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CHALLENGES OF DEVELOPING AN ELECTRO-OPTICAL SYSTEM FOR MEASURING MAN'S OPERATIONAL ENVELOPE

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ABSTRACT

In designing work stations and restraint systems, and in planning tasks to be performed in space, a knowledge of the capabilities of the operator is essential. Answers to such questions as whether a specific control or work surface can be reached from a given restraint and how much force can be applied are of particular interest. A computer-aided design system has been developed for designing and evaluating work stations, etc., and the Anthropometric Measurement Laboratory (AML) has been charged with obtaining the data to be used in design and modeling.

Traditional methods of measuring reach and force are very labor intensive and require bulky equipment. The AML has developed a series of electro-optical devices for collecting reach data easily, in computer readable form, with portable systems. The systems developed, their use, and data collected with them are described.

INTRODUCTION

THE CHALLENGE

The Space Shuttle program brought a challenge to spacecraft designers to accommodate comfortably and efficiently a much larger portion of the population than had been considered previously. The Shuttle was to be operated by persons ranging in size from the fifth percentile female to the ninety-fifth percentile male, a range of approximately a foot in height.

Providing suitable work stations and living quarters for humans operating in a zero-g environment requires consideration of many new phenomena (refs. 1 to 3). For example, the body changes in size and shape: the torso stretches as much as 2 inches and the waist may shrink a similar amount. The natural comfortable posture in space is very different from the normal posture on Earth. Specifically, the legs and arms bend forward from the torso rather than hanging straight down; they are flexed at the elbows and knees. The head tilts downward, lowering the line of sight. In order to produce any effective force, the astronauts must be restrained in some way or they will simply move themselves.

To develop work stations, plan tasks, and design habitable areas, quantitative data are required on the anthropometric characteristics of users in zero g. These data can be collected in various ways: measurements may be taken in one g and extrapolated to zero-g conditions; they may be taken in simulated zero g, as in the Weightless Environment Training Facility; or they can be determined from data collected on Skylab or the Shuttle. No matter how the data are obtained, they should be made available to designers in the early stages of the design process.

Specific measurements desired are the sizes of body components (height, arm length, leg length, chest circumference, etc.), the reach capabilities, the strength that may be applied at various positions, and the time it takes to perform a given motion.

THE APPROACH

The approach to this challenge has been to build an Operator Station Design System which includes a computer-aided design (CAD) system and the Anthropometric Measurement Laboratory. The development of PLAID (Panel Layout Automated Interactive Design), the CAD system, started in 1976 (ref. 4). At the same time, development of automated equipment to collect anthropometric data was begun (ref. 5). The emphasis has been to use computer technology, from a VAX 11/780 computer to a Rockwell 6502 microprocessor, to collect data, process the data, present data to the design engineers, and provide design tools for the engineers. The goal, not yet achieved, is to provide dynamic models of human activities in candidate work areas and habitations. These models would ideally take a task description or checklist, translate it into desired movements, simulate those movements for bodies described in the anthropometric data base, and report to the engineer on such issues as inability to reach items, collision with other bodies or with spacecraft furnishings, the time to perform the actions, the strength required, and other design concerns.

BACKGROUND

ANTHROPOMETRIC MEASUREMENT SYSTEM

The first step in developing an automated anthropometric measurement system for range of motion data was the design and development of a video-based system for joint angle measurements. This device, called a goniometer, and the subsequent anthropometric measurement systems were developed by Southwest Research Institute of San Antonio, Texas, under the guidance of Dr. W. E. Thornton of the JSC Astronaut Office (ref. 6). To measure joint range of motion, a bar with incandescent bulbs on each end is attached to the limb to be moved. The limb is positioned in a neutral, 0° position. The two lights are alternately blinked on and off several times under microprocessor control. The position of the lights is sensed through a video camera and a line is fitted to the two points by the microprocessor. The limb is then moved to an extreme position, the lights are activated, a second line is fitted, and the angle between the lines is displayed on a digital readout.

The goniometer was a first step, a feasibility test, of the possibility of measuring motion through video tracking of point sources of light. The goniometer was a two-dimensional device: the person being measured had to sit or stand so that the axis of rotation was perpendicular to the camera image plane. The total errors achieved during testing did not exceed $\pm 4^{\circ}$ at a distance of 8 feet from the camera; the average error was about 2°.

The next step was the development of a three-dimensional tracking system. This anthropometric measurement system (AMS) locates positions in three dimensions by triangulation. Three video cameras are positioned on three corners of a rectangle. Two small incandescent bulbs, which are to be tracked, are attached to the person, for example, on the fingertips for collecting reach data. Figure 1 illustrates the arrangement of cameras, equipment, and subject. The room is very dimly illuminated. A

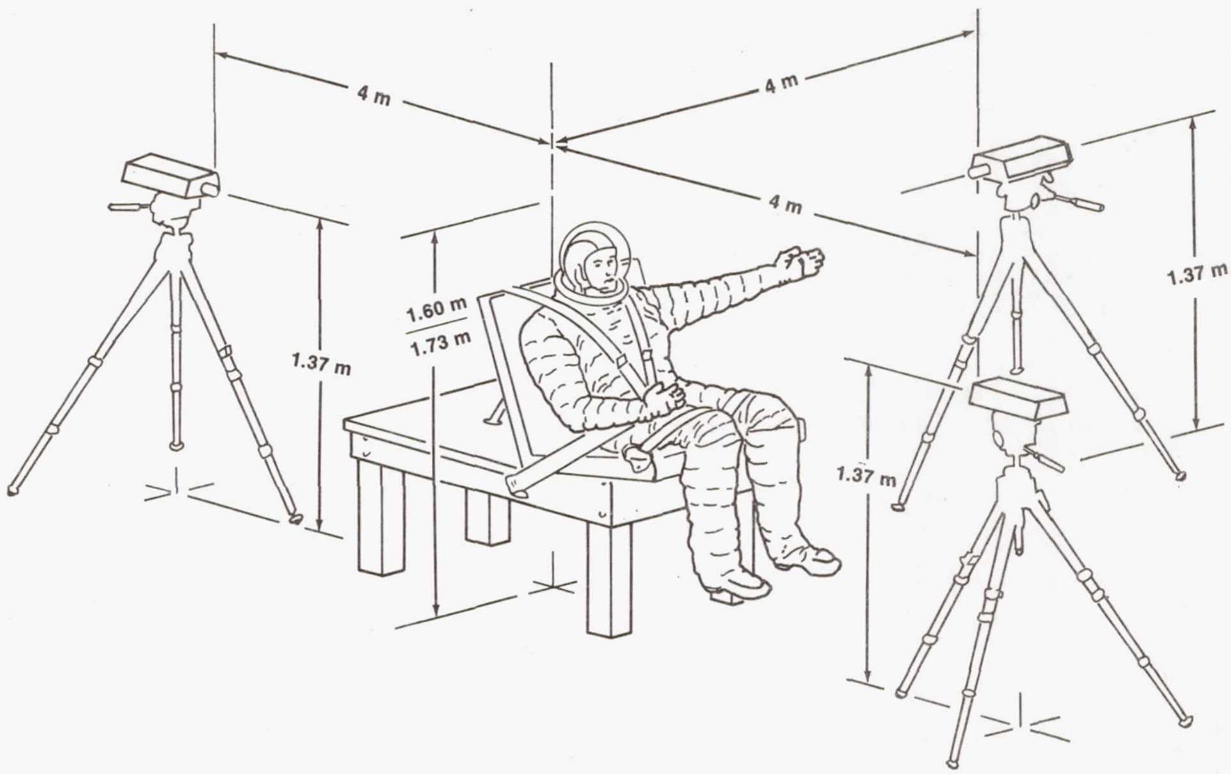


FIGURE 1.- THREE CAMERAS ARE USED TO TRACK A LIGHT ON THE CREWMEMBER'S HAND.

microprocessor turns on one light, analyzes a video scan for the peak brightness, digitally records its position in the video image plane, then sequentially analyzes the video scans from the other two cameras in the same manner. If no signal rises above a preset threshold value, a "no data" flag is stored for that camera, for that scan. The first light is then turned off, the second lit, and the process proceeds. Because of the video processing and the inherent limitations of incandescent bulb cycling, the data rate is about 10 points per second.

The digital data are stored on a floppy disk during the test. Data analysis is performed after the test. The position of a point in three-dimensional space is determined from the camera coordinates (two dimensions) from two non-colinear cameras. With three cameras, 180° coverage is possible.

The AMS also has provisions for force data collection. A commercially available Cybex dynamometer with a special pulley arrangement is connected to the AMS so that force is digitally recorded with corresponding position data.

Development of PLAID began in 1976 (ref. 7). This project was intended to provide a powerful design tool for spacecraft design engineers. Standard CAD features in PLAID include composition of primitive objects to form complex assemblies, data entry through cursor, digitizer, or keyboard, display in wireframe or with hidden line removal, and viewpoint position and orientation specified by user. This capability was developed for JSC by Rothe Development, Inc., of San Antonio, Texas, with the guidance of J. L. Lewis, J. W. Brown, and M. M. Thomas of the Engineering and Development Directorate of JSC.

The extensive use of PLAID in Shuttle operations planning has been reported by J. W. Brown (ref. 8). The conflict detection algorithms permit fit checks to be made early in the design process rather than in mockups. Through viewpoint specification, the areas in sunlight or earthshine can be displayed by specifying the viewpoint to be at the Sun or the Earth. A variable lens focal length feature allows assessment of camera fields of view. Previously, all of these tests had to be conducted with models and mockups, with a high cost in materials and manpower.

The initial human modeling capabilities of PLAID were limited. Bodies had to be constructed in pieces and assembled into the desired position by specifying the angle of each limb to another body part. Digitized data describing one human body in detail were obtained from the Institute for Biomedical Engineering Research at the University of Akron.

An early feature of the system was the REACH module, which provided for the use of data collected with the AMS. The AMS data consisted of a collection of points in three-dimensional space indicating those areas which the subject could reach. Figure 2(a) is an elapsed time photograph taken during the collection of reach data in a pressurized suit. To make use of this, provisions exist for examining one horizontal (or vertical) "slice" of some given thickness and drawing closed contours enclosing the points. Figure 2(b) shows a "slice" of reach points with the boundaries drawn in. The contours could be smoothed, and the sequential contours joined together to form a three-dimensional solid object. This process is illustrated in figure 2(c). The resulting object could then be positioned by PLAID, and its intersection with such elements as work stations, controls, and surfaces to be reached displayed. This capability was used extensively in analysis of thermal protection system repairs before the STS-1 mission. Figure 2(d) shows the model of an astronaut with reach envelope attached for use in evaluating reach capabilities.

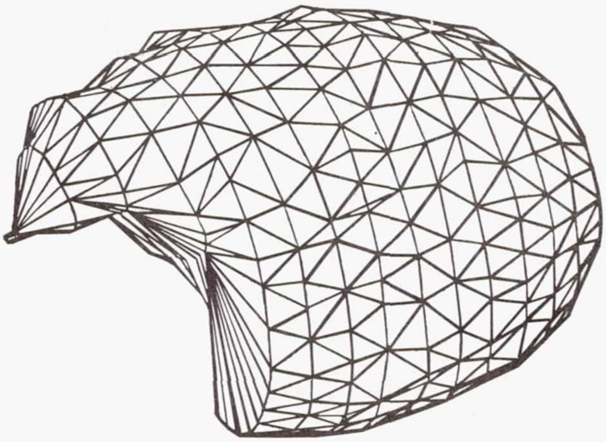
THE EVOLUTION

The limitations of the AMS prototype were the data rate, the number of points tracked, and the requirement for low light levels. A high-speed AMS (HAMS) was developed to surmount these difficulties (ref. 9). The HAMS is based on the commercially available SELSPOT system, which permits tracking up to 30 separate points at rates up to 300 hertz. The SELSPOT used infrared emitting diodes (IRED's) to provide the fast switching rates and to provide a signal in a radiation wavelength not strongly generated by normal room lighting. The light detection is done by a photosensitive plate which generates currents in its "x" and "y" axes in proportion to the location of the center of intensity. The image is focused on the plate by Canon lenses. The output consists of two analog signals (x, y position) which are digitized and initially processed by the SELSPOT control hardware.

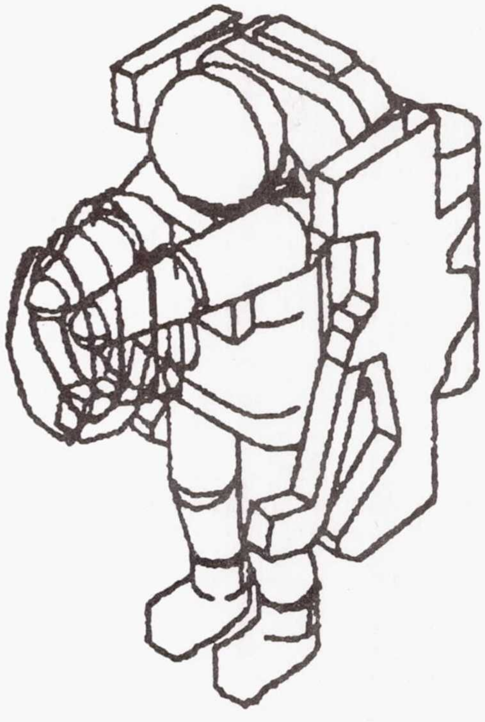
The SELSPOT system was originally designed to feed raw data into a computer at high rates. To provide portability, the unit was coupled with a microprocessor-controlled recording and playback unit in its implementation at JSC. The resulting system can be loaded on a laboratory cart

(a) DATA ARE COLLECTED FOR REACH RANGE IN A PRESSURIZED SUIT.

(b) REACH DATA ARE PLOTTED, AND CONTOURS INDICATING THE REACH RANGE ARE DRAWN BY THE INVESTIGATOR.



(c) CONTOURS FROM DIFFERENT HEIGHTS ARE CONNECTED TO FORM A THREE-DIMENSIONAL SOLID.



(d) A PLAID RECONDITION OF A SUITED CREWMEMBER WITH THE TWO-HANDED REACH ENVELOPE ATTACHED FOR INSPECTION.

FIGURE 2.- STEPS FOR COLLECTING REACH DATA.

and transported to any desired location to collect data. After the test, the system is transported to the computer room to dump the raw digital data to computers for processing. The interface to PLAID through REACH is maintained.

This system has been used to collect range of motion data for use in evaluating alternate joint designs for an 8-psi space suit. Besides its use for collecting reach data, it has been used to replace the goniometer and generates images of the arcs swung by a distal limb when a joint is rotated. Figure 3 shows arcs from two different suit designs generated by movement of the shoulder joint.

FIGURE 3.- SHOULDER ROTATION ARCS IN TWO PROTOTYPE SUITS. IRED'S WERE ATTACHED TO THE UPPER ARM AND ELBOW.

PLAID is undergoing development in two directions. The graphics capabilities are being extended, and the man modeling capabilities are being increased. Additions to the graphics include generation of raster output, the use of color and shadowing, and the use of hardware and firmware implementations of hidden line removal to increase the speed of the output by orders of magnitude.

Man modeling has been an active research area in computer science. One model, "Bubbleman," developed by Dr. Norman I. Badler and his colleagues (refs. 10 and 11), is being integrated with PLAID and the model extended significantly. Figure 4 shows a typical "Bubbleman" standing up. Special features of this model include the ability to select or build a body by specifying a few parameters rather than generating complex solids, and the ability to position a body by specifying a few key points rather than every angle and distance. The current model is a kinematic model. When given a starting position and a desired ending position, the model can generate the intermediate steps necessary to transition from one to the other. This animation technique provides a very helpful tool for the design engineer in checking reachability for detecting possible collisions between one body and another or between a body and surrounding crew station surfaces.

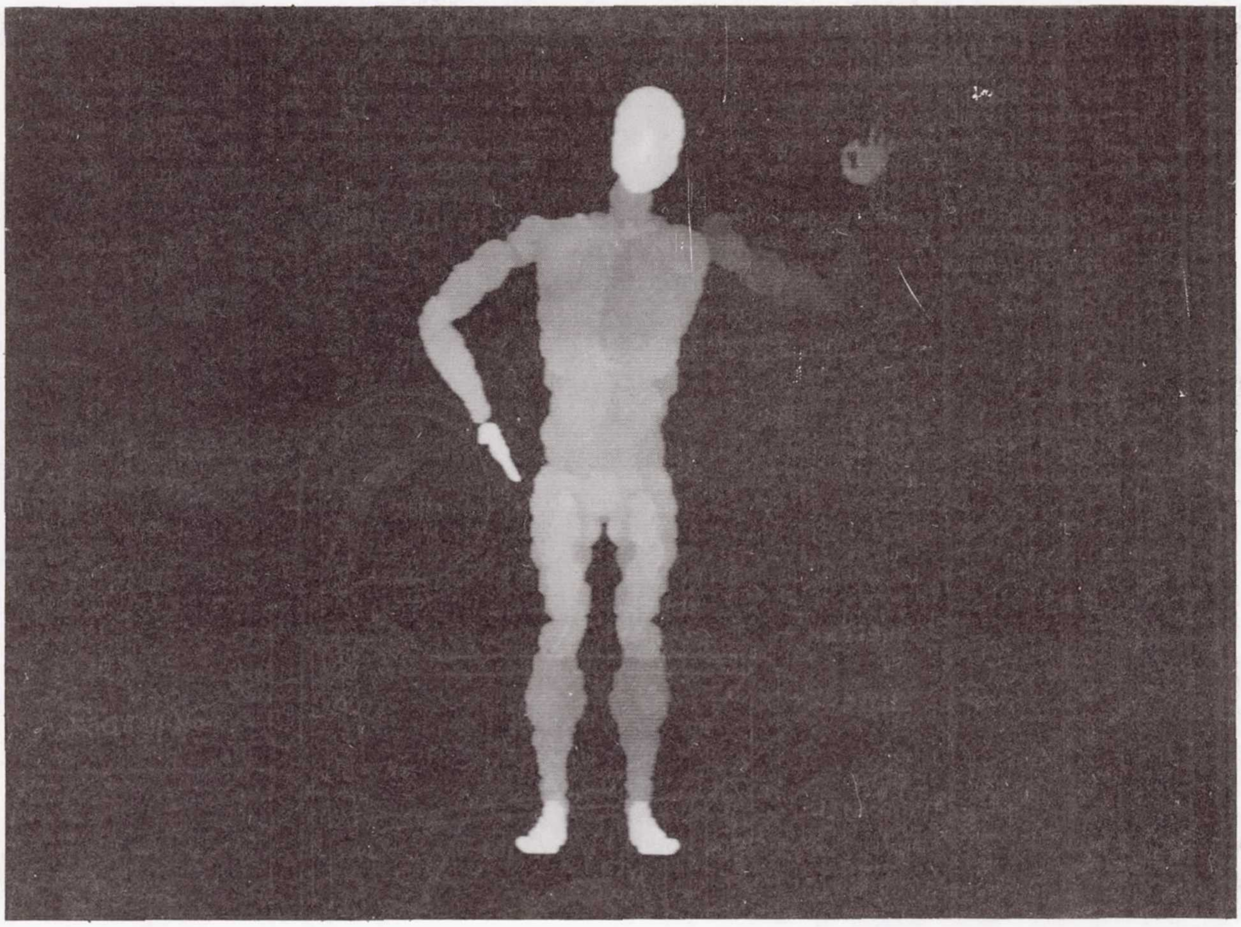


FIGURE 4.- BUBBLEMAN IN A STANDING POSITION.

CURRENT PLANS

SURFACE MAPPING

Further developments of the anthropometric measurement system and of PLAID are planned.

The next stage of the Anthropometric Measurement Laboratory is to develop a technique for mapping the entire body surface. Current techniques for obtaining a digital representation of the surface of a human body are based on manually picking points from stereophotographs. This is an error-prone and laborious method. In conjunction with Wright Patterson Air Force Base (WPAFB), a laser-based anthropometric measurement system (LAMS) is being designed and built. The principal investigator is Dr. Bruce R. Altschuler of WPAFB. The design of this system is described by M. Altschuler (refs. 12, 13, and 14).

The principle involved is again triangulation. In this application, rather than having data from two video cameras or two electo-optical devices, there is an "active" camera and a "passive" camera. The passive camera is indeed a sensitive video camera. The "active" camera is a rectangular array of discrete beams of light which are projected on the object to be measured. Multiple exposures are used to give a position code for each beam position. Figure 5 shows the beam array projected on a model spaceman. There are 128 columns of beams; in this exposure, every other 8 columns are blanked out. Thus, for an array of 128 by 128 beams (more than 16 000 points), there must be a minimum of 8 exposures ($\log_2 N + 1$) to permit a binary coding of the location of the column from which the beam originates. Each exposure currently takes one-thirtieth of a second, because of the limiting factor of video scan rate. Thus, to obtain eight exposures requires approximately one-third of a second. This is adequate for cooperative, stationary objects but is limiting for collection of velocity data.

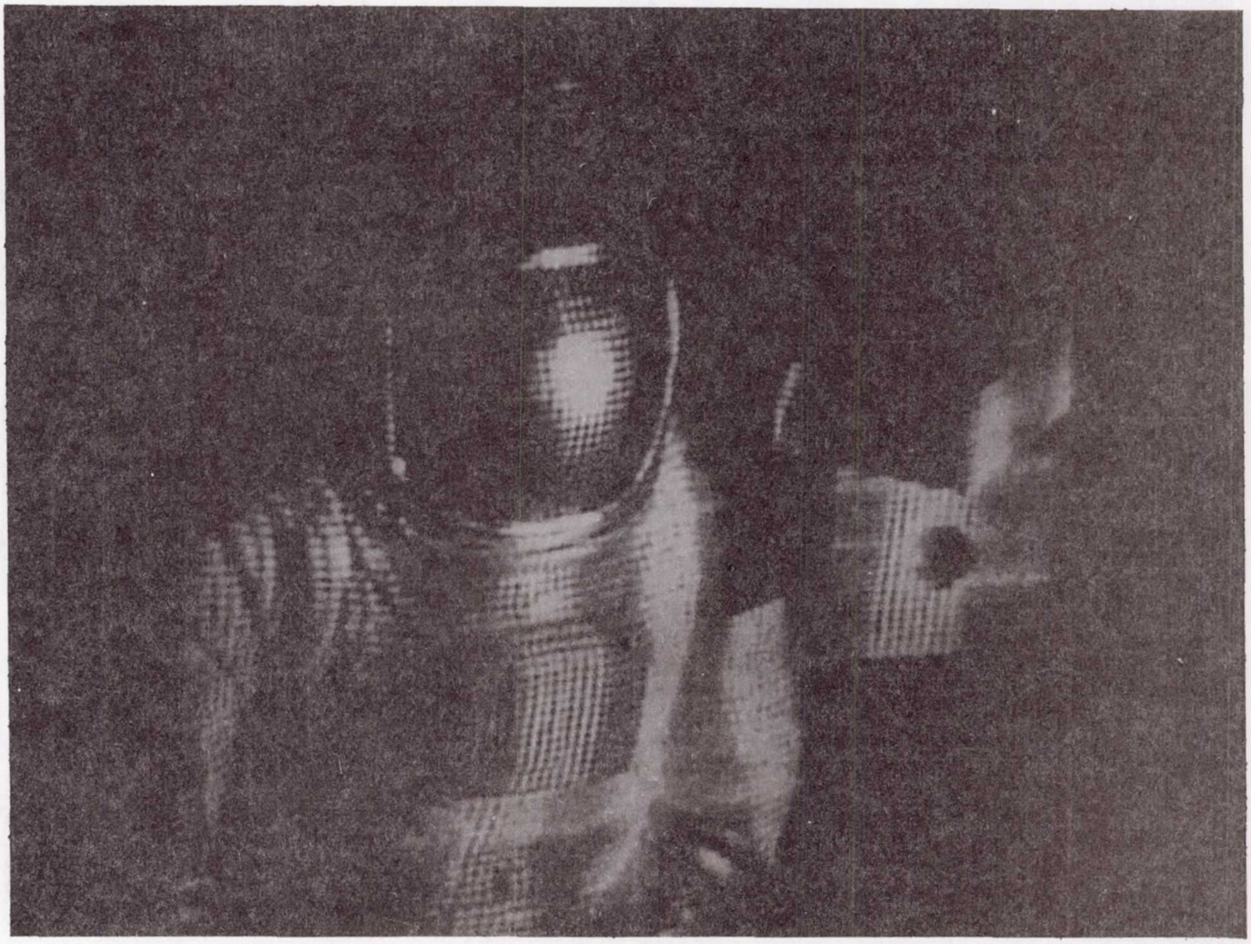


FIGURE 5.- BEAM ARRAYS PROJECTED ON MODEL ASTRONAUT. THERE ARE 128 COLUMNS OF BEAMS. IN THIS PICTURE, THE PATTERN IS 8 COLUMNS OFF, 8 COLUMNS ON.

The design goal is to be able to collect all necessary exposures within 100 milliseconds or less, to permit mapping motion data for kinematic and dynamic models. Two items are currently limiting: the light modulator and the camera. There are several technical challenges in developing a surface mapping system. One is development of an adequately fast "shutter," which is actually not a mechanical shutter but a light modulator whose transparency or opacity is determined by an electric current. The first-generation light modulator was developed by Sandia Laboratory; a second-generation one with lower power requirements and higher speed is under development. Design of a CCD camera with parallel outputs to cut data acquisition time from one-thirtieth of a second to milliseconds is proposed. The multiple-exposure beam position coding technique, the implied algorithm for decoding the beam position, and the calibration procedures in which calibration is performed by viewing an object of known size and shape are technical problems under investigation.

The applications for this device are varied. The project was initiated to map the surfaces of teeth for automatic crown development. NASA applications require a system which can be used (1) to map large objects at long ranges, such as antennas; (2) to map human-sized objects at medium ranges to collect motion data; and (3) to map smaller objects, such as limbs or torso to determine physiological changes caused by fluid shifting and other zero-g effects.

DYNAMIC MODELING

The ultimate goal of the Operator Station Design System is to permit simulation of individual crewmembers or of statistical samples from a specified population performing complex tasks. The simulation would model the motions and the information processing that takes place and would report impossible or very difficult actions, percentage of population capable of performing an action, times of performance, and a measure of workload or fatigue.

The immediate goal is to add enhanced graphics, motion models, and strength models. Graphic enhancements include modeling reflectance properties, modeling multiple light sources, and increasing the speed of the system. The strength and motion models will drive the graphics displays to show how a specific point might be reached (translation, rotation, limb movements, etc.) and how much force can be brought to bear on the object of the task.

CONCLUSIONS

Computerized models and data collection techniques provide a means of placing man in the loop early in a design cycle, saving time and money over the techniques which rely on mockups. With the extensive data base now built that describes the Shuttle, payloads, and workstations, and with the anthropometric data base, operations can be planned and examined for fit, visual access, and physical access without recourse to mockups. Further automation of this process is under development.

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Barbara Woolford, manager of the Anthropometric Measurement Laboratory, has been at JSC for 7 years. She received a B.A. in psychology and an M.A. in mathematics from Arizona State University. Ms. Woolford is a member of the ACM, the AIAA, and the IEEE Computer Society.