DESIGN OF A LOW COST. GENERAL PURPOSE ROBOT*

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Abstract

This paper reports on current work at the University of California at Berkeley whose goal is the design and implementation of a relatively inexpensive, but versatile, experimental, computer-controlled robot suitable for use in either a research or educational setting. The Berkeley robot, dubbed Jason, is nearing completion and hardware tests *are* now being conducted.

Jason is designed so as to permit it to navigate and manipulate simple objects in a real-world environment. It uses a variety of sensory-motor and communication devices; among these are an ultrasonic range, motion, and material detector, an isolated-word speech recognizer, a limited speech synthesizer, six inexpensive proximity detectors, and two arms *for* simple manipulation, all of which are mounted on a platform chassis. The robot vehicle is remotely controlled, using radio telemetry, by a time-shared, virtual memory, HP-3000 mini-computer, utilizing adaptive learning programs.

Jason was primarily constructed to explore:

(1) how an inexpensive, real-world robot system might be designed, and

(2) what problems a robot "encounters" and "creates" while performing tasks in a real-world environment populated by humans.

The results of this research will hopefully enable us to design and build better (more reliable and safer) robots at a modest price that are still capable of performing a variety of interesting and useful tasks.

Key Words and Phrases

Robots, Artificial Intelligence, Problem Solving, Learning, Real-World Environment.

CR Categories

3.62 (Learning and Adaptive Systems)! 3.64 (Problem Solving)-, 3.69 (Miscellaneous-Robots).

I. Introduction

The field of robotics is rapidly becoming an important topic of research and study. This is due in part to the possible widespread applications of robots to tedious, repetitive, or dangerous tasks. While robots with one or two highly sophisticated sensory devices have been extensively investigated, it is only recently that more research is being extended to system design and integration of a robot having a relatively large number of sensory-motor devices.

Current work at the University of California is being carried out with the objective of designing and building a comparatively inexpensive, but general-purpose experimental computer-controlled robot. The Berkeley robot, dubbed Jason, is intended to be capable of operating in a real-world environment populated by human beings. For the sake of this investigation, the real-world environment is taken to consist of the Berkeley Campus at large, especially the second and third floors of Cory Hall, the engineering building on campus. When Jason is fully operational, it will not only be used for research, but also as a teaching aid for young children at the Lawrence Hall of Science, as well as for public demonstrations.

This paper is divided into four sections, The first section explores the background and rationale of the project. The second section presents a brief description of Jason itself. The third section briefly mentions the need for safety precautions. Finally, the last section summarizes and draws some conclusions about the Berkeley robot project.

II. Background and Purpose

Considerable effort has already been directed toward the development of automatic machines for factories, farming, transportation, and so forth. Yet such machines have been carefully contrived to deal with highly constrained environments. The addition of just a few advanced sensors and a small amount of computational ability might enhance the versatility of such machines manyfold.[1] For example, advanced, general purpose robots could carry out diverse real-world tasks such as the following: (1) Space and Underwater Exploration, (2) Teaching-Aid in Schools, (3) Gardening, (4) Harvesting, (5) Bank Security Guard, (6) Warehouseman, (7) Inexpensive Hospital Aid 8) Traffic Controller, (9) Mining Surveilance, 10) Street Cleaning, (11) Deep Sea Farming, and (12) Office-building external window washer.

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In fact, any task which requires only "closed thinking", i.e., a task constrained by a specified goal and set of operators, could be performed by an advanced robot. Furthermore, several robots, carrying out different tasks, could all be supervised by the same time-shared computer system. These robots, with various interchangeable sensory-motor devices and computer programs for different tasks, would be able to carry out a wide variety of jobs for a much smaller cost than the expense of developing special purpose automation for each task.

In the field of industrial robots, a careful survey of the potential marketing opportunities has been made in Coles (pp. 58-74)[2]. In the area of education, Papert[3] has made considerable'strides with his ''turtle" robots.

For this reason, considerable research in robots is currently being carried out at major centers such as SRI[4], MIT[5], Stanford University [6], and the University of Edinburgh[7], Sophisticated automata have been designed and built to operate on table-tops or in carefully controlled environments. However, when trying to perceive and model the real world, AI researchers in the field of robotics have traditionally focused their attention on the television camera as their major source of sensory data. Consequently, a great deal of effort has been directed toward the computational processes needed to make "sense" out of the TV camera image whenever it depicted a typically-cluttered, real-world scene. These processes have tended to become increasingly expensive,even when the environment is ingeniously constrained to capitalize on the idiosyncrasies of the TV camera. The time to process a single complete scene has taken upwards of ten minutes at SRI using a high-powered computer facility. Obviously, a low-cost robot cannot afford to adopt this approach.

Our own research departs from previous work in that it attempts to incorporate the output of a variety of inexpensive sensors to provide more efficient perception of the real world, when tailored to simple navigation and manipulation tasks. Under these conditions such sensors are not only computationally cheaper, but are more reliable, since different sensory modes can mutually reinforce and corroborate one another. If binary sensing-decisions can be made in real time, the possibility for dynamically altering a precomputed path during navigation (to compensate for an unanticipated obstacle) can become feasible.

In an effort to obtain further insight into the problem of operating a real-world robot, our experimental robot project was begun in April of 1972. Special emphasis was placed on designing a small, low cost, but versatile mobile robot capable of performing a wide variety of tasks, such as exploring fairly uncluttered environments and manipulating small objects. Therefore, Jason has been provided with a wide range of sensory and data-gathering input devices, none of which is very sophisticated in itself or imposes severe computational requirements on the control computer, but all of which could be well integrated. Figure 1 gives an overview of Jason in its proposed form.

Jason has the following sensory/motor and interface devices:

(1) an ultrasonic range and material detector;

(2) two simple arms with clasping grippers;

(3) proximity sensors (used in place of microswitch bump detectors);

(4) a 30 to 40 word speech recognizer;

(5) a limited speech synthesizer ;

(6) optical counters for measuring wheel distances traveled by the vehicle;

(7) a robot chassis powered by two 1/4-horsepower permanent-magnetic motors; and,

(8) a ten-watt power output, 467-megahertz radio communication network.

A time-shared, virtual memory, Hewlett Packard 3000 computer with appropriate software serves as Jason's control computer. The HP-3000 is located at the Lawrence Hall of Science and controls the robot vehicle by means of radio telemetry. One of the advantages of a time-shared computer is the possibility of running several similar robots (planned for the near future) under the same executive program, so the Problems associated with multi-robot cooperation and communication can be investigated. However, it should be stressed that neither Jason's robot vehicle, the above mentioned sensory/motor devices, nor the computer programs are very sophisticated. They are not intended to be. Rather, the purpose of the project is to study the problems in designing a simplified and Inexpensive robot system that integrates a variety of sensory/motor devices.

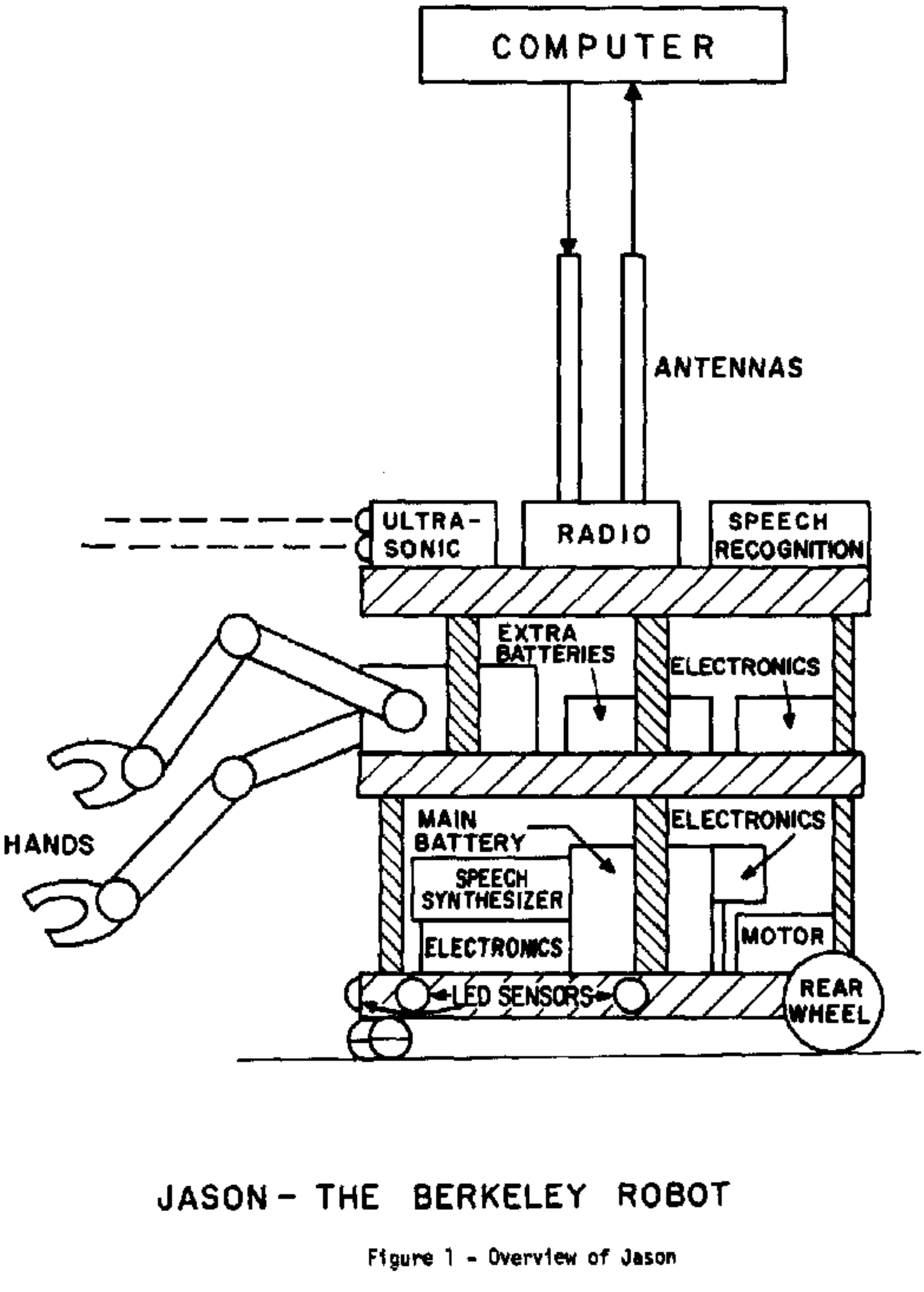
When Jason was designed, one of the important constraints was to minimize the cost of construction. Throughout this paper we shall stress the economical design and the simplicity of the sensory/motor devices. Although the labor involved was considerable, the actual cost of parts, including the radio network, but not the computer or its interface, was well under $2,000. Yet Jason cannot be thought of as a toy. It is capable of carrying out a wide variety of tasks, even though they may be elementary by human standards. It is precisely this generality in the class of tasks which is the key to the project.

III. A Description of Jason

Jason consists of three major subsystems: (A) the chassis, (B) communication and sensory/motor devices, and (C) software control programs. The robot vehicle transports Jason through its environment in a precise manner. Reasonably accurate movement is needed to avoid either the rapid accumulation of errors that would otherwise lead to bumping into walls, etc., or highly inefficient behavior in carrying out the simplest of tasks. A variety of sensory devices are needed to guarantee a rich base of information about the external environment so that reliable decisions can be made. The robot software has the task of integrating the output of these sensors so as to construct an accurate model of the environment and harmoniously control the various sub-systems.

A. The Robot Chassis

The first major subsystem is the robot chassis. It consists of two segments: the actual mechanical wheel assembly and the on-board, electronic logic which controls the vehicle's wheel assembly. The chassis (see Figure 2) by itself weighs about 125 pounds (not including the sensory/motor devices). Its dimensions are approximately 2 feet by 2 feet and it cost about $200 for parts, including electronics, but not including labor and overhead.



JASON - THE BERKELEY ROBOT

Figure 1 - Overview of Jason

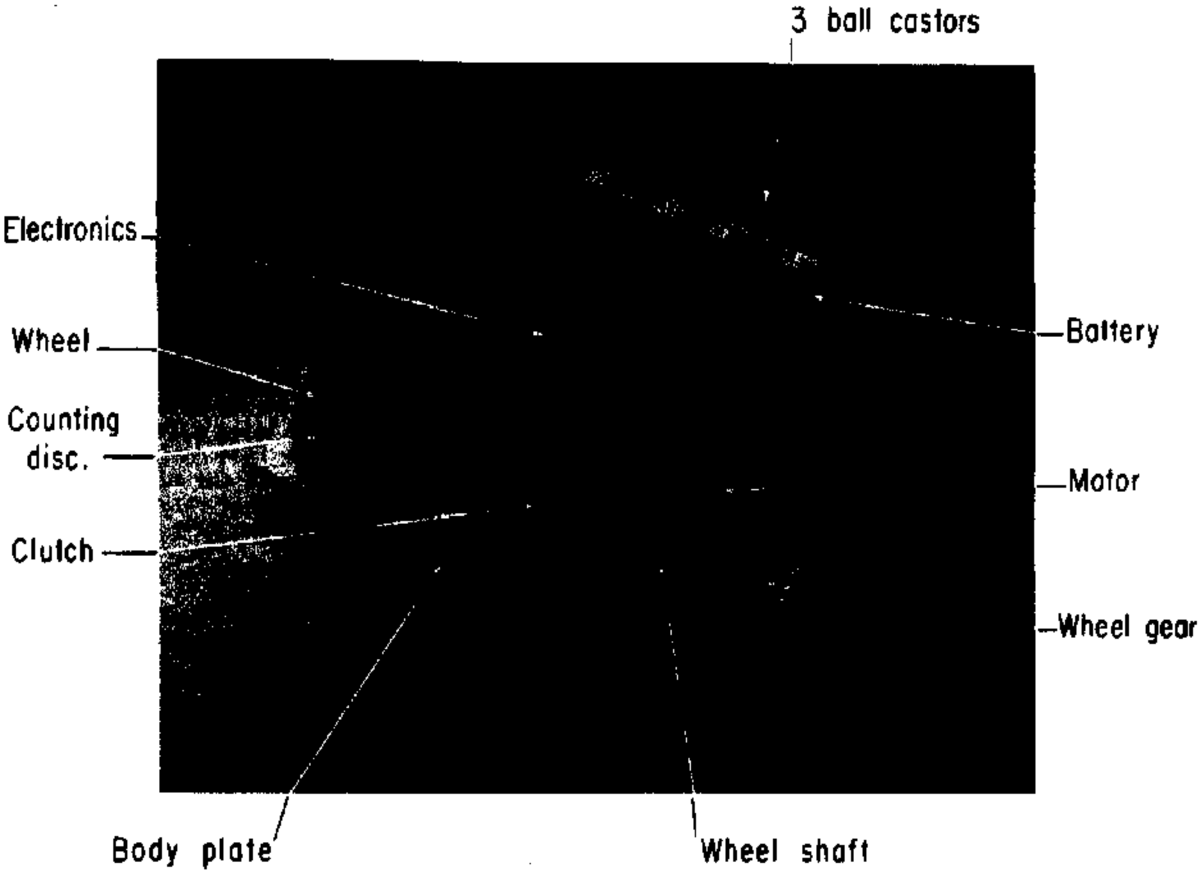


Figure 2 - Jason's Wheel Chassis

The chassis was designed to have the following mechanical properties and subcomponents:

(1) Each of the two six-inch diameter, rubber-covered, rear wheels is gear driven by a separate 1/4 horsepower, permanent-magnetic motor.

(2) The two rear wheel surfaces are mechanically ground to within .001 of an inch in circumference to insure accuracy in rolling movement.

(3) A magnetic clutch is utilized to insure that both *rear* wheels *rotate* together when the vehicle is moving in a straight-line path.

(4) The front of the chassis is supported by three one-inch diameter steel balls in the shape of an equilateral triangle. This design firstly eliminates torque problems otherwise associated with turning, and secondly, *supports* the chassis in the event that one (or two) ball(s) slides into a crack in the floor or pavement.

(5) Two five-inch discs with two rows of 60 holes drilled around their perimeter are mounted on the wheel shafts. When used with optical encoders, they enable the robot *to* determine the distance and direction of travel quite precisely. The vehicle has a maximum linear accuracy of one-quarter inch.

(6) Finally, the chassis is of rugged design with 3/4 Inch diameter steel wheel shafts and a 1/2 inch thick aluminum body plate.

The second segment of the chassis, the basic control logic (electronics) subsystem, is shown in Figure 3. It has the following properties:

(1) The logic circuit is designed such that the computer program is only required to load a 5-bit command *and* a 16-bit location counter (to indicate the distance the vehicle is to travel).

(2) The logic circuit then determines (1) the correct speed (based on distance to be traveled), (ii) direction of travel, and (iii) if any overshoot has occurred (if so, it is corrected by the logic circuit automatically).

(3) The logic circuit, together with the clutch, insures that both rear wheels rotate together.

(4) If the robot, for some reason, cannot move to the desired location, e.g., it encounters an obstacle, an interrupt is generated and transmitted to the computer.

(5) The electronics controls the motor's speed by providing pulses to the motor; this conserves battery power.

(6) Braking is done electronically by placing a variable load (amount determines the rate of braking) across the terminals of each *rear* motor.

(7) The maximum distance it can travel in a straight line without additional computer commands is 120 feet.

(8) Finally, the robot vehicle's motors, control electronics, and sensory/motor and on-board communication devices are powered by an 83 amp-hour lead-storage battery, which is easily recharged as necessary. Other smaller batteries are installed on-board for special purposes. For example, one battery provides negative 12 volts to the speech-recognition detector and provides for fail-safe operation in the event of *a* main battery power failure.

The vehicle has already been built and has proven satisfactory and reliable in manual tests. Actual computer tests are not yet possible because our FCC approval for the assigned robot communication frequency is still pending at the time of this writing.

B. <u>Communication and Sensory/Motor Devices</u>

The second major subsystem for Jason consists of its sensory/motor devicesand a 2-way, half-duplex, radio communication controller. (See Figure 4). The communications-controllerprovides a central distribution system for reception and transmission for Jason's perpherical devices and the host computer. The communication system consists of: (1) a standard serial terminal interface, (2) a high-speed asynchronous modem (up to 2400 baud *max.*, depends on radio), (3) two ten-watt power output, FM modulated 467 MHz transceivers, (4)an antenna system, (5) a communication controller on the robot vehicle, and, (6) Jason's perpherical devices-

1. <u>Radio Network</u>. Because it was desirable to make the controller as independent as possible from the characteristics of any one computer, the controller appears as a bit serial asynchronous data terminal to the host computer, and as a byte-serial interface to any of Jason's perpherical devices. Thus standard serial terminal interfaces can be used; this allows easy interfacing to most time-shared computers without the high cost of building a highly specialized interface. Also, either half duplex (as used presently) or full duplex (planned for the future) transmission can be done. Finally, asynchronous operation is required to allow for transmission interruption by a higher priority device.

Initially, both the host computer interface and the communications controller on Jason will be in the receive mode. If a device wishes to transmit, it must first issue an interrupt request to the controller. If no higher priority device is transmitting and the controller is not receiving data at the time (receive-lock mode), then the controller will issue an interrupt acknowledge to the device. The controller will then switch the transceiver to transmit mode, wait approximately 100msec for the carrier to reach the transceiver at the computer end and for the computer software routine to lock its transceiver to the lock-receive mode, queueing any further transmission requests.

Transmission from Jason to the computer may now begin. If a higher priority device requests to transmit, the current transmission will be terminated immediately and its interrupt acknowledge line will be made false (each device has its own interrupt request and interrupt acknowledge lines). The Interrupt acknowledge for the higher priority device will then be made true. To indicate that the previous transmission was interrupted, a device-interrupted pulse (500nsec) is issued to all devices. Furthermore, the ambiguity of a device thinking that it has been interrupted when in reality it caused the interrupt, is avoided by not having the device look at the device interrupt control line for 750nsec after receiving interrupt acknowledge. Finally, each interrupted device will make a new interrupt request and will then hold the interrupted data in its buffer until it can be transmitted. All interrupt requests are handled in an ascending priority order until all Interrupts have been cleared.

If the transceiver is in the receive mode (normal

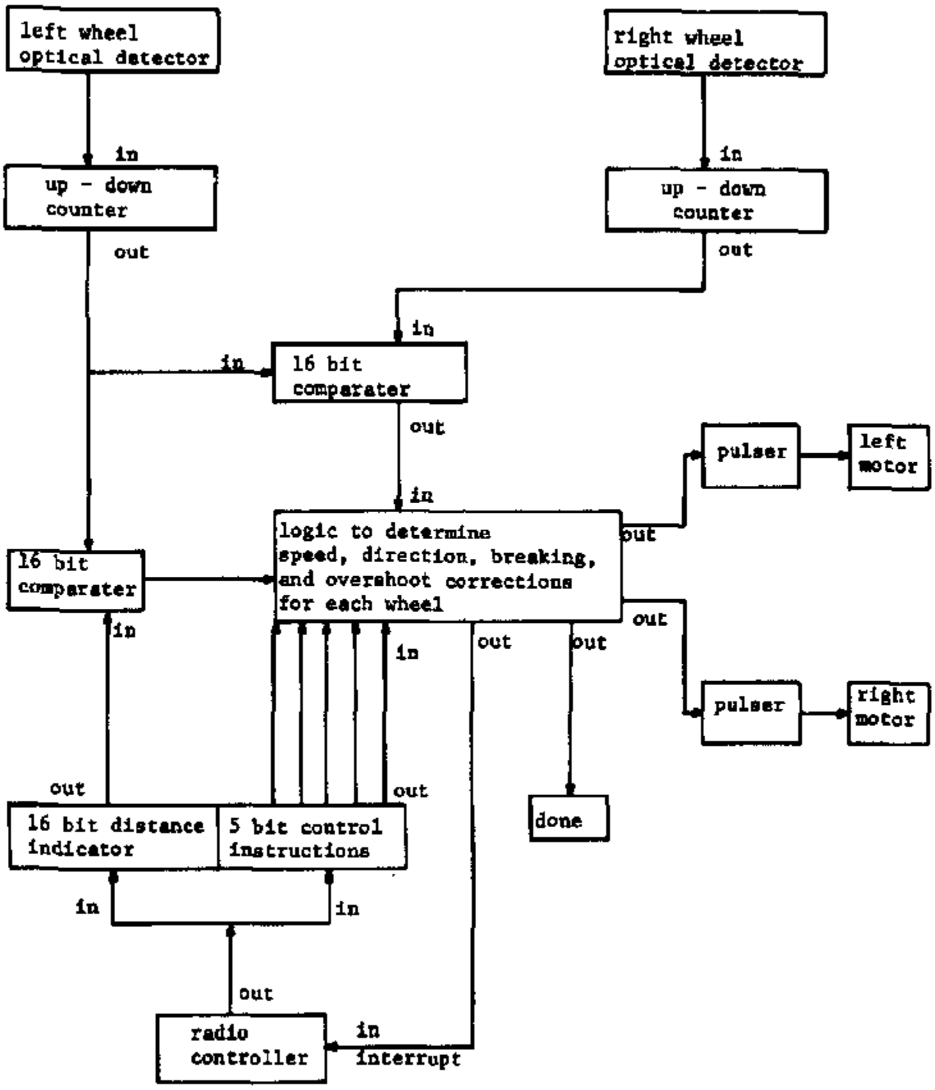


Figure 3 - The Chassis Electronics

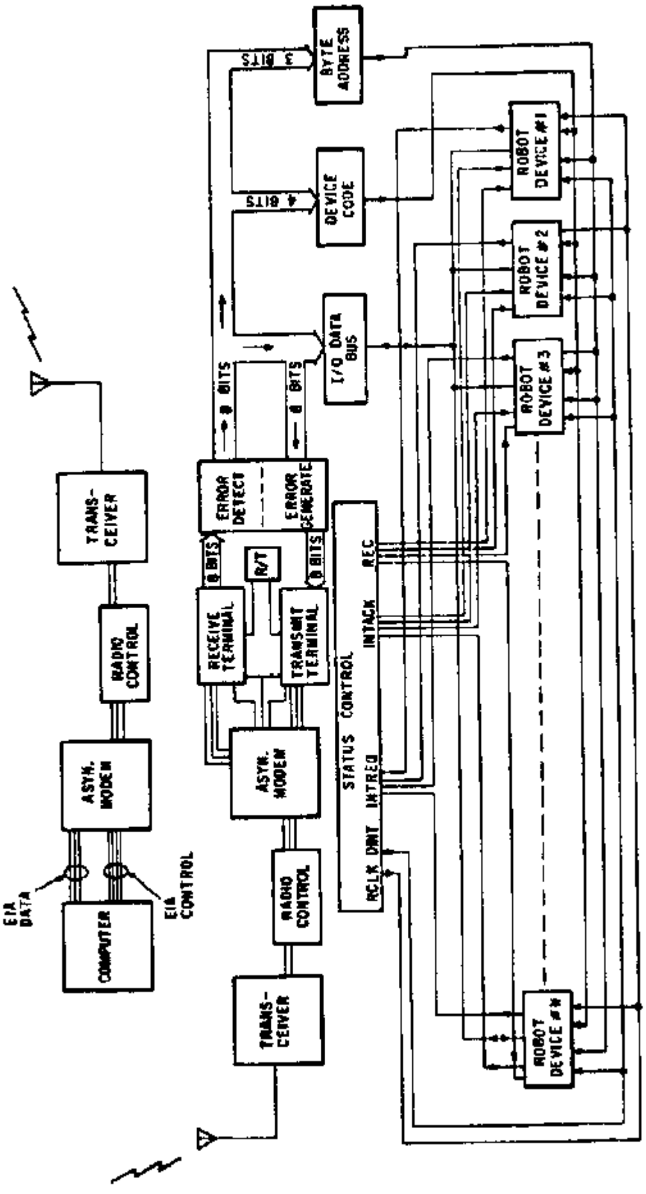


Figure 4 - The Radio Communication Network

default mode when not transmitting) and carrier detect goes true; indicating that the computer end has turned on Us transmitter, then the robot vehicle's controller will go Into lock-receive mode (reception starts and interrupts are no longer acknowledged). After the controller reaches lock-receive mode, it will search the input data stream for the first occurance of a "control" byte. The present of a control byte will start the controller's receive sequencer. The receive sequencer first loads the control byte into a error detection data register, then waits for the reception of the next byte, which is a error-checking byte. This byte is loaded into the error-detection error-byte register. The sequencer then tells the error detection logic to start processing. The error loaic will signal the sequencer when error checking is completed. The tested byte is now loaded into the device code register and the byte count register if it was a control byte; or it is loaded into the outDut data bus register if it was a data byte. When a control byte is received, the device code line, byte select lines, and 'REC' line are set up for the device which is to receive the data. The 'REC line plus the correct device code on the device-code lines is the proper indication to a device that It is receiving data; nete that only data can be passed to a device via the 8 bit I/O bus, and not control bytes. If an error occurs during reception, an error flip-flop is set and remains set until the end of the reception-sequence. The error flip-flop's output is passed to all devices. Since the system will be initially half-dunlex, the computer cannot be informed that an error has occurred until the reception sequence is completed; only then may a special device transmit the error condition back to the computer.

The error code used for *error checking* is *a form of* double error correcting hamming code. The process involved in generating the error code is discussed by Berlekamp in [8, Chap. 5]. Error coding generation is done in hardware on the controller and in software on the computer. It involves calculating the polynomial (x +x +x +x +1) of the parity check matrix formed from the serial data input. A root of the polynomial is assumed to be (x +x+l) and was used in developing the hardware and software. The resulting error code is then transmitted after the data. On reception, the data is first passed to another error-code generator; the resulting error code generated is then compared with the error byte received after the data byte. In the present version of the system, no automatic error correcting 1s done in order to limit the initial expense.

2. <u>Description of Devices</u>. The sensory/motor and communication devices utilized by the robot are summarized below:

(a) Arms — Jason will have two hands of the simple clasping type, each with *three* degrees *of freedom.* These have been roughly designed, but not yet constructed. The arms are not intended to be fast, accurate, or heavy-duty. They will be lightweight and will pick up lightweight boxes, push buttons,and push or pull simple objects.

(b) Ultrasonic Detector -- a narrow-beam, frequency modulation, echo location system in the form of a "torch" is ut111zed[9]. Ultrasonic waves which cover a wavelength range of 2.5 to 5mm are used. Bandwidth compression (achieved by continuous wave, frequency-modulation transmission) is needed since the useful auditory bandwidth 1s approximately 5 KHz while the bandwidth of the Information carrier in air using ultrasonics 1s about 50 KHz. Thus, ultrasonics provide an overall reduction in Information transmitted of 500,000 as compared with vision. The ultrasonic "torch" sensor sweeps downward from 100kHz to 50KHz. The pitch of the return echoes, which are converted to audio tones, are nrooortional to the ranoe of an object (each 300Hz change corresponding to about 1 foot, see Figure 5). The ouality (timbre) of the echo indicates the type of surface from which the echo was reflected, hence indicating the nature of the object. Because soft objects reflect noorly at higher frequencies, these echoes build in strength as the sensor sweeps down. By digitizina the pitch (the width of the echo pulse period) and the relative echo strength (by taking 4 to 6 samples as the sensor sweeps downward), it is possible to determine the range with an accuracy of +10 percent and to obtain textural information. Unfortunately, the angle from which the ultrasonic beam is reflected from an object affects echo strength, and thus appears to change textural information, e.g., a hard object at an angile such as a slanted wall could look to Jason like a soft object directly in front of the sensor. Semantic information is needed to resolve such ambiguities.

Up to three objects at different ranoe and directions within the field of view may be resolved when the torch is held stationary, i.e., multiple tones or "chords" are possible with multiple objects. Dynamic conditions are more complex. However, experienced blind persons using such a device are capable of:

(1) identifying objects such as the following: smooth poles, windows, bushes, trees, parking meters, cars, railings, street sions, doorways, moving pedestrians, traffic liqhts, mail boxes, rising steps, *grass,* plaster walls, *etc,*

(1i) walking up and grasping a one-inch diameter pole from a distance of 12 feet;

(iii) weaving in "slalom" fashion between poles in a row or a circle;

(iv) placing a group of poles in a straight line;

(v) grasping a pole from a group of closely spaced poles;

(vi) walking past a pole at a specified lateral distance, using the rate of change of distance and direction to gage relative positions.

All these skills are normally tauoht to a blind Derson in approximately one week of intensive training [9]. While it is not expected that the robot will be able to do such sophisticated tasks, we do suspect that ultrasonics will be useful to the robot since the information is there. Furthermore, an ultrasonic detector was chosen over a vidicon TV camera as the principal sensory modality because of(fi) its lower cost (about $200 - $400 for a detector), (11) the fact that a considerably reduced information processing Toad is imposed on the computer (as compared with a TV picture whose processing may take upwards of ten minutes on a high powered machine), and (iii) the fact that the ultrasonic detector will probably serve just as well as a TV camera on the class of applications for which Jason was desianed. A detector has been loaned to us from the Veteran's Administration for use on this project and the digitization logic is being tested. For future work, simple silicon image sensors will offer an alternative approach to object detection.

(c) Proximity Sensors — Instead of the standard,

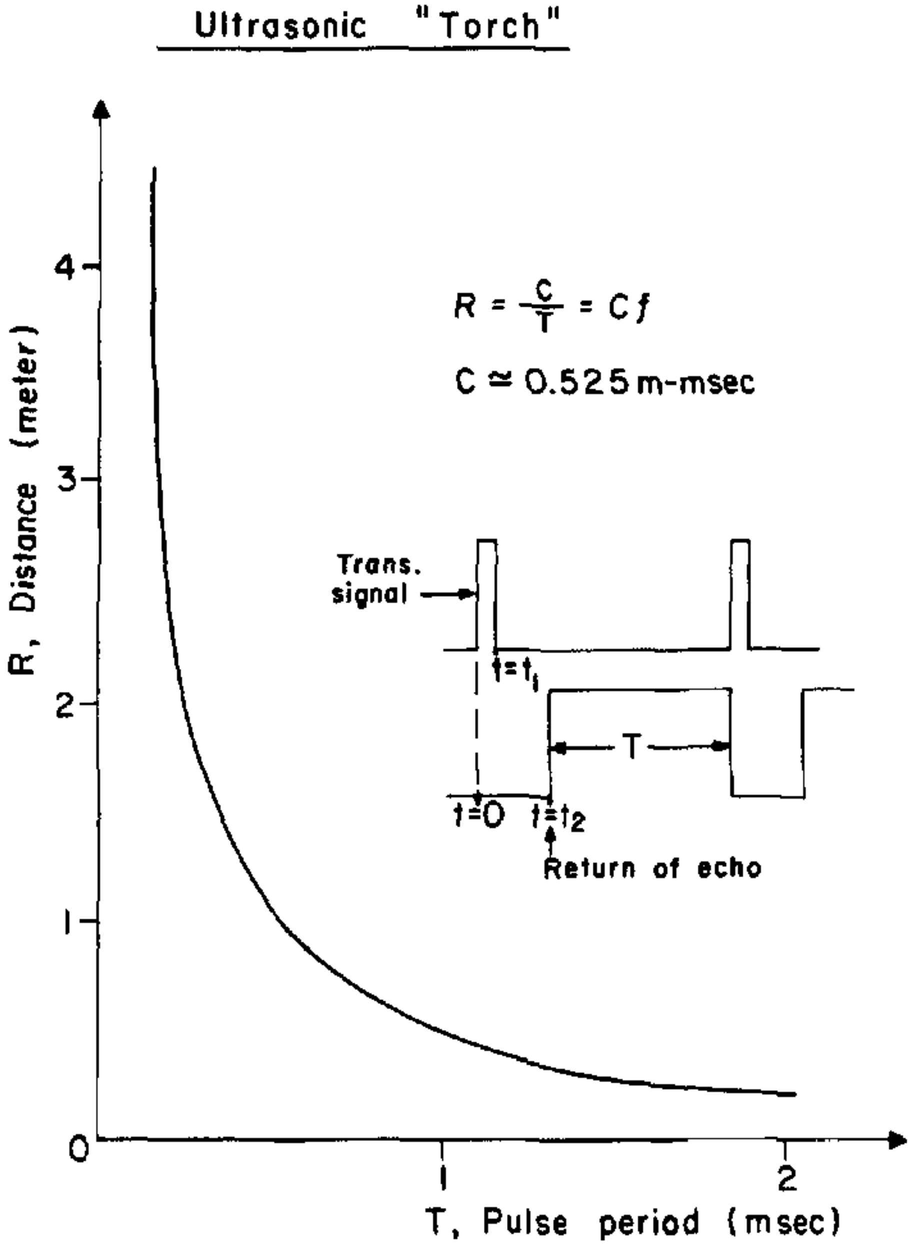


Figure 5 - The Ultrasonic "Torch"

"cat-whisker" style mechanical sense-switch, bump-detectors, Jason will use six LED proximity sensors[10] distributed around the perimeter of the chassis to protect the vehicle against inadvertently bumping into obstacles. The sensors, loaned to us by Scientific Technology, Inc., are able to reliably detect large barriers or small objects of an arbitrary material within a range of up to eight feet.

The detectors operate essentially as follows: an invisible, infra-red, modulated light beam (approximately 9000 angstroms) is projected by a semiconductor gallium-arsenide transmitter module with a fairly *narrow beam angle. Any* obstacle which *intersects* the transmitted beam will reflect light energy back into the receiver module as a function of its distance (and its color and texture to some extent). Thus, if one knows the nature of the obstacle in advance because of semantic information available, it is possible to calibrate the readings and determine distance quite accurately. Because the transmitted light is modulated, the detector can never be falsely triggered by ambient light or heat, or even bright sunlight. Five of the sensors will be positioned so as to form an invisible curtain of protection surrounding the vehicle, while tne last sensor will be beamed down at an angle to detect sharp irregularities on the ground directly in front of the vehicle.

(d) Speech Recognition Detector -- A speech recognition device has been constructed for about $200 in parts which can extract features suitable for recognizing a limited vocabulary of 30 to 40 carefully chosen words when spoken in isolation and tuned to an individual speaker. Words are analyzed by a bank of six filters (eight in the future). The quantity of energy in each filter frequency band is ranked relative to one another *for each* change *in* phoneme. Thfs data is then transmitted to the computer and a learning program identifies the word using its distinctive features. This device must be tuned to one person's voice. However, this is advantageous for safety reasons, since properly formulated commands will not be accepted from just anyone.

The robot will be capable of recognizing words using two methods: (I) either a given word matches with a word stored in memory within a given minimum standard, or, (2) a given word could be matched by sevaral possible candidates', but the syntactic context of the current sentence restricts the set of alternatives to only one possibility. The current plan calls for the following thirty words to be included in the recognition *vocabulary:*

1. alpha
2. beta
3. box
4. correction
5. define
6. done
7. erase
8. follow
9. get
10. goto
11. hall
12. left
13. learn
14. minus
15. point
16. right
17. room
18. stop
19. then
20. zero
21. one
22. two
23. three
24. four
25. five
26. six
27. seven
28. eight
29. nine
30. and

(e) Speech synthesizer — Jason includes a digital speech storage and retrieval device in order to generate verba! responses to commands or to carry on a dialog. A delta-modulator with a clock frequency of IOKHz, 1s utilized to generate a digital bit-pattern corresponding to a spoken word or phoneme. These digital bit patterns are stored in shift registers on board the robot vehicle with about IK bits required for each phoneme (IK shift registers with a cost of about $3.50 each (surplus) are used for this purpose)- A delta demodulator, upon command by the main computer, will convert the string or strings of the desired digital bit-patterns back into audio. Either strings of phonemes can be concatenated to form words or whole words can be stored and demodulated. At Dresent, this device is operating with a small memory of 16K bits, which will be expanded when more memory is obtained.

C. Software

Finally, the third and one of the most difficult portions of the robot is its software. The executive control programs are primarily oriented toward simple problem *solving and adaptation to* variations in the environment. Figure 6 shows a flowchart of Jason's executive program. Techniques such as signature tables [11], shortest paths [12], strategy learning [13], and problem solving methods [14], are under development. Once the mechanical and electronical sub-systems of the robot have been implemented, the bulk of the research pursued in this project will be on the software. A future paper will report on nroaress in this area as soon as some empirical results are obtained.

IV. Safety Precautions

Once a robot with the above capabilities and functions is operational, a major problem remaining is how to achieve adequate safeguards to ensure the safety both of the robot itself and the humans that may be in the vicinity. A robot that is simultaneously mobile, fast, powerful, and unpredictable can be highly dangerous if well-conceived nrecautions are not scrupulously observed. Thus, various hardware and software safety devices, operational precautions, and other ground rules must be formulated and implemented before any robot should be released into the human world to carry *out* even the simplest task. Jason is to have three types of safety devices and controls: (i) those built into the robot's hardware, (ii) those built into the software, and (iii) those observed by the experimenter (s) during robot operation. All of these are being studied and will be implemented before Jason is permitted to operate in a human environment.

V. Summary and Conclusions

The Berkeley Robot Project is concerned with a relatively unexplored area of robotics -- that of designing, implementing, and of operating an economically viable and durable robot, canable of performing useful tasks in a human world. As mentioned in this paper, there remain many Problems to be explored further, such as:safety precautions, planning vs, execution, sensory integration, etc. Such research is clearly required if a robot is to be released into the real-world without an inordinate number of restrictions and constant surveillance. The Berkeley Project is in the midst of design and construction. Some devices have been completed and checked out. Others, such as the arms, are still in the design staoe. It is planned that a fully integrated robot vehicle with elementary control software will be operational in the near future. Once operational, Jason will primarily be used as a test bed for the development of future, real-world robots with considerably greater sophistication and intelligence.

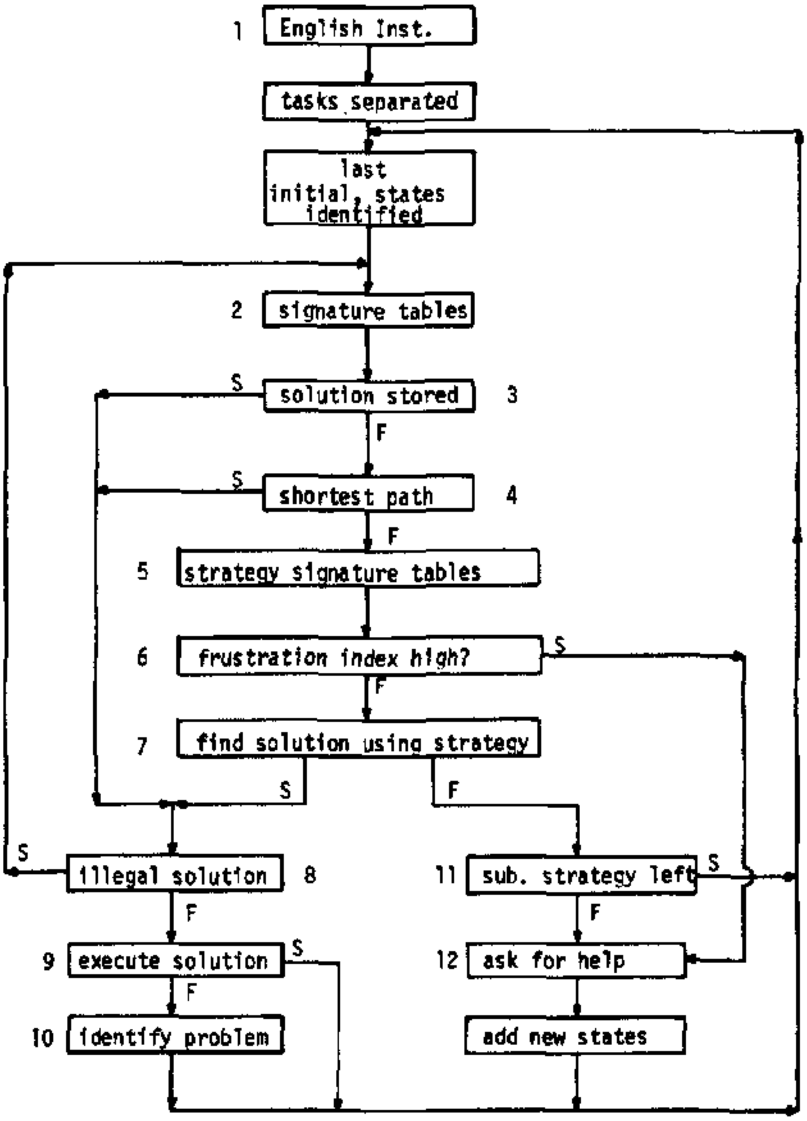


Figure 6 - Flowchart of Jason's Computer Program

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