MANIPULATOR TECHNOLOGY FOR THE SPACE SHUTTLE

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ABSTRACT

A shuttle-attached manipulator is currently proposed as the payload-handling device for the space shuttle. Basic requirements for the manipulator involve length, force, compliance, and control. In this report, approaches for studying control methods are presented and simulation methods are discussed. Basic details about the two earth-based manipulators selected for simulation experiments are related to the test methods. Preliminary data from one test are shown as an example of the direction of the testing. A computer-generated simulation is explained, and the relationship of the three simulations to the design problems is discussed.

INTRODUCTION

The orbital delivery system for space flight in the future will be the space shuttle. The current design for the shuttle orbiter vehicle specifies a payload bay having dimensions of 4.57 by 18.29 meters (15 by 60 feet) and having provisions for handling payloads. The payloads will have a wide variety of sizes, weights, and shapes. Examples of the handling functions to be performed are deployment, capture and retrieval, and stowage of the payloads. The various payloads may be handled either by individual manipulative devices, each designed to perform simple functions, or by a general-purpose manipulator designed to span the range of handling functions. In this report, a preliminary design for a shuttle-attached manipulator (SAM), which is a general-purpose manipulator, is described.

No manipulators have been used in space, except for such simple devices as the Surveyor surface-sampler scoop. However, the technology of earth-based manipulators provides an adequate base from which to design the SAM. Significant aspects of the SAM design deviate from earth-based manipulator designs; thus, a logical program to extend the technological base toward the design of the SAM is necessary. The salient parts of this program and the reasoning used in the extension of the technology are discussed in this report.

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DESIGN REQUIREMENTS

A conceptual drawing of a SAM and its installation in a shuttle is shown in figure 1. The shuttle payloads identified in current mission models can be as small as a few cubic feet and weigh as little as several hundred pounds or can be as large as 4.57 meters (15 feet) in diameter and 18.29 meters (60 feet) in length and weigh as much as 29 478 kilograms (65 000 pounds). The desirability of grasping a heavy module near its center of gravity and the need to grab a small satellite located toward the aft end of the payload bay establish a minimum length of approximately 9.14 meters (30 feet) for the SAM. Apparently, there is no requirement for the length to exceed 18.29 meters (60 feet). Current plans are for a SAM to be 9.14 to 12.19 meters (30 to 40 feet) in length because, with a SAM of this length, 90 percent of all the payloads in the traffic model located anywhere in the payload bay can be reached, and 100 percent of the payloads can be reached if the smaller satellites are not located far aft. The shorter lengths are lighter and easier to control. The degrees of freedom of the SAM are distributed so that they correspond anthropomorphically to a shoulder, elbow, and wrist.

Tip Force

The minimum tip force required for the SAM is primarily a function of the arm length, the payload weight, and the ability of the operator and his control system to control acceleration and velocity safely. The minimum tip force of 44.48 newtons (10 pounds), used with a maximum length arm, is required to provide sufficient energy to complete many operations within a reasonable time. The energy also is required to stop the heavy payloads at residual closing velocities. Arms shorter than the maximum length require larger force because the available stopping and starting distances decrease, and the accelerations must be increased to supply equivalent energy. The maximum useful force is more difficult to establish. Because the heaviest payload imposes design constraints on minimum force, the selection of a force level only marginally greater than the minimum will result in a low-weight system. An upper limit of 444.82 newtons (100 pounds) was established, based on combinations of the heaviest payloads and the shortest arms.

Compliance

Compliance in the SAM is defined as the amount of tip deflection per unit of tip force. Compliance is caused by the flexure of the arm structure, the elastic deflection and tolerances within the joints, and the electronic response of the servocontrols. As in other orbiter systems, the weight of the SAM must be minimized. The values of stiffness (the reciprocal of compliance) postulated in preliminary designs are sufficiently high that the design of the arm structure is controlled by stiffness instead of by stress. Consequently, it would be desirable to allow more compliance (less stiffness), use higher stress levels, and reduce weight. Just as too little compliance increases weight, excess compliance decreases safety and lessens positioning accuracy. The compliance value of 0.06 cm/N (0.1 in/lb) was used in the preliminary designs because it would produce conservatively high weight and better-than-adequate positioning. Recent experiments that will be described have produced data indicating that more compliance is tolerable.

Currently, electric actuators are planned for use in the SAM. Conditioned electric power will be available on the orbiter, whereas hydraulic power sources probably will not be active during payload-handling periods. Electric motors also will be more easily space qualified than hydraulics because of contamination restrictions.

Control System

The effect of man in the servocontrol loop is difficult to assess, particularly because partial computer control probably will be used. In preliminary designs, two desirable modes of computer operation have been identified. In the first mode, active when man is in primary control, system status is monitored by computer, and collision avoidance is ensured by the computation of the position of the arm with respect to all fixed objects. Automatic collision avoidance is particularly desirable with respect to the position of the elbow. Requiring the operator to be constantly aware of the elbow and wrist, points that are at least 4.57 meters (15 feet) apart, reduces his capability to operate the secondary television and information systems while also operating the arm. In the second computer mode, the computer operates the arm and the man is in monitor status. This mode will be used only in situations in which all bodies are at known locations. The reason for using full computer control is to make precise operation of a controller for a long timespan unnecessary. Examples of operations in which the second mode is used are deploying the arm from the stowed position, stowing the arm, and translating a payload between positions near (but not in contact with) other bodies. These operations do not need precise position control from a safety standpoint but do require careful force control to minimize operation times. The operator can prepare the peripheral systems for the next operation to be completed while the computer is in control.

The type of hand controller to be used by the operator for his real-time control is being studied. A variety of types of controllers probably would be suitable. Examples of candidate controllers are hand controllers, joysticks, buttons, and master-slave devices. The current work is to determine which controller offers the best combination of safety, reliability, utility, and weight penalty.

SIMULATION METHODS

The design requirements for reach and force were developed by means of a simple analysis of the payload-handling functions and dynamics. The determination of tolerable levels of compliance and optimal computer and controller mechanization is not susceptible to analysis because man adds an active part to the control equations. Consequently, empirical methods are being used, and the obvious approach is to build and test a SAM. The force levels previously mentioned were in a zero-g environment, but a limited study has indicated that simulating zero-g performance in a one-g field for a SAM is not practical early in the design process.

A review of manipulator technology reveals that there is no manipulator system currently using a combination of reach, force, compliance, and complex control that even approximates the SAM. The remaining approach is to find systems that approximate some characteristics of the SAM and to use appropriate testing to extrapolate their performance. Thus, the performance of the SAM is approximated by a series of simulations using current systems with the man in operational control. This approach is relatively economical and allows the performance of the SAM to be demonstrated by experiment instead of by analysis very early in the design process.

Manipulative Systems

A wide variety of manipulative systems are available for experiment. The systems range from such large but nonadvanced devices as derricks to extremely complex, anthropomorphic systems used in materials handling. The force level of the SAM appears to offer no difficult problems, and the length per se is just a design detail. The experimentation must facilitate information acquisition regarding compliance and control in a remotely controlled, dextrous system. The materials-handling devices that have great dexterity embody the most complicated and versatile control systems. Two manipulators, an E-2 and a CAM 1400, were good choices for study because of performance capability and availability.

The E-2 (fig. 2) is an anthropomorphic, bilateral, six-degree-of-freedom, master-slave, electric manipulator. The motions and distribution of the degrees of freedom of the E-2 arm are anthropomorphic. The controller (master) is a duplicate of the working arm (slave); operations are performed by moving the handle of the master through the motions and with the forces desired of the slave. Bilateral refers to the fact that force feedback generated at the master arm is equal to the working force of the slave arm. A useful test is possible with the E-2, even though the slave arm has approximately one-tenth the effective reach of the SAM. The purpose of the test is to demonstrate the ability of a man to control high-inertia dynamics by the application of small forces and to quantify his response to different compliances. The massive body to be controlled with 26.69 newtons (6 pounds) of available force is a 181.44-kilogram (400 pound) weight suspended from a 6.71-meter (22 foot) pendulum (fig. 2). The weight swings in the plane containing the slave arm and is released from a position 0.61 meters (2 feet) from rest on the far side from the arm. The slave arm captures the weight at the point of closest approach and brings it to a rest as soon as possible. A potentiometer used as a position transducer measures the lateral displacement of the weight from rest for recording on an oscillograph. In figure 3, the data record of the position transducer for one test run of one operator is shown. Different compliances are introduced by making adjustments to the servoamplifiers between runs. The operator reacts essentially the same to servocompliance as to structural compliance of the SAM. Four different compliance values were used. Each of the nine operators made practice runs before making test runs. The data point for each combination of compliance and operator is the average of several consistent runs. In figure 4, the overall average for all operators at each compliance is shown. The significance of the curve is that it shows that operators can adapt to almost any compliance of interest to the SAM design and that only small performance changes result.

The CAM 1400 is an anthropomorphic, bilateral, five-degree-of-freedom, master-slave, electrohydraulic manipulator (fig. 5). The CAM is not bilateral master-slave in all five degrees of freedom. The three degrees of freedom, two at the shoulder and one at the elbow, that translate the end point of the arm are controlled by a master arm that kinematically resembles the slave and that has 22.24 newtons (5 pounds) of force feedback. The remaining degrees of freedom, which position the wrist motions, are controlled by one constant-rate switch and one position potentiometer. A more significant difference between the E-2 and the CAM is that the E-2 has an effective reach of 0.91 meter (3 feet) and the CAM has an effective reach of 6.71 meters (22 feet). The CAM will be used in conjunction with a 5.49- by 10.67-meter (18 by 35 foot) air-bearing surface, air-bearing freebodies, and television systems to simulate all major handling functions of the SAM. Examples of tests are tracking and grasping a moving small satellite, payload stowage and deployment, and payload inspection. In tests presently being conducted, the CAM moves a 3175.1-kilogram (7000 pound) weight mounted on air bearings through a maze in order to evaluate positioning capability and the effects of compliance changes. Compliance will be varied as it was in the E-2 tests, and performance data will be taken. Other tests will be used to evaluate television systems and interactions between direct vision and television. The combination of buttons, potentiometers, and master-slave control methods also will give early indication of operator preference of control types.

Computer-Generated Scene

At the NASA Manned Spacecraft Center, a computer-generated scene, which is a method of simulation not incorporating an actual manipulator, is being used to resolve problems involving control methods. The scene is composed of points, lines, and colors. A typical scene, shown in figure 6, consists of the cargo bay area of the orbiter vehicle, the SAM, and a large payload module. The computer program can handle rigid-body dynamics for the bodies and is capable of imposing such restrictions as rate limiting. The scene is displayed on a television screen. Force feedback is not available currently. A variety of controllers can be used because only programing changes are needed to interface the physical controller with the simulation. Controllers covering the range from a button box to a master arm without feedback will be used.

CONCLUDING REMARKS

The technology base necessary for the design of the SAM is being derived from simulations using earth-based manipulator equipment and computer simulation. These simulations are being used to give operators the subjective feel of a space manipulator and to generate design data. Two hardware simulations, using the E-2 and the CAM, and the computer simulation form an experiment program that covers the characteristics of the SAM that need definition early. The computer scene generator will provide control-system definition, and the E-2 experiments have provided needed data on compliance and man-control interaction. The CAM experiments will allow exploration of compliance, man-control interactions, vision-control interactions, and even such procedures and limited hardware work as evaluation of arm terminal devices. By the use of this program early in the SAM design, the gap between the technology of earth-based manipulators and the technology needed for the SAM can be bridged efficiently.

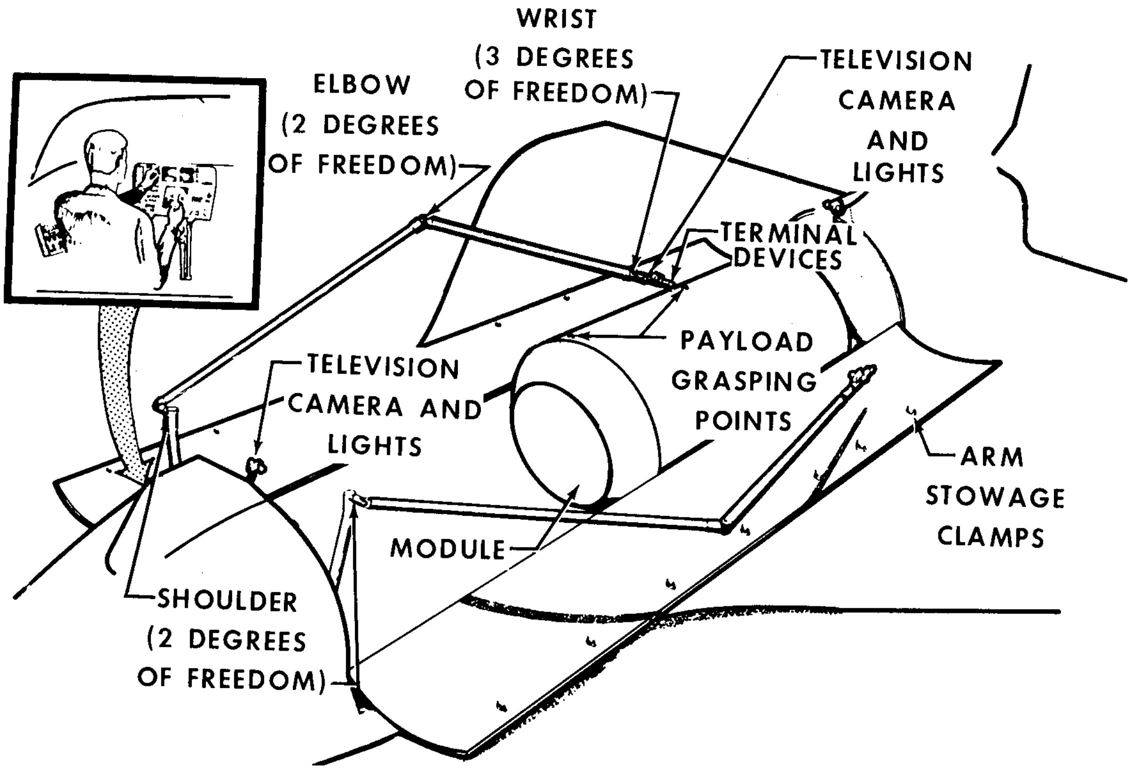

Figure 1. - The SAM installation.

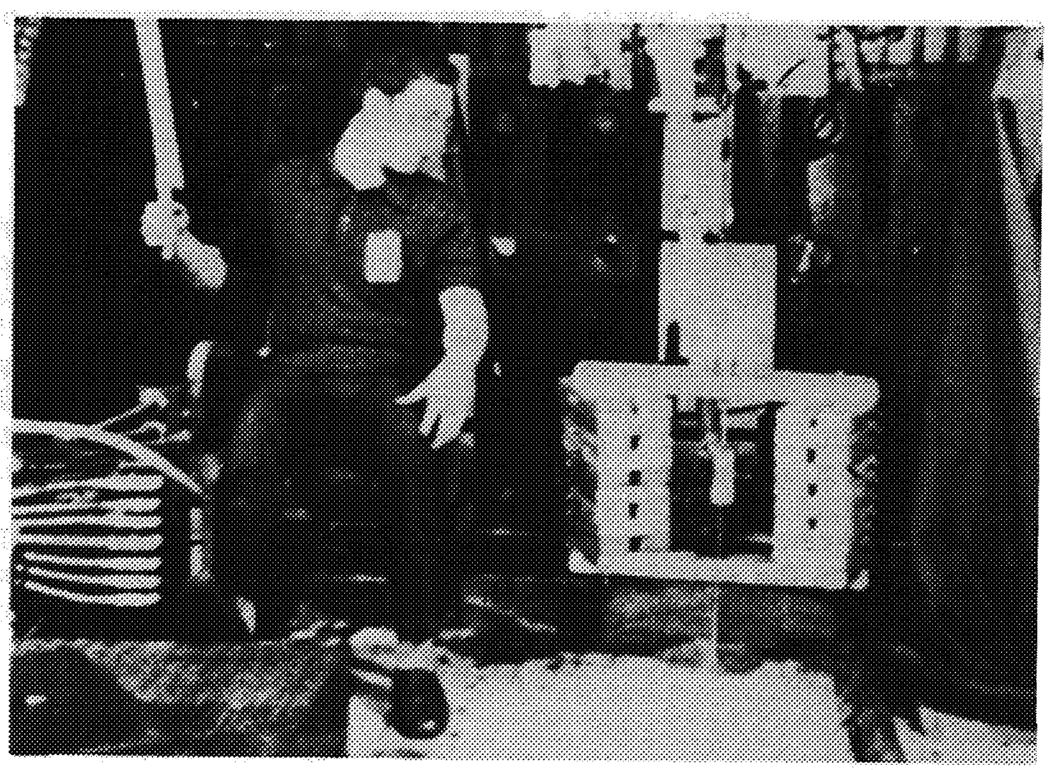

Figure 2. - The pendulum test setup.

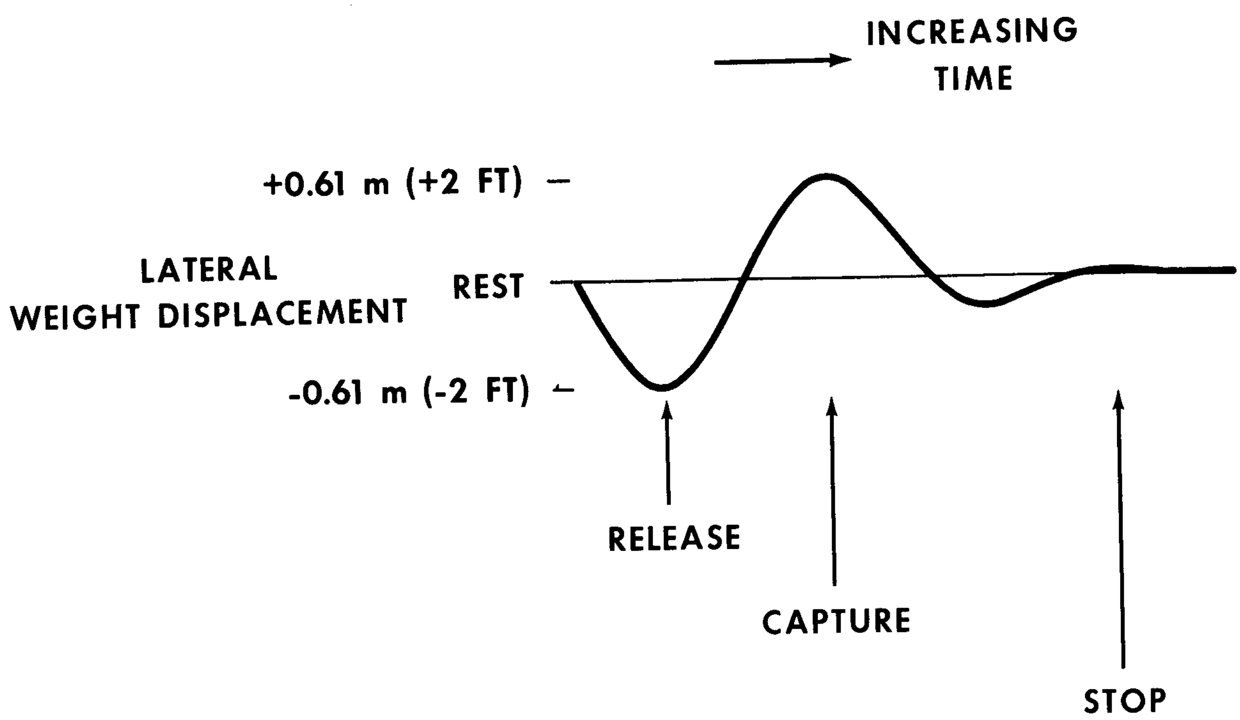

Figure 3. - Sample test data.

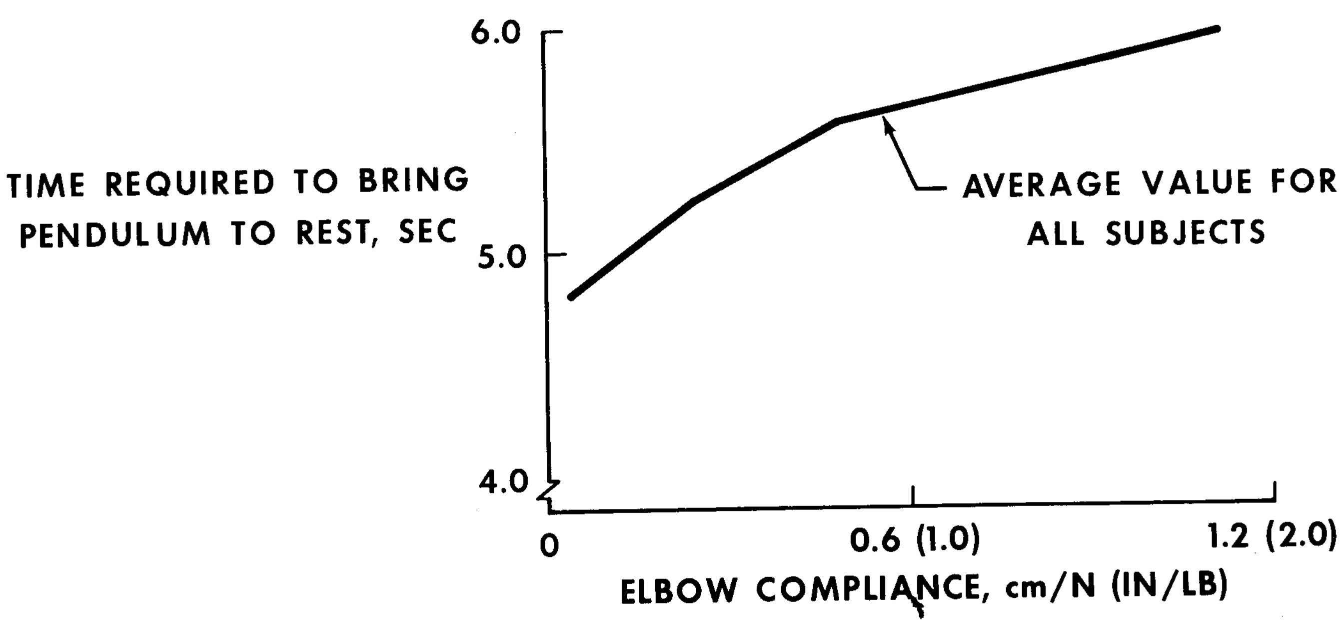

Figure 4. - The effect of compliance on performance.

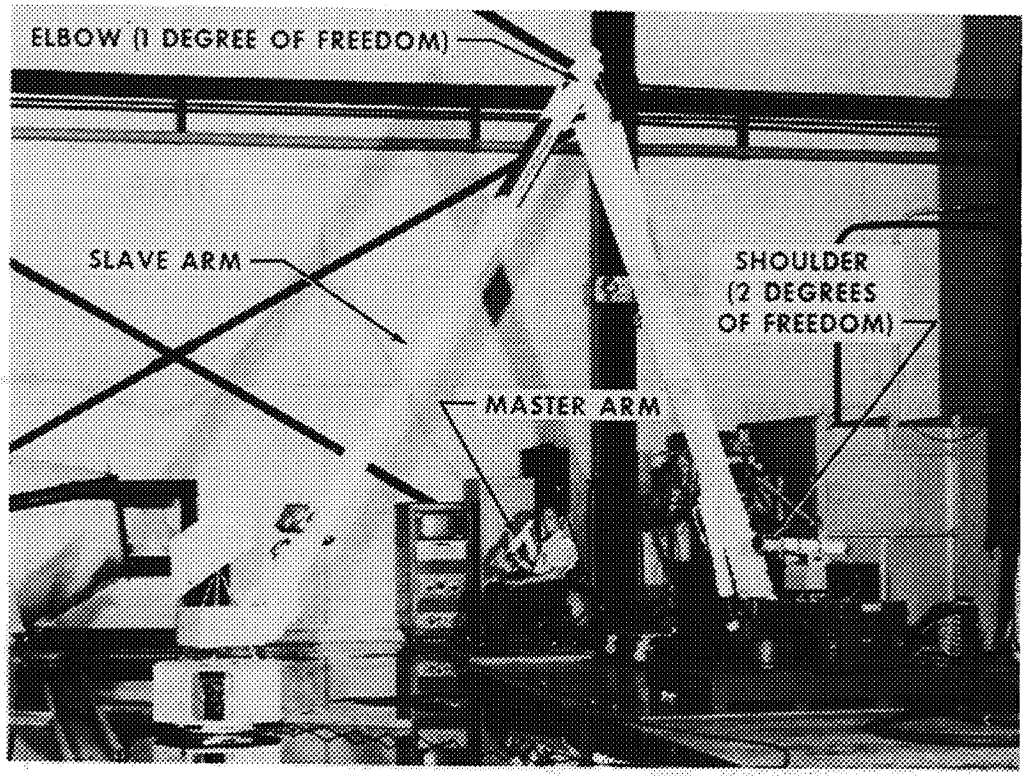

Figure 5. - The CAM 1400.

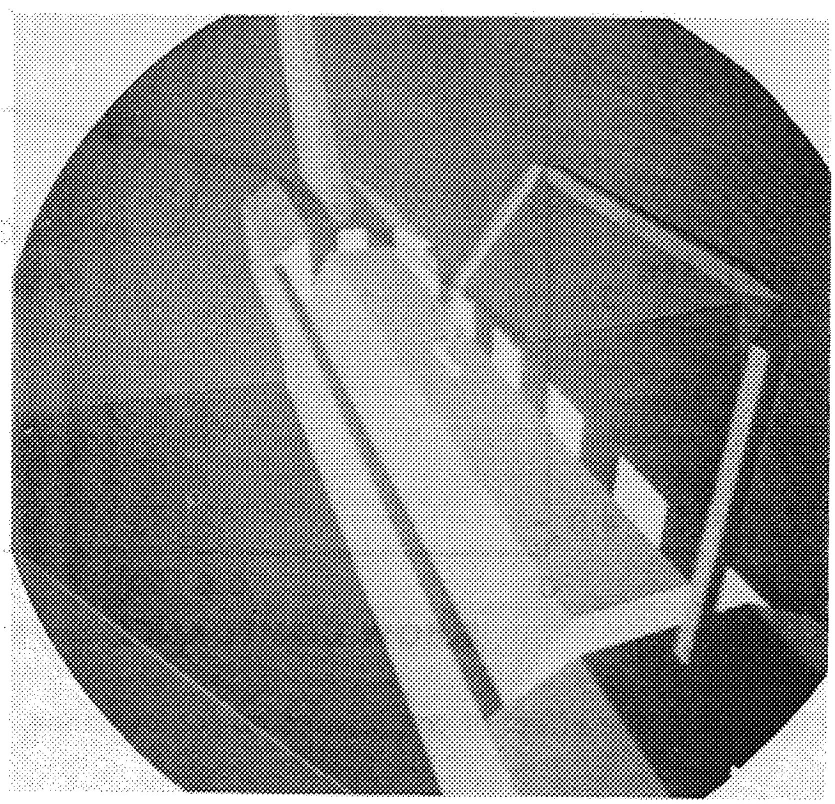

Figure 6. - The computer-generated scene.