NASA TECHNICAL NOTE

NASA TN D-8529 c.1

NASA TN D-8529

REAL-TIME RADIOGRAPHIC INSPECTION FACILITY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON D. C. • AUGUST 1977

1. Report No. NASA TN D-8529	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle REAL-TIME RADIOGRAPHIC INSPECTION FACILITY		5. Report Date August 1977
		6. Performing Organization Code
7. Author(s) Ernest Roberts, Jr.		8. Performing Organization Report No. E-9156
		10. Work Unit No. 505-01
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A real-time radiographic inspection facility has been developed for nondestructive evaluation applications. It consists of four major elements: an X-ray source, an X-ray sensitive television imaging system, an electronic analog image processing system, and a digital image processing system. The digital image processing system consists of a computer with the necessary software to drive the overall facility, with all appropriate interfaces. Descriptions are given of the design strategy, the facility's components, and its current capabilities.

17. Key Words (Suggested by Author(s)) Imagery; Image enhancement; Nondestructive tests; Computer techniques; Minicomputers; (X-) Radiography		18. Distribution Statement Unclassified - unlimited STAR Category 38	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price* A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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REAL-TIME RADIOGRAPHIC INSPECTION FACILITY

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SUMMARY

The development of a computer-aided radiographic inspection facility is described. The objective was to develop a radiographic inspection facility that bypasses film processing and offers an enhanced display. This objective was achieved by combining and refining four distinct technologies into a specialized operational facility. These technologies are conventional X-ray imaging, television imaging of an X-ray signal, electronic analog image processing, and digital image processing. This approach had the following advantages, which are demonstrated in the report: near real-time inspection, elimination of film processing, operator feedback into an interactive process, and improved image enhancement.

INTRODUCTION

There is a need for greater sensitivity and reliability in all types of nondestructive evaluation (NDE). This is coupled with rising pressure to reduce the inspection costs of aerospace components. An approach receiving great interest in the field presently is computer-aided analysis of NDE signals. Hence, one of the objectives of the NDE research efforts at the Lewis Research Center is to extend the capabilities of computer-aided analysis in several NDE methods. Radiography is one of several methods under consideration.

The advantages and shortcomings of radiographic inspection are quite well known. The two most serious shortcomings are these:

(1) Film processing is slow and expensive. An inspector often must see intermediate results from an X-ray inspection in order to determine the next step. Where several successive exposures are necessary, the choice is either to accept several long delays in completing the inspection or to make many more exposures than nec-

essary, realizing that only a few will contain useful information. Paper radiography overcomes some of the disadvantages of film radiography, but it is still slower than real-time radiography. Both paper and film radiography have associated materials costs, which can be very high in many cases.

(2) The variations in density in film radiographs frequently are extremely subtle. The judgment of a highly trained, highly motivated specialist is required to extract meaningful information from them. Such judgment is easily influenced by extraneous factors and is subject to extreme variations.

This report describes the current status of the real-time radiographic inspection facility developed at the Lewis Research Center. The description can best be summarized as that of a research facility, still in the process of development, that brings to bear several technologies from other fields on a specific NDE problem.

The objective of real-time radiographic inspection is twofold:

(1) To eliminate the delays and expense of film processing

(2) To reduce the variability of human judgment in the image analysis

The Lewis system is intended to fulfill these objectives. It is one step in the development of a generally applicable inspection tool. It should not be regarded solely as a tool for conducting research in nondestructive evaluation, although it is receiving extensive use for that purpose. The reason is that even at an early stage of development, the facility offers many advantages over conventional radiographic techniques. The major advantages are the elimination of film processing, the rapid response of the system, and the enhanced image.

DEVELOPMENT APPROACH

The strategy chosen to fulfill the previously stated objectives involves a combination of four technologies:

(1) X-radiography

(2) Television imaging

(3) Electronic image enhancement

(4) Computer-driven image processing

Although each of the separate technologies is well developed, this specific combination is not used widely for radiographic inspections.

Television imaging quite obviously eliminates the delay for film processing.

However, acquiring a visible image from an X-ray source introduces certain difficulties. There are two methods of acquiring a television signal from X-radiation:

(1) Using an X-ray sensitive photocathode in the vidicon

(2) Using a photoconductive electroluminescent screen in the X-ray field

The electroluminescent screen images a larger field than the X-ray sensitive vidicon at the expense of some resolution. Both methods are employed in the subject facility.

Electronic image enhancement in combination with a television signal is a complete real-time system, albeit limited in its capabilities. A similar device, described in reference 1, was the first stage of development of the subject facility. At that point, a conventional radiograph was the image source. The facility provided profiling, length and area measurements, and density discrimination by using pseudocolor generation. These terms are defined in the section CAPABILITIES OF FACILITY.

The insertion of a computer system into the facility greatly extends its capabilities. It provides five services not otherwise obtainable:

(1) A greater variety of enhancements to assist human judgment

(2) Types of image analysis beyond human capabilities

(3) Automatic graphic and tabular presentation of results

(4) Potential for automatic control of the facility in production applications

(5) Compact and readily accessible archival storage of reference images

The computer system used in this facility is a synthesis of four essential elements:

(1) The computer, that is, the central processing unit with its main and secondary memories

(2) The signal conditioning devices (e.g., analog-to-digital converters) through which the computer communicates with the other facility components

(3) The computer operating system, that is, that package of computer programs that provides support services

(4) The applications programs package, which performs the processing unique to the facility

The approach has been to develop the facility in stages. The first stage, as previously described, was the development of an electronic image enhancement facility. In the second stage, two steps were taken: the insertion of a computer system and the addition of X-ray sensitive television equipment. In the third stage the computer system hardware and software were enlarged. The planned extensions of the facility involve the incorporation of advanced analysis techniques for other NDE techniques.

DESCRIPTION OF FACILITY

Figure 1 schematically illustrates the elements of the radiographic inspection facility. Figures 2 to 5 depict the physical appearance of the system. Figure 2 shows the control panels of the image acquisition system. The surface behind the instrument cabinets is one of the walls of a shielded enclosure that contains the X-ray generator and the fixtures and manipulators to hold the test object. One of the video monitors provides an interior view of the X-ray room, permitting remote control of a manipulator that moves the test object with respect to the X-ray beam. The other monitor provides an X-ray view of the test object. It may be switched to show the same view after computer enhancement. Figure 3 shows the low-light sensitive camera, a remotely controlled zoom lens, and the radiographic amplification screen. The control panels for the image conditioning system are shown in figure 4. These panels, along with the computer shown in figure 5, are housed in a separate room from the image acquisition system. The elements are herewith described in terms of their respective systems.

Image Acquisition System

The image acquisition system consists of an X-ray generator, specimen fixtures and remotely controlled manipulators, and standard television components. Two types of camera are available in the system: X-ray sensitive and light sensitive. The X-ray sensitive vidicon has target dimensions of approximately 10 mm by 12 mm (3/8 in. by 1/2 in.). Its greatest usefulness is in inspecting small items or small sections of large items. It produces an image comparable in quality to film radiography.

Where a larger area is to be inspected, a light-sensitive vidicon with focusable optics is used, in this case, with a photoconductive electroluminescent screen. Conventional fluoroscopic panels suffer from several well-known shortcomings. The subject system uses a solid-state radiographic amplification screen (RAS). Such screens have recently become commercially available, in sizes to 20 cm by 25 cm

(8 in. by 10 in.). They are described in detail in reference 2.

Several factors define image quality. Among them are resolution; brightness; contrast; sharpness; graininess; and shading, that is, uniformity of picture brightness for a given grey value. It is desirable to have high values of resolution, brightness, contrast, and sharpness and low values of graininess and shading. The properties of the test object itself greatly influence these factors. To a great extent, the properties of the test object determine the voltage and current settings of the X-ray generator and the nature and disposition of filters in the X-ray stream. However, there is a range of values available, and the operator may vary these to produce a range of image parameters. When using the RAS, the operator may vary the X-ray voltage, the X-ray current, the RAS excitation voltage, and the RAS excitation frequency. Unfortunately, high values of these parameters produce bright images at the expense of other image parameters. (Resolution, which is determined by the television system, including the RAS, is an exception.) Correspondingly, the life of the RAS is also shortened. Therefore, it is desirable to use settings that produce dim images. Frequently, the brightness of the most desirable image is below the sensitivity of the vidicon. A low-light sensitive television sensor must be used. At the present state of development, certain of the image parameters produced by a RAS in conjunction with a low-light television sensor are somewhat inferior to film radiography. However, there are many trade-offs possible in the manufacture of the equipment and its operation. Various combinations of the manufacturing and operating parameters result in many different types of images, each of which has certain advantages and disadvantages, just as in film radiography. Four different panels are available in the subject facility for evaluating these variables.

Image Conditioning System

The image conditioning system performs three functions:

(1) It is the interface between the image acquisition system and the image processing system.

(2) It provides a visual indication of the current status of the inspection.

(3) It adds a certain image enhancement capability.

The system uses television standards. In 1/30 second it acquires an interlaced frame of 490 lines, each containing 512 picture elements. Each picture element defines one of 256 shades of grey. The frame is digitized at that same rate and stored on a high-speed magnetic disk "refresh" memory for transmission to the computer. Transmission is performed line by line. It is two-way transmission, permitting visual display of a computer-modified image.

One of two images may be displayed; either the image captured by the image acquisition system or that stored in the refresh memory (which may have been previously processed). The display is on a color television monitor. Color is added by a pseudocolor generator, which substitutes color for grey value. Up to 13 colors may be substituted for an arbitrary range of grey values.

A joystick-operated cursor permits identification of any arbitrary picture element. The cursor is displayed as a blinking dot on the television screen. Its coordinates are available on demand by the computer.

Image Processing System

Presently, the image processing system hardware consists of a 16-bit minicomputer, a typewriter terminal and two video terminals, 64 000 words of core memory, two 1.2-million-word disks, a nine-track industry-standard magnetic tape unit, and a floating-point arithmetic processor. The computer is controlled by a standard real-time operating system. It provides the following services, among others: an event-driven executive, a relocatable assembler, a FORTRAN compiler, a text editor, a linker, and input/output and file control services. The applications programs package provides a large number of distinct functions. The nature of the major functions is described in the next section.

Software is the critical element in the development of a computer system. Computer programs are complex, programming is manual, and there is no certified method of verifying programs. One study (ref. 3) has shown that over the life of a computer system, software costs are 65 to 75 percent of the total cost. Of that, approximately 50 percent is for verification. Continuous maintenance is required because programs do not perform as expected, mission requirements change, or latent software errors become manifest. The referenced study discloses that, in large computer programs, there is an average of one error per 400 lines of coding and that 40 man-hours of labor are required to locate and correct each one.

To minimize these problems to the greatest extent possible, three decisions were made in developing specifications for the system software:

(1) An off-the-shelf executive would be used.

(2) "Top-down" programming would be employed.

(3) The greatest possible amount of coding would be performed in a higher level language.

A custom-written executive would not need to be as versatile as one supplied by the computer manufacturer. Therefore, it would reasonably be expected to require less memory and to operate faster. This would be especially true of the input/output services, where the file structure and the executive would be designed together, and only one specific type of input/output operation would be supported. However, a standard executive, despite its greater complexity, would require less maintenance because many hours of use would have already been accumulated by other customers. Also, obviously, the cost of its development would be shared by many users.

Top-down programming requires greater effort in the planning stage, but this approach makes errors easier to detect. Reference 4 cites a 50-percent reduction in cost and a 25-percent reduction in overall development time. Among other things, it requires that a computer program be synthesized from a number of discrete processing elements, each of which has been independently tested and verified. This requirement resulted in the specification that each service provided by the applications programs package be performed by a FORTRAN-callable subroutine, even though it may have been written in the assembly language.

The choice of FORTRAN for the programming language was practically unavoidable. It is well developed, it is available from most suppliers, and it is capable of producing efficient programs. The programs produced by the FORTRAN compiler are sometimes somewhat longer and slower than those produced by a competent assembly language programmer. However, this disadvantage is far outweighed by the greater ease of program writing and verification.

The system was developed in two steps. It started as a small system with a simple disk operating system. It was then enlarged to the present configuration. The present large system is necessary to support efficient FORTRAN programs. Here, a low-cost machine was traded for low-cost programming. The large core memory and the floating-point arithmetic processor are necessary to support a FORTRAN compiler that can produce reasonably fast programs.

The following advantages have accrued from the preceding decisions:

(1) All hardware and software were delivered within 5 months of placement of order.

(2) The computer system was operational within 1 working day of delivery.

(3) The overall facility was operational within 1 week of delivery.

(4) The initial software cost was 36 percent of the total computer system cost.

(5) Engineers having only limited programming skills have been trained to design and implement their own inspection schemes in less than 1 week.

(6) A large number of extensions to the system have been installed and tested with minimum effort.

CAPABILITIES OF FACILITY

The facility has been designed in such a manner that it evolves from one well-defined stage to another. Each stage is chosen so that the effect of any major addition in technology is easily isolated from the rest of the facility for testing. The ultimate objective is a facility that an operator with no programming skills can operate from a computer terminal. Startup of the facility should be a simple and straightforward matter, and all instructions should be provided conversationally by the terminal. The services provided by the facility should be accessible individually to the development engineer to enable him to develop an inspection procedure by using minimal programming skills.

There are several major services provided by the current configuration of the facility. They fall into two categories: those required to support the hardware and those that directly perform image analysis. Into the first category fall the input/output routines, diagnostic routines, and certain supporting routines, such as an alphanumeric character generator. Of the remaining services, some provide graphical displays on the monitor (either separately or superimposed on the image), some produce measurements, and some modify the image displayed on the monitor. They are initiated by responding to "prompts" on the system terminal. Typically, the operator is presented with a list of services available and is requested to enter the name of one of them. Upon doing so, he is prompted either to enter the required parameters or to move the joystick-operated cursor to the appropriate coordinates. The services are summarized in the following subsections.

Graphical Displays

Profiling. - A plot of grey value against distance is produced on the monitor across any desired horizontal or vertical cross section of the image. It is accomplished by locating the cursor at the desired position and entering the word "horizontal" or "vertical" when prompted to do so.

Histogram. - The grey-value distribution of the image is displayed as a plot of the number of picture elements against grey value. The mean, median, and variance are displayed. The histogram is useful in object classification, measurement of dynamic range, or analysis with reference to the original image. One example of its use is in object classification. Imagine that the histogram has several peaks. Further imagine that the grey value at each peak is substituted for the range of grey values in the neighborhood of the peak (see Grey-scale expansion in the next section). The resultant image is not continuous toned. Rather it delineates each feature as a monotone grey value distinct from all other features in the image.

Measurements

Lengths. - The length of any line segment on the image is defined by the cursor, and its length displayed. The line segment in question can be plotted. The length is presented in standard units of length or in terms of an arbitrary reference length. In conjunction with the histogram, this feature can be used to measure the grey values plotted and to determine the actual number of them in the image.

Areas. - The area occupied by an arbitrary range of grey values can be measured. This is quite useful in density discrimination.

Image Modification

Rectification. - The effects of optical and electronic geometric distortions can be compensated for. A reference image having a large number of known coordinates is digitized and stored. The digitized coordinates are compared with the known coordinates, and a table of residuals is produced. On the assumption that any subsequently digitized image would suffer from the same amount of distortion at the same points, corrections based on the residuals are applied, and the rectified image is displayed.

Summing. - The grey values of any two stored images can be summed (or differenced), point by point, and the result displayed. This feature is useful for signal averaging, where several successive images are summed in an effort to reduce random noise. It can also be used to subtract random artifacts from an image.

Grey-scale expansion. - Any arbitrary range of grey values can be linearally transformed to any other arbitrary range. Hence, an image may be given more or less contrast, or certain portions of it may be highlighted.

Reducing pictorial data. - The total amount of data to be processed can be reduced by altering either the number of picture elements, the number of grey values, or both. The number of picture elements is reduced by replacing all the grey values surrounding any given picture element (e.g., 3 x 3) by the average of all the grey values in that neighborhood. This is repeated over the entire image. In the example given, this reduces the number of picture elements by a factor of 9. Similarly, the total number of grey values can be reduced by replacing each grey value encountered by the average for some arbitrary band within which it falls. For example, the 256 possible grey values could be reduced to 32 bands of 8 values each, and every grey value replaced by the average of its band.

Image complementation. - An image can be replaced by its complement. Hence, a negative image can be replaced by its corresponding positive image, and conversely.

Spatial filtering. - Both low-pass and high-pass filtering can be performed. To understand this operation, it is helpful to visualize every point of the image as being represented by a spectrum of "spatial" frequencies. The units of spatial frequency are cycles per millimeter, rather than cycles per second. In a region of an image where the brightness values are changing only gradually, the spatial frequencies are defined to be low in magnitude. In a region where there are rapid changes, the spatial frequencies are high. Obviously, an edge is a region of high spatial frequency. Furthermore, if the low frequencies are filtered out, the edges appear more pronounced. That is the definition of high-pass filtering. Low-pass filtering reduces noise, and high-pass filtering enhances edges. In this system, both processes start with a low-pass filtering. Each point of the image is replaced by the average grey value of its neighbors. The size of the neighborhood is specified as an input parameter. (There is a distinction between this process and the averaging process that is described as reduction of pictorial data. In that process, each picture element is replaced by a box of several picture elements, effectively producing a smaller number of larger picture elements. In this process, the total number of picture elements remains the same, but high-contrast gradients are reduced.) This averaging process tends to eliminate the type of small artifacts introduced by random noise. Furthermore, subtracting this image from the original image produces a high-pass-filtered image.

Edge enhancement. - The edges of any given image can be enhanced by applying either a root-mean-square gradient or a Laplacian operation about each point.

Shifting. - The image can be shifted either horizontally, vertically, or both by any number of picture elements. Subtracting a shifted image from its original results in an edge enhancement.

Rotation. - The image can be rotated through an arbitrary angle.

Zoom. - The image can be magnified by different amounts in the horizontal and vertical directions, if desired. The upper left corner of the magnified image is specified by the cursor, and the magnification parameters are entered at the terminal.

Example of Capabilities

The facility's capabilities are illustrated in figures 6 to 8. Figure 6 depicts a test object contrived for this example. The five elements depicted are all bonded together. They all have different thicknesses and different absorption characteristics. Obviously, a single radiograph cannot simultaneously reveal the coins, the two different sets of steps, and the holes in the aluminum backing plate. For example, exposure parameters that are proper to show the holes wash out the coins. Figure 7 schematically illustrates how two different exposures may be combined to reveal all the information in a single radiogram. For this example, the RAS and the low-light sensitive vidicon were used. The first exposure was at a high voltage, and the second was at a low voltage. No filters were used in the system. The first exposure produced the results shown in figure 8(a). The coins and aluminum step wedge can be seen, but the plastic step wedge and drilled aluminum plate are overexposed. Figure 8(b) shows the results of an exposure that displays the plastic step wedge and the holes in the plate, but underexposes the coins and the aluminum step wedge. Figure 8(c) shows the result of one computer process - the averaging and superposing of the two images. Figure 8(d) shows an enhancement of that image, in which the grey scale is expanded, increasing the contrast of the image.

All these processes are performed in a matter of minutes and are continuously visible to the operator. They are shown here for illustrative purposes only and do not suggest a typical method of inspection or indicate the full capabilities of the process. The use of the system to inspect an aircraft engine component fabricated from a fiber-reinforced resin is described in reference 5.

CONCLUDING REMARKS

The work described in this report was conducted to develop a radiographic inspection facility that bypasses film processing and offers an enhanced display. The objective was achieved by combining and refining four distinct technologies into a specialized operational facility. This approach had the advantages of near real-time inspection, elimination of film processing, operator feedback into an interactive system, and improved image enhancement. These technologies add a completely new dimension to nondestructive evaluation. They provide a mode of inspection beyond unaided human capability. Furthermore, the variability due to operator fatigue is reduced.

Computers are also being used in other fields of nondestructive evaluation (ref. 6), especially for ultrasonic inspections (ref. 7). The subject facility is planned to be expanded into that area. Another, more straightforward, extension is into other types of inspection that produce an image, such as thermography or holography. Its advantages in terms of an immediate display and elimination of the time and costs of film processing are self-evident. Not as immediately evident are the advantages that accrue from applications of classic image processing techniques (refs. 8 and 9) to this class of problem. In this technique, the image is analyzed and certain features are extracted and classified. It is anticipated that the application of this technology will lead to a degree of automation in the detection and description of anomalies within the test object. Related to that is the application of spectral analysis to the signals being processed (whether waveform or image). Therein, a signal is analyzed into its fundamental components and filtered or otherwise processed to provide additional information (ref. 10).

The subject system is complex, containing a large amount of expensive equipment to which additions are made with great frequency. This is typical of equipment used in research, which is the function of this system. Great versatility is required to perform such a function. However, many simplifications can be made to produce a lower cost system that is more suitable for a production or field environment.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 20, 1977,
505-01.

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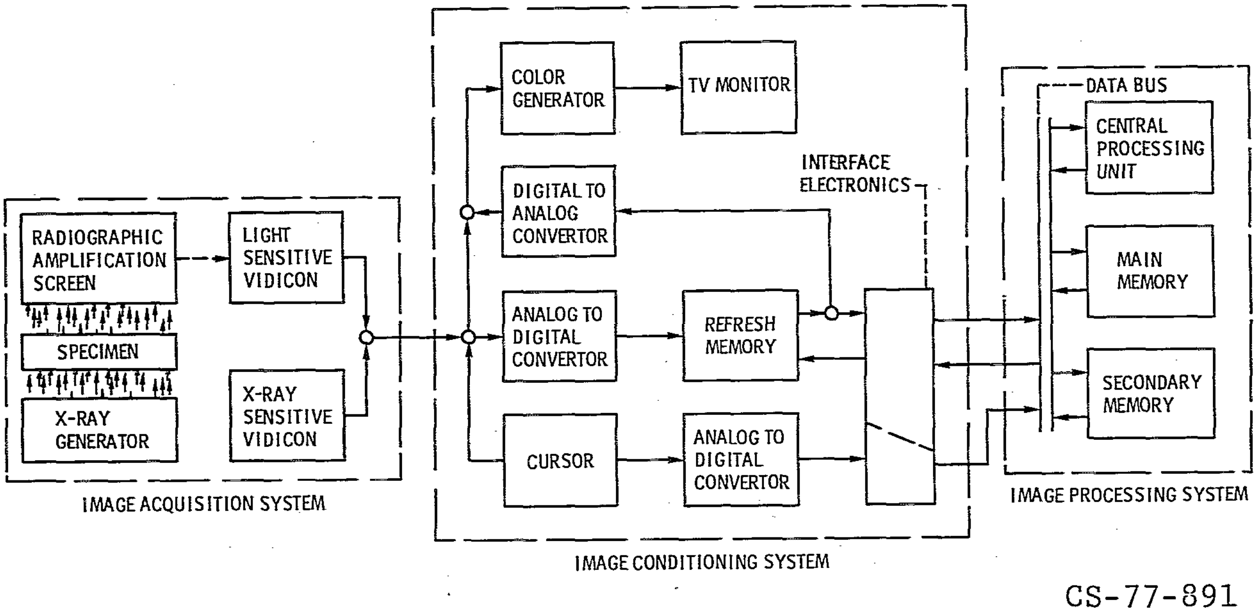

Figure 1. - Schematic of radiographic inspection facility.

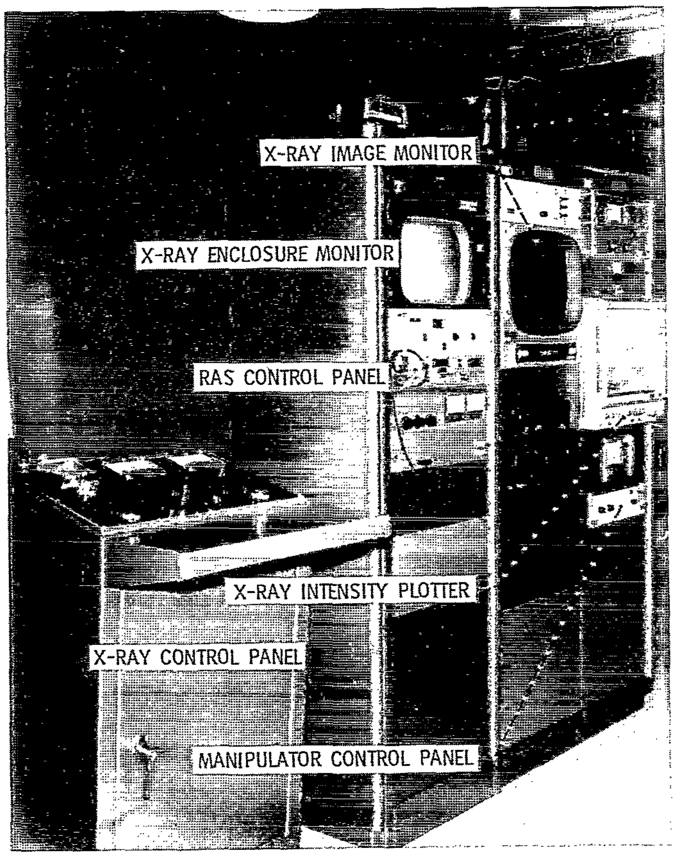

Figure 2. - Control panels for image acquisition system.

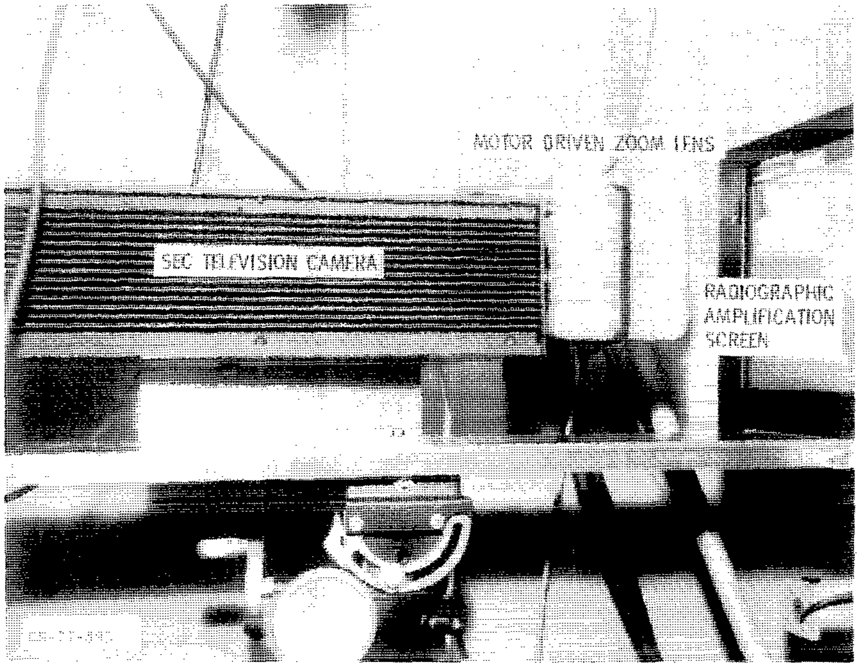

Figure 3. - Image acquisition system.

Figure 4. - Control panels for image conditioning system.

Figure 5. - Computer.

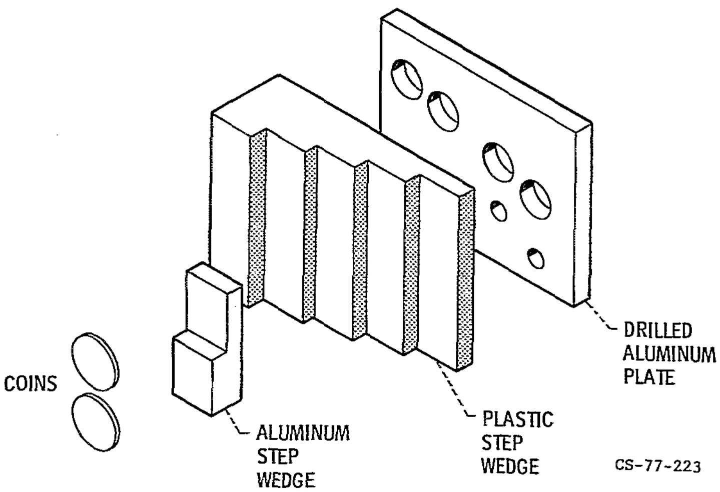

Figure 6. - Exploded view of test object.

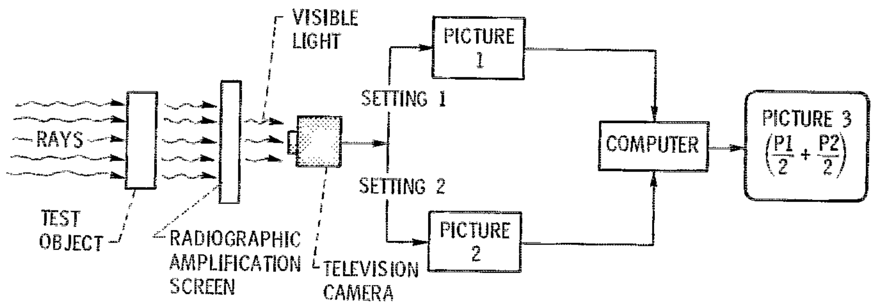

Figure 7. - Schematic diagram of inspection procedure.

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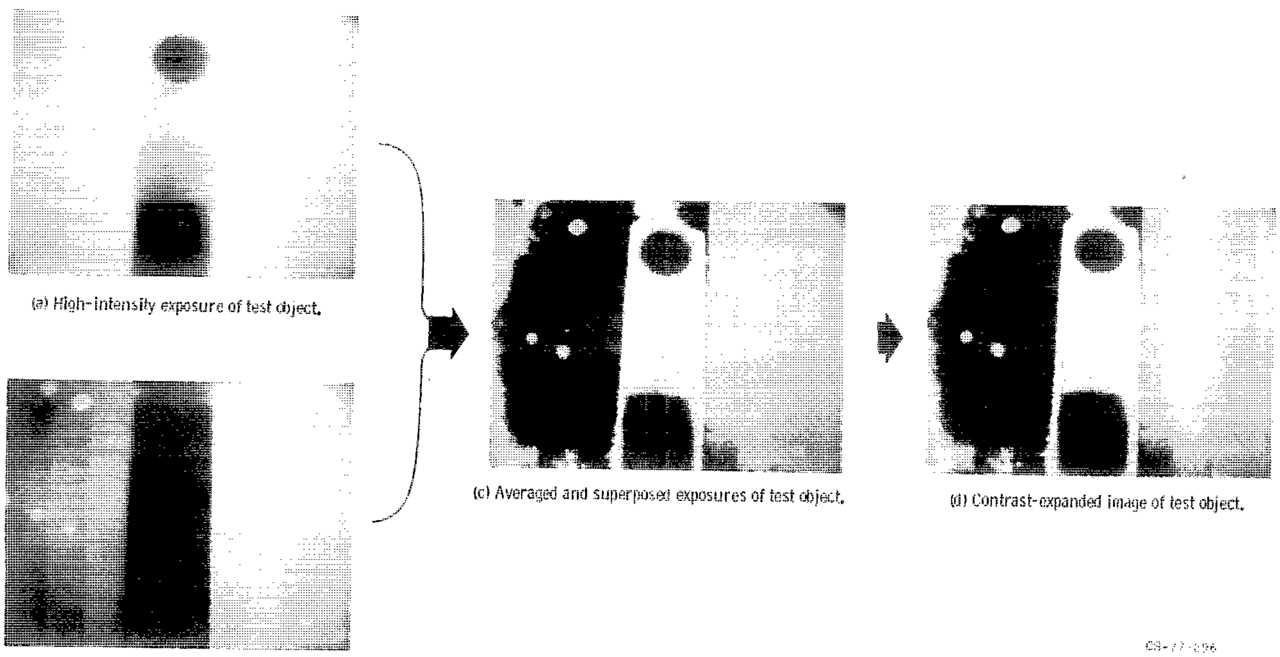

(a) High-intensity exposure of test object.

(b) Low-intensity exposure of test object.

(c) Averaged and superposed exposures of test object.

(d) Contrast-expanded image of test object.

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Figure 8. - Example of facility's capabilities.

NASA-Langley, 1977 E-9156

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