATION OF MOSAICS • BUBBLE CHAMBER DISTRIBUTIONS • MULTITEMPORAL CLASSIFICATION

process pairs of images can also be employed for multiple image problems. If this is not the case and if many images must be concurrently processed, the difficulty of the problem is considerably increased.

Digital image transformations vary widely in complexity and unless one selects a specific problem it is often very difficult to say which one of a number of alternative special-purpose computers is the best suited to a given class of problem. Furthermore, with a slight alteration of only one or two of the major subroutines it is often possible to increase the processing throughout significantly. Nevertheless, there is a need to characterize the complexity of a given digital image processing transformation.

This is commonly done in the following way. First a list of the types of operations is made. This includes all arithmetic operations such as additions (including subtractions), multiplications, divisions, square roots and transcendental functions—such as exponential, logarithmic and trigonometric transformations. It also includes various logical operations, such as conditional testing, transfer jumps and masking, which are commonly used in pattern recognition algorithms. The next step is to determine the number of times each of these operations must be performed to complete the processing of a given frame of imagery. Next, with reference to a particular special-purpose computer, the speed of each operation is reduced to the number of equivalent additions. Having reduced everything to a common denominator the total number of equivalent additions is computed. The number is finally normalized by dividing it by the number of picture cells (pixels) in the entire frame. After completing this step one now has the equivalent number of additive operations per pixel. This is a measure of the complexity on a given machine of the digital image transformation.

Because this exact number is dependent on the algorithm selected by the programmer and on the architecture of the particular digital computer which is employed it is not a number with absolute significance. In spite of this it is useful as a method of characterizing the complexity of an image processing transformation. Figure 2 shows the result of applying this technique to several specific problems. A typical frame of imagery might contain 10^6 picture cells. Thus an image registration problem or a simplified pattern

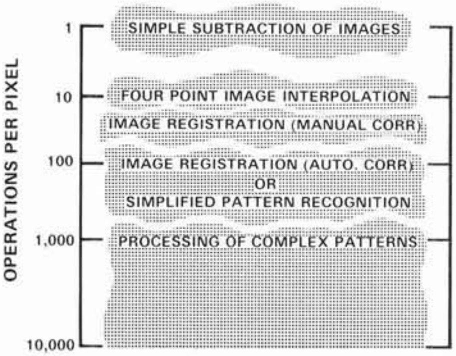


FIG. 2. Complexity of image processing.

recognition problem might involve 10^8 equivalent additive operations for the entire frame.[14-17]

Typically the rate at which imagery must be processed varies from 10^5 to 10^8 bits per second. Data from satellite communication systems provide roughly 10^8 bits per second. Off-line precision processing is considerably slower. In the case of aerial photographic imagery its exceptionally high resolution yields as many as 10^9 picture cells per frame and this in turn forces one to design for a very high digital throughput. For example, a digital image processing system which is capable of processing 10^6 picture cells/second may require more than 15 minutes to process a single frame of aerial photography. For many applications this is still too slow by a factor of ten. Lower rates can be allowed for the processing of X-ray imagery and values of 10^5 to 10^6 bits/second are acceptable. However, the complexity of the transformations employed in the digital image processing of medical imagery is often sufficiently great that the throughput problem is not significantly reduced.

To illustrate the effect of these rates on total frames processed per year Figure 3 is shown. For example, if a system can process one frame per minute and is operated an average of 20 hours per day for 250 days per year, then a total of 300,000 frames can be processed in a year. For some applications this is far short of the requirement. A case in point is provided by the example of chest X-ray images where approximately 180 million images are collected per year in the United States alone. If only 10% of these justify digital processing, a throughput of about 18 million images per year results. This means that sixty systems of the type referenced above would be needed. In certain military and industrial applications even more frames are produced per year so this example is not extremal.

As previously noted the images under consideration vary widely in the number of bits needed to capture the information which they contain. If one simply samples an image over a uniform grid and encodes the image in a straightforward manner the digital size of the image varies approximately as shown in Figure 4. The gray-scale word length varies from 4 to 10 bits. Taking the extreme values, the size of these images varies from a low of about 2×10^5 picture cells (pixels) to a high of 2×10^9 pixels. An optimal system for the low end of the scale, particularly in terms of the digital memory requirement, will be quite different from the system used at the high end of this scale. The large digital size of aerial photographs frequently forces one to subdivide the image and process each subsection separately in order to keep the memory cost down.

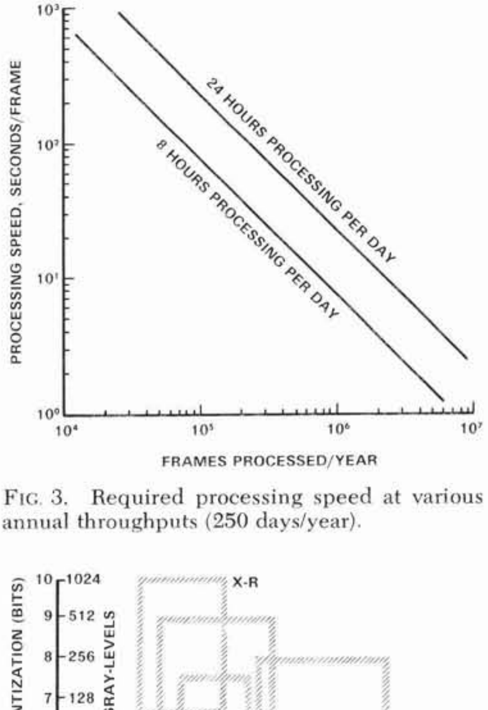


FIG. 3. Required processing speed at various annual throughputs (250 days/year).

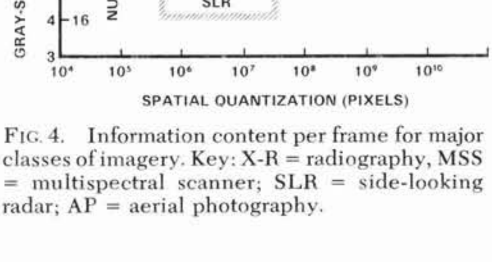


FIG. 4. Information content per frame for major classes of imagery. Key: X-R = radiography, MSS = multispectral scanner; SLR = side-looking radar; AP = aerial photography.

To circumvent, or at least to minimize, the problems associated with the large digital size of the images shown in Figure 4 there are several transformations which can be considered. Commonly these are used to minimize the required bandwidth of an associated communications system although, as was mentioned above, these steps also make it possible to store the digitized image on a smaller memory.

There are an almost infinite variety of types of data compression. Table 4 lists a few. The first method listed, called Huffman Encoding, is based on the frequency of occurrence of various gray levels and maps the original set of encoded levels from the scanner into a more compact set.[18] Huffman Encoding therefore requires a knowledge of the histogram of the gray-scale levels. The second method simply records the length of a run of the same gray-scale number. This is conveniently done one dimensionally along a scan line. It produces the greatest digital bandwidth compression when there is a limited amount of gray-scale information. The exact extent of data compression possible is very difficult to exactly specify but the example shown in Table 4 gives 2 to 8 for Methods 1 and 2. When a run-length encoded image or a Huffman encoded image is finally decoded the resultant image will be identical with the original—unless, of course, noise has been introduced into the system by some extraneous source.

For the case of Spatial Frequency Filtering this will not be the case, and the price of data compression is a degraded image. Presumably this modified image contains almost all of the information of potential interest to the user which was contained in the original image. The key issue is whether or not the features of interest can be characterized by a certain spatial frequency content. If they can, a large amount of data compression might be achievable with a minimum loss of relevant information.

Method 4 simply involves reducing the number of bits contained in the image matrix which is produced by the scanner. There are various methods of achieving this type of data compression but they all result in either a smaller matrix and/or a shorter gray-scale word.[19] Figure 5 illustrates this method and shows images which vary from 1 to 3 bits in gray-scale content and from 640 to 10,240 pixels in matrix size.

TABLE 4. METHODS OF DATA COMPRESSION

METHOD	TYPICAL EXTENT OF DATA COMPRESSION
1. HUFFMAN ENCODING	2^1 to 2^3
2. RUN-LENGTH ENCODING	2^1 to 2^3
3. SPATIAL FREQUENCY FILTERING	2^2 to 2^5
4. MATRIX COMPRESSION	2^2 to 2^8
INFORMATION EXTRACTION FOR APPLICATION IN QUESTION	$> 2^{10}$

In the case of Methods 1 through 4 of Table 4 all data compression steps are presumed to occur prior to performing the principal image processing transformation. The principal transformation itself will usually involve a very high degree of data compression and the residue will commonly either be an image with very little feature content or an alphanumeric summary of the statistical information content of the image.

At the extreme end of this spectrum is the answer to the question: "Does this image contain any information of interest?" Since the answer must be either "yes" or "no," the original image bit content will have been reduced to a one bit output. Although this special case evokes a simple answer and represents the highest degree of data compression for a given image, it should not be assumed that this final one bit answer will be easy to achieve in terms of the complexity of the required digital image transformation.

As a matter of philosophy it often proves to be efficient to use the digital processor for the

FIG. 5. Illustration of data compression through reduction of size of image matrix and truncation of gray-scale word length.

first stages of the information extraction process (or for the data compression process if one prefers to use this term) and then to use a human interpreter for the final and more complex stages of this process. In this way one uses the computer at the point in the process where there are a very large number of pixels and arithmetic operations to be completed—sometimes called number crunching—and one uses the human at the point where the amount of information to be handled is reduced to a minimum but where the complexity of the interpretation is at a maximum.

DESIGN CONSIDERATIONS

If one examines the types of digital image processing facilities in use today three principal configurations are found. These are shown in Figure 6. They are designed for different purposes and differ significantly from one another in their image processing throughput.

When the principal goal is experimental algorithm development a general-purpose computer has many advantages. This is shown as Processing Sequence 1 of Figure 6 and normally involves a tape to tape transfer for each individual image processing transformation. Because the programs are written in Fortran they are easily altered. Dozens or perhaps even hundreds of passes through the GP computer may be required in order to achieve the desired result.

When engaged in an image research problem the computer programmer has two problems. First, he must select the major image processing transformations and link them together to form an efficient processing sequence. Some transformations are order-dependent; others can be done in any order.

PROCESSING SEQUENCE	TYPICAL THROUGHPUT (FRAMES/DAY)	CHARACTERISTICS
(1) A/D→T→GP→T→D/A	10-100	GENERALLY GP IS INEFFICIENT ON IMAGE PROCESSING PROBLEMS. ALTHOUGH GP HAS MAXIMUM VERSATILITY, TURNAROUND IS NORMALLY SLOW WHEN NEW ALGORITHMS ARE BEING DEVELOPED.
(2) A/D→T→SP→T→D/A ↑ LOAD	100-1000	SPECIAL PURPOSE SYSTEM HAS HIGH POTENTIAL FOR THROUGHPUT. VERSATILITY IS ACHIEVED BY USING STANDARDIZED IMAGE PROCESSING SUBROUTINES ON MICROPROGRAMMABLE MACHINE.
(3) A/D ⟶ SP ⟶ D/A	1000-10,000	PRODUCTION IMAGE PROCESSING SYSTEM ELIMINATES TAPE DRIVES AS INTERMEDIATE MEMORY. SPECIAL PURPOSE PROCESSOR PERFORMS SAME TYPE OF TRANSFORMATION ON EACH FRAME OF IMAGERY.

FIG. 6. Image processing hardware configurations. Key: A/D = analog to digital; T = tape drive; GP = general purpose computer; SP = special purpose computer; LOAD = load microprogram from memory.

Next, once he is satisfied that the overall approach is correct, he begins a series of parameter optimization studies. Typically there are 10 to 20 principal processing parameters to which values must be assigned. Often it is very difficult to establish an even near-optimal set of values and the fact that the best set of parameter values is somewhat dependent on the particular scene being analyzed compounds this problem.

When statistical conditions are such that a greater cross-section of imagery must be examined as a prelude to the construction of a production image processing system, the general-purpose computer used in Processing Sequence 1 will be found to be inadequate. Furthermore, when the volume of image processing increases the other users of a computing facility can be expected to exert pressure for off-loading the GP. When this happens a dedicated image processing system of the type shown in Figure 6, Processing Sequence 2 may be justified. Systems of this type are just now emerging and they will significantly increase the rate of progress on problems of digital image processing as they become more extensively used.

Basically these systems consist of an array of microprogrammable special-purpose processors. Any one of 20 or 30 image processing subroutines can be loaded from disk storage into the micro-control memory. These subroutines may also be loaded from a host general-purpose computer. Since this is now a dedicated image processing system, the programmer can sit at the console and operate the system himself in what is called a hands-on mode. Normally the images being processed will reside on magnetic tape as shown at the left of Figure 7. He then performs the desired transformation and displays the modified image on a CRT as well as compiling statistical information on a printer. As shown at the right of Figure 7 he may also elect to produce a high quality hard copy image, if he feels that a particular image

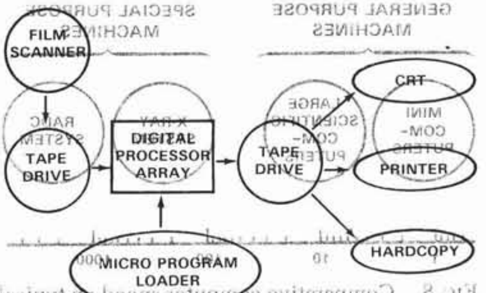


FIG. 7. Digital image analysis system.

merits preservation. If he is not satisfied with the image which appears on the CRT he simply introduces a new algorithm or new parameters and reruns the original image through the system.

By ping-ponging the image back and forth he can rapidly develop new image processing procedures. It is expected that systems of this type will permit the development of new techniques which are more than a factor of ten faster than is generally possible with today's general-purpose computers. This, in turn, will allow us to solve problems in a few months which now require several years.

When each frame of imagery can be subjected to the same digital processing transformation, a production system can be considered. Of course it is also a necessary condition that the volume of imagery be sufficiently large to justify the construction of such a system. It is difficult to establish the exact limits at which production type systems can be considered but, as shown in Figure 6, a daily throughput of at least 10^3 frames will probably be needed. A production mode is also sometimes justified when it is necessary to process data on-line as it comes in from a communications system.

Previously an example was given which involved 10^8 additive operations per frame processed. Aerial photographs commonly involve an even greater number of operations—10^{10} to 10^{11} per frame. With this large number of operations the question arises as to the suitability of general-purpose machines for image processing problems. Figure 8 provides an estimate of throughputs for several classes of computers. The two shown at the right are general-purpose machines. At the left the two systems refer to arrays of special-purpose microprogrammable machines which were designed specifically for image processing. The data path organization for one of these machines is described later. The X-ray system consists of four such machines arranged in a pipeline (serial) fashion; the RADC system consists of four parallel channels, each of which contains an identical parallel/pipeline configuration. It is to be noted that these special-purpose arrays of micro-programmable processors have a throughput capability which is in excess of 100 times the capability of the general-purpose systems. In the future one can expect this advantage to increase to a value of about 1000 times for processors of comparable cost.

Typically in image processing in terms of throughput, a pipeline array is needed more than is a parallel array. When pipelining an algorithm, which was probably originally developed on a general-purpose computer, it is partitioned serially and the compute load is divided more or less equally between processors. If the data rate is very high and if the complexity of the image processing transformation is also very high, situations can arise in which the problem cannot be handled with a single pipeline. Table 5 illustrates two cases, each of which involves 10^8 operations per second. This example shows that if the data rate is very high (say 10^8 pixels/second, as might be the case for imagery coming in off a wide band communications channel) and if the complexity of the transformation is very low (one operation/pixel in this case), then a parallel processor array might be appropriate. On the other hand, with only 10^6 pixels/second coming into the system and 10^2 operations/pixel a pipeline array would be appropriate. If an image processing system is to be sufficiently versatile, it must be constructed in a modular fashion which permits easy shifting from one pipeline/parallel arrangement to another.

To develop a better appreciation of the kinds of equipment needed for digital image processing it is instructive to compare this processing problem with that which is typically encountered in general-purpose com-

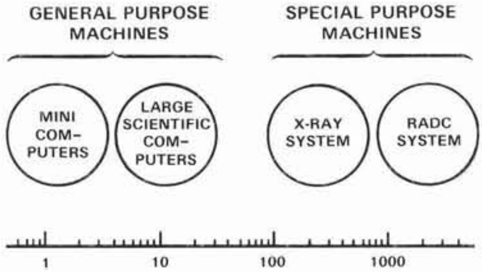
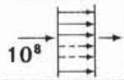


FIG. 8. Comparative computer speed on typical image processing problem consisting of image correlation, map warp and photo correction.

TABLE 5. MULTI-PROCESSOR EXAMPLE

	INPUT DATA RATE (PIXELS/SEC)	NUMBER CHANNELS	OPERATIONS / PIXEL	OPERATIONS / SECOND
PARALLEL 	10^8	10^2	1	10^8
PIPE LINE 	10^6	1	10^2	10^8

puting. The most obvious difference lies in the nature of the data itself. General-purpose computing facilities have been designed to provide whatever degree of accuracy the user desires in manipulating numbers. In the case of scientific data processing, input numbers requiring word lengths which are approximately 36 bits in length are commonly used. Typically these numbers are called "floating point" and have two parts: a mantissa and an exponent. In contrast, for digital image processing we are dealing with a large matrix of numbers which have been extracted from an analog image by a scanner so they start in analog form. After encoding, the word length is relatively short rather than the long words used as inputs to general-purpose machines. Typically eight-bit words are used and this permits one to encode up to 256 gray levels.

Since the image analyst is normally interested in "features" he is less interested in each discrete gray-scale number and much more interested in the values of contiguous arrays of numbers. Characteristically there is a high degree of overdetermination in the image information. Because of this, error rates which are as large as one in 10^6 can be tolerated whereas for general-purpose computing error rates must be held to less than one in 10^{11}. Finally, after all of the processing is completed the user is interested in creating a modified image and he must again transfer from the digital world to the analog world. Admittedly, he will also want to gather statistical compilations which characterize the image, but these are straightforward in terms of digital computing equipment.

The equipment needed for a digital image analysis center is shown in Figure 9. In terms of input/output devices the key contemporary issues center around the problem of achieving high speeds which are commensurate with that of the central processor. The major problems revolve around

- the degree of spatial quantization,
- the geometric accuracy of the spatial sampling and plotting, and
- the fidelity of the gray-scale quantization and plotting as related to detector and emitter noise.

Since the images are often large, digitally speaking, the cost of image storage devices can also be large. These devices commonly include tape units, disks and core storage. The manner of usage of these devices during the time the image is being transformed is of principal concern to the system designer in building a cost effective system.

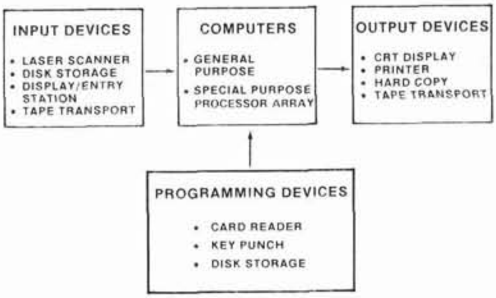


FIG. 9. Types of equipment needed for a digital image analysis center.

There are a number of analog-to-digital image converting devices available on the market today. These machines run the gamut from video cameras and CRTs to microdensitometers. Each of the devices has its advantages and disadvantages and merit utilization where qualified.

Video cameras are commonly employed when scanning devices of low resolution can be used. These devices have a high encoding rate and allow sample densities of from 500^2 pixels to 2000^2 pixels with approximately 5 bits or 32 levels of gray-scale resolution.[20] Some of these devices like the image disector or CRT scanner are capable of higher gray-scale resolution at the cost of longer integration times for each pixel and thus pay the penalty of reduced scanning rates.[21]

The other extreme in scanning resolution is the realm of the microdensitometers. These devices have resolution and positioning accuracies which get down to 1 μm. Again because of the integration time for each pixel these devices have an upper limit on scanning rate but can provide density values to an accuracy of between 8 and 10 bits (256 to 1024 density levels). The time to scan a 9" × 9" transparency with 25 μm spot diameter and sample interval can run approximately 15 hours for a very fast microdensitometer. Scanning 9" × 9" frames at even higher resolution with these types of machines becomes infeasible not because of the machine's limit but because of environmental changes to the image over the time period of the scanning.

Another class of scanning devices which has great potential for both speed and accuracy is the laser raster scanning device. These units have resolution capability down to about 6 μm and scan position accuracies down to 1 or 2 μm. Because of the laser power they are not restricted by the integration time for each pixel density measurement, however, the light source does have noise restriction and coherent interference problems which limit gray-scale resolution to between 6 and 8 bits (64 to 256 gray levels). The scanning rates of these devices are generally limited only by the ancillary data receiving units. Current laser scanners are easily capable of data rates of 10^6 pixels per second, and can scan 9" × 9" frame imagery in less than 5 minutes.

For many systems the image processing rate is determined by the response capability of the operator or the image interpreter. In these cases the selection of a suitable scanner is determined by factors extrinsic to the technology. For high throughput production systems the average processing rate is increased to the point where only laser or electron beam scanners become a viable image data input source.

There are a number of digital devices which are temporarily used for image input devices such as magnetic disk and tapes. These units are generally the recipient of the scanner data and retain the data for manipulation by the computers. They also are used as recipients for the computed results and thus fall into the category of output devices also.

In general, image output devices parallel the input devices. There are the CRT video devices which have the capability of matching the on-line processing speeds but have limited resolution and fidelity.[23,24] The microdensitometer class of image printers produce superb images at the cost of time and the laser printers produce fine imagery at on-line rates.

The principal advantage of the CRT devices is that they permit dynamic monitoring of a process. Detail may be viewed by zooming the image and subtle density variations are exaggerated artificially so that they are discernible.

The other output devices tend to be hard-copy plotters and suffer the delay of the photo development cycle. Thus they are relegated to the realm of permanent documentation output for the complete process.

For advanced image processing systems computing is tending to become distributed. Whether the basic unit is a small general-purpose computer or a special-purpose computing unit, the speed requirements for production processes are requiring parallel and pipeline configurations.[25,26] As a result, the computational units are becoming small, highly sophisticated computers capable of talking to each other in either a serial or parallel mode. These units are held together in a system by a supervisory computer whose primary task is the distribution of the work load. This is accomplished by identifying the next subsection of the desired process which can be made available to the next computational unit which has finished its present task. The supervisory computer may be any general-purpose machine capable of interfacing with a system of the computational units much in the sense of addressing of a peripheral device. Thus for a stand-alone system the supervisory machine tends to be a small general-purpose computer. When special-purpose image processors are in a satellite configuration the host computer may be any general-purpose machine.

The modular computational units must be capable of handling a high data throughput. These units essentially off-load the supervisory computer's limited image data handling capability. Thus they must be able to handle digitally large images and effecting a complete transformation upon the images as they are passed through.

Such a computational unit is represented by the Flexible Processor shown in Figure 10. This is a dual bus organized microprogrammed machine which has a 48-bit micro instruction. The micromemory word contains both bus decode and direct control functions which move operands between sources and sinks on the buses. The functional units, which are modular and thus selectibly removable in the hardware, feature high arithmetic computational rates, considerable character handling, an advanced input-output structure and semiconductor register file memories for data storage. Table 6 summarizes the characteristics of this machine.

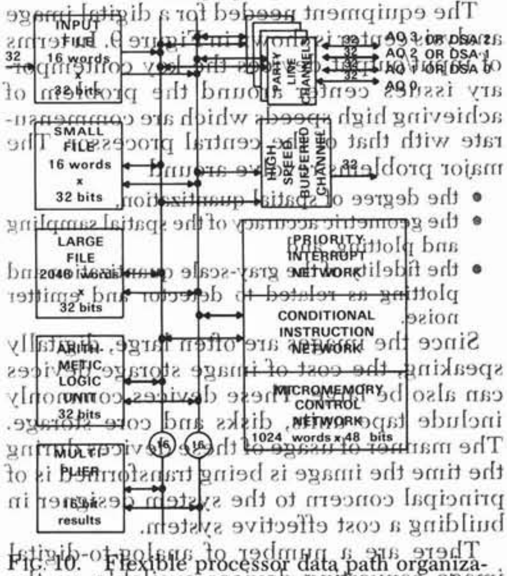


FIG. 10. Flexible processor data path organization. Key: DSA = direct storage access; AQ = one word buffer.

TABLE 6. FLEXIBLE PROCESSOR CHARACTERISTICS

- MICROPROGRAMMABLE — RANDOM ACCESS MICROCONTROL MEMORY
- 32-BIT OR 16-BIT WORD LENGTHS
- ARRAY HARDWARE MULTIPLIER
- 16 LEVEL HARDWARE PRIORITY INTERRUPT MECHANISM — 3 LEVEL MASK CAPABILITY
- SPECIALIZED LOGIC FOR SQUARE ROOT AND DIVIDE
- 8 mHz FILE BUFFERED WORD TRANSFER RATE — 16 WORD x 32 BIT OR 16 BIT INPUT FILE BUFFER
- 2 mHz DIRECT MEMORY ACCESS WORD TRANSFER RATE
- 1 mHz REGISTER-BUFFERED WORD TRANSFER RATES
- DUAL 16-BIT INTERNAL DATA BUS SYSTEM
- 0.125 μs CLOCK CYCLE
- 0.125 μs 32-BIT ADDITION; 0.250 μs BYTE MULTIPLICATION
- REGISTER FILE CAPACITY UP TO 4128 SIXTEEN BIT WORDS
- HARDWARE NETWORK FOR CONDITIONAL MICROINSTRUCTION EXECUTION — 4 MASK REGISTERS AND A CONDITION HOLD REGISTER

TABLE 7. RANGE OF VALUES OF DIGITAL IMAGE SYSTEM DESIGN PARAMETERS

	VALUES	UNITS	DYNAMIC RANGE
INPUT DATA			
• DIGITALLY ENCODED IMAGES	10^5 to 10^9	BITS/IMAGE	10^4
• DATA RATE	10^4 to 10^8	BITS/SECOND	10^4
EQUIPMENT			
• IMAGE TRANSFORMATION COMPLEXITY	10^1 to 10^3	OPERATIONS/PIXEL	10^2
• VOLUME OF IMAGERY	10^0 to 10^6	FRAMES/ALGORITHM	10^6
• ACCESS TO IMAGE	10^{-2} to 10^3	SECONDS	10^5
• PROCESSOR RAM MEMORY	10^4 to 10^8	BITS	10^4
OUTPUT DATA			
• DISPLAY INFORMATION	10^5 to 10^8	BITS	10^3
• FINAL APPLICATIONAL INFORMATION IN OUTPUT	10^2 to 10^6	BITS	10^4
ECONOMIC			
• COST OF DIGITAL PROCESSING SYSTEM	10^4 to 10^7	DOLLARS	10^3
• COST OF DIGITAL PROCESSING	10^0 to 10^3	DOLLARS/FRAME	10^3

ECONOMIC FACTORS

The size of the solution space for a designer of digital image processing systems is much larger than most people realize. Table 7 illustrates this for ten representative parameters used to characterize a digital image processing system. Because the range of possible parameter values varies so widely—two to eight decades—the system designer and the user must work together closely to realistically determine the final system specification. Because economic constraints are almost always tight, some basic questions need to be asked by a user before picking processing equipment. The term "advanced" in the title of this paper refers not only to raw compute power, but also to such factors as cost/performance ratio, software flexibility, the image transformation complexity and the peripheral equipment associated with a digital image processing system.

At the low end of the economic spectrum, such as is characteristic of a small university image research facility, one might find that the solution time is rather extended because the digital manipulation of the image is done on a small general-purpose computer, that scanning and display equipment with limited resolution forces the use of sub-frame sampling and that standard peripheral equipment associated with a university computing center is used for input/output. Occasionally a line printer is used for image output recording. At the high end of the compute power spectrum (and also the economic spectrum), one might find: on-line processing being done directly from wide bandwidth satellite-to-ground communication links, a dedicated special-purpose processor which is capable of very complex image transformations, and the use of very high resolution hardcopy output equipment which has an ability to produce color images. These two extremal cases can easily differ in the number of computer operations per second by as much as 1000:1.

At the low cost end of the spectrum equipment manufacturers are not yet able to respond adequately to the user's needs. This is due to relatively large total number of moderately costly individual pieces of equipment necessary to achieve a total image processing capability. At the other end of the spectrum, the technology is now available but the hardware is just emerging for a number of applications. Also, at this end of the spectrum one finds that the applications software is often inadequately developed even though the hardware is now available. Whereas (1) the university needs for research purposes are continual algorithm flexibility, low imagery rate, and a low-cost system, (2) the large governmental or industrial application usually requires less immediate algorithm flexibility, a very large imagery volume and a low per frame cost for production applications. By and large, equipment manufacturers have not yet adequately met user needs for either of these extremal cases.

From an economic point of view if this market is to be developed it is essential that digital equipment manufacturers first address the large volume problem. To illustrate this, consider the hypothetical example shown in Figure 11. Assume that we are dealing with the medical X-ray market in the United States and that our goal is to automate the process of image subtraction for purposes of detecting disease progression. Also assume that if we must charge \$1000 per frame processed, then there is an annual demand for only 100 frames per year. Presumably these would be insurance cases where there are a large numbers of dollars at stake and the progression of some industrially rated disease must be determined with extreme precision. On the other hand, if we are able to reduce our charge for digital processing to one dollar per frame, assume there is an annual demand for 100 million digitally processed frames per year. For intermediate costs per frame, assume that the price elasticity varies logarithmically as shown in Figure 11. The point of this example is now derived by computing the market size in dollars/year. At the highest price cited the market is only $100,000 per year whereas at the lowest price cited it has increased to $100 million per year. We believe that if digital image processing is to be widely used, the price per frame must be kept as low as possible—perhaps within a factor of ten or so of the cost of analog processing. There are many cases in which the information extraction advantage of digital processing is much greater than ten times that which can be achieved with analog methods and to the extent that this information extraction/cost ratio is superior the digital market will expand.

A summary of the costs for a recently configured image processing system is shown in Table 8. This system consisted of a small general-purpose computer plus several modular microprogrammable processors. It is perhaps surprising that the cost of the computers is only 16% of the total system price. The cost of the associated software is almost twice this value. Because image processing systems involve a large amount of specialized peripheral equipment, both at the input and the output of the system, this item is very large, being 42%. In this regard one method of reducing the system cost is to tie the image processing system into an existing computing facility thereby eliminating duplication of some equipment such as disks, tape drives and extended core memories. The last item shown in Table 8, System Integration, includes final system checkout, delivery and installation at the customer's site and the training of customer personnel.

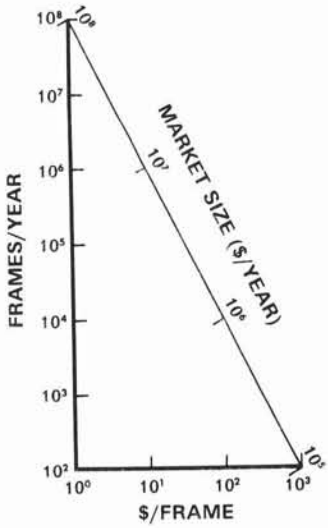


FIG. 11. Example illustrating dependence of market size on unit processing cost.

ILLUSTRATIVE IMAGERY

There are many types of digital image transformations and it is difficult to know how to select appropriate examples for the present article. Since our laboratory has concentrated on the problem of change detection, several illustrations of this type of image processing are given. In the case of these systems, images of the same scene taken at different times are correlated. One of the two images forms the reference and the other is digitally stretched to place the two in registration. If we are to achieve a low noise subtraction image later, the map warp must be performed to a very high degree of accuracy.[27,28] Next, the images are digitally photo-equalized by providing each with the same mean density and contrast. If the grayscale values differ non-linearly, more than two parameters must be included in the photo-equalization function. The photo-equalization function is not perturbed by changes in the scene or by shadow changes since only those pixels lying close to the photo-equalization regression line are used in this process. A biased tonal subtraction image is next created in which the condition of no change is shown as an intermediate shade of gray. Features which have increased in brightness are shown as brighter than the mid-gray level while those which have decreased in brightness are shown as a darker tone. Various enhancement techniques are then used to accentuate the changes.

TABLE 8. TYPICAL PRICING BREAKDOWN FOR IMAGE PROCESSING SYSTEM. BASIS: New system configuration. Hardware previously developed. System software already developed; applicational software available in Fortran but not developed for special-purpose system.

DIGITAL COMPUTERS	16%
PERIPHERAL EQUIPMENT	42%
SOFTWARE	30%
SYSTEM INTEGRATION	12%
TOTAL	100%

A scene from the Baytown, Texas area is shown in Figure 12. These images are portions of aerial photographs forming a stereopair and were taken at a time interval of about 100 seconds. The prominent feature which has moved is the tugboat and barge. Other features appear as faint ghost images because they were viewed from a significantly different aspect angle. It has been found that a photo analyst can detect changes between one and two orders of magnitude faster when using a tonal subtraction image of the type shown—depending on the number of changes, the characteristics of the scene being analyzed and on the resolution of the sensor.

High resolution aerial photos of the same scene are often very difficult to analyze when they are taken at differing altitudes, nadir points, conditions of solar illumination and seasons. Under these conditions tonal difference images of the type illustrated in Figure 12 may contain a bewildering array of complex changes which are difficult to interpret. To circumvent this problem one can add the gradient of one image to another. This is somewhat like adding a hand-drawn map containing only lines and an ordinary photograph. The line-type gradient image[29,30] can be used to outline various features on the original image and the tonal information can be used for contextual analysis. This type of cueing technique is illustrated by the example shown on the cover of this issue of *Photogrammetric Engineering.*

Images often differ significantly in the exact placement of features. These distortions have their source in such factors as varying sensor geometrical distortion or in the effect of terrain undulations when viewed from varying aspect angles. To illustrate this map warp problem Figure 13 is included. The first image was taken with an aerial camera. The second image was collected with a multispectral scanner mounted on an aircraft flying at a few thousand feet altitude. The third image was taken with a camera from the Apollo 9 spacecraft. The grid shows the form of a bivariate cubic polynomial which was used to place these latter two images in registration.

Chest radiographs present a difficult and challenging problem in change detection. By subtracting one image from an earlier image a tonal difference image can be created which shows the features which have changed. Using this technique the physician is free to concentrate on the problem of interpretation rather than that of detection. All of the problems of chest radiograph change detection have not yet been adequately solved, but significant progress is being made as a result of image research investigations now under way which are addressing the difficult problems of correlation, map warp and photoequalization. To illustrate this technique consider Figure 14. X-ray Image B was taken 16 months after Image A and contains a malignant lesion (which is 2½cm in diameter) in the lower left-hand corner of the lung field. When these two images are superimposed and one subtracted from the other the lesion has the appearance shown in the last image of this series. In the case of this latter image only four gray levels are used even though the original images were encoded to sixty-four levels.

CONCLUSIONS

Advanced digital computers for image processing are now being characterized by such words as modular, microprogrammable and pipelined. Arrays ranging from 4 to 40 individual processors are now being constructed. In terms of compute power and transformation complexity a need exists for systems which are capable of performing additive operations in as little as 10 nanoseconds and which perform up to 10^3 operations per pixel. The forcing function for high speed is the increasing ability of today's electronic sensor systems to rapidly collect imagery data along with the wide bandwidth of associated communications system to transmit data to the user. The need for a high level of processing complexity is the result of the magnitude of the problem of extracting information from the original images.

The design of cost effective image processing systems requires a careful consideration of digital memories. Per frame memory sizes ranging from 10^6 to 10^{10} bits are common and data base management often involves 10^3 to 10^6 or even more individual frames. Usually the high cost of random access memories prevents the system designer from carrying any but a small fraction of one frame of imagery in the system at any one time. Thus the need for cost effective data base management forces the system designer to employ a hierarchy of memories in the system. Commonly these differ by several decades in terms of access time, read/write time and cost per bit.

For the analyst, digital image processing involves many degrees of freedom in the selection of computer algorithms. The time taken to conceive a new processing approach is only a matter of seconds whereas the time taken to evaluate the approach is often a mat-

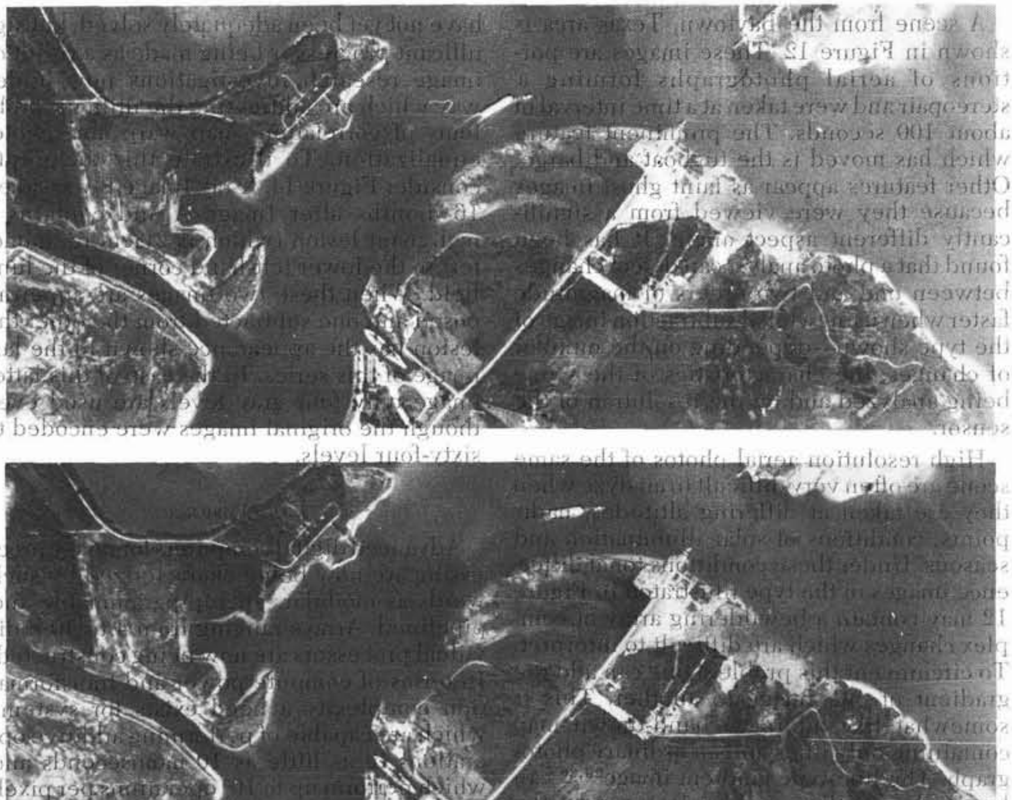


FIG. 12. Barge scene. Top = first image; middle = second image; bottom = tonal subtraction image.

ter of days or weeks or even longer. This problem must now be resolved by providing the analyst with a digital image processing system which allows a more rapid turnaround. Such systems are on the horizon.

Because of the large opportunity for creative accomplishment in this rapidly growing field, it must be considered as somewhat of an art when taking a software application specialist's point of view. It is clear that digital image processing, which concerns the alteration of natural images, is an art in the same sense that painting is an art. In this sense digital image processing is to the original

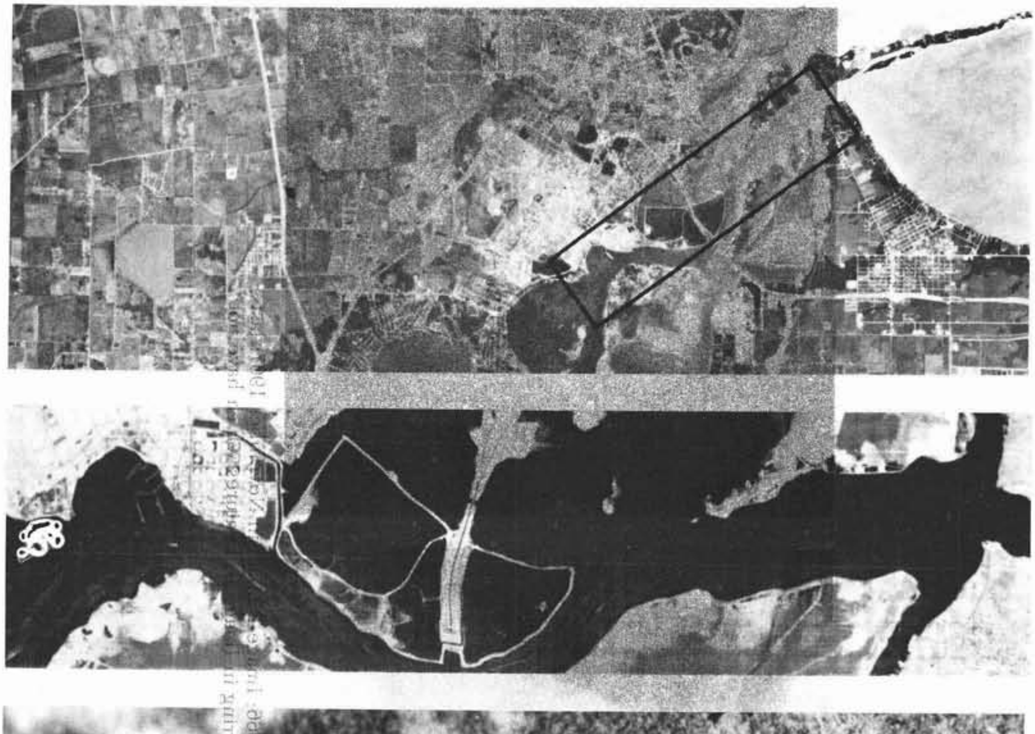


FIG. 13. Baytown area. First = aerial photo showing region of interest; second = multispectral scanner image; third = Apollo 9 image; fourth = map warp required to register second and third images.

photograph as painting is to the original scene. Both generate a transformed image.

In terms of its technical content it is perhaps even more appropriate to compare digital image research with musical composition. Today we continue to compose new music, even after three or four hundred years of intensive activity. Musical composition is thus a very rich art form with an almost unending potential for new patterns of sound. Similarly digital image analysis is a rich art form and progress can also be expected over a time scale of hundreds of years.

Nevertheless, within a few years these

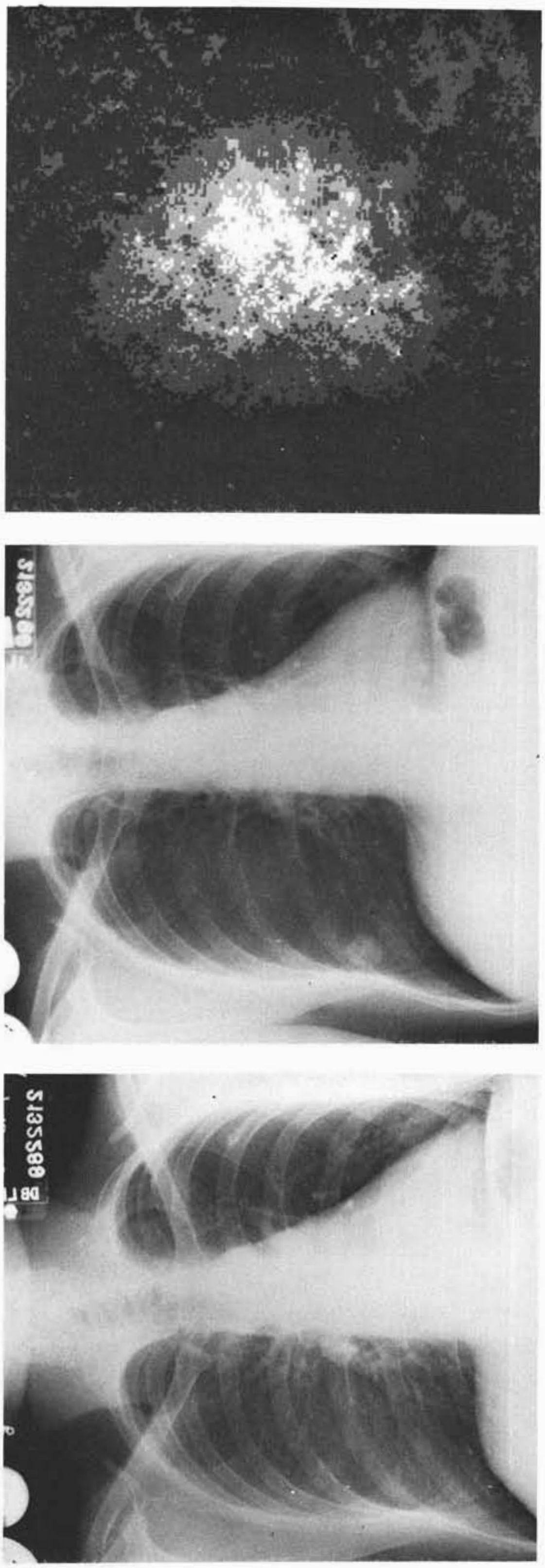


FIG. 14. Chest X-ray image. Image A taken in July 1966; Image B taken in November 1967; last image shows enlarged view of malignant lesion occurring in Image B. Features which have not changed have been eliminated by subtraction.

techniques will be sufficiently developed for wide-scale application. If the manufacturers of digital image processing systems adequately tailor their equipment to meet the needs of this rapidly growing market, a new industry will be created which involves the fusion of digital computers and photogrammetry.

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