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Interim Report

Covering the Period 1 November 1972 — 30 June 1973

STUDY OF EQUIPMENT NEEDS FOR ARTIFICIAL INTELLIGENCE RESEARCH

By: N. J. NILSSON, H. BARROW, L. COLES, G. GLEASON, B. MEYER, and D. NITZAN

Prepared for:

NATIONAL SCIENCE FOUNDATION
1800 G STREET
WASHINGTON, D.C. 20550
Attention: MR. NORMAN CAPLAN

GRANT GK 36487

SRI Project 2308

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Approved by:

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ABSTRACT

This report describes interim results of a project to specify special equipment for research in Artificial Intelligence. After surveying several potential users it was decided that there was a need for standardized equipment for robot research. Such equipment includes a vision subsystem, an arm subsystem, and a mobile cart subsystem. Some users desire a robot consisting of all three subsystems, while others need lesser combinations.

Taking into account these user needs, and equipment cost and availability considerations, we recommend a list of modular components that in total comprises a complete mobile robot system. Alternatively, subsets of the component list can be used to suit particular user needs. The recommended systems include a small minicomputer to be used for arm trajectory, vehicle navigation, and interfacing with the user's main computer. Use of the minicomputer provides needed research flexibility in that control algorithms can be easily revised and additional user sensor and effector equipment can be easily added.

The complete vehicle-arm-vision robot system will be controlled from the user's main computer over a radio link to the on-board mini-computer. The robot will be able to operate in an office or laboratory environment, and will be powered by rechargeable storage batteries. Television pictures from the vehicle will be sent back to the main computer over a video-bandwidth radio link.

Cost estimates for both the prototype equipment and future copies are given.

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I INTRODUCTION

A. Intent of the Project and Summary of the Report

This report describes the status of work done on an NSF grant to develop a set of specifications for experimental hardware for facilitating artificial intelligence (A.I.) research. Work on the grant has progressed to the point where preliminary specifications and recommendations about such equipment can be made. These will be described in full in this interim report. We will also discuss all of the other supporting work done to date under the terms of the grant.

The purpose of this grant is to meet an important, unfilled need. There has been a great interest in the last few years in research and experimentation with computers connected to peripheral effectors and receptors such as mobile carts, manipulator arms, and television cameras. Such robot-like systems are often expensive, one-of-a-kind devices that are generally unavailable to all but a very few universities and other large research organizations. It can reasonably be expected that if lower cost, flexible, modular, standardized robotic research equipment were more available, then progress in robotics research generally and advanced automation tasks in particular would markedly quicken because the amount of experimentation in these areas would be greatly expanded. Common equipment would also facilitate verification of one laboratory's results by another and would permit more widespread sharing of computer programs. To date we have accomplished two major objectives. First, we have surveyed a large number of research organizations with actual or potential interest in robot equipment to determine their opinions on the requirements for this kind of equipment. Second, we have made preliminary recommendations of equipment to meet these needs. These recommendations are based on a thorough examination of existing components.

The results of the survey are discussed in detail in Appendix A of this report. Briefly we found a need for four major categories of equipment:

A. Self-powered, wheeled cart

B. Manipulator arm

C. Modest vision system

D. Elaborate vision system.

The difference between categories C and D is that category D involves rather expensive and specialized equipment that would best be assembled by the research group using it. We feel that it would probably not make sense to try to specify standardized elaborate vision systems.

In this report we make recommendations about equipment for Categories A,B, and C. In the rest of this section we summarize the work performed and yet to be performed under the present grant. In the two following sections we give the detailed equipment recommendations and their rationale. Supporting material is included in the appendices.

B. Summary of Work Covered by the Present Grant

1. Survey of Needs

To determine the possible needs for robotic equipment, a questionnaire was sent to individuals at several laboratories and universities throughout the world. A copy of the questionnaire is included in Appendix A. We received 33 responses that indicated an interest in robotic equipment.* The evaluation of these responses is also contained in Appendix A.

*In addition we received 14 responses indicating no interest in robotic equipment.

2. Survey of Available Components

While we were attempting to determine needs, we also made efforts to acquaint ourselves with the range of components that might be used. We had discussions with several builders of mobile carts, arms, television systems, computer components, and the like. Whereas most of the components that we recommend are "off-the-shelf" items, we found that there existed no ready-made arm or cart to suit our purposes. For these items we decided to expand our search for suppliers to include those who would modify existing designs and those whose designs were still in early stages.

To make sure that we did not overlook promising components from foreign manufacturers, we made a special survey of Japanese and European equipment. To survey Japanese equipment we sent a member of the project staff, Mr. Gerald Gleason, to visit several Japanese companies. His report is included as Appendix B. We commissioned a special consultant, Professor Donald Michie of Edinburgh University, to survey European equipment. His report is included as Appendix C. On the basis of these reports we decided that there were no compelling reasons at this time to recommend purchase of foreign components.

3. Preliminary Specifications

On the basis of the survey results, we concluded that it would be reasonable to provide standardized versions of a mobile cart, a manipulator arm, and a modest vision device. A given user may desire a complete mobile robot consisting of cart, arm, and vision device. Other users may want only a subset, for example an arm and vision device or a vision device alone. We decided to specify modular cart, arm, and vision devices that could be used in various combinations to suit a variety of user needs. With standardized components, there will be a consequent reduction in cost for all users. These components are listed and described in the next two sections of the report.

4. A.I. Equipment Workshop (to be held)

We plan to hold a one-day workshop at SRI (in conjunction with the International Joint Conference on Artificial Intelligence at Stanford University) on August 24, 1973 to which anyone interested in A.I. equipment will be invited. Participants will be supplied in advance with a copy of this report. The goal of the workshop will be to obtain feedback from the A.I. community about our preliminary recommendations. The suggestions will be studied and could influence our final recommendations.

5. Final Report

At the end of the present grant in November 1973, an updated set of specifications will be presented in the final report.

II SPECIFICATIONS AND RECOMMENDATIONS

A. Overall Specifications

Our analysis of the survey results indicated that the union of most of the needs would be met by a mobile cart carrying a vidicon television camera and manipulator arm plus the necessary radio and interface equipment. In describing the recommended equipment, we will for convenience make the assumption that the equipment will be part of one complete mobile robot system. It will be apparent, however, that various subsets of this equipment can be used alone.

The specifications for the equipment are a compromise among user desires, available equipment, and cost considerations. We will be describing a system that we think will meet most user needs at reasonable cost.

We will first present a short overall summary of the equipment specifications. Then we will describe recommended equipment for each subsystem in some detail. In Section III of this report, we will give some additional background in support of our recommendations.

We specify a mobile cart with a square base of about 25 inches so that it can easily pass through a standard sized doorway. The cart should be able to maneuver easily inside a small room (such as an office). The entire system should be protected by a system of proximity sensors (such as bump detectors) so that it will not harm itself or others by high speed collisions.

There are strong requirements for having the vehicle self-powered (e.g., by batteries) and unfettered by cables of any kind under normal operation. It should be able to travel at speeds of, say 3 feet/ second over reasonably smooth floors such as one might find in an ordinary laboratory or office or outside on smooth surfaces. A complete system might weigh 600 or so pounds fully loaded. In fact, a sturdy system is desirable to provide stability and precision for the camera and arm systems. The robot system should have extra capacity (in terms of space, power, and control interface) to invite users' special equipment such as other types of sensors and effectors.

The visual system should be able to provide pictures of at least about 240 x 320 spatial resolution with 64 levels of gray scale. Color vision is also specified. Field of view of the visual system should be variable between roughly 10 degrees and 40 degrees. The visual system should be capable of panning and tilting. The picture information is to be made available as a stream of digital data ready for input into either fast computer core or some kind of user-supplied buffer. We have specified that an optically collinear range-finding device should be able to be added later with minimum difficulty.

The manipulator arm must be capable of grasping small objects whose weight can be up to about 3 pounds. It must be able to pick up, load, and transport objects such as books or small boxes. It must be able to be used in making assemblies of things. It should be able to operate near the floor (e.g., to pick up items it might have dropped) and above a desk or table. It is desirable to be able to add an optional second arm.

For I/O capabilities on board the vehicle we have specified a display and keyboard; a microphone and speaker can be easily added. The system should include all necessary interface equipment to allow easy connection to a user's time-shared computer and should be equipped with any software needed in controlling this interface equipment. A chart listing these and other specifications is shown in Table 1.

We have been able to arrive at preliminary design decisions for equipment to meet these specifications. In brief, we recommend a

TABLE 1

ROBOT SYSTEM SPECIFICATIONS

A. Vehicle

- Indoor operation in and out of rooms and corridors
- Three feet/second maximum speed
- Maneuverable within small rooms
- Free of power and communication cords
- Self-contained power supply that can provide power for at least three hours continuous operation.
- Space for minicomputer and other control circuits
- Extra space for miscellaneous user equipment
- Space for carrying small objects
- I/O capabilities such as microphone, speaker, keyboard, and display.

B. Manipulator

- Tasks to be performed

  Stacking and/or sorting of simple objects such as blocks, books, etc.

  Assembly of simple structures out of simple components

  Assembly of simple equipment

  Acquisition and handling of irregular objects.

- Types of hand

  Specialized attachments and tools can be fitted on

  Gripper jaws with perhaps some extra articulation. Maximum grip dimension about three inches.

- Feedback from the manipulator

  Positions and velocities of the joints, forces on the joints and hand, tactile feedback from hand.

- Hand should be able to lift objects up to about 3 pounds weight.
- Reach should be up to about 2 feet
- Accuracy of positioning of hand should be about 2 mm.

C. Visual System

- Capable of accommodating an optically collinear rangefinder
- Spatial resolution should be 240 x 320 picture elements
- Up to 64 levels of intensity at each picture point
- Color information
- A complete picture must be readable in 0.1 second or less
- Vision device should be able to work in rooms having normal illumination ranges
- Field of view variable between 10° and 40°
- Vision device should be steerable (pan and tilt)
- Parameters to be under program control:
  scan rectangle size and position, electrical sensitivity, focus, iris, focal length.

four-wheeled, battery-driven cart carrying a Scheinman-MIT electric arm and a TV camera mounted on a pan-tilt head. The cart will also have a minicomputer on board to handle interface functions and to provide low-level control of arm, camera, and wheel motors. The cart will be radio-controlled from the user's main computer and will send television pictures back to this computer over a special video radio link. A simplified drawing showing the approximate appearance of the vehicle is shown in Figure 1. Plan views of the system are shown in Figure 2. Detailed descriptions of all of the components of the system follow. (Additional discussion of design decisions is contained in Section III.)

B. Components

1. Vehicle

a. Chassis, Drive, and Power Supply

We undertook a general review of 12 commercial electric vehicle manufacturers. After a more detailed investigation of products offered by four of these manufacturers, including site visits to their distributors, we recommend the Electro Limb Corporation of Downey, California as the prime supplier for our robot vehicle, including chassis, drive motors, control electronics, and power supply. Additional discussion of this choice is contained in Section III. The electronic control, motors, drive belts, power supply, etc. will be derived from the SCAT Electric Wheel Chair manufactured by Wheelchairs, Inc. (a sister company of Electro Limb) also in Downey, California. The vehicle platform and wheel configuration will be redesigned by Electro Limb according to our own specifications (see Figures 1 and 2).

The overall outside dimensions of the vehicle chassis are 25 inches x 25 inches. The main-frame vehicle height (not counting TV-pan/tilt mount or arm guide post) may be as high as 38 inches depending on

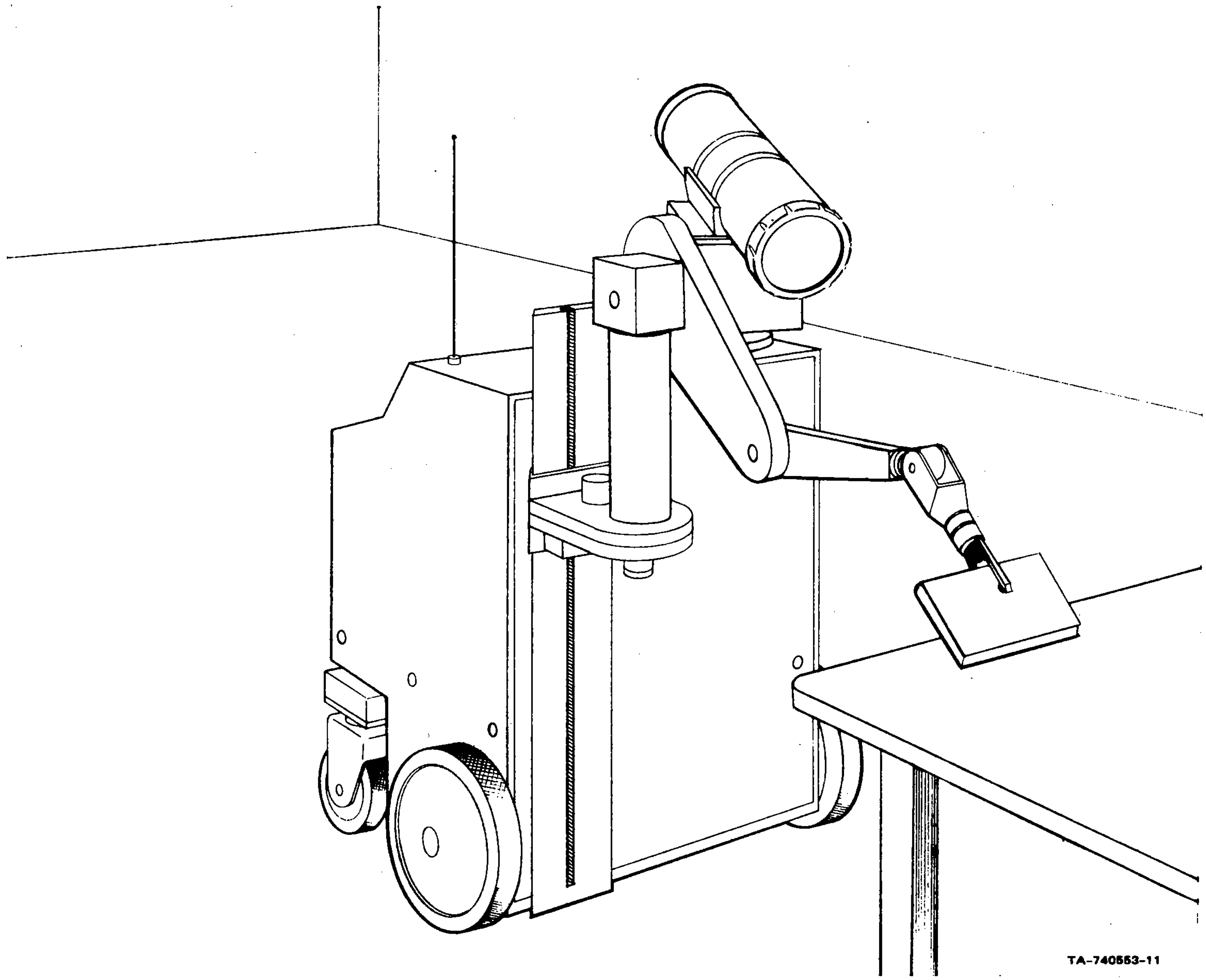

FIGURE 1 PROPOSED ROBOT VEHICLE

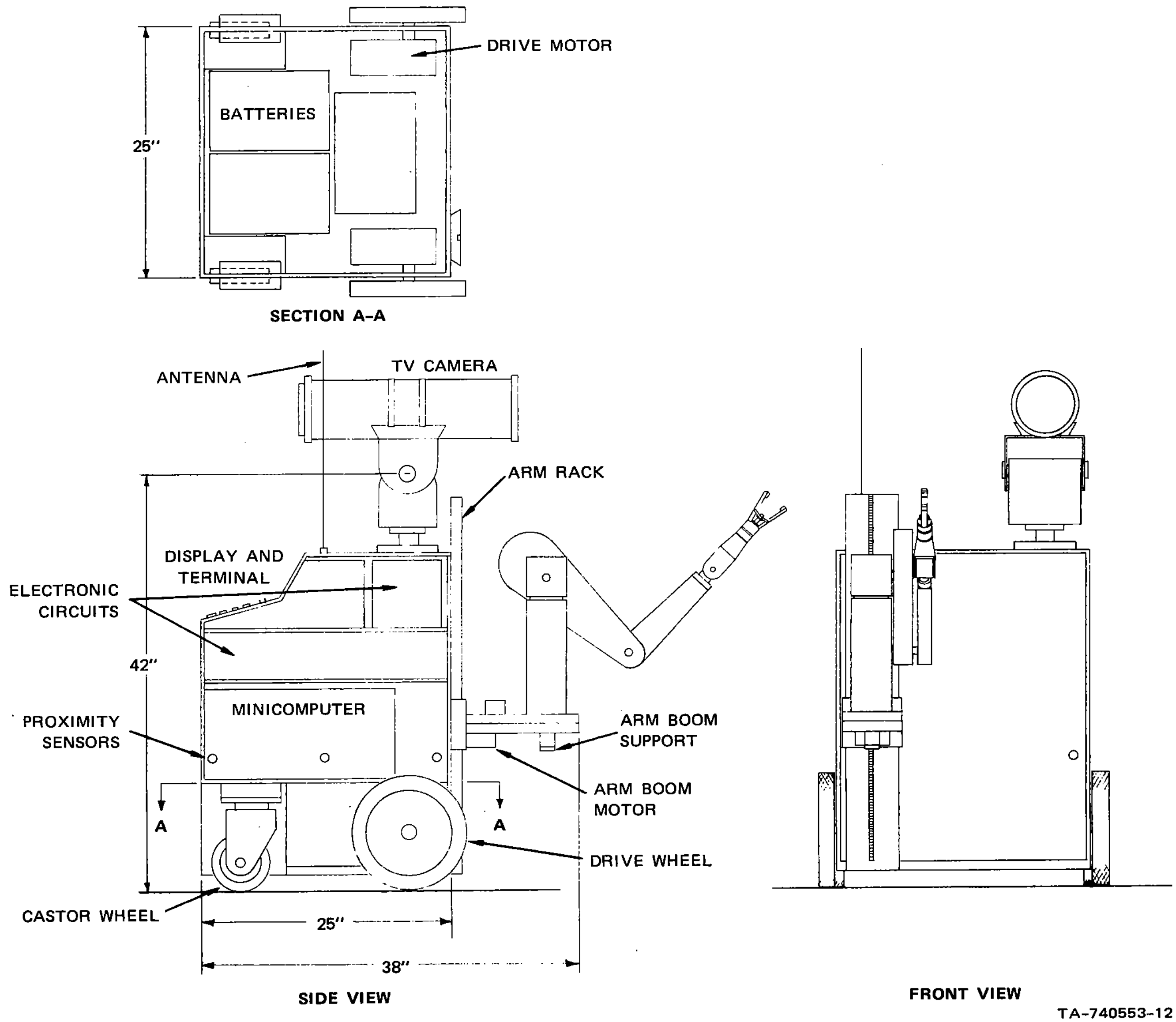

FIGURE 2 PROPOSED ROBOT VEHICLE—THREE VIEWS

the number of shelves of on-board equipment required. The vehicle will have two 12 inch diameter, belt-driven wheels (zero-pressure, solid rubber tires) and two 6 inch diameter, floating-hub, rear swivel castor wheels. The vehicle will be able to rotate about any point on the axis through its front wheels. All four wheels will be $1\frac{1}{2}$ inches in width. The SCAT vehicle traction, suspension, and stability are all within acceptable limits, as witnessed during a live demonstration of the vehicle under human control while traversing a slope of 25° at full forward speed of 6 feet/second, far more severe a demand than we expect to impose in normal operation.

Speed of the redesigned vehicle will be variable up to about 3 feet/second. The time to accelerate to maximum speed is about 2 to 3 seconds, and deceleration time (with drive-train braking) is about 1 second to full stop. The requirement for dead-reckoning with high precision under remote control will probably be satisfied by optical encoders on one of the castor wheels rather than by a clutch-coupled axle between the drive wheels. The vehicle is driven by two permanent magnet 12-volt, $\frac{1}{4}$-HP, electric motors and powered by a single 12-volt, 95-AH, conventional storage battery. Two additional 12-volt storage batteries will be used to power the on-board minicomputer and other sensory-motor equipment. Section A-A of Figure 2 shows their approximate location on the lowest shelf of the vehicle. The batteries will be housed in such a way that they can be easily replaced. It will be possible to recharge them either in place on the vehicle or disconnected and separate from the vehicle. When recharging on board, due regard must be given to proper protection of the vehicle components from acid and fumes.

b. Proximity Sensors

To protect the vehicle from inadvertently bumping into obstacles in its environment, the vehicle will use small, solid-state, LED proximity sensors distributed around the perimeter of the vehicle. The sensors are able to reliably detect large barriers or small objects (even as small as a thread) of an arbitrary material within a range of up to 8 feet. The detectors are manufactured by Scientific Technology, Inc. of Mountain View, California. The detector operates essentially as follows: an invisible, infrared, modulated, light beam is projected by a transmitter module with a fairly narrow beam angle. Any obstacle that intersects the transmitted beam will reflect light energy back into a receiver module as a function of its distance (and its color and texture to some extent). Because the transmitted light is modulated, the detector can never be falsely triggered by ambient light or heat, even bright sun light. By judiciously positioning transmitters and receivers around the perimeter of the vehicle, one can create a curtain of protection against inadvertent contact with physical objects, walls, and the like. A possible distribution is shown in Figure 3. By dynamically measuring analog voltage output from the various proximity detectors rather than just a threshold level, we can extract approximate range information. Using the proximity detectors in this mode, together with a minicomputer control program, it should be possible to measure the rate of approach toward an object and therefore possible, for example, to move smoothly through an open doorway. For this reason we think this type of proximity detector is preferable to "cat whiskers" connected to mechanical switches.

c. Arm Rack and Boom

As shown in Figures 1 and 2, the Scheinman-MIT manipulator subsystem will be mounted on a 1-foot cantilever boom capable of sliding up and down under computer control along a channel-mast rack attached rigidly to the front of the vehicle chassis. This design was chosen to maximize the reach of the arm over the surface of a table top while minimizing vibration or instability. A special feature of the design

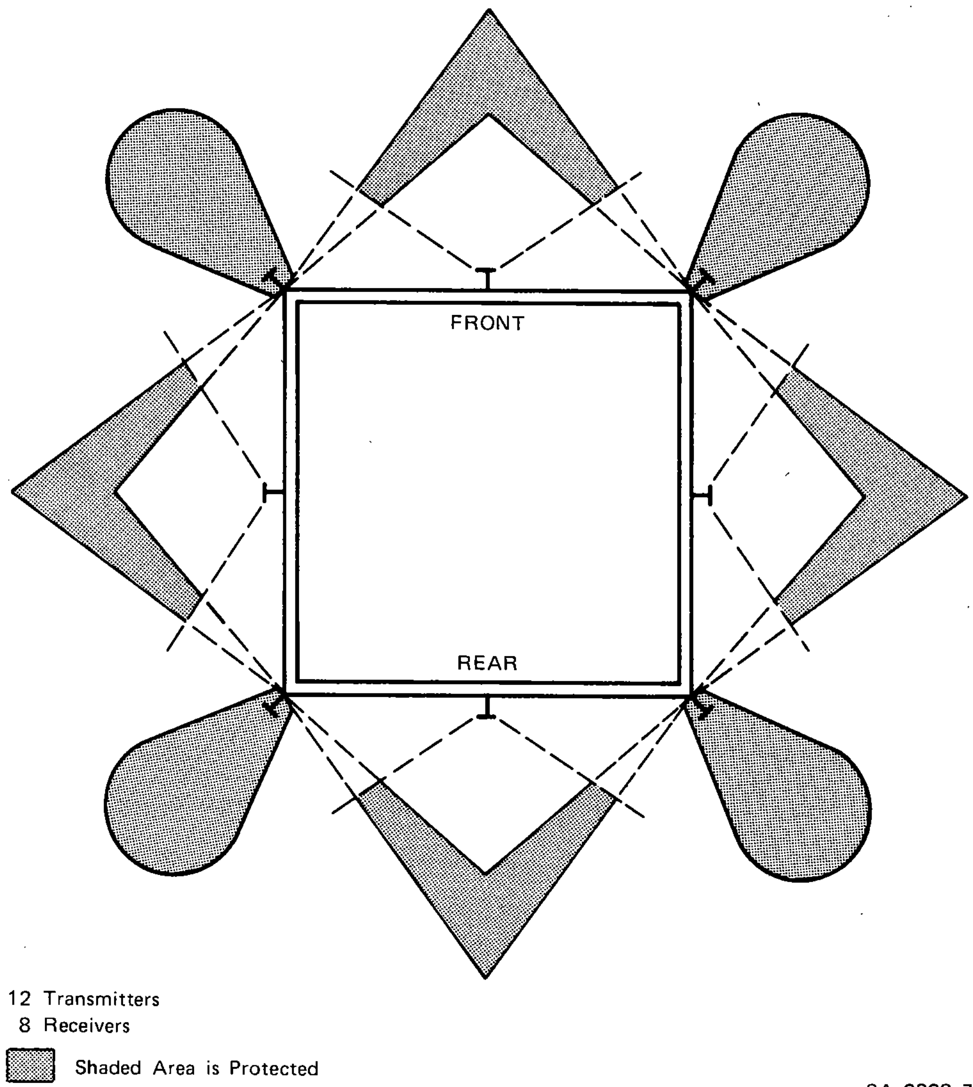

FIGURE 3 PROXIMITY DETECTOR INVISIBLE CURTAIN FOR PERIMETER PROTECTION

is a simple elbow support below the cantilever boom so that the arm can rest its shoulder on the table while carrying out manipulation tasks on top of the table and thereby minimize positional error due to distributed torques extending into the vehicle itself. The vertical translation of the boom along the channel mast could range from 12 inches to 42 inches above the floor, thereby satisfying the requirement for manipulation operations both at table top heights and on the floor as necessary.

In addition to the arm boom, it might be desirable to add some sort of pushbar in front to aid in pushing objects.

2. Arm

We have investigated many types of arms for robot research. Most of these arms are designed for industrial materials handling applications, (e.g., Unimate, Versatran) and hence are too large for a robot vehicle that will operate in an office environment. Any arm that is hydraulically powered was ruled out because of the size, weight, and noise of a hydraulic power plant. (For example, the M.B. Associates NAT arm was ruled out because of this consideration.) The Los Ranchos Amigos RAM arm and the Stanford (Scheinman) arm are electrically powered, but both are too large for this application. The most ideal arm is the one designed for desk-top use by Victor Scheinman for the M.I.T. A.I. Laboratory. It was designed in the Fall of 1972, and currently 10 arms are being constructed. It is approximately of two-thirds human size and shape and has six electrically powered rotary joints plus a parallel jaw hand. The first five joints have electromagnetic brakes to hold the arm in a given position without requiring continuous motor power. The arm has a 40-cm radius hemispherical workspace (centered on the "shoulder" joint). It has a lifting capacity of approximately 1.5 kg (3.3 pounds) at full extension and takes approximately 1 second to complete simple (nontrajectory) motions. The resolution of arm motions is approximately 1 mm and the accuracy can be 2 mm using calibration look-up tables with interpolation. A sketch of the arm is shown in Figure 4.

Space is available to allow the modular addition of a second arm on the same movable boom if two-handed tasks are desired. Of course, the software to support two arms is complicated by the need for collision avoidance. The arm will have proportional touch sensors in its fingers in addition to a wrist-mounted strain gauge force balance.

3. Servo Systems

Each of the on-board servo systems (with the exception of the vehicle drive motor controls) will be a conventional analog servo amplifier with velocity feedback for maximum performance. The drive motors will be controlled with pulse-width modulated servo amplifiers to minimize wasted power at low speeds. Each drive wheel will have a quadrature incremental shaft encoder which will allow the minicomputer to monitor and control the path of the vehicle. We expect the design of the servo systems to be straightforward.

4. Vision System

The visual system specifications given in Table 1 serve as a rough beginning point for defining this subsystem. One of our first questions was whether or not a solid-state image sensing array could be used to meet these requirements. In Section III we discuss these arrays in more detail and conclude that they might well form the basis of a future vision system, but that because of present cost and availability considerations we must recommend a conventional television vidicon camera.

We took quite seriously the requirement that some kind of scanning range finder be usable with the vision system. To simplify vision system computation, we specified that it must be possible to

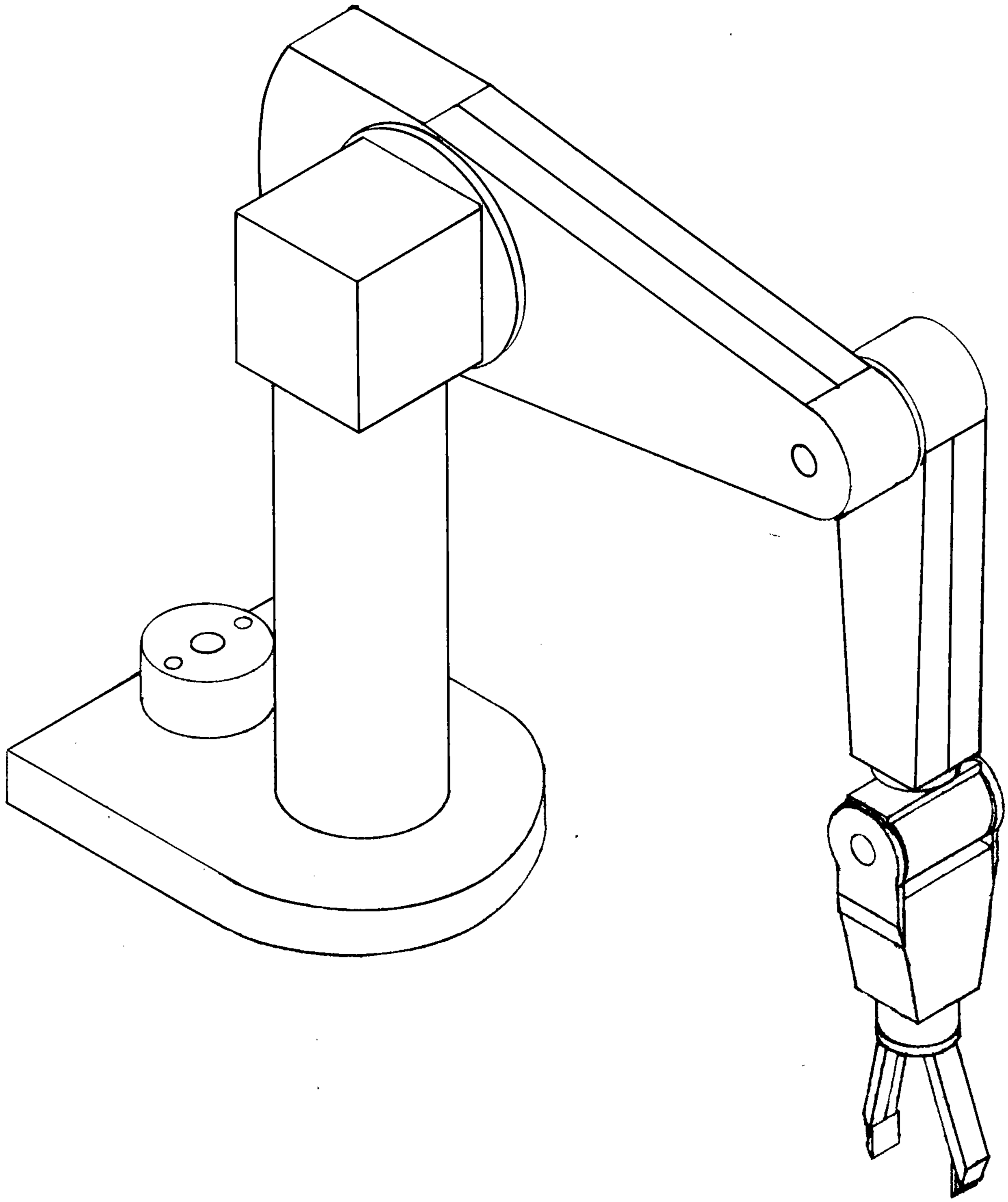

FIGURE 4 SCHEINMAN — MIT ELECTRIC ARM

mount the range finder in such a way that its field of view is optically congruent with that of the TV camera. At the present time such a range finder is under development at SRI. This range finder is described in detail in Appendix D.

We have done a rather detailed job in our visual system specifications and thus devote a major part of Section III to this subject. Here we will briefly summarize our conclusions.

a. Mounting of the Camera System

We have specified the following requirements that affect the way in which the camera is mounted:

- ± 180° pan angle
- ± 90 tilt angle
- A high view position
- Confinement to within the vehicle area
- A low position for mechanical stability
- Optical congruence with range finder

To meet these requirements, two arrangements have been considered, and the one shown in Figure 5 is recommended. The camera is mounted on a pan-and-tilt mount (Pelco Model PT-550-M) that is mounted on the robot frame. As shown in Figure 5, the range finder system can be mounted on the camera to give optical congruence.

b. Camera Performance Specifications

We have made the following detailed specifications for the TV camera. These items are discussed at length in Section III.

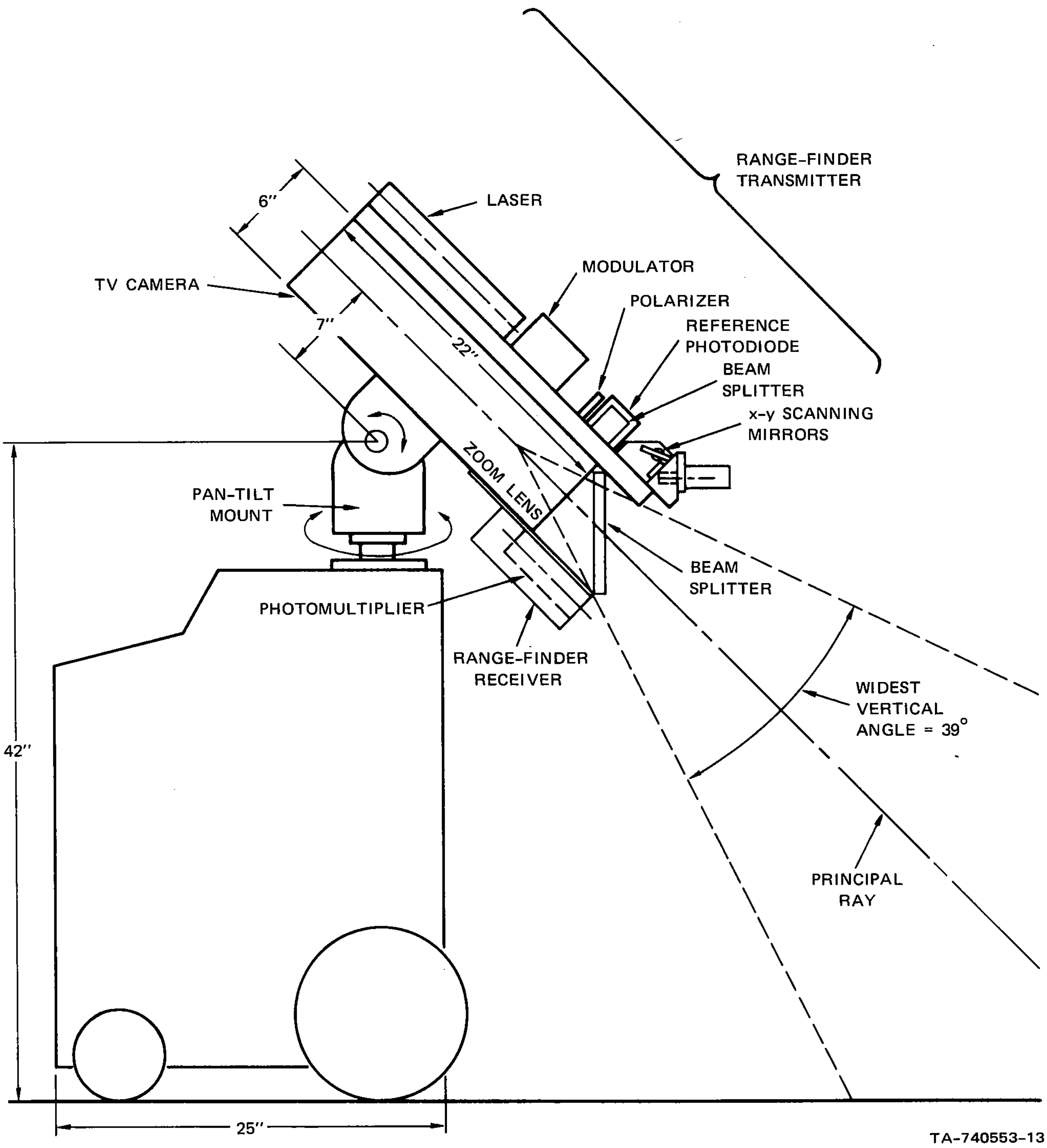

FIGURE 5 MOUNTING THE TV CAMERA AND RANGE FINDER OF A ROBOT ON A PAN AND TILT MOUNT

Electrical Characteristics

(1) Resolution: 320 x 240 (using one field) or 640 x 480 (using four fields)

(2) Bandwidth: 3.0 MHz

(3) Sensitivity: High and flat spectral response of a Silicon-Diode-Array Vidicon

(4) Signal-to-noise: 300:1, i.e., 50 db

(5) Dynamic range: $I_{max}/I_{min} = 75$ for $(I_{min}/I_{noise})_{min} = 4$

(6) Gray scale levels: 64 levels (logarithmic scale preferred).

Optical Characteristics

(1) Focal length: Variable, 12.5 mm to 50.0 mm, using a 4:1 zoom lens (the corresponding view angle varies from $53^\circ \times 39^\circ$ to $14^\circ \times 10.5^\circ$)

(2) Focus range: 4 feet (with open iris) to infinity.

Color Characteristics

Four-position color-filter wheel (red, green, blue, and neutral), internally mounted.

Mechanical Characteristics

Size and weight: 22-inch long (constrained by 4:1 zoom), 6-inch diameter (constrained by internal color wheel), about 25 pounds (including electronics and casing).

Remote Control: Drive motors and readout potentiometers for controlling focus, zoom, iris, and color wheel.

c. Camera Recommendations

On the bases of existing provisions for mounting a color wheel internally, the lowest overall cost of the required camera system, and the satisfactory experience we have previously had with COHU cameras, we recommend the following camera system:

COHU Model 2850 modified to include a four-position, remotely controlled color wheel, with a remotely controlled 4:1 zoom lens (12.5 to 50-mm focal length). This system is 22 inches long, 6 inches in diameter, and weighs about 21 pounds. The overall cost with modifications is about $7,000.

For users who might not require color and/or zoom lens features we provide a list of recommended cameras in Table 2.

5. Video A/D Equipment

a. Video Data Acquisition

The high rate of data generation of a TV camera imposes particular problems upon data transmission, digitization, and interfacing. Because of this interdependence, these topics will be discussed together in this section. (Additional background is given in Section III.)

It is desired to encode a TV picture into 240 x 240 picture samples, each of 6 bits of intensity on a logarithmic scale. Moreover, for activities such as real-time visual control of robot actions, it is desirable to perform the digitization as rapidly as possible, preferably in the time of one field scan (1/60 second). One such picture represents about 460,000 bits of information.

The robot minicomputer does not have enough memory nor input channel capacity to deal with such TV data. It is proposed, therefore, to transmit the picture from the TV camera via a video transmitter/receiver link back to the main computer. The digitizer will be connected

TABLE 2

RECOMMENDED TV CAMERAS

Type	4:1 Zoom	Internal Color Wheel	COHU Model No.	Length (in.)	Diam. (in.)	Weight (lbs.)	Approx. Cost ($)
1	yes	yes	2850	22	6	21	7,300
2	yes	no	2850	22	3	21	6,000
3	no	yes	2850	20	6	20	5,800
4	no	no	4254-100	16	6	20	1,850
			or 4500	20	3	6	3,000

directly to the main computer. It will be capable of digitizing a picture and storing it automatically in core memory in the time of one TV field. Remote control of the camera (pan, tilt, iris, etc.) will be exercised via the radio link between the main computer and the robot through the on-board minicomputer. Control of any digitizer parameters will, however, be direct from the main computer as for any other peripheral of the main computer.

In some cases, such as in visual control of movements when very simple picture processing will suffice, it may be advantageous to provide the minicomputer with TV data so that it may perform the necessary computations and correct movements. Therefore, it is proposed to provide as an option a simplified digitizer connected directly between the camera and the minicomputer. There are two alternative schemes:

(a) Encoding by comparing with a computer pre-set reference level, and returning 1-bit samples packed 16 to a word. Control logic of the digitizer will be almost identical to that of the main digitizer,

(b) Encoding via a sample-and-hold circuit and A/D converter. One 8-bit sample per TV line can be digitized, and samples packed two to a 16-bit word, to take advantage of special half-word handling operations possessed by many minicomputers (particularly the PDP-11 and Nova computers). Control logic will be extremely simple: the computer will be responsible for selecting the word sample point.

The first scheme is useful when dealing with a large number of picture points each of which need only be classified into black or white depending on a threshold level. The second scheme is useful when the converse is true, i.e., coarse sampling with high accuracy per point. A block diagram of the video data acquisition system is shown in Figure 6.

b. Digitizer Components

A more detailed block diagram of the TV digitization equipment is given in Figure 7. The major components are as follows:

TV Receiver-- The details of the TV transmitter/receiver link have still to be determined (see Section II-B-8).

Conditioner and Clamp --The video signal is standardized by controlling its amplitude and dc offset, so that black and white correspond to two predetermined voltages. At this point a logarithmic amplifier could expand the dark signals and compress the bright ones.

A/D Converter-- This will be constructed using commercially available sample and hold units and an A/D converter (probably ADCUH8B, Datel Systems, Inc.).

Packer and Interface-- The samples from the A/D converter are packed together into words of the size of those of the main computer (possibly with overlap across words). The packer can be designed to be modifiable for main computers of a variety of word lengths.

Format Specification and Output Interface-- Sampling can be performed within a window of the TV image specified by position and size in two dimensions. The sample density can also be specified. Since these functions could be simulated in the core memory of a large computer, the format specifier is optional.

Control Logic-- This unit decides when to sample the input data, given the format specification and synchronizing signals from the TV input. It automatically samples all the required points in the window in sequence.

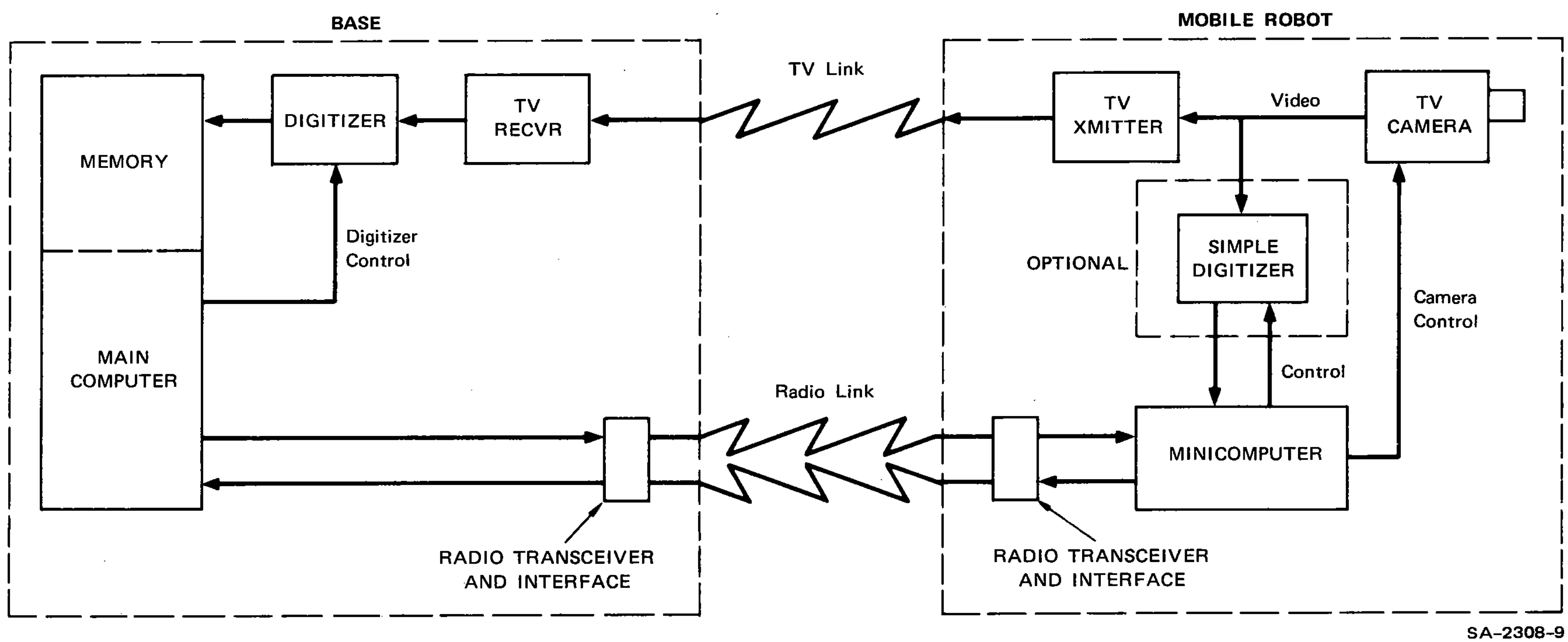

FIGURE 6 VIDEO ACQUISITION SYSTEM

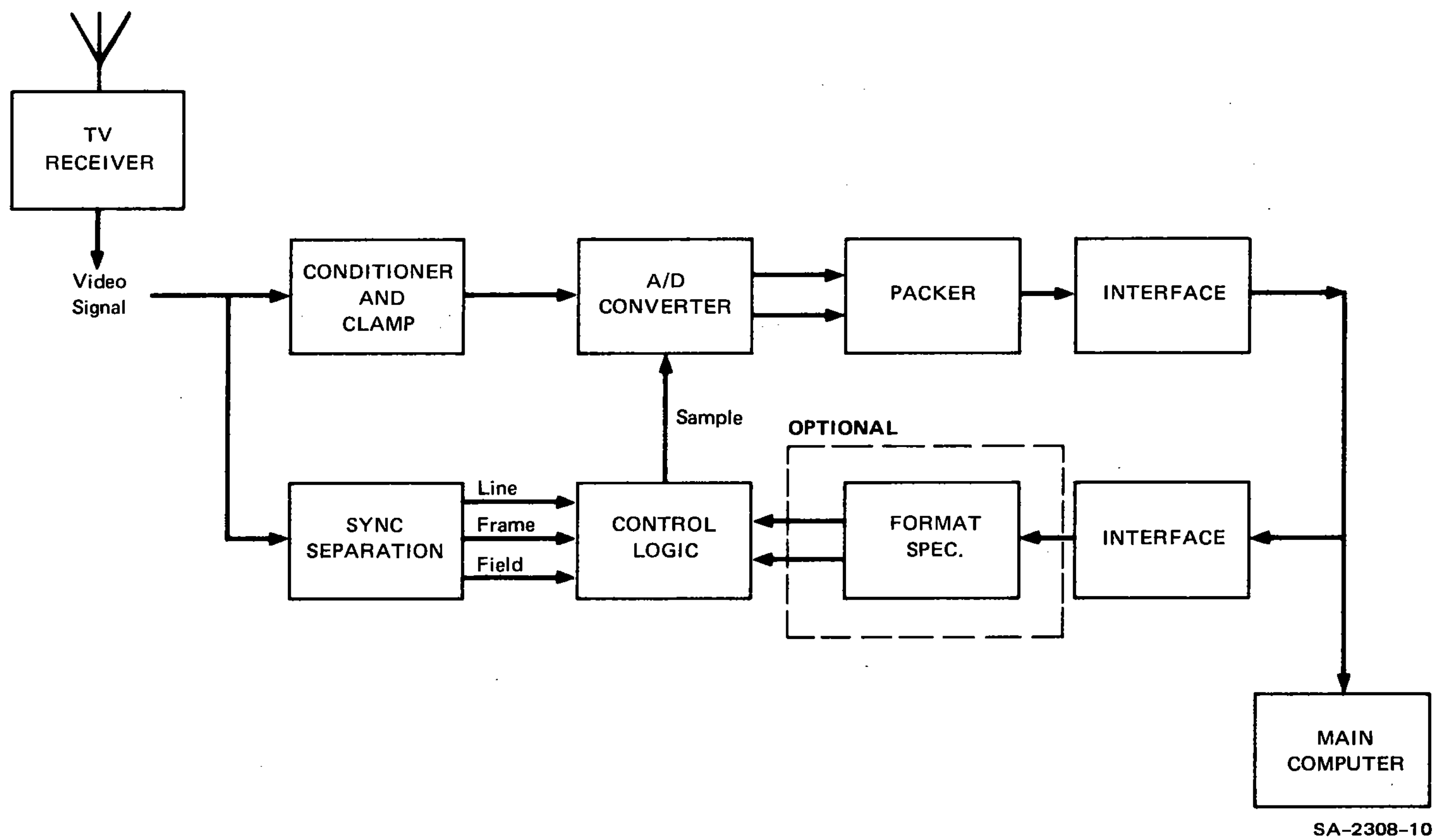

FIGURE 7 VIDEO DIGITIZATION EQUIPMENT

Sync Separator -- The line and frame synchronizing signals are extracted from the video signal, and cleaned up for presentation to the control logic. The sync separator also determines which fields are odd and which are even.

In keeping with the philosophy of the proposed robot system, the digitizer components will be constructed with standardized interface conventions for the connections between them. It will therefore be possible to modify or redesign modules to meet particular user requirements, while avoiding redesign of the whole TV data acquisition system.

6. On-board Logic and Control

To provide maximum flexibility and expandability, all control systems and sensors will be interfaced as I/O devices on an onboard minicomputer. This philosophy allows additional future devices and sensors to be easily added. The minicomputer will also serve to decode the high-level commands from the main computer via the radio link. In addition, since real-time response is required, calculations for control of the arm trajectory and for vehicle navigation will be accomplished by the minicomputer. The minicomputer will then set the command signals for all of the on-board analog and digital controls.

The minicomputer should have at least 8k of core memory to support the command interpreter, the arm trajectory control model, the navigation control program, and the other servo and sensor control programs. (Extra core memory modules can be added if desired.)

The communication between the on-board minicomputer and the main computer will be in standard ASCII teletype format, since this standard is the most widely used. This allows the robot vehicle system to "look" like a teletype; hence the interface to the main computer will be as straightforward as possible. The modem on the on-board minicomputer will allow transmission rates up to 50,000 bits/second. The actual data rate will be determined by the maximum rate of the host computer's teletype interface. The program for the on-board minicomputer will be assembled on the main computer and loaded via the 50,000 bps radio link. At this rate, an 8k program will take $\frac{8 \times 10^3 \times 16}{50 \times 10^3} \cong 2.5$ seconds. Therefore, the on-board minicomputer programs can be quickly modified.

The two most suitable minicomputers for the robot vehicle are the DEC PDP-11/20 and the Data General NOVA 1220. Both of these companies have developed extensive software for their minicomputers, and both have excellent service organizations. If the cost of the minicomputer systems were the same, we would choose the PDP-11/20 because of its more powerful instruction set. However, in the system required for the robot vehicle, the PDP-11/20 configuration costs approximately 20 percent more than the equivalent NOVA 1220 configuration. We therefore have tentatively chosen the NOVA 1220 configuration based on this substantial difference in price. The final choice will be based on the relative ease of developing software and a competitive bid on the entire minicomputer system.

The configuration of the minicomputer's I/O bus is shown in Figure 8. The 64 channel multiplexer and analog-to-digital converter, teletype interface, real-time clock and 50-kbs synchronous modem are standard, readily available computer peripherals. The left and right drive motor controls consist of 8-bit digital-to-analog converters (D/As) and analog proportional speed controls. The arm boom height needs only an 8-bit D/A for its servo control since its function is only to place the arm in its workspace. The first three arm joints have 12-bit D/As because any errors will be multiplied by the lever arm of the other joints. The last three joints require progressively less accuracy as shown in Figure 8. All of the TV controls except the color wheel require only binary control, i.e., a 2 bit digital control will specify direction and "go" for each function (10 bits total). The analog position of these functions will be read by the A/D. The keyboard and display will each

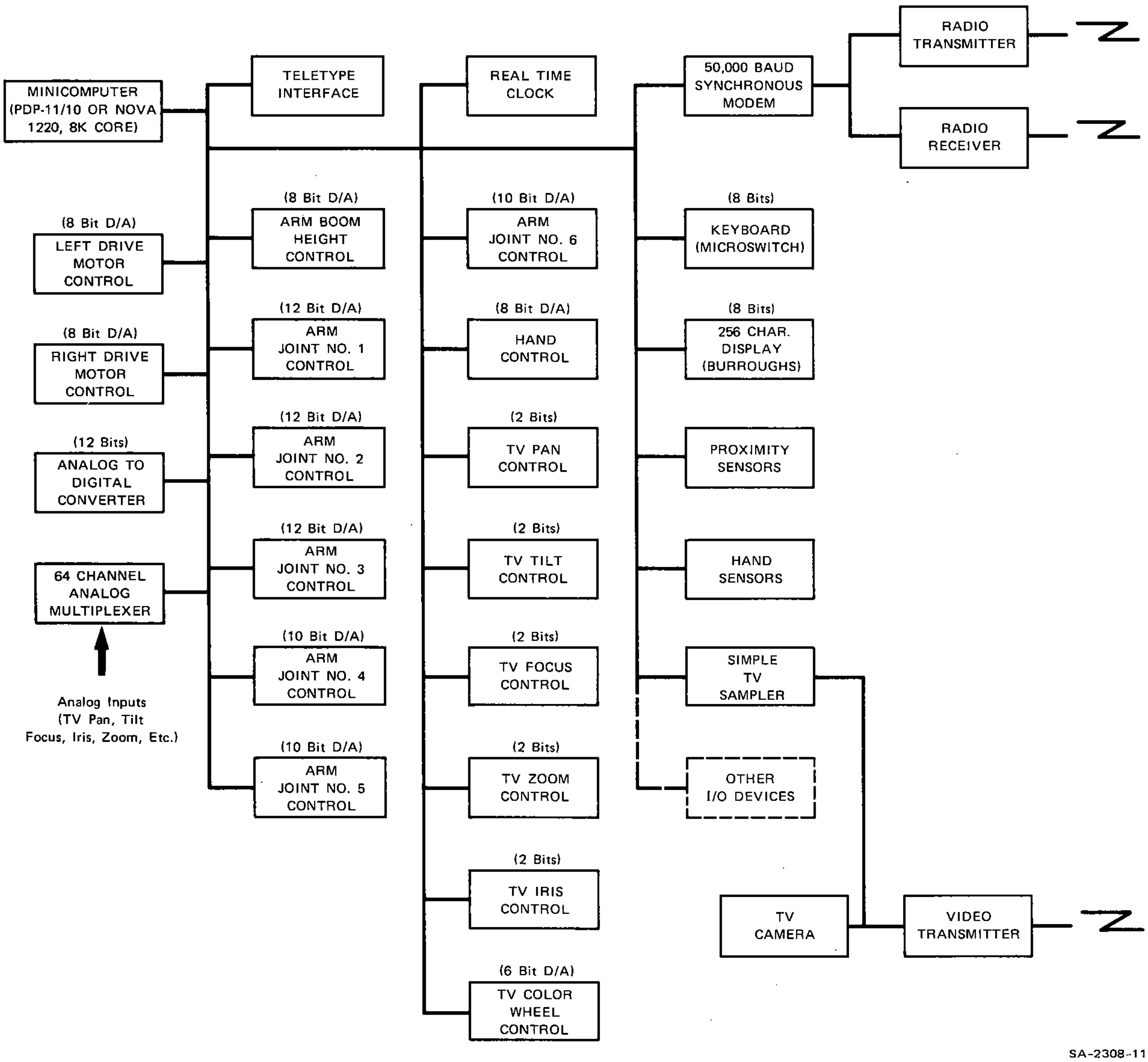

FIGURE 8 BLOCK DIAGRAM OF ROBOT CONTROL SYSTEM

be connected to the I/O bus via a standard 8 bit digital interface. The vehicle proximity sensors and the proportional hand sensors will be read by the 64-channel A/D.

7. <u>Other I/O Devices</u>

A microswitch keyboard with an 8 x 32 character Burroughs display will be mounted on the rear of the vehicle to allow an experimenter to communicate with the main computer or to modify the program in the minicomputer. Consideration has also been given to adding a microphone and loudspeaker so that audio communication can be provided to a speech analyzer and synthesizer on the main computer via a simple radio communication link. Because of the extendability of the minicomputer's I/O bus, special user devices can easily be added to the basic system.

8. <u>Radio System</u>

Two communication links are required for the robot system. One is a unidirectional television link from the robot vehicle to the main computer, and a second is a bidirectional control link of about 50,000 baud capacity. Since both transmission and reception are required at the robot vehicle, and to avoid the complexity of time-sharing the same channel, two separate radio frequency channels will be necessary. The separation between these channels must be sufficient to prevent the continuous video transmitter aboard from interfering with the digital control link through the on-board control-link receiver. This will most easily be handled in the selectivity of the control channel receiver.

Through use of the video transmitter the vehicle-to-control station control link may be carried via an additional subcarrier above the normal sound carrier. This not only saves some space and power requirements aboard the vehicle, but permits full duplex operation on the control link since the control-to-vehicle link is a separate radio frequency.

Spatial dropout that might occur in the GHz range for the video link will be avoided using two techniques. The first is to lower the operating frequency to a point where multipath is less likely to occur. The second is to provide multiple receiving and transmitting points (e.g., a distributed antenna) for the control station. On-site measurements to explore both techniques will be made before an operating frequency is selected.

Preliminary contacts with the FCC indicate that these transmissions fall in the category of Experimental Radio Service (Volume II, Part 5, Subpart E of FCC Rules and Regulations). As such, a license will be required regardless of power output, but essentially the entire spectrum is open for this type of license.

To save both materials and labor costs, we have tried to use common commercially available items. In this respect we would propose the use of land mobile transmitter and receiver modules for the control station-to-vehicle channel. As mentioned, the reverse control channel could be frequency multiplexed onto the video carrier. A conceptual block diagram of the communication system is shown in Figure 9. To provide drift-free stability in the video link, crystal-controlled oscillators will be used.

9. Manual Control

Typically, the robot will be under the total control of a computer. There are circumstances, however, in which it is desired, or even necessary, to control the robot manually. We distinguish among three cases that require manual control: testing, teaching by doing, and bypassing irrelevant functions. Each of these cases is described separately as follows.

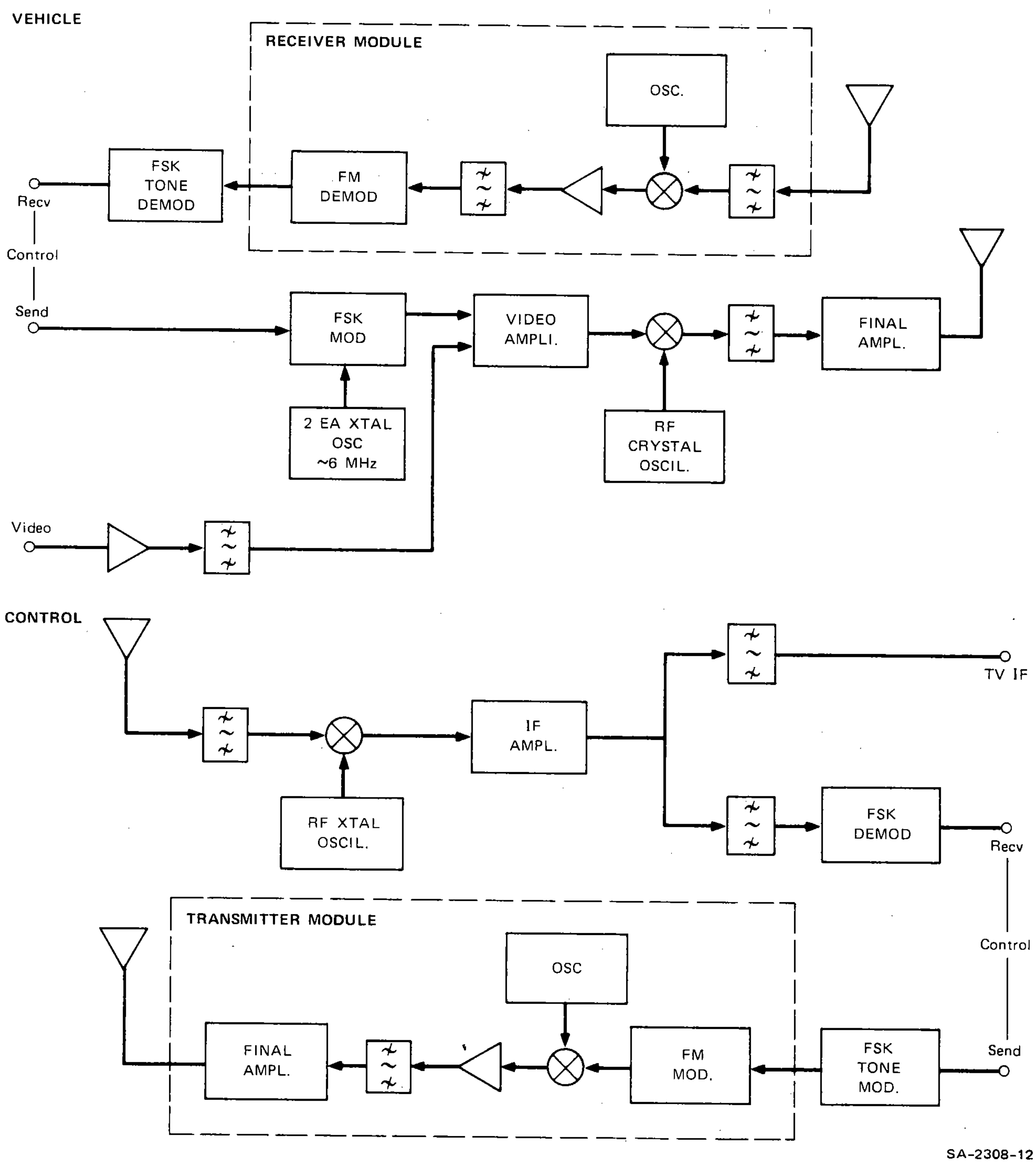

FIGURE 9 CONCEPTUAL DIAGRAM OF ROBOT COMMUNICATION LINK

a. <u>Testing</u>

In this case, an individual function is tested independently during the period of robot assembly, maintenance, or repair. The testing may include any one of the following control functions:

(1) Left and/or right drive wheels

(2) Each of six arm joints

(3) Hand grip

(4) Arm-boom height

(5) Each of the following camera parameters: pan angle, tilt angle, iris, focus, and zoom

(6) Position of the color wheel.

b. <u>Teaching by Doing</u>

Programming a known sequence of robot operations might be implemented most economically by performing the sequence of operations manually and recording position parameters in the minicomputer during the execution period. We call this process "teaching by doing." The efficiency of teaching by doing is high because both the programming and the minicomputer trajectory-control processing time have been eliminated.

The various control functions described above under "Testing" will be used manually in the process of teaching by doing. There is, however, one exception: Manual control of the six arm joints is usually very tedious because it may involve a large number of sequential iterations for each of the arm-joint angles. A simple solution to this problem is to turn off the brakes of the joints and to manually move the arm itself from one position to another, during which period the position angle of each joint is recorded as a function of time.

c. Bypassing Irrelevant Functions

Suppose that we wish to perform a specific robot task that must be preceded by another task whose execution, when performed automatically, is rather complex. For example, we wish to perform a vision experiment away from where the robot happens to be. Automatic navigation of the robot from one location to another may be too bothersome when we only want to take a few pictures somewhere. In this example, it makes sense to drive the robot manually toward its destination, using the left and right drive-wheel control.

Any one of the control functions described above (see "Testing") may be under this category. In some cases we may want to move individual arm joints manually, in other cases we may want to move the entire arm manually.

d. Control Panel

The functions under "Testing" are common to all three cases of application. The components for controlling these functions will be mounted on a hand-held board, as shown in Figure 10. These components include the following:

(1) One joy stick for controlling the two drive wheels

(2) Six helipots for controlling the positions of the arm joints.

(3) One on-off switch for controlling the arm-joint brakes

(4) One helipot for controlling the hand grip

(5) One double-pole double-throw, center-spring-return switch for controlling the height of the arm boom

(6) Five double-pole, double-throw, center-spring-return switches for controlling the pan angle, tilt angle, iris, focus, and zoom of the TV camera

(7) One four-position switch for selecting the position of the color wheel.

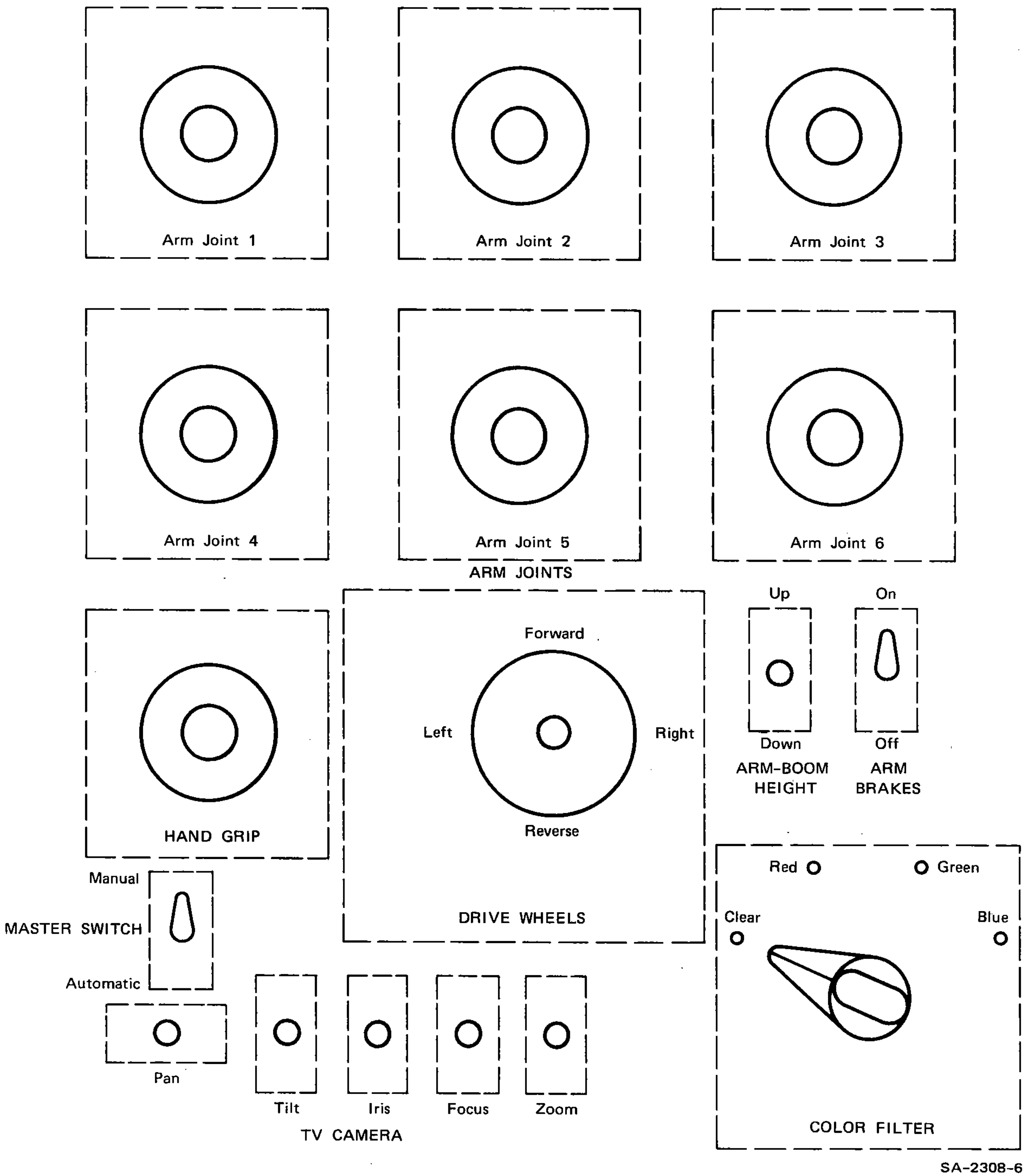

FIGURE 10 MANUAL CONTROL PANEL

In addition, there is an on-off master switch for controlling the mode of operation: manual operation, in which the manual control panel is effective, and automatic operation, in which the control is done by the minicomputer. It will probably also be useful to have certain indicator status lights mounted on the control panel. The communication between the manual control panel and the robot will most likely be via a wire cable bypassing the radio link.

C. Summary of Components

In Table 3, we have listed all of the major components and have provided information about their cost, suppliers and other statistics. Dollar cost figures are given for all equipment to be purchased. These cost amounts are based either on catalog prices or special quotes and estimates provided by the suppliers. Labor figures are estimates of the needed effort by a prime contractor responsible for designing, assembling and testing the system. The labor figures represent approximately a 50 percent-50 percent mix of engineer-technician level. The cost and labor estimates are divided into two headings: (1) development cost and labor applicable to designing, constructing, and testing an initial version and (2) recurring cost and labor applicable to limited production runs.

We list the weights, dimensions, and power requirements of all components to be placed on the vehicle. On the basis of these statistics, we estimate that the weight of the vehicle will be approximately 600 pounds. Also, its general size as shown in Figures 1 and 2 will be adequate to contain its necessary electronic components with room left over for special user equipment. The average power requirement is just about a kilowatt, which indicates that the average continuous use between battery replacements or recharging will be about 3 hours.

Table 3

ROBOT SYSTEM COMPONENTS

Item	Cost ($) Ini-tial	Cost ($) Recur-ring	Labor (m/m) Ini-tial	Labor (m/m) Recur-ring	Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
A. Vehicle Subsystems										
1. Chassis, drive motors and controllers, frame, wheels, speed and brake controls, suspension system, shaft encoders, drawer for batteries.	2,900	2,000			200		350.	0.5	175.	Electro-Limb, Inc.
2. Arm slide, rack, boom, motor and controller, position sensor	(in above)				25		100.	0.05	5.0	Electro-Limb, Inc.
(1 & 2 will include complete engineering drawings)										
Specification of 1 & 2			1.0	-0-						
3. Pan/tilt mount and motors	645	645			25		150.	0.1	15.	Pelco PT-550-M
Angle sensors on mount	100	100								
4. Batteries (set of 3)	150	150			165	7x12x9 (each)				Sears, Die-Hard truck batteries, each 100 amp-hr 12 volts
spare set	150	150								

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($)		Labor (m/m)		Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
	Initial	Recurring	Initial	Recurring						
5. Inverters and regulators	150	150			5		100.	1.0	100.	1 kw, TRIPP-LITE
6. Proximity sensors 12 transmitters 8 receivers	700	700			1	½x½x2 (each)	40.	0.5	20.	Scientific Technology, Inc., Model 7064
Assembly & Test			0.5	0.25						
7. Miscellaneous design, assembly and test of entire vehicle subsystem			1.0	0.5						
Subtotals vehicle	4,795	3,895	2.5	0.75	421		740.		315.	
B. Arm Subsystem										
1. Scheinman-MIT arm and gripper	5,000	5,000			10		250.	0.2	50.	V. Scheinman
wrist force sensor	(in above)									
angle & velocity sensor	(in above)									
controllers and sensors	(in above)				10	6x4x4	(in above)			
electronics for wrist force sensor	250	250	1.0	0.5						

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($)		Labor (m/m)		Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
	Ini-tial	Recur-ring	Ini-tial	Recur-ring						
2. Design, mounting on vehicle, and test			1.0	0.5						
Subtotals arm	5,250	5,250	2.0	1.0	20		250.		50.	
C. Vision Subsystem										
1. TV camera with 4:1 zoom lens; internal color wheel; special dot on lens center;	7,300	7,300			25	22" long 6" diam.	35.	1.0	35.	Cohu #2850, special color wheel
controls for color wheel, zoom, focus and iris; controls for camera electronics (see Table 2 for prices of some optional cameras without all of above features)	(in above)						25.	0.1	2.5	

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($)		Labor (m/m)		Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
	Ini-tial	Recur-ring	Ini-tial	Recur-ring						
2. Video A/D equipment										
Main digitizer										
Signal conditioning circuits	200	200								
A/D converter	3,000	3,000								Datel System ADC-UH8B 8-bit 10 MHz
Sync. separator	75	75								
Control logic	400	400								
Packer	100	100								
Optional format specifier	100	100								
Power supplies	300	300								
Design, assembly, and test			2.0	1.0						
Optional simple digitizer (on board vehicle)	2,000	2,000	1.0	0.5						
3. Vision subsystem test			1.0	0.5						
Subtotals Vision		13,475	4.0	2.0	25		60.		37.5	
										(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($)		Labor (m/m)		Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
	Initial	Recurring	Initial	Recurring						
D. Minicomputer and Interface Subsystem*										Data General
1. Type 8154 NOVA 1220 W/8K core	6,300	6,300			25	19x10½x25 (includes items 1-13)	400.	1.0	400.	
2. Type 4008 real-time clock	400	400								
3. Type 4015/CPU communications controller (50 kb synchron. modem)	2,250	2,250								
4. Type 4020 internal clock (for above)	175	175								
5. Type 4014 I/O interface for A/D	200	200								
6. Type 4032/1200 basic A/D interface	700	700								
7. Type 4036 I/O interface for D/A	200	200								
8. Type 4037/1200 D/A converter control	300	300								

*Prices are based on NOVA 1220. Digital Equipment Computer PDP-11/10 prices might run approximately 20% higher.

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($)		Labor (m/m)		Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
	Ini-tial	Recur-ring	Ini-tial	Recur-ring						
9. Type 4007 I/O interface	200	200								
10. Type 4010/1220 TTY I/O interface	150	150								
11. Type 4040 16-bit digital interface	450	450								
12. Type 4041 I/O register (for above)	100	100								
13. Type 4044 WW pins and sockets	260	260								
14. Type 4009/1200 TTY mod. kit	100	100								
15. Type 4055B/1220A/D Chassis	1,200	1,200			5 (includes items 15-19)	$19x3\frac{1}{2}x25$	25.	1.0	25.	
16. Four each type 4055N 16-channel Multiplexor @ $300	1,200	1,200								
17. Type 4055I buffer amplifier	200	200								
18. Type 4055E A/D converter	750	750								

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($) Initial	Cost ($) Recurring	Labor (m/m) Initial	Labor (m/m) Recurring	Wt (lbs)	Dimensions in x in x in	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
19. Type 4055K Timing and Control	230	230								
20. Type 4056H D/A decoder and chassis	2,600	2,600			5 (includes items 20-23)	19x3½x25	25.	1.0	25.	
21. Five each type 4056B 8-bit D/A converter @ $250	1,250	1,250								
22. Three each type 4056C 10-bit D/A converter @ $275	825	825								
23. Six each type 4056D 12-bit D/A converter @ $300*	1,800	1,800								
24. Computer Programs			4.0	-0-						
25. Miscellaneous design assembly & test of computer & interface subsystem			3.0	1.0						
Subtotal interface subsystem	21,840	21,840	7.0	1.0	35		450.		450.	

*Includes 3 spare D/As for future devices

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($) Initial	Cost ($) Recurring	Labor (m/m) Initial	Labor (m/m) Recurring	Wt (lbs)	Dimensions in x in x in	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
E. Radio Subsystem										
1. Transmitters, receivers, antennas, filters, etc.	3,700	3,700			10	6x12x12	30.	1.0	30.	
2. Design, fabrication and test			3.0	0.5						
F. Vehicle I/O Devices										
1. 256 character	995	995			10	12x6x4	50.	1.0	50.	Burroughs BDS-40832-200 Self-scan panel display
Power supply	100	100					25.	1.0	25.	
2. Keyboard	250	250			10	18x4x10	5.	1.0	5.	Micro-switch 78 SWI
Power supply	50	50								
3. Assembly and test			0.75	0.5						
Subtotal I/O Devices	1,395	1,395	0.75	0.5	20		80.		80.	
G. Miscellaneous										
1. Manual controller	500	300					negligible			Electro-Limb Inc.
specification			1.0	-0-						
2. Battery charger	100	100								Electro-Limb Inc.
H. Documentation			4.0	-0-						

(cont. on next page)

Table 3 (continued)

ROBOT SYSTEM COMPONENTS

Item	Cost ($) Ini-tial	Cost ($) Recur-ring	Labor (m/m) Ini-tial	Labor (m/m) Recur-ring	Wt (lbs)	Dimensions inxinxin	Power Watts	Duty Factor	Avg. Power Watts	Description and Comments Probable Supplier
I. General Design, Assy and Test of Entire System			4.0	1.0						
Totals	51,055	49,955	28.25	6.75	531		1610.		962.5	

III DISCUSSION OF DESIGN DECISIONS

In this section, we give more details on the rationale behind certain key design decisions.

A. Vehicle

The two general, operational requirements imposed on the vehicle that were the most sensitive in restricting the choice of supplier, were as follows:

(1) The requirement to operate the vehicle in a normal office environment of corridors, hallways, and offices.

(2) The requirement to permit a manipulator to operate both at table top and floor levels.

As a corollary to the first requirement, the robot must be able to navigate easily through a standard 30-inch doorway and turn comfortably around within the confines of a typical office with conventional office furniture in place. This implies that the vehicle should be able to turn on its own axis and have outside dimensions of length and width no greater than 26 x 36 inches. This conclusion alone virtually elimates the vast majority of commercially available industrial-electric and golf-cart vehicles from further consideration. Golf carts are normally too wide, and most industrial electric vehicles are typically too long and/or wide. From a spectrum of products offered by most industrial-vehicle suppliers, usually only the smallest model out of dozens was even remotely feasible.

Two other important considerations in recommending a commercial supplier for the vehicle chassis were:

(1) The ease with which the vehicle could be modified for remote control, since all the commercially available vehicles we surveyed (except for one) were designed to be manually controlled by a human operator, and

(2) The extent to which the manufacturer would be willing to modify his product or customize it to satisfy our peculiar specifications.

A preliminary list of twelve potential suppliers is shown in Table 4. After examining the literature provided by these companies, we rapidly narrowed this list down to four suppliers (indicated by an asterisk) for more detailed investigation. The vehicles we considered were the SCAT Wheelchair supplied by Electro Limb Corporation, the Crown Intermediate Walkie Stacker Electric Fork-Lift Cart supplied by Hamerslag, the Laher "Stand Up & Go" Model 531-CA supplied by Harley-Davidson, and the SS/T supplied by Taylor-Dunn.

TABLE 4

POTENTIAL VEHICLE SUPPLIERS

1. Electro Limb Corporation
   7425 Leeds Street
   Downey, California

* 2. Harley-Davidson Golf Cars
   H. Coster Enterprises, Inc.
   1757 E. Bayshore Road
   Redwood City, California 94063

3. Laher Spring & Electric Car Corporation
   2615 Magnolia Street
   Oakland, California 94607

* 4. Taylor/Dunn Company
   2114 West Ball Road
   Anaheim, California

5. Programmed and Remote Systems Corporation
   899 West Highway 96
   St. Paul, Minnesota 55112

6. The Toro Company
   8111 Lyndale Avenue South
   Bloomington, Minnesota 55420

7. Honda Engineering Co., Ltd.
   1-10-1 Shinsayama Sayana-shi
   Saitama Prefecture, Japan

8. Westinghouse Electric Corporation
   Electric Vehicle Division
   P. O. Box 712
   2670 Redlands Boulevard
   Redlands, California 92373

9. Viking Corporation
   210 N. Industrial Park Road
   Hastings, Michigan 49058

10. Huffman Manufacturing Company
   P.O. Box 1204,
   7701 Byers Road
   Dayton, Ohio 45401

11. The Keyes-Davis Company
   64 14th Street
   Battle Creek, Michigan

* 12. Hamerslag Equipment Company
   370 Lany Road
   Burlingame, California 94010

Excluding the SCAT Wheelchair for the time being, the remaining three vehicles suffered from many disadvantages:

(1) They were all three-wheeled vehicles with tiller-type steering. This would have presented additional problems of stability, remote control of the steering, and supporting any sort of load on the front wheel.

(2) They were generally on the large and heavy side and would have been awkward to turn around inside an office.

(3) They were generally overdesigned for an office environment application, and would have been more suitable for a partly indoor/partly outdoor setting.

(4) The manufacturers were all heavily back-ordered and were generally reluctant to consider any prototype development work or modification.

On the other hand, the SCAT Wheelchair did not suffer from any of the above disadvantages. To the contrary, the size, steering, level of design, and potential for customization were satisfactory. Moreover, as an added benefit, the Electro Limb Corporation is closely affiliated with the Communications, Power, and Control Engineering Division of the Rancho Los Amigos Hospital, which has had considerable mechanical design experience with prosthetic arm manipulators and teleoperators for the AEC and NASA.

B. TV Camera System

1. General Objectives

We wish to examine and recommend a visual system consisting of a TV camera and accessories which will serve as the "eye" of a moving robot. We have been helped by a similar study made by Binford.[1]* In general, we require that:

(1) The camera characteristics meet given performance specifications (to be discussed in Subsection 3)

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*References are listed at the end of the main body of this report.

(2) The components of the camera system are commercially available at acceptable cost off the shelf of an established company with good service facility.

(3) The camera system is modular with regard to the optical attachments, i.e., the lens, filter, and color wheel

(4) The components of the camera are of high quality in order to achieve high reliability and long life without degradation.

(5) The field of view of the camera is essentially identical with that of a range finder and precisely registered with it.

The camera characteristics under Item (1) depend on the illuminated scene, which is discussed first.

2. Scene Illumination

The illuminance of a surface element on the faceplate of a TV camera depends on the following factors:

(1) The source of illumination (point or flat, natural or man-made), which is characterized by its intensity and spectral distribution

(2) The angle of incidence of illumination and the angle of reflectance

(3) The surface reflectance, which depends on the texture and the spectral absorbance of the surface.

The combined effect of these factors on the light reaching the camera may be expressed in terms of the brightness and spectral distribution of the scene elements.

We measured the brightness of indoor scenes illuminated by fluorescent light, using an SEI (Salford Electronics Instruments) brightness spot meter, and found it to vary between 0.5 foot-lamberts (dark, shaded area) and 50 foot-lamberts (bright table top). The brightness of objects illuminated by sunlight through large windows was found to be much larger, e.g., up to 6000 foot-lamberts. For most cases, the variation in brightness, within a given indoor scene, is not likely to exceed 100:1.

Anticipating man-robot interaction (to facilitate research in robotics as well as for its own sake), we assume that the spectral distribution of the scene will at least cover the visual spectrum of a human (400-700 mμ). However, there is no need to restrict the spectral response of a robot camera to that of a human eye. We anticipate that infrared and ultraviolet light may also be utilized by future robots to augment their sensory information in certain conditions (e.g., detection of hot objects).

3. Camera Characteristics

The camera characteristics are classified into four categories: electrical, optical, color, and mechanical. Each of these characteristics is discussed separately as follows:

a. Electrical Characteristics

Resolution

Resolution measures the distinguishability of details on the TV camera; it is proportional to the number of data points for a given scene. Vertical resolution describes the ability to resolve horizontal lines, and depends primarily on the number of the horizontal scanning lines. Horizontal resolution describes the ability to resolve vertical lines, and depends primarily on the system bandwidth.

The resolution is determined on the basis of the following considerations:

(1) The higher the resolution, the higher the visual information in the picture of a given field of view.

(2) The higher the resolution, the lower the signal-to-noise ratio because:

(a) The size of the beam spot is smaller and, hence, the output signal is smaller, as shown in Figure 11, requiring compensation in the video amplifier.

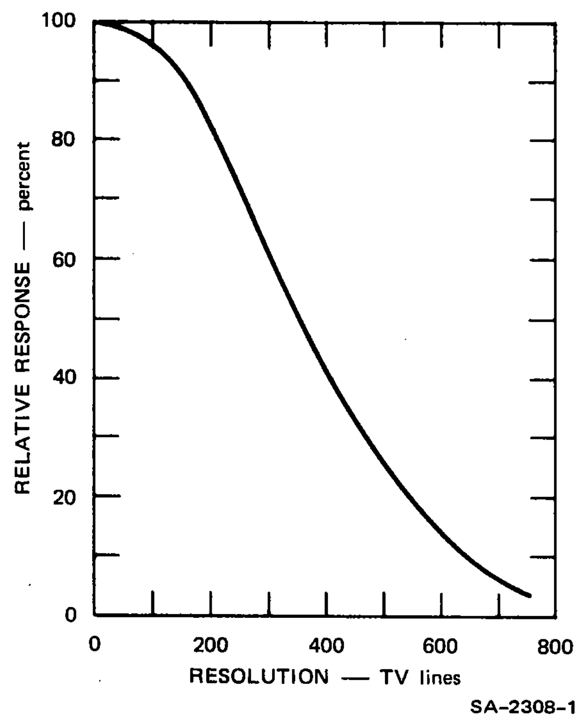

FIGURE 11 UNCOMPENSATED RELATIVE HORIZONTAL PEAK-TO-PEAK SQUARE-WAVE RESPONSE AT CENTER OF PICTURE TUBE VERSUS RESOLUTION

(b) The higher the horizontal resolution, the wider the required bandwidth of the camera system and, consequently, the higher the noise.

(3) The higher the picture resolution, the longer the computer processing time.

(4) The majority of those responding to our questionnaire have specified the maximum number of picture elements to be 500 X 500, but most arm/vision/cart users would be satisfied with 250 x 250 picture elements.

(5) Off-the-shelf TV cameras have standard 525 lines per frame and a 4:3 aspect ratio (the ratio of the picture-frame width to its height).

(6) For a given area of field of view, more panoramic information is stored in the picture if the width of the field of view is larger than its height (for this reason, the aspect ratio of movies and TV screens is 4:3 rather than 1:1).

Based on the above considerations, we specify a resolution of 320 X 240 picture elements to be recorded by one field of a standard 525 lines per frame TV camera. If needed, this resolution may be increased to 640 x 480 picture elements without increasing the amplifier bandwidth (and thus keeping the noise to the same level as for 320 x 240 elements) by using two frames (four fields) in which the built-in 2:1 vertical interlace is utilized and the horizontal sampling time is shifted by half a sampling interval, resulting in the sampling points shown in Figure 12. If a square picture is preferred, then 240 x 240 (or 480 x 480) elements may be obtained by eliminating 40 x 240 (or 80 x 480) elements on each of the left and the right sides of the picture.

Bandwidth

The bandwidth corresponding to either one of the above two schemes of resolution is determined as follows. We designate the field rate (vertical deflection frequency) by f_F (in the U.S.A., f_F = 60 Hz), the number of vertical lines per field (including the ones in the retrace)

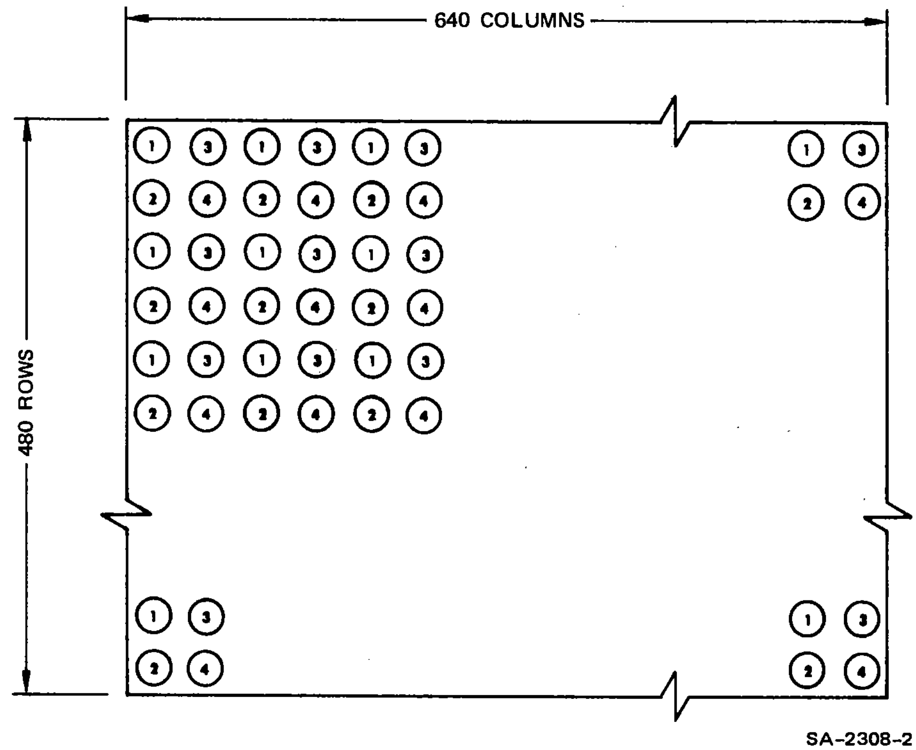

FIGURE 12 A SCHEME FOR OBTAINING A RESOLUTION OF 640 x 480 ELEMENTS USING THE BANDWIDTH FOR 320 x 240 ELEMENTS (POINTS ① ONLY)

by N_f, and the horizontal resolution by N_h. The horizontal scan period is $1/f_F N_f$). Assuming that the horizontal blanking time is 17 percent of this period, then $N_h/2$ cycles of video signal must be resolved during a period of $0.83/(f_F N_f)$ second. The corresponding bandwidth is

$$f_{bw} = (N_h/2)(f_F N_f)/0.83 \cong 0.6 f_F N_f N_h.$$

Substituting standard values of $f_F = 60$ Hz and $N_f = 525/2$, we obtain the relation $f_{bw} = 9{,}450 N_h$. Thus, for $N_h = 320$, we get $f_{bw} = 3.0$ MH_z. Note that the same bandwidth is required for either one of the resolutions discussed previously, i.e., 320 X 240, 640 X 480, 240 X 240, or 480 X 480.

Sensitivity

The sensitivity of an image tube is the generated signal current (or voltage) per unit of incident radiation density (in radiometric units of watts/meter^2 or in photometric units of lumens/foot^2 = foot/candles) on the tube faceplate. The spectral response of an image tube is its sensitivity vs. the wavelength of the incident light. The spectral response curve is bell shaped: the long wavelength cutoff depends primarily on the target material, the short wavelength cutoff depends primarily on the faceplate glass. If the spectral response is not specified, the sensitivity corresponds to radiation of unfiltered incandescent source of 2854°K, expressed in foot-candles.

The noise in a camera system is generated primarily in the video amplifier, especially the input stage. Hence, the signal-to-noise ratio increases by increasing the signal out of the image tube. Thus, from this viewpoint, we would like the sensitivity to be as high as possible.

As explained previously, we would like the spectral response to be wider than that of a human. Furthermore, this response should be as flat as possible in order to facilitate determination of the chromaticity coordinates R, G, and B for color information.

Plots of relative sensitivity as a function of wavelength[2] are compared in Figure 13 for four types of image tubes: ordinary Vidicon (V), Intensifier Vidicon (IV), Silicon-diode-array Vidicon (SV), and Silicon-Intensifier-Target Vidicon (SIT). We select the Silicon-diode array Vidicon on the basis of the above requirements for high sensitivity and flat spectral response and because, compared with a SIT Vidicon, its cost is lower (less than half), its resolution is higher (by about a factor of 1.2 at the center and 1.7 in the corner), and its signal-to-noise ratio is higher.

Signal-to-Noise Ratio

The signal-to-noise ratio of a TV camera tube is the ratio of peak-to-peak signal (voltage or current) output to the corresponding RMS noise. The peak-to-peak signal is measured on an oscilloscope. The RMS noise should be measured using a wideband true RMS meter, but is commonly and more conveniently (but less accurately) estimated on the basis of peak-to-peak noise displayed on the oscilloscope while the camera is pointed at a uniform white background.

Since the noise is generated primarily in the video amplifier, the signal-to-noise ratio is approximately proportional to the signal. Silicon-Diode-array Vidicons are characterized by peak signal current of 300nA to 500 nA.[3] The frequency spectrum of the noise is approximately flat; the RMS noise due to this factor alone is approximately proportional to the square root of the bandwidth of the camera system. However, the gain of the video amplifier is increased linearly with frequency, using a "hi-peaking" circuit, in order to compensate for the high frequency roll-off caused by input capacitance of the amplifier. As a result, the RMS noise at the output of the amplifier is proportional to the frequency to the 3/2 power. At 3.0 MHz, we should be able to

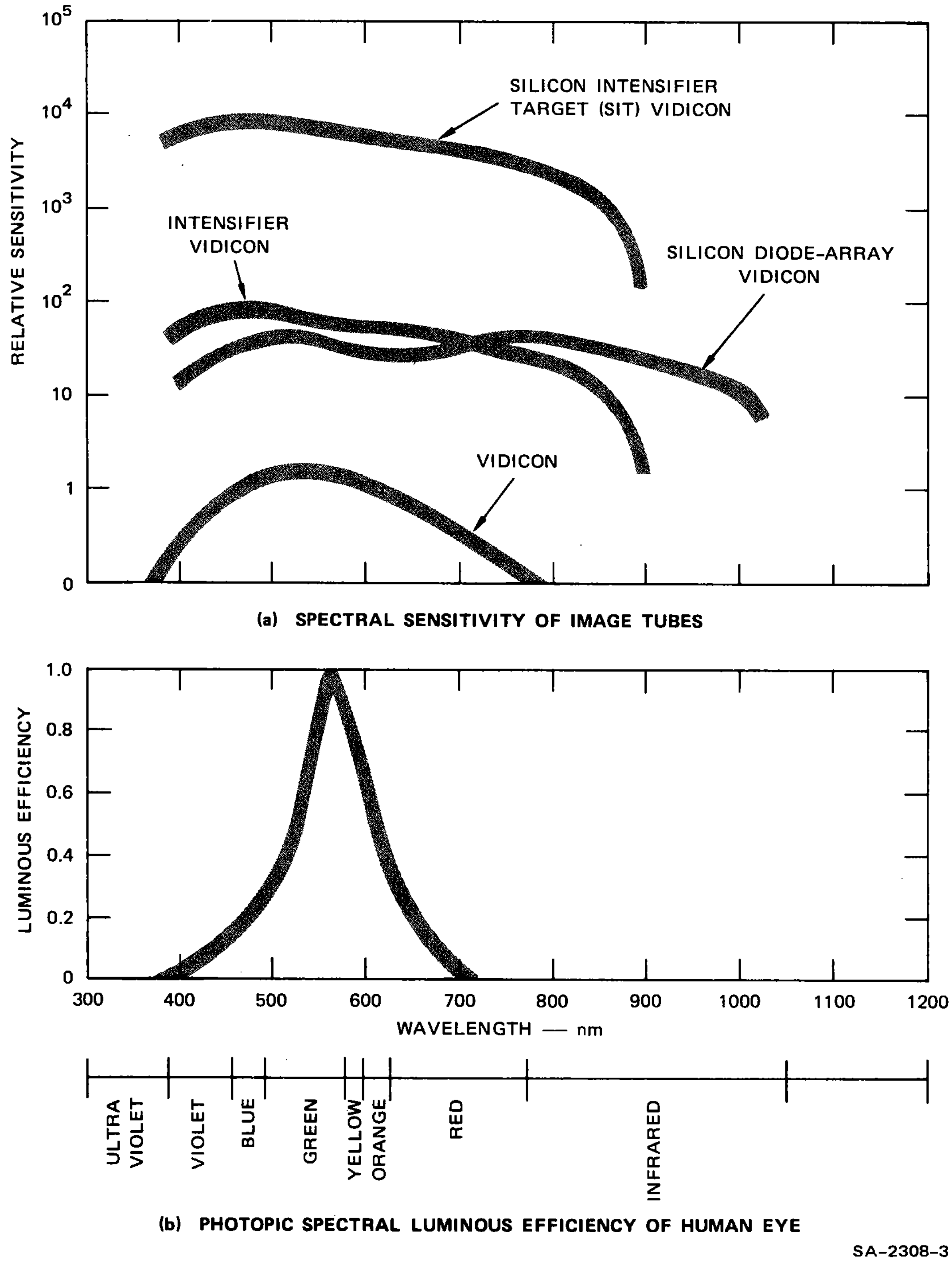

FIGURE 13 SPECTRAL SENSITIVITIES OF IMAGE TUBES AND HUMAN EYE

obtain a maximum effective signal-to-noise ratio of about 300:1 (≈ 50 db).[3] On the other hand, we specify a minimum signal-to-noise ratio of 10:1, or 20 db, for the darkest part of the scene.

A number of TV camera manufacturers attach a "weighting" filter to the video-output terminals during noise measurement in order to reduce the response of the measuring instruments to high-frequency noise. The reason for this practice is that high-frequency noise has been found experimentally to be less objectionable to the viewer than low-frequency noise. The resulting effective RMS noise is lower than the true RMS noise in the system and, consequently, the quoted signal-to-noise figure is higher than the actual value.

Dynamic Range

Consider a TV camera whose maximal and minimal peak-to-peak signal currents are I_{max} and I_{min}, respectively. The value of I_{min} is based on the requirement for minimal signal-to-noise ratio, $(S/N)_{min} = I_{min}/I_n$, where I_n is the RMS noise. Since $I_{max}/I_n \approx$ constant, then

$$(S/N)_{min} \cdot R = I_{max}/I_n \approx \text{constant} \quad ,$$

where $R = I_{max}/I_{min}$ is the <u>dynamic range</u> of the camera.

We would like to match R to the ratio of brightest to darkest elements in the scene, i.e., $R \gtrsim 100$. However, for $I_{max}/I_{min} \cong 300$, and if we accept for the darkest scene the value $(S/N)_{min} = 4$, then $R = 75$. Data averaging will decrease the noise and thus increase R, but this method increases the time for data acquisition.

Gray Scale Levels

The measured analog output signal current from a TV camera is converted into a digital form, using G <u>gray-scale levels</u> between I_{min} and I_{max}. As pointed out by Earnest,[4] a distinction is made between a linear scale and a logarithmic scale.

For a <u>linear scale</u>, each step size is equal to $(I_{max} - I_{min})/G$, and the required signal-to-noise ratio must exceed 2yG, where y is the argument of the normal probability density function that determines the confidence level of the measured value.

For a <u>logarithmic scale</u>, the jth step size, $I_j - I_{j-1}$, increases with I_j since, by letting $\log_j - \log I_{j-1} = (1/G/ \log R =$ constant, we get $I_j = I_{j-1} R^{1/G}$. The required signal-to-noise error must exceed y/ρ, where $\rho = (I_j - \sqrt{I_j I_{j-1}})/I_j = 1 - R^{-1/2G}$ is the maximum relative error for any gray-scale level. The larger G and/or the smaller R, the larger the required signal-to-noise ratio. Logarithmic scale is more useful than linear scale because a relative error is more important and usually smaller than an absolute error. Note that the input to a gray-scale device is the output current from the TV camera; hence, the selection of the gray scale is independent of the selection of the TV camera.

Strictly speaking, G should be matched to the signal-to-noise ratio, i.e., $G \cong 300 \approx 258 = 2^8$. Nevertheless, we specify $G = 2^6 =$ 64 gray scale levels because the majority of those who answered our questionnaire preferred this value, i.e., for most cases, 256 gray scale levels are more than necessary. Also, standard A/D converters closest to the 6-bit A/D converter required for 64 levels are 4-bit, which is inadequate, and 8-bit, which is considerably more costly than a 6-bit A/D converter.

<u>Linearity, Distortion, and Stability</u>

In addition to the above characteristics, the quality of the TV picture is affected by other features, such as

(1) <u>Linearity</u> of the sawtooth current waveform of the horizontal and vertical sweeps

(2) <u>Geometric distortion</u> due to improper magnetic fields

(3) Stability of the black-level output signal at the A/D converter.

The adverse effects of nonlinearity and distortion should be low, e.g., less than 2 percent relative to the picture height. Using a 6-bit A/D converter, the black-level output should not drift by more than 100/64 percent.

b. Optical Characteristics

Focal Length

What the camera sees is affected, among other factors, by three lens properties: magnification, view angle, and depth of field (the range of objects that are in sharp focus). Each of these properties depends on the focal length of the lens, f: As f increases, the magnification increases, the view angle decreases, and the depth of field decreases. (The depth of field decreases also as the lens opening increases and the camera-to-object distance decreases.)

Occasions may arise in which the view angle (and magnification) should be changed without being able (or wanting) to move the robot. To accomplish this task, we need to be able to change the focal length (see Figure 14). Consequently, our TV camera system will have a variable focal-length lens as an option.

To meet the requirement of a variable focal length, two alternatives are considered, a zoom lens and a turret with, say, four lenses of different, fixed f values.

Compared with a turret, the advantages of a zoom lens are:

(1) The magnification can be adjusted continuously to the required value.

(2) Specific objects in the scene can be tracked incrementally as the resolution is changed.

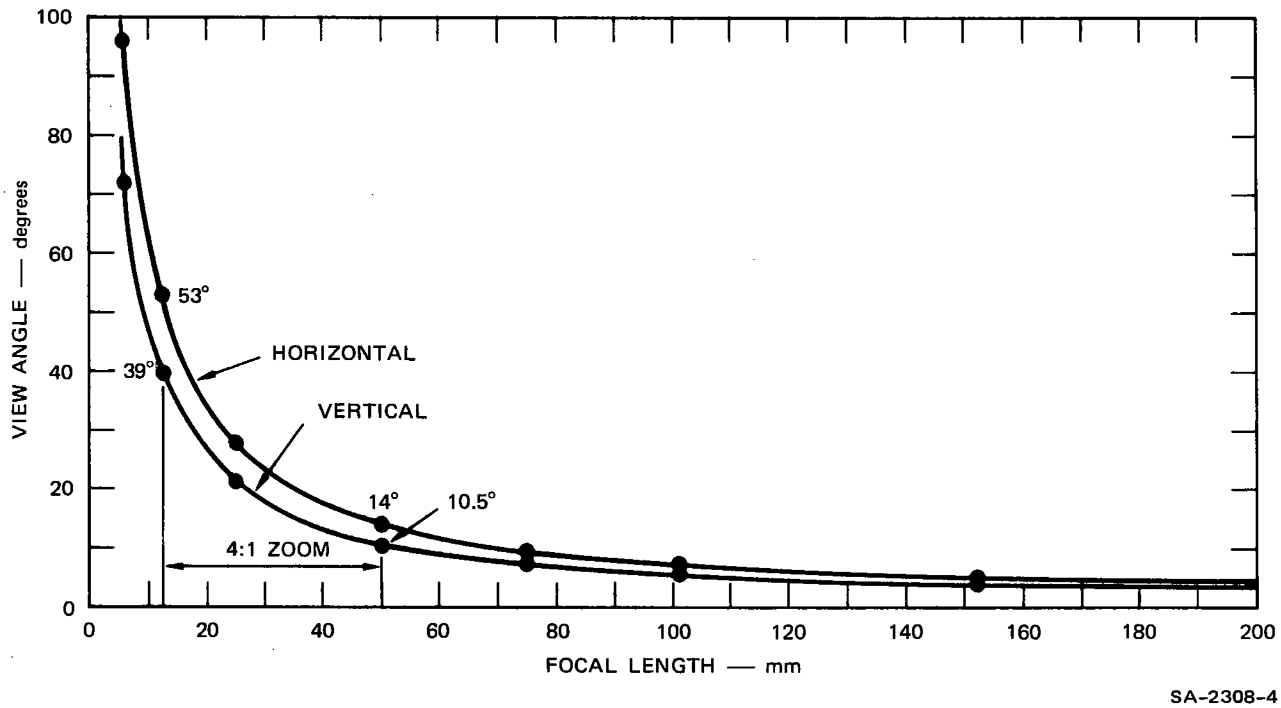

FIGURE 14 VIEW ANGLES OF A TV CAMERA

(3) A zoom lens has become more popular than a turret, making it more readily available off-the-shelf. (The cost of a zoom lens is comparable to that of a turret.)

The drawbacks of a zoom lens, compared with a turret, are:

(1) Camera calibration is more complex because the focal length is an additional calibration parameter.

(2) The minimal focal length of a standard zoom lens is longer than can be achieved with a fixed focal length lens (i.e., 12.5mm vs. 5.7mm), thus limiting the width of the field of view.

Based on the comparison above, we have concluded that a zoom lens will be used to vary the focal length.

Next, we have to specify the zoom range. One of the tasks of the robot will be to perform scene analysis of a room that may be as small as, say, 10 feet by 10 feet. Execution of this task will be facilitated by a wide-angle (short focal length) lens. The shortest focal length of a zoom lens is around 1/2 inch. Referring to Figure 4, the horizontal and vertical view angles of a lens of 12.5 mm focal length are 53^{o} and 39^{o}, respectively, for a vidicon tube whose active area is 1/2 inch wide by 3/8 inch high. (If the field of view were square, the horizontal view angle would be reduced to 39^{o}. This is the main reason for specifying a resolution of 320 X 240 or 640 X 480 picture elements.) On the basis of this example, we prefer to have a zoom range whose lower focal-length value is minimal, i.e., 12.5 mm (obtained with a retrozoom).

Consider next the upper focal-length value. On one hand, we would like it to be as large as possible in order to get the highest magnification. On the other hand, the longer the maximal focal length, the longer the camera, the smaller the depth of field, and the longer the minimal focal length. Hence, a compromise must be reached. Practically, off-the-shelf zoom lenses of high quality and reasonable cost (such as the ones made by Augenieux and Canon) have either 4:1 or 10:1 zoom range.

We choose the 4:1 zoom lens for the above reasons, in particular because the minimal focal length of 12.5 mm is not available with a standard 10:1 zoom lens.

In conclusion, we specify a 4:1 zoom lens whose focal length varies from 12.5 mm to 50 mm. The corresponding view angle varies from $53^\circ \times 39^\circ$ to $14^\circ \times 10.5^\circ$, as shown in Figure 14.

Range of Focus

The range of focus is the distance between the nearest and farthest object points that can be focused on the faceplate of the image tube. Due to the finite size of the scanning beam and the granular structure of the photosensitive material of the image tube, the scene appears to be in focus within a range containing the object point in focus. This range, called the depth of field, increases as the camera-to-object distance increases, the lens opening decreases, and the focal length decreases.

Having selected the 4:1 zoom lens, the range of focus is 4 feet to infinity.[5] The minimal distance of depth of field corresponding to 4 feet can be decreased by reducing the diameter of the iris opening. This will usually necessitate increasing the level of illumination.

c. Color Characteristics

Color (hue and saturation) is an additional attribute that may be used by the robot in scene analysis. Color capability is, therefore, another option that will be specified in our TV camera system.

Color information consists of the intensity values corresponding to the three primary colors of each raster point. Two alternatives are considered for obtaining this information: a black-and-white TV camera with a color-filter wheel, and a color TV camera. Compared with a black-and-white TV camera system, the drawbacks of a presently available color TV camera are:

(1) Higher cost (by several times)

(2) Lower spatial resolution (by about a factor of 2)

(3) Lower signal-to-noise ratio (by about a factor of 3)

(4) Fixed red-green-blue colors, which are suitable for human perception, but may be too restrictive for robot perception. The latter may be based on a set of filters other than red, green, and blue.

On the other hand, the main advantage of a color TV camera is that, since no color wheel is necessary, color information is obtained much faster and in parallel.

Based on the comparison above, we prefer the color wheel. However, future development and the increased popularity of the color TV camera may reduce its cost and increase its resolution and signal-to-noise ratio to the point where we may prefer the color TV camera instead.

Having selected a color wheel, we need to specify the filter colors. Although red, green, blue, and neutral filters would be used in most cases, we leave the final decision up to the user. We only specify that a four-filter wheel will be mounted on the camera. (The use of more than four color filters will add unwarranted mechanical complexity.) Two alternative mounting arrangements are considered next, internal and external.

Internal mounting involves placing the color-filter wheel inside the camera, between the lens and the image tube. This can be accomplished with certain cameras that include a space for a neutral density filter wheel, designed originally to control the faceplate illuminance when the scene brightness is high and the iris opening is minimal. Such a wheel is replaced by the required four-position color wheel. To make up for the loss of the neutral density filters, a dark dot may be added at the center of the lens nearest to the image tube. The smaller the iris opening, the more effective is such a dot in reducing the face-plate illuminance.

External mounting involves placing the color-filter wheel outside the camera, in front of the lens. In order to block unfiltered illumination from reaching the camera lens, an enclosure, black inside, will be custom built around the color wheel and the camera lens.

External mounting results in a camera system that is less rigid, less compact, and longer than the one using internal mounting. On the other hand, internal mounting requires the use of a camera with a larger cross section (e.g., 6 inches in diameter) to accommodate the color-filter wheel. The cost of well designed, custom made external mounting is likely to be comparable to the cost of internal mounting. Weighing all these factors, we prefer to have internal mounting of the color filter wheel.

d. Mechanical Characteristics

The mechanical characteristics of the camera are classified into two categories: the size and weight of the camera and the capability to remotely control and monitor the optical parameters and color-wheel position of the camera.

Size and Weight

The size and weight of the camera are affected by the following three constraints:

(1) The camera should include a built-in 4:1 zoom lens.

(2) The camera should include an internal four-position color-filter wheel.

(3) The camera system should be a commercially available product in order to reduce its cost.

The minimal length of the camera is affected by the length of a Silicon-Diode-Array Vidicon (about 6.5 inches), the length of a 4:1 zoom lens (about 7 inches), the distance between the Vidicon faceplate and the rear element of the zoom lens (0.69 inch), the various electrical connectors associated with the electronic circuitry, and the protective camera casing. The requirement for our internal four-position color wheel imposes a lower limit on the diameter of the camera, which is about 6 inches. (The diameter of a camera without a color wheel may be as small as about 3 inches.) Ruling out a custom-made camera system in accordance with Constraint (3) above, all the standard electronic circuitry will be contained in the camera casing. We find that the length of the required camera is about 22 inches, its diameter is about 6 inches, and its weight is about 25 pounds.

Remote Control

It is essential that the optical parameters of the camera and the position of its color wheel will be controlled and monitored by a computer. We, therefore, require that a driving motor and a readout potentiometer be included in the camera for each of the following functions:

- Focus
- Zoom
- Iris
- Color wheel.

For certain applications the iris control should be automatic, while for others it should be computer controlled. A computer-controlled provision should, therefore, be included in order to switch between these two modes of operation.

4. Camera Selection

In addition to the required camera characteristics described above, we require that the components of the camera system be available commercially. We have contacted several manufacturers of TV cameras and studied their catalogs. From the viewpoint of the required specifications, these cameras may be classified into three groups:

(1) Cameras that meet our specifications, except that they have no remote control and no provision for color wheel. Such cameras are relatively inexpensive (less than $500), and are made by Ampex (Model CC-400), Panasonic (Model WV-200P, WV-240P, or WV-250P), and other manufacturers.

(2) Cameras that meet our specifications, except that they have no provision for a color wheel at an acceptable price. Such cameras are made by

(a) Diamond Power Corporation, Lancaster, Ohio (Model LL-1), which estimated the extra cost of modifying the filter wheel into a remotely controlled color wheel to be between $8,000 to $10,000.

(b) Sierra Scientific Corporation, Mountain View, California (Model MINICON), which proposed no way of adding an internal color wheel.

(3) Cameras that meet all our specifications. Such cameras are made by COHU Inc., San Diego, California. This company will charge less than $2,000 extra cost for modifying the filter wheel into a remotely controlled color wheel. The cost of a proper camera without modifying the color wheel is about $1,000 less than its Diamond Power Corporation equivalent.

In view of these considerations, and since we have previously had satisfactory experience with COHU cameras, we have decided to recommend this manufacturer. Model numbers, costs, and other statistics of the recommended cameras were shown in Table 2.

5. Mounting of the Camera System

a. Requirements

The mounting of the camera system is affected by the following requirements:

(1) The camera system should be able to pan within ±180° and tilt by ±90°.

(2) Scenes in different directions should be viewed from a high enough position (e.g., at least 4 feet) to reduce occlusion.

(3) The camera should be confined as much as possible to within the area of the robot cart (which is approximately 25 inches wide and 25 to 32 inches long) for two reasons: to protect the camera from bumping into objects (e.g., door jambs) and to increase the mechanical stability of the robot.

(4) The center of gravity of the camera should be as low as possible to increase the mechanical stability of the robot.

(5) The view angle of the TV camera should be identical with that of a range finder.

From the viewpoint of design of the camera mounting, requirements (2) and (4) conflict with each other; also, requirements (1) through (3) conflict with the required camera size and weight. Requirement (5) imposes additional complication on the design of the camera mounting because the range finder must be near the camera. The range finder is divided into two parts: a transmitter, which consists of a laser and x-y scanning mirrors, and a receiver, which consists of a lens and a photomultiplier.

To meet the above requirements, we consider two alternative methods of mounting the camera and range-finder, one using a pan-and-tilt mount and the other using relay lenses and a tilter mirror. Each of these methods is described briefly as follows.

b. Pan-and-Tilt Mount System

The range finder is mounted on the camera, the camera is mounted on a pan-and-tilt mount, and the pan-and-tilt mount is mounted on the frame of the robot, as was shown in Fig. 5. The Pelco Model PT-500-M pan-and-tilt mount may be used for this purpose.

The red laser beam is reflected by the x-y scanning mirrors onto a beam splitter, from which it is partially reflected onto the scene and scattered. Part of this scattered light is picked up by the photomultiplier receiver. The registration between the fields of view of the TV camera and the range-finder transmitter is achieved by detecting the bright spots in the scene that are illuminated by the laser beam. Using the proper calibration, the angular amplitudes of the x-y scanning mirrors will increase as the focal length of the camera zoom lens decreases so that the field of view of the range-finder transmitter is the same as that of the camera. The field of view of the range-finder receiver will be somewhat larger than the widest field of view of the camera in order that the first will include the latter within the required range by slightly tilting the receiver axis relative to the camera axis. If it is found that the field of view of the receiver should track the field of view of the camera, then a 4:1 zoom may be added to the receiver (there are other solutions to this problem).

c. Relay Lenses and a Tilted Mirror System

In this scheme the camera and the range finder are mounted vertically side by side on a mount, which can be panned, and view the scene via relay and field lenses and a mirror, which can be tilted, as shown in Fig. 15. The function of the relay and field lenses is to effectively raise the level of the camera focal plane in the same fashion as is done in a periscope. In the example shown in Fig. 15, the effective focal plane is raised by two feet (the focus point F is effectively raised to Point F′). The relay and field lenses should be installed between the camera and the zoom lens in order to keep their size within practical limits.

The maximal field of view is shown by dashed lines in Fig. 15 for the case of maximal tilt angle (found to be 26°) of the principal ray and no occlusion by the relay lenses. The closest point in the corresponding view is 46 inches in front of the robot. If the mirror is tilted further, closer points can be observed, but then part of the lower portion of the view is occluded by the housing of the field and relay lenses and the range-finder receiver.

Since the photomultiplier of the receiver does not tilt with the mirror, it must have an extra wide lens, e.g., 160°, to cover any possible field of view in front of the robot.

d. Comparison of Methods and Conclusion

Let us compare the two mounting methods we have considered. The main drawback of mounting the TV camera and the range finder on a pan-and-tilt mount (Fig. 5) is the negative effect on the robot stability

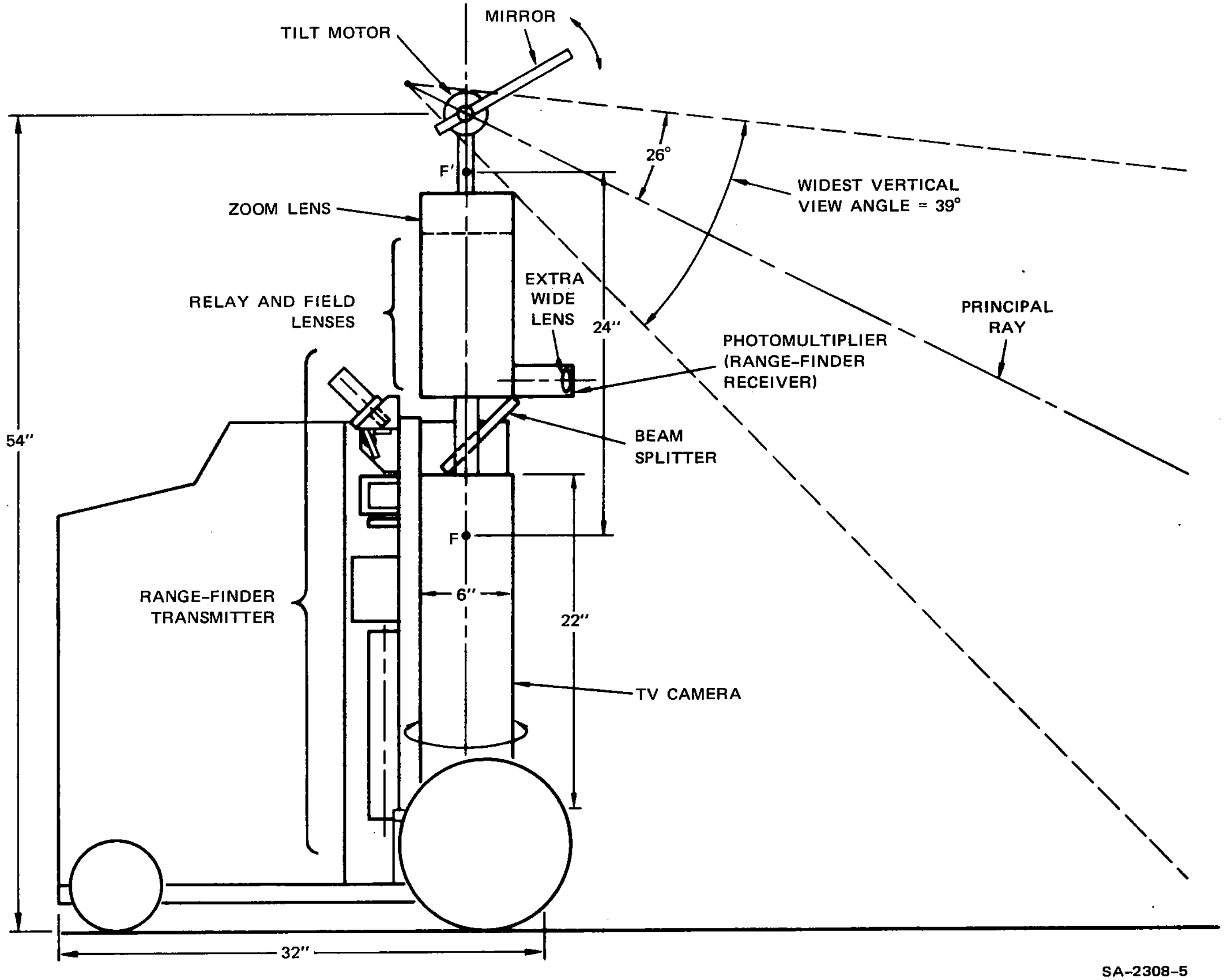

FIGURE 15 MOUNTING THE TV CAMERA AND RANGE FINDER OF A ROBOT VERTICALLY ON A PAN MOUNT AND VIEWING THE SCENE VIA RELAY AND FIELD LENSES, A ZOOM LENS, AND A TILTED MIRROR

because an appreciable mass is positioned higher than in the second method (Fig. 15). Specifically, the weights of the pan-and-tilt mount, camera, and range finder are approximately 25, 25, and 10 pounds, respectively, so that a total mass of 60 pounds is located approximately 40 inches above the frame of the robot cart. Two types of mechanical stability are adversely affected by this condition.

- Static stability--requiring that the center of gravity stays within the region whose vertices are the supporting wheels.
- Dynamic stability--requiring that the oscillatory displacement of the camera system is below an arbitrarily accepted value.

Lack of static stability will topple the robot off its wheels. This may happen if the grade is too steep, the acceleration (linear or centrifugal) is too high, or the robot, travelling at an excessive velocity, is suddenly stopped. A simplified analysis of the static stability and the dynamic stability for the pan-and-tilt mount (Fig. 5) is given in Appendix E.

Consider now the method of mounting the camera and range finder on a pan mount and viewing the scene via relay and field lenses and a tilted mirror Fig. 15 Compared with the pan-and-tilt mounting the drawbacks of this method are as follows:

- The system is more expensive because of the additional cost of the relay and field lenses and because a special optical system has to be designed and constructed.
- The extra wide lens in the range-finder receiver will sense spurious reflections of the laser beam in the scene due to the reflectivity of the target objects, causing errors in range measurement.
- Some light coming from the scene to the camera and from the laser to the scene is absorbed by the relay lenses.

- The lower portion of the scene may be occluded by the housing of the relay and field lenses and the receiver of the range finder.

Comparing the drawbacks of the two methods considered, we prefer the pan-and-tilt method in Fig. 5. This choice has an additional merit associated with modularity. If either a range finder or a zoom lens or both are not used, then the method of pan-and-tilt mount is preferable because of the reduction in mass.

6. Future Camera System

Our recommendation for a TV camera system is based on what is available commercially today. Clearly, as the technology advances, this recommendation will have to be reexamined. We have already mentioned that color TV cameras should be reevaluated in the future.

Another future contender is a solid-state image sensor array, which is characterized by small size, ruggedness, geometric accuracy, low power, and low operating dc voltage (less than 20 V), compared with the Vidicon. Presently, the main drawbacks of such commercially available devices are low two-dimensional resolution (e.g., no more than 50 X 50 elements) and high cost (e.g., $4,400 for a black-and-white camera system with a standard lens).

Two types of array are distinguished; a linear array (a row of elements), and a matrix array (N X N elements). Reticon Corporation, Mountain View, California, manufactures both types: linear arrays (varying from 16 to 512 elements), and matrix arrays (32 X 32 and 50 X 50 elements). Within a few months, Reticon expects to be able to produce a 1024-element array and a 100 X 100-element matrix array. Fairchild Camera & Instrument Corporation, Mountain View, California, has just announced a 500-element linear array. Two additional manufacturers make linear arrays, Integrated Photomatrix Limited and Mullard Limited, both of England.

It is too early to predict if and when the solid-state image sensor array will replace the Silicon Vidicon for robot application. However, where size and weight are important features, this will probably be the case, e.g., adding an "eye" to the "hand" of a robot arm.

C. Constraints on Video Transmission and A/D Conversion

1. Signal Generation

Experience has shown that an appropriate level of picture detail for scene analysis is approximately 256 X 256 picture elements, each encoded into 6 bits of brightness information. A standard closed-circuit TV system employs 525 lines per frame, and 30 frames per second. Each frame is scanned as two interlaced fields ("odd" and "even") of 262 1/2 lines, only about 240 of these containing useful picture information. Since the aspect ratio of a TV picture is 4:3, each line represents about 320 elements (with the same spacing as the lines of a field). Each line scan contains useful picture information for about 52.7 μs. Hence a line scan transmits

$$320/52.7\ \mu s = 6.05 \times 10^{6} \text{ samples per second.}$$

This figure is important; it is the rate at which picture elements are scanned.

If we consider analog transmission of data, the finest checkerboard or grating we can resolve has its elements spaced at the same separation as the picture sample points, alternately black or white. The maximum spatial frequency that can be resolved is thus half the frequency of the sampling grid (i.e., one black/white cycle takes two sample points). The maximum temporal frequency is thus 3.03×10^{6} Hz. If data are transmitted in analog form, a channel bandwidth of 3.03 MHz is required.

If we consider digital transmission, since each sample has 6 bits of brightness information we need to transmit

$$6 \times 6.05 \times 10^{6} = 36.3 \times 10^{6} \text{ bits per second.}$$

This can be done via a channel of 18.2 MHz. (The difference in the above channel capacities occurs because in the first case spatial frequency is encoded as temporal frequency, spatial amplitude as amplitude, whereas in the latter case, both spatial frequency and amplitude are encoded in the temporal frequency domain, and no information is transmitted via amplitude. The latter scheme is, of course, much less sensitive to amplitude variations (fading, etc.) (It is, of course, possible to reduce the rate of generation of data by slowing the TV scan. This scheme has the disadvantage of making TV equipment nonstandard and perhaps more costly but perhaps should be left open as an option.)

2. Data Transmission

Clearly, we can digitize the TV waveform before or after transmission to the central installation. We have the choice of sending analog or digital data, with the trading of bandwidth for reliability noted in the previous section.

There is a further possible tradeoff scheme: We have the choice of transmitting picture data as they are generated, or we can store the data temporarily and transmit them at a lower rate. In this case, we reduce the bandwidth required, at the expense of increasing transmission time and reducing the number of pictures that can be sent in a given time.

An acceptable upper limit for transmission time is about 1 second. If we take this time to send a complete picture, the bandwidths required are now:

50.4 KHz	analog
303 KHz	digital

To reduce transmission rate we have a choice of two techniques: (1) only transmit data for every nth picture element; do this for n fields to obtain full picture; (2) buffer part or all of a picture and send it later at a lower rate.

For (1) we need to be able to sample every 60th picture element (i.e., 4 per line) over 60 fields to fulfill our maximum transmission time constraint.

For (2), if we buffer a complete line we need $6 \times 240 = 1440$ bits of storage per line; we also need to transmit four lines per field over 60 fields to satisfy the transmission time constraint. If we buffer a whole picture we need $6 \times 240 \times 320 \cong 460,000$ bits. This is approximately equivalent to 12,800 36-bit words or 28,600 16-bit words. The buffer memory must be capable of accepting the picture data at the rate at which it is generated by the TV camera.

3. Computer Input

The rate of generation of the quantized TV data is 36.3×10^6 bits/second. This corresponds to 1.01×10^6 36-bit words/second, or 2.25×10^6 16-bit words/second.

The PDP-10 computer, for example, has 36-bit words and 1 μs or 2 μs core memory with interleaving of core modules. It is thus possible to connect a TV camera directly to a PDP-10 memory bus. For most smaller computers, however, input bandwidth is much less, e.g., 833,333 16-bit words/second for Nova 1200, 2.04 M 16-bit words/second for PDP 11 (with interleaved 900 ns core). For such smaller computers, some form of bandwidth reduction is necessary (e.g., 120×120 picture). (Most 16-bit minicomputers have halfword operations. It is therefore possible to use 8-bit picture samples packed two to a word (instead of 2-2/3 words for 6-bit ones), sacrificing storage space for speed and convenience of handling. Picture sampler bandwidth is therefore $8 \times 6.05 \times 10^6 = 48.4 \times 10^6$ bits/second = 3.03×10^6 16-bit words/second. Hence a 120 column $\times$ 8 bit picture could be transferred to memory of a PDP 11 (and would occupy 7200 words). A Nova 1200 could accept a 60 column, 8-bit picture in one TV field.)

IV CONCLUSIONS

In the foregoing we have presented specifications and recommendations for robotic equipment. Estimates were also made of both the first-time and recurring costs of this equipment. It is our conclusion that this equipment in various combinations would be broadly useful in robot research. Some additional work needs to be performed before such combinations can be made generally available, however. As a first step in making this equipment available, we recommend that some appropriate organization be charged with designing, constructing, and testing the mobile robot system we have described above. Such a system should also be fully documented. After an initial prototype is finished, some organization should be selected to produce copies of subsets of this equipment to order.

It is possible that during the phase of design of this equipment, additional cost-saving ideas will surface. For example, we recommend that the following areas in particular might be further researched to explore certain possible economies:

- Slow-scan or several-frames-per-picture TV. Although the cost of a slow-scan TV might be higher than that of a conventional system, certain economies may be possible in the video transmission system if lower bandwidths could be used. Perhaps such an alternative could be explored further as an option for systems using a mobile vehicle.

- Servoing of all motors through the minicomputer. Some of the equipment specified in Table
face with analog servo circuits. There may be some savings possible if servoing were done through the minicomputer itself.

Further research is necessary to determine whether or not this alternative places an intolerable load on the minicomputer. Our initial suspicion is that the minicomputer will be quite busy with other functions.

- Reduction of the 50-Kb radio link data rate to say 10 Kb or 1200 baud. Somewhat less expensive equipment can be used with the lower data rate. Our recommendation of a high rate is based on the desire for fast loading of the minicomputer core plus rapid transmission of range finder data from the vehicle to the main computer.

From the estimates given in Table 3, we see that an initial prototype of a complete robot system would cost about 50,000 plus 28 man-months of effort. Additional copies could be produced at about 50,000 plus 7 man-months.

Certain special subsets of this equipment will also be of interest. In Table 5 we list some of these and give estimates of the costs to build additional copies of them.

Our initial goal of attempting to specify modular components seems to have been well-founded. We expect that this modularity will allow us to capitalize on improvements in the technology of any of the components.

In concluding we want to emphasize that the recommendations contained in the above represent a preliminary design effort. To assemble subsystems of these components will require further detailed design, and we should be open to changing our recommendations should further design reveal good reason to do so.

Table 5

SPECIAL ROBOT EQUIPMENT COMBINATIONS

Name	Components	Recurring Cost	
		$	Labor in mm
1. Vision system*	TV camera video A/D equipment	11,475	1.5
2. Arm/vision system	TV camera, video A/D equipment, minicomputer, plus necessary interface equipment	35,690	4.0
3. Cart/vision	TV camera, video A/D equipment, radio link, minicomputer, plus necessary interface equipment	41,575	5.25

*All systems with vision include a Cohu 2850 camera.

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3. R. E. Johnson, "Application of RCA Silicon Diode Array Target Vidicons," RCA Camera Tube Application Note AN-4623 (July 13, 1971).

4. L. D. Earnest, "Choosing an Eye for a Computer," Stanford Artificial Intelligence Project, Memo No. 51, Stanford University, Stanford, California (April 1, 1967).

5. COHU Closed-Circuit Television Catalog (1973).

6. J. M. Tenenbaum, "Accommodation in Computer Vision," Stanford Artificial Intelligence Project, Memo AIM-134, Computer Science Department, Report No. CS 182, Stanford University, Stanford, California (October 1970).

Appendix A

SUMMARY OF RESULTS OF THE SURVEY OF ROBOT EQUIPMENT NEEDS

by

N. Nilsson

Stanford Research Institute

1. General

As part of an SRI study on equipment needs for Artificial Intelligence research, we circulated a questionnaire to various universities and laboratories throughout the world. We received 33 responses indicating an interest in robotic equipment and 14 responses indicating no interest in such equipment. In this Appendix we shall summarize and analyze the results of this survey. (A copy of the survey form itself is included at the end of the Appendix.)

From the survey results it appears that there are four major categories of users of robotic equipment (some groups are interested in more than one category):

Category	Description
Arm/Vision	These users want a manipulator (or two) fixed to a table top plus some sort of vision device (seven groups).
Arm/Vision/Cart	These users want a manipulator (or two) plus a vision device on a mobile cart (eleven groups).
Modest Vision	These users want a vision device alone with moderate requirements (five groups).
Elaborate Vision	These users want a vision device alone, and they have quite demanding requirements (eleven groups).

In analyzing the responses, it appears that except for the last category (elaborate vision), the needs of the other users can be largely met by three common modular subsystems, a cart, a manipulator(s), and a vision device, that can be put together in various combinations. To be sure, the vision requirements of the arm/vision group might be slightly different than those of the arm/vision/cart group; the first may be willing to use floodlights for example. Also the manipulator workspace might be different for the arm/vision and arm/vision/cart groups. But, in general, we feel that common equipment can be specified that would meet the needs of most researchers with the consequent reduction in cost that accompanies the larger number of copies.

Since the demands of the elaborate vision group are quite severe, it seems certain that they can only be met by special equipment. So that the present study can more effectively focus its resources, we will not be making recommendations about desirable equipment for this group. The survey results from the first three categories of users (together with cost and availability data) determined the specificiations listed in Table 1 in the main body of this report.

2. Summary of Responses

The following individuals and organizations responded to the questionnaire and indicated that they might reasonably have a need for robotic equipment of one of the four categories listed. We have divided these respondents into two classes according to the sizes of the groups that might be working with such equipment.

Small Groups (2 through 7 people)

The Australian National University
Canberra City, Australia
Professor S. Kaneff

Carnegie-Mellon University
Pittsburgh, Pennsylvania
Professor R. Reddy

Case Western Reserve University
Cleveland, Ohio
Professor G. Ernst

CSIRO
Division of Computing Research
Canberra City, Australia
Dr. J. O'Callaghan

Essex University
Colchester, Essex, U.K.
Dr. P. Hayes

Georgia Institute of Technology
Atlanta, Georgia
Professor M. Kelly

Department of Information Science
Kyoto University
Kyoto, Japan
Professor T. Sakai

Laboratoire de Cybernetique des Enterprises
Reconnaissance des Firmes et Intelligence Artificielle
Toulouse, France
Professor S. Castan
Professor G. Perennou

Lockheed Research Laboratories
Palo Alto, California
Dr. Martin A. Fischler

M.I.T. Draper Laboratory
Cambridge, Massachusetts
Dr. J. Nevins

National Bureau of Standards
Washington, D.C.
Edwin G. Johnson

National Physical Laboratory
Teddington, Middlesex, U.K.
Dr. J. Parks

New York University
New York, New York
Mr. U. Ramer

Purdue University
Lafayette, Indiana
Professor K. Fu

State University of New York
Buffalo, New York
Professor J. Wexler

USC Information Science Institute
Los Angeles, California
Dr. R. Anderson

University of Sussex
Brighton, U.K.
Mr. A. Mackworth
Professor M. Clowes

University of Texas
Austin, Texas
Professor J. Aggrawal

University of Tokyo
Tokyo, Japan
Professor J. Nagumo

University of Washington
Seattle, Washington
Professor A. D. C. Holden

University of Wisconsin
Madison, Wisconsin
Mr. J. Lester
Professor L. Uhr

Large Groups (more than 7 people)

Artificial Intelligence Center
Stanford Research Institute
Menlo Park, California
Dr. Richard Fikes

Department of Machine Intelligence
Edinburgh University
Edinburgh, Scotland
Professor Donald Michie

Electrotechnical Laboratory
MITI
Japan
Dr. K. Sato

Hitachi Ltd.
Central Research Laboratory
Tokyo, Japan
Dr. M. Ejiri
Dr. T. Goto

Institute de Programmation
University of Paris
Paris, France
M. G. Guiho
M. J. Jouannaud

Jet Propulsion Laboratory
Robot Research Program
Pasadena, California
Dr. W. Whitney
D. A. Bejczy

Jet Propulsion Laboratory
Teleoperator Laboratory
Pasadena, California
Dr. D. O'Handley

Massachusetts Institute of Technology
Artificial Intelligence Laboratory
Cambridge, Massachusetts
Dr. B. Horn
Professor P. Winston

Project MAC
Massachusetts Institute of Technology
Cambridge, Massachusetts
Dr. W. Martin

Stanford University
Stanford, California
Professor C. Green
Mr. K. Pingle
Dr. T. Binford

University of Illinois
Urbana, Illinois
Professor R. Chien

University of Maryland
College Park, Maryland
Professor Azriel Rosenfeld

In the following pages we tabulate answers to some of the more important questions asked in the survey. The answers are grouped according to the respondent categories arm/vision; arm/vision/cart; and modest vision only. (We have excluded the elaborate vision responses from this summary.) Each response is indicated by the letter S or L depending on whether the group responding was small or large, respectively.

SUBJECT	Arm/Vision	Arm/Cart/Vision	Modest Vision Alone
General			
Aside from feedback from vision, touch sensors, motors, shafts, etc., our research requires other specialized sensors such as:	current and voltage probes - L; nonvisual imaging - S;	acoustic - S,S,L temperature, pressure - L proximity - L	VOCODER - S Laser - S
Vision The number of picture elements should be approximately:			
500 x 500	L L S S	L L S	S
250 x 250	L	L L S	S S S
100 x 100 (or less)		L S	
The number of intensity levels at each picture point should be:			
128	L L S	L L	
64	L	L L S S	
32			S
16 or less	S	L S	S S S

SUBJECT	Arm/Vision	Arm/Cart/Vision	Modest Vision Alone
The vision device should be able to provide color information:			
yes	L L	L L L L S S	
maybe	L L S S S	S	S S S S S
no		L	
The vision device should directly provide depth or range data:			
yes	L L S	L S	
maybe	L	L L L S S	S S S
no	L S		S
Manipulators The tasks to be performed include:			
assembly	L L L L S S S S	L L L L S S S S	
moving large objects such as chairs	L S	L S	
handling irregular objects such as rocks	L S	L L L L L S S S	
handling tools	L S	L S	

SUBJECT	Arm/Vision	Arm/Cart/Vision	Modest Vision Alone
The objects to be manipulated will be of the following sizes:			
less than 50cm	L	L S	
less than 25cm	L L S S	L L S	
less than 10cm	L S	L L S	
and the following weights:			
less than 10kg	L	S	
less than 5kg	L L S S	L L L	
less than 2kg	L S	L L S	
More than one manipulator working in cooperation is required:			
yes	L L L	L L	
maybe	L S S S S	L L S S S	
no			

SUBJECT	Arm/Vision	Arm/Cart/Vision	Modest Vision Alone
<u>Mobile Vehicles</u>			
The range over which the vehicle must travel is:			
Within a single room		L L L L S	
In and out of several rooms and corridors		L L S S	
Outdoors on paved surfaces		L S S S	
Outdoors over rough terrain		L L S S	
Cruising speed of vehicle should be:			
up to 1 meter/second		L L L L S S S	
up to 2 meter/second		L S	

27 December 1972

Survey of Robot Equipment Needs

The Stanford Research Institute is conducting a study to determine future needs of research and educational groups for special computer-controlled sensing, manipulating and mobile devices. Examples of such "robotic" equipment would include television cameras, manipulator arms and mobile vehicles. As part of our study we are circulating the attached questionnaire. We would like to find out if there is enough commonality of needs to warrant the design of some standard items that several of us could use. We would appreciate your taking the time to fill out this questionnaire. Please put check marks in the appropriate blank spaces--use double check marks for emphasis. We have left space for extra comments; they will be most welcome! Please feel free to circulate copies of this questionnaire to colleagues. We would like to have responses by 31 January 1973. Return to Nils Nilsson, Artificial Intelligence Center, Stanford Research Institute, Menlo Park, California 94025.

Name____

Organization__________________________________

Position______________________________________

A. General

1. We are now doing research in which we are using special computer-controlled equipment such as television cameras, manipulator systems or vehicles.

   _____ yes

   Please describe ____.

   _____ no

2. If some standardized robotic equipment were available at reasonable cost, we would use it in our future research.

   _____ yes

   _____ maybe

   _____ no

3. A primary goal of our research will be to develop specific, practical applications of robotics involving automatic assembly, manipulation and/or perception.

   _____ yes

   _____ maybe

   Please name application ________________________________.

   _____ no

4. A primary goal of our research will be to develop general, basic artificial intelligence concepts needed by intelligent robots.

   _____ yes   _____ no

   _____ maybe

5. We are interested in computer analysis of visual scenes such as might be obtained by television cameras.

   _____ yes

   _____ maybe

   _____ no

6. We are interested in developing programs that involve locomotion and/or manipulation.

_____ yes

_____ maybe

_____ no

7. Our research will involve integrating several aspects (e.g., vision, touch, and manipulation) of robotics into a single system.

_____ yes

_____ maybe

_____ no

8. The size of our project is likely to be

_____ small (1 or 2 people)

_____ medium (3 to 7 people)

_____ large (more than 7 people)

9. Our research will concentrate on tasks requiring

_____ fixed manipulator arm

_____ mobile vehicle

    _____ with attached arm

    _____ without attached arm .

10. Aside from feedback from vision, touch sensors, motors, shafts, etc., our research requires other specialized sensors.

_____ yes

_____ maybe

Please specify: ____.

_____ no.

11. Our equipment is likely to be operated by

_____ undergraduate students

_____ graduate students

_____ professional research and technical people

_____ other .

12. Please describe the computer system you are now using:

CPU ____

____

Amount of core storage ______________________________

____

13. Please describe the computer system you intend to use in conjunction with your research with robotic equipment.

CPU ____

____

Amount of core storage ______________________________

____

B. Vision

If your research plans include research on vision, please answer the following questions:

1. We are interested in a vision device

_____ on board a mobile vehicle

_____ fixed at one or more surveillance positions.

2. Which of the following parameters need to be under program control

_____ scan type (e.g. random access or raster)

_____ picture element resolution (sampling interval)

_____ number of gray levels

_____ electrical sensitivity (e.g., target voltage)

_____ focus

_____ iris

_____ focal length

_____ zoom lens

_____ turret

_____ format (e.g., window size)

_____ orientation (i.e., pan, tilt)

_____ other. Please specify ______________________________

____

_____ none. (i.e., automatic adjustment for "good" overall picture).

3. Our vision device should be able to provide a picture with ______ by ______ picture elements with _______ levels of intensity at each picture point.

4. Our vision device should be able to provide color information.

_____ yes

_____ maybe

_____ no

5. We must be able to read into the computer a complete picture in

_____ less than a second

_____ between a second and ten seconds

_____ other. Please specify ________________________________.

6. Our vision device should directly provide depth or range data.

_____ yes

_____ maybe

Range accuracy required

_____ .1%

_____ 1%

_____ 10%

_____ no

7. Our vision device will be operated in work spaces

_____ illuminated by floodlights if necessary

_____ having normal room illumination

_____ out-of-doors during daylight

_____ with subdued lighting

8. The objects or scenes we will be primarily viewing will be

_____ at close range (0 - 3 feet)

_____ at medium range (3 - 10 feet)

_____ long range (10 - 30 feet)

_____ distant (greater than 30 feet)

_____ variable

9. The objects we will be looking at will have linear dimensions on the order of

_____ 0.1 to 1 inch

_____ 1 inch to 10 inches

_____ 10 inches to 30 inches

_____ 30 inches to 100 inches

_____ larger .

10. Please comment on any special interface requirements between the vision sensors and the controlling computer.

11. General comments about vision:

C. Manipulators

If your research plans include the use of manipulators (either fixed or on board a mobile vehicle) please answer the following questions.

1. We are interested in the following tasks involving manipulation

_____ stacking and/or sorting of simple objects such as blocks

_____ assembly of simple structures out of simple components such as blocks

_____ assembly of simple machines

    _____ with easily-handled parts

    _____ with complex parts

_____ moving large objects (such as chairs) from place to place

_____ handling irregular objects such as rocks

_____ other. Please specify _____________________.

2. Our research requires manipulator hands that

_____ are simple gripper jaws

_____ have articulated fingers

_____ are themselves specialized tools (such as a drill or screwdriver). Please specify _____________________.

_____ other. Please specify _____________________.

3. Our research requires the following types of feedback from the manipulator

_____ positions of the joints

_____ velocities of the joints

_____ forces at the joints

_____ tactile feedback from the hand

_____ forces at the hand

_____ visual information from the viewpoint of the hand (provided, say, by fiber optics)

_____ other. Please specify _____________________.

4. The objects we want to manipulate will range in size from _____ __________ to __________________ . They will range in weight from _________________ to _____________________.

5. When our manipulator is working with objects on a table, we want the top of the table to

_____ be fixed

_____ be translatable and/or rotatable under computer control. Please specify size of table _________________ and extent of translation ___________________ and rotation __________.

_____ have computer controllable attachments such as a vise. Specify ____.

6. Our research requires more than one manipulator working in cooperation.

_____ yes

_____ maybe

Specify how many _____________________.

_____ no

7. The "work space" for our manipulator could be enclosed roughly in a cube with a side of about

_____ 3"

_____ 1'

_____ 3'

_____ 10'

_____ other. Please specify ___________________________________.

8. The open-loop accuracy of positioning of the hand of our manipulator must be about

_____ .001"

_____ .010"

_____ .050"

_____ other. Please specify ___________________________________.

9. The hand must be able to move between extreme positions of its work space in about

_____ 0.1 sec.

_____ 1 sec.

_____ 3 sec.

_____ other. Please specify ______________________________.

10. Our research requires the ability to "program" the motions of the manipulator by recording its trajectory as we guide it through a task.

_____ yes

_____ maybe

_____ no

11. Please comment on any special interface requirements between the manipulator and its controlling computer.

____

____

12. General comments about manipulators.

D. Mobile Vehicles

If your research plans include working with a mobile vehicle, please answer the following questions.

1. The range over which our vehicle must travel is

_____ on a table top

_____ within a single room

_____ in and out of several rooms and corridors

_____ outdoors on paved surfaces. Please specify range _______ _________________________.

_____ outdoors over rough terrain. Please specify range ______ _________________________.

2. It is important that our vehicle be free of umbilical cords for power and communication

_____ yes

_____ maybe

_____ no

3. For self-powered vehicles, our research could tolerate recharging or replacement of batteries, or refueling, once every

_____ hour

_____ three hours

_____ day.

4. The normal cruising speed of our vehicle on level surfaces must be approximately

_____ 1/4 to 1 foot per second

_____ 1 to 3 feet per second

_____ 3 to 6 feet per second

_____ faster. Please specify _______________________________.

5. The size of the vehicle should be no larger than

height ______________

width ______________

length ______________

6. The tasks to be performed by the mobile vehicle require abilities to

_____ navigate around obstacles

_____ navigate from room to room

_____ open and close doors

_____ pick up, carry and set down objects. Please specify types of objects ______________________________.

_____ push objects. Please specify types of objects __________ ______________________________.

_____ other. Please specify ______________________________.

7. Our experimenters would want to communicate with the vehicle through the following I/O devices on board the vehicle

_____ microphone

_____ synthesized speech generator

_____ touch (including special key-boards on vehicle)

_____ on-board display

_____ other. Please specify ______________________________.

_____ none.

8. Our research requires more than one vehicle working in cooperation

_____ yes Please specify how many __________

_____ maybe

_____ no.

9. Please comment on any special interface requirements between the vehicle and its controlling computer.

____

____

10. General comments on vehicles

Appendix B

ROBOT RESEARCH AND EQUIPMENT IN JAPAN

by

J. Gleason

Stanford Research Institute

1. Introduction

As part of a study sponsored by NSF to recommend hardware for artificial intelligence research, Victor Scheinman (of Stanford University) and I spent two weeks in Japan visiting universities, industrial research laboratories, and factories. We were impressed to find that a substantial effort is being devoted to image processing techniques and to the development of robots for industrial automation. The largest effort is an eight-year, 100 million dollar program sponsored by the Japanese Ministry of International Trade and Industry (MITI). This is a National research and development program under the over-all direction of Dr. Hiroji Nishino of the Electrotechnical Laboratory (ETL). The PIPS project (Pattern Information Processing System) has five major goals to be accomplished by 1978: (i) Recognition of 2000 printed characters (including Chinese Kanji characters), (ii) Recognition of pictures, (iii) Recognition of 3-D objects, (iv) Recognition of voice, and (v) Recognition of sentences. In this report, I will summarize some of the things we saw at various Japanese laboratories.

2. ETL

At the Electrotechnical Laboratory in Tokyo, under the direction of Dr. Kohei Sato, we saw five manipulators, a demonstration of an image dissector/laser ranging system, and a small mobile robot which had a TV camera with a flexible fiber-optic light guide, a manipulator with 68 tactile sensors in its hand, and a mini-skirt around its perimeter equipped with an additional 16 tactile sensors. (The latter was developed by Dr. Hirochika Inove and Dr. Hideo Tsukuno.) The computer used by this laboratory was a 20K PDP-12. The ETL-HAND is a hydraulically-driven, multi-joint manipulator with six degrees of freedom (three modes of motion for both rotation and flexion respectively and finger tips with tactile sensors which detect contact with an object. The ETL-HAND has been designed with special attention paid to its driving mechanism and the entire shape of the system for a minimum number of motions. The finger tips are replaceable as necessary.

Receiving signals from the sensors on the finger tips, the computer sends out action signals to define what steps the HAND should take to perform the task.

3. Hitachi

The HIVIP Mark I hand/eye system at the Hitachi Central Research Laboratory can assemble simple structures given appropriately shaped blocks and a three-view assembly drawing of the desired structure. It is currently being modified to permit the introduction of tactile sensors on the fingers of the hand.

Dr. Masakuzu Ejiri and Dr. Tadamasa Hirai then demonstrated the HIVIP Mark III hand/eye system, a successor to the Mark I, which used a TV camera to determine the location and orientation of different blocks moving down a conveyor belt, acquire and track a moving block, and finally pick it up and place it in a standard position. They also showed us a soon-to-be-announced printed circuit board inspection system which displays cracks and other defects in red on a color TV monitor, while the boards are moving on a conveyor belt.

4. Mitsubishi

At Mitsubishi Central Research Laboratory, Dr. Takayasu Ito demonstrated a minicomputer-controlled manipulator that used two TV cameras: one provides an overview of a rotary conveyer table, and the other is mounted in the hand to provide visual feedback for arm positioning. The system "reads" the Kana Character on each of several blocks placed on a fixed table and stacks them on the moving table in the desired order. This system uses a PDP-8/I with 8K core. The program, however, occupies only 5K of core, including the storage areas for the video image and reference tables for 20 different shapes and characters. A paper describing this sytem will be presented at the Third International Symposium on Industrial Robots on May 29-31, 1973, in Zurich, Switzerland.

Dr. Ito's group, which was formed two years ago, is interested in studying the mathematical theory of computation, theoretical aspects of AI, theorem proving, and improvements of Planner for program writing. Dr. Ito has a 32K PDP-15/40, a 16K PDP-11/20, an 8K Super-Nova, a 16K Melcom 350-5F, and an 8K Melcom 70 (which is similar to a Super-Nova). All of these computers are interconnected using the PDP-11's Uni-bus. An XDS Sigma 5 is going to be added to this system sometime this year. Mitsubishi also had on display an 80x80 electroluminescent (EL) panel TV, a 200x240 EL Computer display with 3 bits of grey levels, and a multicolor liquid crystal display.

5. Waseda

At Waseda University, Dr. Ichiro Kato had several arms and articulated hands with tactile sensors that were developed primarily for prosthetic applications. Dr. Kato has developed several "walking machines," the latest of which has two arms with hands and a dual TV system for eyes. Drs. Atsuya Seko and Hiroshi Kobayashi have developed an experimental, parallel-image preprocessor which utilizes the dead-time used to extract the boundary of high contrast objects, detect moving objects, and perform logic operations on images such as a+b, axb, and the like.

6. Other Laboratories

In addition to the above, we visited Toshiba Research Laboratory, which has a self-navigating, mobile robot for delivering and picking up packages and Kyoto University, where Dr. Toshiyuki Saki is doing research in automatic speech processing, pattern recognition, picture processing (including computer analysis and classification of photographs of human faces), and processing of natural language. We also visited Tokyo University, where Dr. Jin-ichi Nagumo is doing research on associative memory systems and Dr. Yasuhiro Doi is studying new techniques for real time processing of holographic images. At RiKen Information Science Laboratory, Dr. Takashi Soma is developing an ultra-high resolution CRT (16,000x16,000) for use both as a flying spot scanner and as a large-scale memory. Dr. Eiichi Goto (who is also on the faculty of the University of Tokyo) is developing a graphic system with halftone and area color capabilities based on a Data Disk 6500 display system.

RiKen has the largest computational facilities that we encountered. These included a FACOM 270-60, (a Dual cpu with a 256 kw x 32 bits and 200 x 10 bytes of disk storage) and a FACOM 270-30 (65 kw x 16 bits with a large graphics system). By the end of the year the 270-60 will be replaced with a FACOM 270-75, which is five times faster (and reputed to be the largest computer in Japan).

7. Industrial Facilities

We visited four manufacturing facilities:

- Aida Engineering, which manufactures one- and two-handed industrial robots for working with punch-presses
- Nikon, where we watched the assembly of the F-2 camera (which contains over 1000 parts!)
- Honda Engineering Company, where the assembly of Honda cars is accomplished
- Furukawa Electric Company, which is the fourth or fifth largest communications cable manufacturer in the world. Dr. Kazuniko Masuda at Furukawa (and former International Fellow at SRI) has designed many systems to automate the assembly of a wide variety of cables.

8. Conclusion

It seems to us that the Japanese are working very diligently to acquire the technology to carry out advanced image processing and also to apply AI technology to industrial automation within the next few years. On the other hand we saw comparatively little interest in the major software and theoretical aspects of AI research. We did not see any equipment that we thought could be used as components of the AI research equipment we are recommending.

Appendix C

ROBOTICS HARDWARE IN EUROPE

by

D. Michie
C.M. Brown

Edinburgh University

I. Summary

This appendix covers industrial and research robotics hardware available or planned in Continental Europe, the U.K., and the U.S.S.R. The survey is in three parts; hardware that is probably constrained strictly to industrial environments, hardware designed and built for industry but which may be useful in academic research work, and research hardware.

II. Industrial Hardware

Much information and bibliographic data on industrial robots may be found in references (0) and (36) of this appendix. The latter includes descriptions of some 138 industrial robots available at present; 91 of these are Japanese, and 15 are made in North America. Of the remaining devices (from the U.K., Scandinavia, West Germany and Hungary) most seem to have little potential for AI research either because of their limited action repertoire or control systems, or both. A few devices which may be useful in a research environment appear in section III.

U.K. Firms

Swiss Assembly Products
3 St. John
Warwick
England

This firm, with its manufacturing partner Lanco-Economic, CH 4513 Langendorf, Switzerland, makes a variety of pick-and place devices and assemblies specifically for screwdriving operations. The cost of individual devices is between £375 and £700. The 'hand' is at best a mechanical collet, suction device, chuck, or the like.

Hawker Siddeley Dynamics Eng., Ltd.,
Manor Road
Hatfield
Hertfordshire
England

Hawker Siddeley manufactures its own versions of the American AMF Versatran series. The Minitran is described under the University of Nottingham entry in this section; the Versatran and Versaweld are described in section III; here we mention the Simpltran, which costs £4,500 - £5,900.

This machine is a point-to-point device which can access a rather large working area. It has fewer degrees of freedom than the Versatran; it forms the basis for the Versaweld, which is the same machine fitted with a minicomputer control system.

University of Nottingham
Department of Production Engineering and Production Management
University Park
Nottingham NG7 2RD

The University of Nottingham has been instrumental in designing the Minitran, and this machine and their Programmable Assembly Machine are both well described in (4).

The Minitran is a modular system; it has a variety of goalpost pick-and-place motions, both in arcs and straight lines, and incorporates the possibility of various rotations along the path. The Minitran control is a sequencing system which can send signals to other control modules, allowing the sequences of different modules to fit together. The control modules are electronic, and use microcircuit logic. The average price of a Minitran plus control circuitry is around £1,200.

The Programmable Assembly Machine is a swinging-arm pick-and-place device mounted on a travelling platform above a travelling table. Its control system uses a program drum, with positioning done by digital feedback control; a Minitran control module is coupled with the positioning system.

In both these devices emphasis was placed on producing a product which is economically competitive with human assembly; enough manipulative generality has been sacrificed on the altar of profit to make these devices uninteresting from an AI research point of view.

Wickman Machine Tool Sales Ltd.
Auto Assembly Division
Bodmin Road
Wyken
Coventry
England

This firm makes linear and goalpost action pick-and-place devices for £240 - £500, excluding control circuits, which are relay logic with limit switches. Richardson, in (35), shows how these units cooperate in some fairly complex assembly operations.

Bowl Feeders (Automatic) Ltd
37 Lower Moseley Street
Manchester X 2
England

This firm manufactures the Transferobot 210, a parts placing device which requires mechanical setup, cycles on demand, and costs £700.

University of Birmingham
Department of Mechanical Engineering
Edgbaston
Birmingham B15 2TT
England

The University of Birmingham has developed at least three manipulators. The Mark I Manipulator and the Wolfson Handler are described in (37). Both are fixed-stroke devices controlled by cam timers and relays. The former is a goalpost pick-and-place device, the latter (which also has a transistorised control system) incorporates a possible rotation into its pick-and-place operation, which is done along an arc.

The Loc-au-man is a prototype device with six degrees of freedom (41), controlled again by relay logic and a plugboard, which will sequentially address fixed mechanical stops on a multisided bar. It is capable of a much wider range of motions than the other two devices, and is designed to do much of what a Unimate can do, only more cheaply and simply.

Vaughan Associates Ltd
Trent Works
Lenton Lane
Nottingham
England

The Vaun Loader is a specialized device for machining. It seems to be a pick-and-place device with a lateral wrist movement, but the description is unclear.

The Metal Box Company
U.K.

The Metal Box Company developed their own Programmable Handling Arm when they decided a Versatran was too large and complex for their job. This arm is briefly described in (8); it appears to be a rather simple pick-and-place type.

Hymatic Eng. Company Ltd
Redditch
Worcestershire
England

The Autoarm Mark 5 seems to have a good range of motions, and sells for only £300 - £400, but it is pneumatically controlled, with mechanical stops, and mechanical setup is required to determine stroke length.

Transamatic Ltd
Mount Road
Burntwood
Staffordshire
England

Transamatic makes gantry transfer units for large weight ranges, and the Translave 101 and 102, as well as the Mechanical Hand. The latter are all more general manipulators for moderately heavy and hot loads from forging machines. The control is sequential and set up by switches on a control panel. The Mechanical Hand, Translave 101 and 102 cost at least £2,750 - £5,400, and £3,000 respectively.

Frazer-Nash Engineering Group Ltd
The Wharf
South Street
Midhurst
Sussex
England

The F-N Transfer Unit is a goalpost pick-and-place device for heavy loads, controlled by timer cams and costing about £400.

E.G.P. Design and Automation Ltd
92-94 Holdenhurst Road
Bournemouth
England

The Transmit Component Transfer arm is a goalpost pick-and-place device for heavy loads, controlled by a sequence timer and eight cams, and costing about £355.

B and R Taylor
Sandy Lane
Preston PR5 IDA
England

The Transiva, manufactured by B and R Taylor, is thoroughly described in (17). It must be set up mechanically for each stroke length, and is unique in that all its movements are simple harmonic motions. The programming is basically done with a uniselector, which may be augmented with a plugboard or punched card device. It costs £3,850 - £5,800.

The Churchill Machine Tool Co. Ltd
Broadheath
Altrincham
Cheshire
England

This firm makes a gantry loader, controlled in a fixed sequence by micro-switches.

Scandinavian Firms

This information is from (31).

R. Kaufeldt AB
Box 2068
141 02 Huddinge 2
Sweden

The Robot types A13, A4, A5, A6, and A30 are a series of robots with rather wide repertoires of actions, controlled by stepcounters and the Ericsson sequence control unit, with mechanical stops. This combination affords flexibility intermediate between that of cam programs and NC controls. The cost of these units is between £2,400 and £3,200.

Electrolux AB
Luxbacken 1
Lilla Essington
105 45 Stockholm
Sweden

The Electrolux MHU Junior and MHU Senior (the latter costs £5,300) are controlled as are the Kaufeldt robots above. Both MHUs are capable of reaching into a large volume of space. The MHU Senior is modular, with degrees of freedom added as needed; the hand design is not clear from the description provided.

Ekström Industri AB
Postfack
560 23 Bankeryd
Sweden

The Ecomat I is a pick-and-place device with manually set arm length, controlled by pneumatic valves and relays, and costing £1,200 - £1,600.

German Firms

RDN-Maschinenbau VDMA der Rheinische Nadefabriken GmBH
Postfach 1408
51 Aachen
German Fed. Rep.

The T 200 Manipulator is cam-controlled with three degrees of freedom.

Vereingte Flugtechnische Werke-Fokker Gmbh
Werk Varel
Varel/Oldb.
German Fed. Rep.

The VFW Transfer-Automat is programmed by a plugboard, has a wide range of motions, includes a hand with optional lateral wrist motion, and costs £7,100 - £7,300.

Hungarian Firms

Hungarian Industries
Foreign Trade Co.,
Budapest
Hungary

The Samat has four degrees of freedom, and is limited to loading and unloading presses.

III Industrial Robots for Research

The distinguishing characteristics of robots of this type are computer-compatible control systems, or those that are potentially so, and a wide range of motions. Some U.S. robots (e.g. Unimate, Versatran) have such capabilities and are at work in AI labs already. Some of the Versatran models are described in this section; though they might be considered U.S. robots, they are manufactured in the U.K., and Versatran UK tends to use the minicomputer control more than AMF in the U.S., which favours a magnetic tape controller for continuous path capability.

R.F. Cakebread predicts in (9) that a second generation of industrial robots will emerge in the 1970's with many characteristics now found only in academic research devices. Thus this sort of research-applicable industrial robot may become more common in the near future, and will probably first be available through the large U.S. firm presently conducting research and development programmes for second generation devices.

According to Cakebread, the second generation industrial robot will have six controllable articulations, extensible local and library memory, fast, 'instinctive' programming, random access bulk memory, moving target synchronization, intermixed point-to-point and continuous path control, compatible computer control interfaces, high reliability, and fast reaction time.

U.K. Firms

Hawker Siddeley Dynamics Engineering Ltd
Automatic Handling and Welding Division
Manor Road
Hatfield
Herts
England

The Versatran is modular, allowing from one to six degrees of freedom plus gripping in the hand, and a choice of four controllers, ranging up to a continuous path controller in the form of an M.C.L. Elbit minicomputer. Moving target synchronization is also available. The cost is from £6,900 to £15,000. The system is described in (1) and (9); the latter reference goes into some detail on the control systems. Several types of grippers are available, and custom ones can of course be made. The Massachusetts Institute of Technology has a Versatran arm with a specially designed hand; we will not pursue details of their arm here.

The Versaweld is a Simpltran with a minicomputer controller. The machine is 'taught' the path to traverse by means of a joystick, and the start and finish of each weld is recorded. The computer computes the path between points; the basic point-to-point control of the Simpltran is not abandoned.

Scandinavian Firms

Retab AB
Box 153
S-181 21 Lidingö
Sweden

The Retab system uses a Tokyo Keiki robot IRB-10 or IRC-30, at £6,000 - £7,000 or £9,000 - £10,000, respectively, along with a Retab control system, the RC-700, for point-to-point numerical control. The system is described in detail in (2) and (31).

Tesa
Storgaten 43
4300 Sandnes
Norway

The Tesamat is still under development, and no price information is available for it. It is described in (31) and (36).

Trallefabrikken
Box 113
4341 Bryne
Norway

The successful and rather well-known Trallfa paint spraying robot is described in (31), and in detail in (13). It costs £7,900 - £8,100. It is a continuous-path machine; the record is made by a human operator leading the sprayer through its programme, which is stored at the rate of 80 positions a second on magnetic tape. It is not fitted with an effective hand, since it usually only requires a paint sprayer.

IV Research Robots

The most recent version of the Edinburgh facility is described in (6) and (38).

The approximate parts cost for the Mark 2 facility (39) was £4,200, exclusive of the Honeywell H316 perpheral computer. To produce another such facility now that design has been done would cost around £10,000 if done at the University, including all labour, interfacing electronics, cameras, arm, and supporting structure. Since various overhead expenses vanish when work is done in a university environment, industrial cost estimates are typically about a factor of three greater than those by university personel. Thus the extension of the Mark 1.5 hands to the Mark 2 configuration, which includes six force sensors and rotating palms and involved some nontrivial engineering, was bid at £1,000 by the university and at £2,500 by a private consultant firm.

The Mark 3 facility has been the subject of a design study by the G.E.C. Hirst Research Centre (11). Cost figures (12) are £29,000 with cameras, support structure, table, servos, arms, interfaces, and installation. Subsequent models would cost about £17,000. The Mark 2.5 robot was to have been a Salter arm in conjunction with a Scheinmann-Stanford arm; this configuration was bid at £32,000, the high cost being principally due to the engineering needed for the Scheinmann arm.

University of Warwick

The Warwick robot is almost entirely the work of one technician and Dr. Mike Larcombe, who keeps too busy to write things up; the best description of his mobile and tactile-sensing robot is (29).

The robot is a tactile-sensing one because this was cheaper than a visual one, and the same sorts of interesting perceptual problems and world-modelling opportunities arise. The project will ultimately include a vision robot and an attack on almost every AI front. The following facts are presented (30) about the now and future robots:

Hardware Status 6/2/73
<u>Warwick Tactile Robot Project</u>

Existing fully operational:

Tactile Robot MK7 Code Name ARFA Class OM811

Mechanical configuration:

Cylindrical carapace.

Frame castor supported.

Two independent drive motors; diametrical mounting.

Pincer transverse action hand mounted on vertical swing.

Boom; no wrist action, no elbow action. Screwdrive positive action.

Hand: dense packing tactile sensors (graphite matrix type).

64 addressable sensors .3CM resolution on pincer face,

.5CM resolution elsewhere.

Excursion and current limit switching on hand motor.

Vertical boom carrying hand and one telescopic tactile

tip probe (5ft. reach). Winch operation with excursion limit switches.

Horizontal tactile tip probe (5ft. reach). Two tangent-aligned

cats-whisker tactile probes, carapace mounted.

Carapace cylindrical with aperture for hand and boom.

Tactile sensitive in twelve segments of angle. No vertical

resolution. Graphite pad and microswitch sensors.

Umbilical pylon on cylinder axis. Umbilical consists

of light 3 wire link to ceiling-mounted swivel and

automatic reeling gear.

Fabrication: meccano + nylon bearings.

Robot motor configuration:

I Reversible motor each for:

Claw	1 amp 6v
Boom	1 amp 6v
Boom probe)	) 5 amps at 6 volts
Horizontal probe)	)
Left drive	1 amp 6v
Right drive	1 amp 6v.

Two Electro-magnets on tangential cats-whisker facility (used for surface following).

Power source: lead-acid accumulators 10 A/hr.

Electronic specification:

Onboard system:

Implemented in T.T.L. consuming 12 watts at 5 volts.

I/O Modem: 2Kc/s carrier P.W.M.

Command staticiser: 110 baud.

Command Decode tree: 128 channel.

Sensor interrogation tree: 128 channel.

Interrupt poll unit: 8 active interrupts.

response serialiser: 110 baud.

Interchannel patch system (reflex logic).

Real time clock (10 second interrupts).

Audio monitor.

Alarm oscillator.

Local control circuits.

Power stabilisor.

Reactive motor brake circuits.

Power: Lead-acid accumulator 24A/hr.

Estimated component cost £500.

Under Construction

Tactile Robot MK8   Code Name Undecided   Class OM811

Mechanical configuration: Fabrication Proto + meccano.

Cylindrical carapace

Frame caster supported.

Two independent drive motors diametrical mounting.

Four finger claw action hand, positive screw drive.

Vertical plane wrist action, mounted on vertical boom.

Hand sensors: under development, sought resolution 1mm.

Wrist drive: positive screw action.

Arm drive: winch operated boom.

No probe facility other than hand.

Cats-whisker tangent system.

All other mechanical design features under development.

Electronics

On-board system: Implemented in CMDS. Power .3amp at 6v.

Wide range interface: 110 - 9.6K baud.

Command staticiser: 128 channel.

Command decoder: 128 channel.

Sensor word select exchange 16 words of 6 bits (expandable to 32K).

Response buffer and interface 115 - 9.6K baud.

Interchannel patch system (reflex logic).

Real time clock (variable).

Group of eight hardware subroutines.

Group of eight programmable hardware microroutines.

Fixed system

Under design: 32K, 24 bit word special purpose robot control processor. This processor is not a computer but is a hardware realisation of the Warwick software features. It could be termed a multi-processor wide interrupt capability machine with limited arithmetic facilities, or a programmable switching network.

The processor would lie between the robot and the host machine which would then supply only file-handling facilities.

The machine does not use programs in the usual sense and the language used to describe tasks to it is more like a simulation language.

Estimated component cost: Robot £500
Processor £500

Dr. Larcombe's opinions (30) about the utility of a standardised robot system might be of interest also:

> The experience we have had with firstly the T.T.L. systems and now the CMOS systems have suggested to us that any form of standardised system is unlikely to find favour. Such is the availability of LSI and MSI that the radical redesign of a processor is a matter of days. I might add that I produced a sophisticated digital logic simulator to help us in our design work. This simulator is written in our AI software system (an interesting bootstrap process: software implementing itself in hardware!)
>
> I do not know why you are attempting to specify a standard system. It would seem more sensible to centralise design experience.
>
> Incidentally we intend to move into visual process after we have perfected the tactile system. The hardware on the MK8 is intended to cope with two vidicon channels using guided scanning at some point in the future.
>
> With my hardware/software merging any standardisation is unlikely to be satisfactory to me! and my system is no use to anyone else.

I find my design of T.T.L. for robot control very satisfactory (It has been used on MK5, 6 and 7; MK5 was the first online version-earlier marks were mechanical design feasibility tests). Although designed for 110 BAUD the data rate can be boosted to about .5 MMz by changing half a dozen timing components. Incidentally you need a high level of reflex circuitry (automatic braking on impact etc) at the low data rate of 10 commands/sec.

University of Southampton

The control group at the Department of Electronics at Southampton is concerned with practical solutions to real problems; some of their work is supported by the Ministry of Health, since they apply themselves partly to prothesis development.

Briefly (42), the relevant prosthetic work involves control of an artificial hand with joints and sensors closely modelled on those of a human hand. A control system is sought which allows complex actions to be evoked by simple muscular cues. The adaptive control aspect is outlined in (34), and the hardware is described in (43), (44).

In the prototype hand, little attention was paid to considerations of miniaturization or indeed of weight problems generally. The prototype is electrically powered, using small D.C. permanent magnet motors; hot-stretched Terylene cords are used for power transmission to the digits so that those motors can be mounted close to the elbow. D.C. chopper power controllers have been developed to drive the motors, to minimise power consumption.

This work needs transducers analogous to sensors in the human hand; measurements are needed for normal and tangential forces and displacements, slip velocities, joint angles, and certain derivatives.

The high level control commands should be simple; complete actions whose success requires much sensory information should be accomplished as results of simple commands with no high-level notice being taken of the large amount of sensory data needed.

Two types of contact transducer have been looked into: a capacitative device which is of high impedence and requires local amplifiers for signal matching, and a balanced transformer device which has good electrical properties but less mechanical flexibility. Position transducers can be based on the capacitance of a coil spring as it expands within a cylindrical ground electrode; the springs also can provide return forces.

A wide range of grips is achieved with three gripping actuators and one to adjust the thumb attitude; appropriate finger curling is accomplished by mechanical design.

Self-locking worm gears are used in the power train of the hand, as are the Terylene cords; the cords can break under high dynamic loads, and the worm gears are inefficient. The power-train and electronic systems need to be reworked to make the prosthesis viable for real world use; the weight might not be a problem in an AI laboratory. Work is contemplated also to develop transducers to detect things like 'imminent slip', surface friction characteristics, tangential and normal forces at the edges of the gripping area, etc. Also object modelling based on tactile input is being investigated. An electronically stored model would (they say) allow planning and control of the arm and hand attitudes through axis transformations of the model, and exploratory hand movements can be automatically initiated if more information is required.

Work on the power train is concentrating on A.C. motors with high intermittent power ratings and efficient locking drives; high output power is required at speeds differing by a factor of ten, and weight, noise and size militate against gearboxes. The development of a motor has been started by the Machines Group of the Department of Electrical Engineering at Southampton.

No information is given about the 'positioning accuracy' of the prototype hand; this question may well not arise in prosthetic work, since a human has so many extra degrees of freedom under his control. The lateral shoulder movement in one prosthetic arm of advanced design (but not Southampton's) was only repeatable to about one inch (5).

Universität Karlsruhe

A somewhat dated account of the Karlsruhe system may be found in (25). A more recent paper (15) describes three preprocessing methods for grey scale photographs, two of which seem to take place in a computer (although the possibility of special hardware is mentioned) and one of which uses preprocessing of the analog signal from a picture scan.

The Forschungsgruppe für Information Verarbeitung and Mustererkennung consists of about fifteen members; at present they have a flying spot scanner in operation (256 x 256 grid with 64 grey levels), feeding a CD 3300 computer (40). They do research on hardware and algorithms to process pictures and analyse scenes, concentrating on noise removal, line finding, and isophote tracing. They are building a programmable matrix processor to perform low-level processing.

Queen Mary College, University of London

Professor M.W. Thring of the Department of Mechanical Engineering has been very active in mechanical design for many years, and has designed several practical auto-motive devices (stair climbing wheel chairs, etc.). Photographs of several impressive wooden models of multi-armed mobile robots were on display at the 1st Conference on Industrial Robot-Technology, as was one of the models itself.

From the chief technician for Professor Thring (45) it was learned that these complicated mechanisms were dreamed up at a great rate, but that none of them would ever advance beyond the model stage since the real engineering problems underlying their control and powering were never even addressed.

No written information about working robot devices was obtainable from Queen Mary College.

University of Nottingham

As well as developing industrial robots which will be immediately cost-effective, Nottingham has an interest in developing industrial robots incorporating computer control and vision. Much of the resulting work has an AI flavour; the latest description of the hardware appears in (14).

The U.S.S.R.

As far as concerns research robotics, our findings are negative. On the basis of a fairly extensive programme of visits to Soviet computer science research laboratories, it can be concluded that, with one probable exception, no research projects have yet generated experimental devices worth reporting here. The exception is the Leningrad Polytechnical Institute, under the Ministry of Education, where a blind touch-sensitive robot is said to be in experimental use under Professor Urevitch. Unfortunately it was not possible to visit the project in the time available, but full documentation was promised by post, and is awaited.

Other research centres visited were:

Leningrad:	Economics - Mathematics Institute.
Moscow:	Institute for Information Transmission.
	Institute for Control Problems,
	Moscow University.
Kiev:	Cybernetics Institute.
Academgorodok, Norosibirsk:	Mathematics Institute.
	Computer Science Institute.
	Institute for Electrometry.

In all the above laboratories careful enquiries were made among the scientific staff not only concerning robotics work or plans of the given laboratory but also concerning any work elsewhere in Russia which might be known to them. The only well-developed plans were on the theoretical side, a study of the adaptive adquisition of walking skills by a 6-legged robot (Computer Science Institute, Norosibirsk, under the direction of Academician Ershov) and, on the experimental side, plans for technologically oriented hand-eye work at the Kiev Cybernetics Institute under the direction of Professor Glushkov.

This negative result should be regarded as valid for experimental robotics of an AI character. No attempt was made to locate or survey instrumentation developed for strictly industrial purposes. A similar statement, on the basis of a less thorough enquiry, can be made about continental Europe as a whole, where to the best of our knowledge no experimental hardware has yet been developed beyond the stage of rather general plans.

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Appendix D

A TIME-OF-FLIGHT LASER RANGE SCANNER

by

A. E. Brain
Stanford Research Institute

1. Introduction

For the purpose of scene analysis in a three-dimensional world, it is desired to generate a "picture" analogous to a television picture, but where each picture point is associated with an analog value denoting range rather than light intensity. The simplest method for determining the range of each picture point might seem to be by measurements on stereo pairs of images taken by the same television camera. In practice this method has proved to be seriously limited on at least four counts:

- Inadequate resolution: at the 120 x 120 element resolution we have been using, the displacement (measured in elements) between corresponding points in the images is not enough.
- The range accuracy falls off rapidly with distance.
- The calculations for so many points consume too much computer time.
- There are difficulties due to occlusion, because a picture element visible from one lens viewpoint may not be visible from the other.

A scanning range finder currently under construction eliminates all of the above problems in that it possesses high range resolution that does not vary with distance, and gives direct readout without computation. In addition, since it is a "one-eyed" device, the occlusion problem does not arise.

2. The Experimental Model of the Range Scanner

A simplified block diagram of the range scanner is given in Figure D-1 and a more detailed diagram in Figure D-2. The range scanner consists of three functional components:

- A transmitter that amplitude modulates a light beam with a 9-MHz sine wave.
- A mirror scanner that sweeps the modulated beam over the field of interest.
- A receiver that picks up the light from whatever object intercepts the scanning beam. After amplification the output from the receiver is demodulated by a phase demodulator.

The demodulator effectively measures the length of time required for a light beam to make the round trip from range scanner to light scattering object and back. The range value, of course, is a constant multiple of this time.

The merits of the phase demodulator are worth emphasizing. In this device the output from the receiver is compared with the phase of the modulating signal feeding the transmitter, and a dc level is derived that is a function only of this phase difference. Since the phase difference varies linearly with the distance to the light scattering object, the dc level is a measure of the range of the object. The method has the virtue of being a one-frequency method not depending on the amplitude of the received signal; it is therefore possible to trade range discrimination against signal integration time. The sensitivity calculation described later indicates that it should be possible to make 1,000 measurements per second with a range discrimination of 0.1 inch using a transmitter power of only 1 milliwatt.

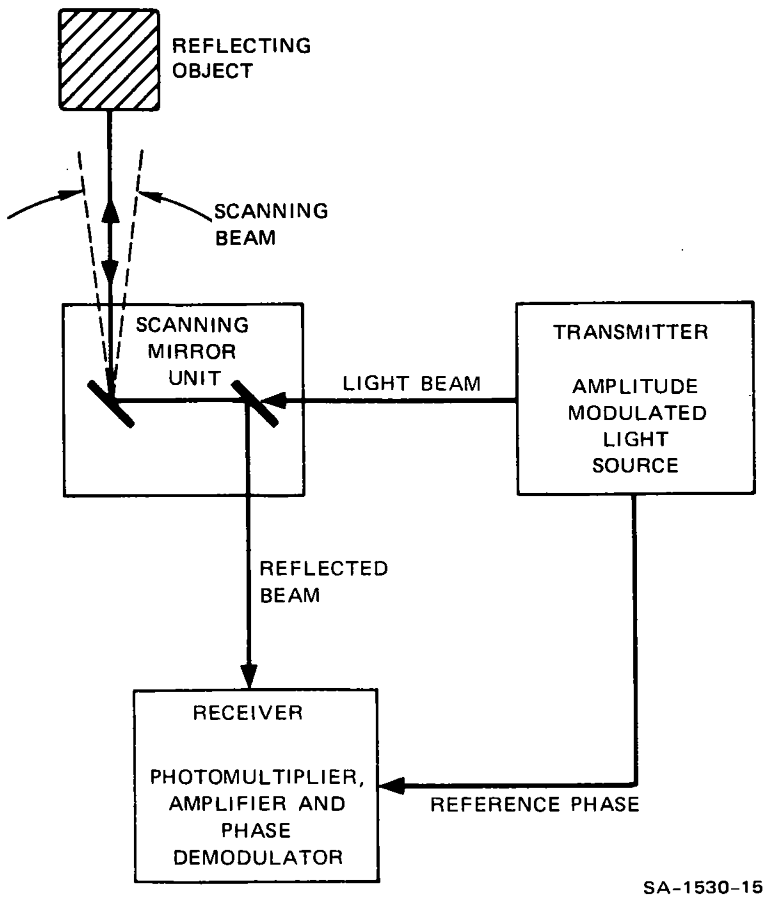

FIGURE D-1 SCANNING RANGE FINDER—SIMPLIFIED

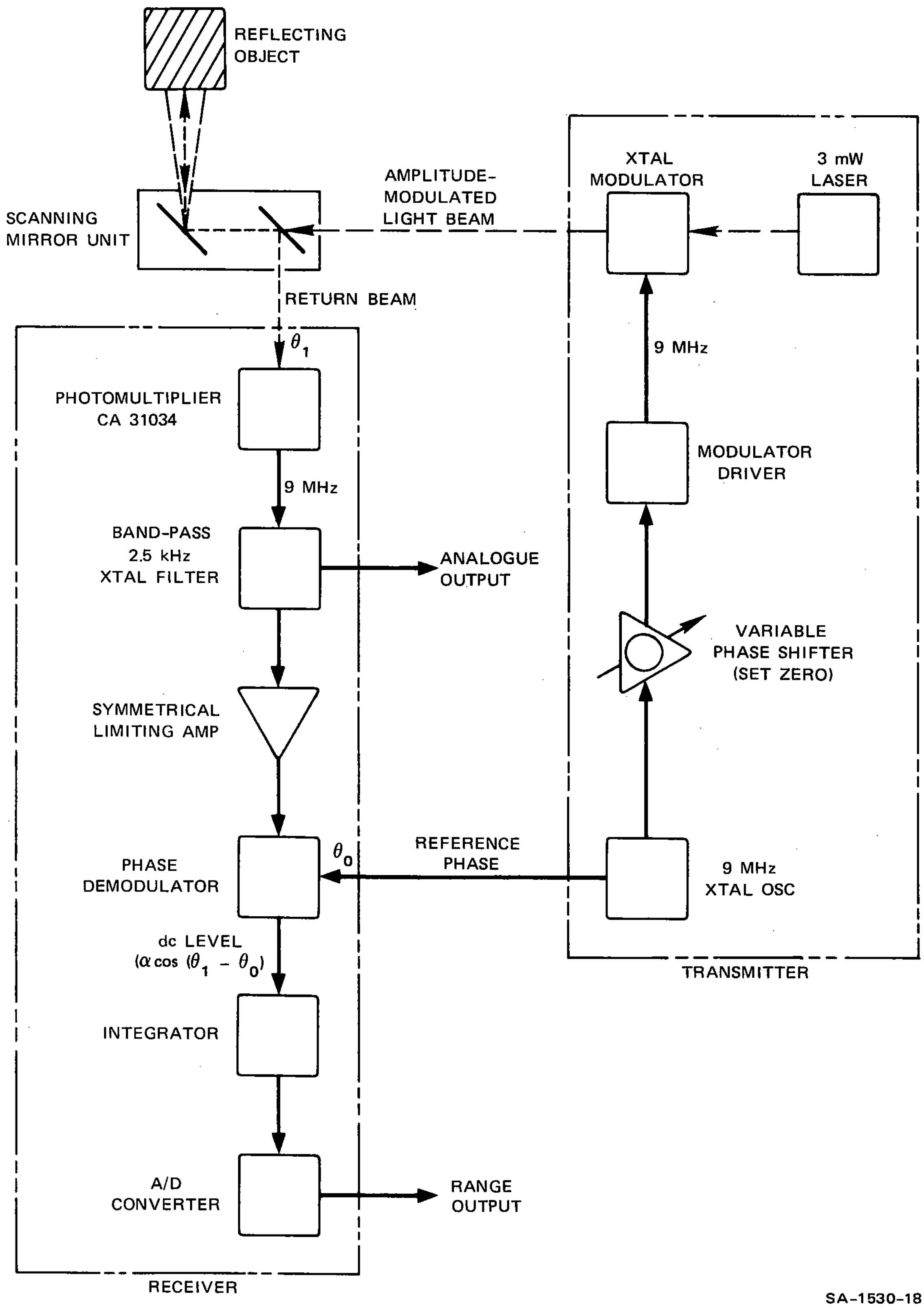

FIGURE D-2 SCANNING RANGE FINDER—DETAILED

Considering the transmitter section, the process begins with the 9 MHz crystal oscillator that drives the modulator via an adjustable phase shifter. The phase shifter provides an adjustment of approximately ± 60° so that one may adjust for a precise zero or, alternatively, off-set the minimum range and use increased sensitivity in the read-out. The zero may also be displaced by fixed amounts and with great precision by short lengths of coaxial cable inserted between the various units. The modulator then provides amplitude modulation of the light source, which may be either a 9050 A.U. gallium arsenide diode or a 6328 A.U. helium-neon laser. The latter will most probably be used since it can provide a smaller spot size (better lateral resolution). Although gas lasers typically show 1 percent amplitude noise modulation, this does not interfere, except to a minor extent, with the precision of the phase measurement. The modulated light beam is then deflected by a scanning mirror system (in two orthogonal directions) so that it scans the field of view that is of interest.

The receiver section makes use of the same scanning unit so that its line of sight coincides with that of the laser beam. The return signal is put through an interference filter to eliminate the ambient illumination and passes to a high-grade photomultiplier, an RCA CA 31034, where it is converted to electrical form. The use of a premium quality photomultiplier is warranted since it is here that the signal-to-noise ratio of the system is determined. The primary requirements are for an efficient photocathode and low dark current. It is anticipated that the signal level from the CA 31034 will be at least 1 millivolt. This signal is then put through a narrow band-pass filter at the first opportunity in order to minimize effects due to electrical interference, in particular before any saturation can occur. The filter is followed by a symmetrical limiter to remove amplitude variations due to inverse square law, orientation of the surface, reflection coefficient, laser noise, and so on. Note that the limiter must limit the top and bottom halves of the sine wave symmetrically since asymmetry introduces a shift in phase.

Perhaps the most stringent part of the design occurs in the phase demodulator. What is required is a clean multiplier. We wish to multiply together the reference signal, $e_1 \sin \omega t$, and the reflected signal that has passed down the receiver chain, $e_2 \sin(\omega t + \varphi)$. We do not have a great deal of control over the various phase shifts that occur down the receiver chain, but we assume they can be nulled out by the phase shifter mentioned previously. We are interested in developing a dc level that varies linearly with the variable part of φ; i.e., the part due to the variable path length between the deflecting mirrors and the reflecting object. The output, M, from the multiplier is

$$M = k \cdot e_1 e_2 \cdot \sin \omega t \cdot \sin(\omega t + \varphi)$$

$$= ke_1 e_2 \cdot \sin \omega t \quad \sin \omega t \cdot \cos \varphi + \cos \quad \omega t \cdot \sin \varphi$$

$$= ke_1 e_2 \cdot \quad \cos\varphi \; (1/2 - \frac{\cos 2\omega t}{2}) + \frac{\sin 2\omega t}{2} \cdot \sin\varphi$$

where k is an arbitrary constant. The terms in $2 \omega t$ are easily removed by a low-pass filter leaving an output depending only on $\cos \varphi$; we will be working over the linear region either side of 90°. Note that the output also varies with e_1 and e_2, and therefore these must be kept constant to at least the precision of range measurement. In the hardware that has been constructed, the output fluctuation is of the order of ±3 millivolts for a working output range of ±3 volts.

3. Calculation of Sensitivity

The initial design assumptions are as follows:

Scanning transmitter power (collimated beam) = 10^{-3} watt

Maximum range = 10 ft

Minimum reflectivity = 1 percent

The reflected power is assumed to be scattered uniformly over a hemisphere.

Receiver capture area = 1 sq in.

The received power, P, applied to the photomultiplier is

$$P = 10^{-3} \cdot 10^{-2} \cdot \frac{1}{2\pi \cdot (120)^2} = 10^{-10} \text{ watt}$$

The sensitivity of the RCA CA 31034 photomultiplier is given as 4×10^4 amps per watt at 6328 A.U., and 1×10^4 amps per watt at 9050 A.U. For an input of 10^{-10} watt at 9050 A.U., the output current = $10^{-10} \times 10^4$ amps, which equals 10^{-6} amps. Assuming a load impedance of 2,000 ohms

$$\text{Output level} = 2 \cdot 10^3 \cdot 10^{-6} = 2 \text{ millivolts}$$

For a bandwidth of 2.5 kHz in the receiver chain, the self-generated noise level referred to the input terminals should be less than 2 microvolts; this is compatible with 10-bit accuracy for the range output and 1,000 measurements per second.

Appendix E

SIMPLIFIED ANALYSIS OF ROBOT STABILITY

by

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1. Static Stability

The plan view of the robot is shown in Figure E-1. The numbered points show the positions that the wheels and castors contact the ground. The castors are shown in their least stable condition, that is, swiveled in from the edge as far as possible. The polygon formed from the numbered points is the region of static stability. If the center of gravity lies above that region, the robot is said to be statically stable.

Center of gravity can be located in any direction by summing the distance from a reference point in that direction times the mass of each part and then dividing by total mass.

$$x_{c.g.} = \frac{\sum_i X_i m_i}{\sum_i m_i}$$

Table E-1 shows the values of mass and distance from the reference point marked by * in Figure E-1 for three orthogonal directions fixed to the robot. The range of values in Table E-1 corresponds to the extremes of positions for the parts that can move with respect to the reference point. It should be noted that the extremes in two different directions cannot be achieved at the same time. For example, the arm cannot reach as far forward and as far to the side as possible simultaneously. Thus the plan view extremes of this center of gravity should be an ellipse within the rectangle of extremes plotted on Figure E-1.

The position of the center of gravity is within the numbered polygon for all conditions. Therefore, the robot as designed is statically stable.

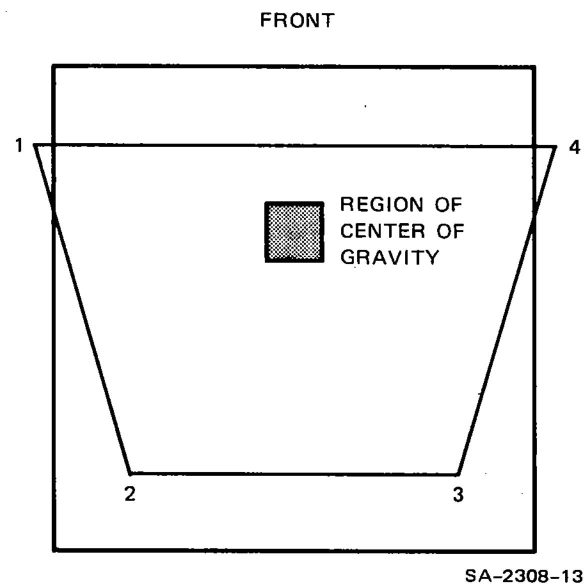


FIGURE E-1 PLAN VIEW OF ROBOT SHOWING CENTER OF GRAVITY AND STABILITY BASE

Table E-1

CENTER OF GRAVITY ASSUMPTIONS

	Height Above Ground (in)	To Left of Center (in)	Forward of Rear (in)	Mass (lbm)
Load	0 - 70	-39 - 20	15 - 65	5
Arm	3 - 50	-19 - 1	28 - 47	50
Track and Mount	10 - 35	9	30	15
Pan & Tilt Mechanism	42	6	21	25
TV Camera	47 - 50	5 - 7	21 - 25	25
Range Finder	40 - 50	4 - 8	30	10
Forward Battery	6	0	17	55
2 Rear Batteries	6	0	6	110
Computer	15	0	10	60
2 Drive Motors	6	0	21	20
Keyboard	30	0	7	10
Display	33	0	13	10
Circuits (upper)	30	0	21	10
(lower)	24	0	12	20
Radio Transceiver	30	0	15	15
Miscellaneous	18	0	13	40
C.G. (result)	15.7-22.4	1.44 to -1.45	15.2-17.9	480

2. Degree of Stability

How stable something is must be measured in terms of how much of something will upset that stability. In the case of the robot, the measure of how stable is best given by the angle of the floor which will upset the stability. This information is equivalent to constant acceleration (either starting, turning, or stopping) on a flat floor which will cause the robot to topple. The relationship is

$$\frac{\text{Acc to cause toppling}}{\text{Acc of gravity}} = \tan \theta$$

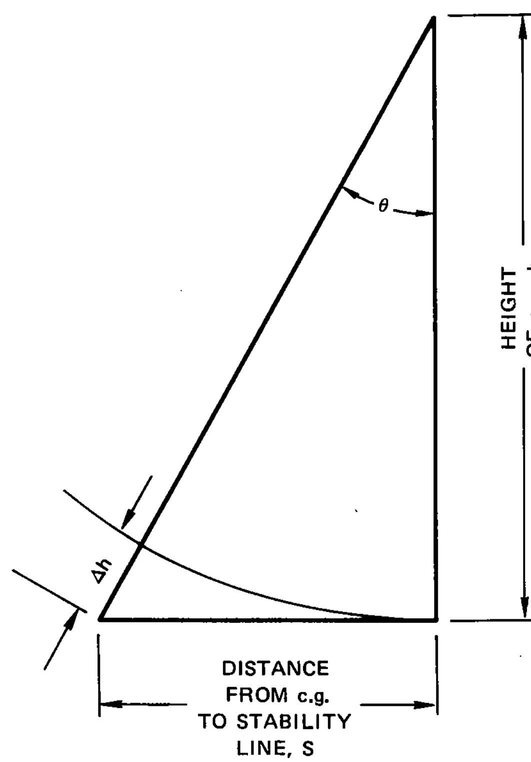
where θ is the angle of the floor from the horizontal or as shown in Figure E-2.

Another measure of the degree of stability is the amount of energy required to upset the device. This energy can be calculated by determining the height, Δh, through which the center of gravity must be lifted in toppling, as shown in Figure E-2. In the case of a robot it seems meaningful to express this energy in terms of the velocity of the robot below which a sudden stop (as by hitting a curb) cannot upset it. This velocity can be calculated by equating the robot kinetic energy to the toppling potential energy.

$$\frac{m\,v^2}{2} = mg\Delta h$$

$$v = 2g\Delta h$$

Table E-2 shows the stability results for worst and expected cases. Note that two vertical positions of the center of gravity are assumed to correspond to two arm heights. The robot can safely climb a steeper grade with the arm lowered.



θ – Stability Angle

Δh – Height c.g. Must be Lifted to Topple Robot

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FIGURE E-2 STABILITY VECTOR RELATIONS

Table E-2

MEASURES OF STATIC STABILITY

C.G. @ 20" above Ground

	S (in)	θ (degrees)	Acc (g)	h (in)	v (ft/s)
Minimum Stability					
Forward	3.1	8.8	0.16	0.24	1.13
Sideways	10.2	27.0	0.51	2.45	3.63
Backward	11.2	29.2	0.56	2.92	3.96

C.G. @ 16" above Ground

Minimum					
Forward	3.1	11.0	0.19	0.30	1.26

It should also be noted that even if the robot does topple off its wheel base, that it might not actually fall over. Additional feet could be added to ensure this.

3. Oscillation

Figure E-3 shows the models used for calculating the forward-backward rocking frequency. The pivot point will essentially be the castor, with the rubber tires of the driving wheels acting as springs.

The essence of the model is the suspension system, a mass and a moment of inertia so that a torque-moment of inertia equation can be written:

$$I \ddot{\alpha} + C \dot{\alpha} + K \alpha = \text{Applied Moment} \quad (1)$$

In our case the moment of inertia of interest is that about the pivot point beneath the castors. That moment could be carefully calculated but that does not seem to be justified. The moment of inertia can be taken to be that about the center of gravity plus the dominating term $m \ell^2_{c.g.}$

$$I = I_{c.g.} + m \ell^2_{c.g.} \quad (2)$$

$I_{c.g.}$ has been estimated as that of a disc of radius about its axle axis:

$$I_{c.g.} = m r^2/2 \quad (3)$$

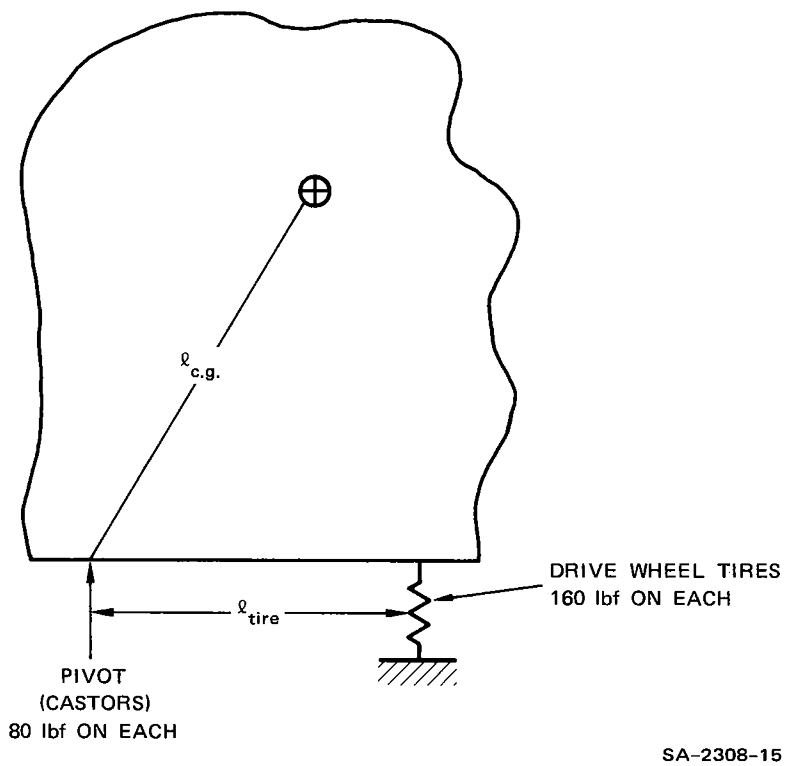

FIGURE E-3 SUSPENSION MODEL

Assuming r = 10 inches and v = 20 inches, the resulting values, 24,000 96,000 in^2 lbm, are likely to bound the value of the actual $I_{c.g.}$ The important term, however, is $m\ell^2_{c.g.}$ which has a value of 238,000 in^2 lbm when $\ell_{c.g.}$ is taken to be 22.3 in.

In Eq. (1), the other terms are as follows:

$$K = 2K' \ell^2_{tire} \tag{4}$$

where K' is the tire spring constant, i.e.,

$$\text{Force} = K' \ell c\ s, \tag{5}$$

and x denoting displacement,

$$C = D\ \ell^2_{tire} \tag{6}$$

where D is the tire damper coefficient, i.e.,

$$\text{Force} = D\ \ell c\ x \tag{7}$$

The homogeneous solution of Eq. (1), when there is no damping, is

$$\alpha = \sin(\omega_n t + \Psi) \tag{8}$$

where Ψ is an unspecified angle and

$$\omega_n = \frac{K}{I}, \tag{9}$$

is the natural angular velocity.

Critical damping is achieved when

$$C = 2\omega_n I \tag{10}$$

If K' is assumed to be 600 lbf/in (a value which could easily be changed either way by tire selection) and ℓ_{tire} = 17 inches (see Figure E-3) then the natural frequency is calculated from (4) and (9) to be between 3.2 and 3.6 Hz, corresponding to I = 304,000 and I = 262,000 $in^2 \ell bm$, respectively. Following (6) and (10), corresponding tire damping coefficients of 106 and 120 lbf/in/s will achieve critical damping of the rocking.

4. Dynamic Stability

Stability in the overall sense cannot be determined without details of the robot control system. What has been done in the previous section is to outline the characteristics of the suspension system which would then be a part of an overall system analysis.

One can say at this point, however, that the natural frequency and its multiples should be avoided by active components. Command signals should not be sent at a rate corresponding to that frequency, for example.

If critical damping is applied, one can say that the dynamic deflection under oscillating force, even at the natural frequency, will not exceed the static deflection. This information can be of use to a designer. For example, consider that the arm moves in and out at the natural frequency on command so that the center of gravity of the arm goes according to

$$A \sin \omega_n t \tag{11}$$

The designer knows that the oscillatory deflection of the robot will not exceed the static deflection of the maximum force

$$F = m_{arm} A\omega^2 \qquad (12)$$

applied at the arm.

5. Conclusions

- The center of gravity will be above the stability base for all possible arm positions, as shown in Figure E1.
- Referring to Table E-2, the worst stability condition is forward toppling: the robot can descend a ramp of $\theta < 8.8°$ or come to a sudden stop from a velocity $V < 1.1$ ft/s without toppling.
- The forward-backward rocking frequency is expected to be about 3.4 Hz. For critical damping, the tire damping coefficient should be about 110 lbf/in/s.