WATSON/I: WATerloo's SONically Guided Robot

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Research Report CS-82-16

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Don't cry, robot, you will rust your transistors!
From: Lost in Space

1. Motivation

It may seem a valid point to question the wisdom of building yet another mobile robot. References [1,2] are two of the more well known of such attempts. Robots, in addition to their apparent fascination for human beings, have also proved valuable tools for research into the areas of vision analysis , manipulators, and space probing [3,4,5]. There were several reasons behind our attempt at such a project, but the two reasons most relevant to discussion of this report are that of building a sophisticated programmable machine, as an aid to teaching; and of investigating the problems and potential of using sonar sensing in the guidance of a task oriented vehicle.

The value of a highly tangible programmable device in the process of introductory programming is already shown [6,7]. Through construction of the robot, we are extending that argument into higher levels of programming sophistication and hope to show that the programming of a complex but highly tangible system is equally useful in learning the skills of certain types of advanced programming.

Traditional modes of computer access, either batch or time sharing, are useful in teaching of many of the programming skills (like business applications), but have considerable shortcomings when they must deal with teaching of computer applications in which computers must interact directly with their environment through the use of sensors and actuators. With the emergence of microcomputers and their increasing application to direct control, there will be more and more need for experienced graduates trained in such areas.

The need for this type of programming expertise has been recognized and acted on for a long time in this department. Initially, model race-cars, forced to move within grooved tracks, were used. More recently, the 2nd generation of a rather sophisticated model train-set with several intersecting tracks and trains has replaced the older system. Our experience shows that this type of programming has been very rewarding, and many students have consistently praised the learning contents of the course.

Relative to the train-set, a mobile robot has the additional property of dealing with a more real environment, as well as a 2nd degree of freedom in movement. The world of the train is limited to its linear movement and is further idealized by the fact that, except for other trains, equally under the same computer control, there are no unaccounted-for-objects to evade. The two dimensional world of the robot is full of other unpredicted objects like people, chairs, desks, flower pots, ... and so forth. Therefore the challenge of programming a robot will exceed that of a train-set or other semi-idealized devices, both in complexity and in reward. Malone thinks [8,9] the characteristics that make instructional environments interesting can fit naturally to one of three categories: challenge, fantasy and curiosity. We are of the opinion that the mobile robot easily satisfies the requirements of the first two characteristics and may stimulate enough curiosity amongst many.

To accomplish its task, WATSON looks at and hypothesizes about its surrounding world by measuring the proximity of objects at its eyelevel and plans its course with the objective of reaching some destination while going around the both permanent and temporary objects and obstacles. WATSON measures the proximity of objects by sending directional ultrasonic waves and measuring the time of their echo.

The world of a sonar robot, scanning only the horizon and measuring the distance of objects around, is a shadeless, dull, two-dimensional Flatland [10] projection of the three-dimensional environment surrounding the robot. Our assumption in construction of WATSON has been that the amount of information present in one such representation of environment is rich enough to enable the programmer to devise interesting algorithms and navigate the robot in a sufficiently intelligent form, while, on the other hand, it is abstract and simple enough to handle it efficiently without unwarranted complexity usually required by scene analysis algorithms.

The final product would, therefore, be a reasonably complex machine with great programming potential, which can be controlled at different levels of sophistication always within the capabilities of a single programmer, though perhaps as a major project. It has all the flavour necessary for direct programmed interaction with the environment, such as the use of motors and sensors, plus the very important characteristic of non-ideal behaviour expected from real objects, like being almost blind to shiny objects.

Watson's design has been based equally upon the expectation that the use of simple inexpensive sensors in mapping or surveying an environment could also be useful and is a challenging problem worth looking into. Some such simple sensors have already been used in the past but a complete study of the potentials of sonar probing seems to have been overlooked.

D. Wood [11] has shown that such 2 dimensional maps are also of theoretical interest, and through the use of WATSON we hope to look for their application in the navigation of vehicles through typical and non-idealized environments.

2. Design Goals

Even after one justifies the need for a programmable robot of medium complexity the process of design and construction can be influenced significantly by the goals that one sets for achieving the result.

First, we found that even though the robot is used for research and teaching, it would be instructive to set a functional goal for its use. Towards this end, we have arbitrarily chosen that of a messenger robot to carry mail and messages (including heavier parcels) between the offices of one floor in the faculty building. The messenger function immediately sets boundaries on the size and the ruggedness of the robot, while the specification of the environment in which it is supposed to work sets the rule for many other design considerations such as the type of the traction wheels (to produce enough friction with the floor) or the power of the motor for climbing over small barriers.

To keep the design, construction and debugging within the span of one generation of student's interest, we decided to use off-the-shelf products as much as possible which in turn helped to keep the project cost low (itself, another of our objectives). We also decided to use the functional components whenever possible to simplify the interfacing tasks, as the electrical and mechanical design details were not the objectives of learning. In the rest of this report, we will discuss the functional design of the robot and explain the way that it interacts with the programmer. The detailed electronic, electrical, and mechanical hardware description has been intentionally kept to a minimum to help the clarity of functional design.

3. System Architecture

WATSON can be broken into three major components or sub-systems. These are: the chassis, the sensing subsystem and the drive subsystem.

The chassis itself is an aluminum frame supported at the rear by two wheels, each driven by an independent 24 volt permanent magnet motor, coupled to the drive shaft by a high ratio worm gear, and a free wheeling caster in the front [Fig. 1 and 2].

The chassis also includes the sonar antenna assembly: The sonar system is mounted on a short vertical axis scanning the horizon through the stepping of a stepping motor. It is mounted at a height of about 29 inches, to easily pick the table and desk surfaces unable to be picked by its front impact sensors.

Motivated by the initial decision of employing the off-the-shelf products and complete subsystems, whenever possible, Polaroid's Ultrasonic Ranging Unit [12] and Sparky Electronic's Stepping Motor Evaluation Kit [13] were selected as the prime sensing organ and the associated directional positioning mechanism.

The rear drive wheel assemblies, including the motor and the manual control box, all originally used in control of wheelchairs, were donations of LUCAS Industries Canada Ltd.

Polaroid's Ultrasonic Ranging Unit is comprised of an acoustical transducer and an Ultrasonic Circuit Board. It is a modified version of the one used in some of the company's cameras, specially prepared for easy interfacing with other electronic systems and sold in kit form. The principal component of the Ultrasonic Ranging Unit is the transducer, which acts both as the loudspeaker for transmitting the high frequency inaudible sound waves and then is switched to microphone mode, waiting and listening for the echo. The Ultrasonic Circuit Board controls the transduction operation and performs all analogue range finding operations and, therefore, greatly simplifies the use of the system. It is expected to be capable of detecting the distance of objects placed approximately within the range of 0.9 to 35 feet with an accuracy of 1/10 of a foot.

Sparky Electronic's Stepping Motor Evaluation Kit is comprised of a 5 volt DC, two phase, permanent magnet stepper motor with a build-in 20 to 1 gear train and a Drive Control Board. The Drive Control Board provides simple interfacing and control logic between the computer ports and the stepping motor. Its great advantage rests with the fact that the commanding computer can specify the number of steps and the direction of moves for the board and let the board generate all the necessary stepping pulses in a completely autonomous form, while the computer spends its time on other tasks. In addition to this basic function, the drive control board can be used for other useful control functions, such as the abortion of the stepping action under some limiting conditions.

The two DC motors driving the rear wheels are independently controllable in both directions. Forward straight motion is obtained by driving both motors at the same speed with the forward polarity. Similarly, reverse motion is obtained by driving both motors at the same speed with the reverse polarity. Right or left turns are obtained by driving both motors forward, but at different speeds. Turns on the spot are obtained by either driving only one motor or both with the same speed but in opposite directions.

Our initial design called for an open loop control of the two rear drive wheels, as, at least theoretically, all deviations from ideal performance should be detectable by the sensory sub-systems and corrected through the issuing of proper corrective commands or by incorporating the off-course behaviour in the design of the next command.

In practice, we found that the asymmetric behaviour of the electonic drive circuits, the motor characteristics and, particularly, the position of the front wheel caster at the completion of the previous command was of enough magnitude to cause a completely unacceptable behaviour by the drive subsystem. This forced us into a late introduction of some closed loop feedback mechanism within the drive-subsystem itself, which has enormously improved the performance. Under the present condition, the drive-subsystem will take corrective measures for compensation of short-term misbehaviour, while the sense subsystem is still responsible for the overall accuracy over longer distances.

If the robot collides with an object too low or too small to be picked up by the scanner, the sensory subsystem will be interrupted by the bumper switch, which, in turn, will instruct the drive subsystem to halt the robot and possibly execute some object avoidance manouver.

4. Computerized Drive Circuit

The drive control mechanism consists of a microcomputer, the manual controller box, the programmable relay circuits and the wheel movement feedback circuits.

The microcomputer is a slightly enhanced veron of Intel's SDK-85 [14], which is an 8085 based microcomputer.

To further simplify the motor controls, the decision was made to modify and use the existing wheelchair manual control box, by replacing the human oriented joystick control on the box with corresponding signals generated by the computer.

The manual controller box consists of speed control electronics and a number of microswitches, all coupled to a joystick. These switches are used for controlling the power, applying the brakes and also setting up the polarity of the applied voltages to the motors. In manual control, all these switches, along with a couple of potentiometer are controlled by the complex and delicate movement of a single joystick.

In order for the microcomputer to simulate the operation of the joystick actuated switches, computer controlled relays were connected in parallel with the microswitches of the manual controller. To preserve the manual control, i.e., moving the robot without the computer control, additional manual switches were added to switch the total system between the manual or the computer controlled modes.

The first step in controlling the drive motors is to set up the relays which control the polarity of the voltages applied to the motors. This will specify the direction that the motors will turn when energized. There is also the power switch relay and the relay for the brake. The brake relay must be opened and the power relay closed, before any motion can take place. These relays are individually controlled by the bits of output port E0. The bit assignments and typical control words are shown in Figure (3).

In practice, we found that simultaneous operation of some relays may cause serious problems, by generating a noisy environment and sometimes allowing very large currents to flow. Instead of choosing a hardware solution, we have decided on the software tricks. The users are cautioned that the relays should never be opened or closed when a large amount of current is flowing to the motors; and, when closing or opening a number of relays, a good practice would be to open or close one at a time, separated by intervals of at least 20 milliseconds.

A permanent magnet DC motor's speed, and therefore the speed of the robot is controlled by the amount of voltage applied to its two terminals. To generate a controlled variable voltage source, the duty cycle of a pulse generator can be varied and the resulting pulse is averaged by the mass of the motor itself. Therefore, by varying the signals' duty cycle, the motor speed can be controlled.

A programmable pulse width modulation circuit was designed to have a programmable duty cycle ranging from 20% to 80% at a frequency of 300 pulses per second. The pulse width modulation circuit uses an astable multivibrator, which triggers a programmable monostable multivibrator, both of which are implemented using the 555 IC.

The control voltage of the monostable multivibrator is varied from 0.0 to 4.7

volts, which, in turn, varies the pulse width. The control voltage is generated by the MC 1408 digital to analogue converter. The 555 based design has the disadvantage of generating duty cycles not linearly correlated with the control voltage produced by the D/A converter. Fig. (4) illustrates the measured characteristic. The two 8-bit D/A converters for control of the pulse width and, therefore, the right & the left wheels, are connected to ports 21 and 22 of the SDK-85 system and, therefore, are under the direct control of the microcomputer.

Early in the implementation process, an experiment was performed with the robot in order to determine the controller's open loop behaviour. The robot was pointed east in a room which had slight downward slope to the north of one inch in every 15 feet. Then, applying equal pulse width control signals to both motors, the robot was allowed to go forward. In 10 feet forward, the robot wandered 3 feet to the north! Similarly, for a westward move it also wandered 3 feet to the north in 10 feet forward. This clearly indicated that the open loop control could not overcome even slightly unbalanced forces and the decision was made to augment the system with a closed loop servo drive system.

Pressed by time and lack of initial space planning, we were forced into the use of a very simple and readily available wheel rotation measurement mechanism, namely that of a bicycle alternator that can be easily installed and touches the wheel, generating electrical signals representative of the move.

The present feedback technique uses two 4-pole single phase alternators (one on each rear wheel). The sinousoidal signal of each alternator is first convered to a square wave and then fed to an input port as well as an 8 bit counter. The signal appearing on the input port can be repetitively sampled by the computer to compute the wheel speed, while the pulse count in every counter shows the wheel displacement. The period of the wave forms is 0.07 seconds when the robot moves at 0.5 mph and 0.1 seconds at 0.33 mph. Each pulse count in the displacement counters represents a displacement of 0.59 inches. The signals are applied to the bits 1 and 2 of the port 08, and the values of the two counters are available at ports 00 and 01. This again allows the programmer easy and direct access to the actual behaviour of the robot under the commands applied to the motors.

Obviously, the implemented feedback mechanism is unable to account for the slippage, but so far we have not found that to be of any problem.

5. Navigational Subsystem

The navigation subsystem consists of a considerably enhanced SDK-85 microcomputer, an ultrasonic sensor system, a sensor positioning system and a communication channel to the drive subsystem.

The ultrasonic sensor itself consists of an acoustical transducer and the associated electronic support circuitry. Together, they are capable of detecting the presence and distance of objects within a range of approximately 0.9 feet to 35 feet. In operation, an accoustical wave must be transmitted towards the target and the time of receiving the echo is measured. The electronic support circuitry is responsible for generating the pulse, adjusting the amplifier's gain during the waiting time for the echo, and, finally, converting the measured time into distance with consideration of the speed of sound. Times expected to be measured for typical distances are in the order of a few milliseconds. A full description of the transducer and the associated circuitry can be found in [12].

In WATSON the ultrasonic transducer (sonar antenna!) is mounted at the end of a vertical shaft which scans the horizon for a full 360 degrees under the control of a vertically mounted stepping motor Fig. (5).

The sensor has a peripheral vision of 5.7 degrees from its straight forward vector. Using this hardware, the navigational computer is capable of seeing objects in its environment, unless the object moves too quickly to be picked up, or is too low to fall within the vertical vision angle, or unless the face of a shiny object is not perpendicular to the sensor signal.

To trigger the sensor to generate the sonar pulse, a logical "1" must be written into the bit 1 of the 00 port (i.e., 02 hex into 00 port), followed by a "0" into the same bit and port position. This will generate a positive edge to the sensor trigger signal and returns the signal back to low level.

The ultrasonic board, on receipt of the echo and completion of the time to distance conversion, generates an interrupt on the RST2 signal of the 8259A interrupt controller installed in the SDK-85. Meanwhile, the Electronic Board has been interfaced to the microcomputer in such a way that the converted distance measurement can be read from port 01 of the microcomputer in units of 1/10 of a foot. The navigational computer can control the angular position of the ultrasonic sensor, which permits the microcomputer to scan the horizon and measure the proximity of objects from it.

The stepping motor support circuitry has a 12-bit step-count-register, which can be loaded through the output ports B8 and B0 of the microcomputer. The number of stepping pulses that the motor receives is one half the binary value stored in the step-count-register. The stepping motor which drives the sensor shaft rotates 0.375 degrees for every step pulse it receives, which is much finer than the resolution of the sensor itself. Therefore, one is usually inclined to step the shaft through a number of steps at a time, rather than to single step it between any two measurements.

The direction of rotation of the stepping motor is controlled by bit 4 of port B8. To initiate the stepping motor operation, the controller is first loaded through port B8 with the required direction of rotation, and the low order 4 bits of the binary step count, followed by port B0 with the 8 high order bits of step count.

Once the stepping motor completes its autonomous operation of stepping through the required number of steps, it provides a low to high transition on the RST1 signal of the interrupt controller.

To implement a homing position for the positioning shaft, therefore enabling proximity measurements relative to the vehicle's coordinate system, two limiting switches were installed on the shaft. Any attempt to rotate the shaft and the sensor beyond these limits (in either direction) will cause the limiting switches to be actuated. The signals from these switches can be seen by the computer through bits 0 and 1 of the input port B0. These signals are, therefore, interrogated by the computer to determine if the sensors have reached their rotational limits. Both switches are installed in a way that the combined effect of them in both directions provides us with in excess of 360 degrees of visibility around the cart.

To home position the shaft the step-count-register should be loaded with a large value, so as to rotate the shaft to one of its two limits. The computer will then poll the limit switch and, on receipt of the limit signal, finds one of its two homing positions. Any other directions (including the front view) is then a question of loading the count register with known quantities, starting from the homing position.

6. Inter Computer Communication

The navigational and the drive computer must interact to close the overall control loop for navigating the system over large and complicated courses.

Watson achieves this by simply passing data bytes, in parallel form, between two pairs of i/o ports on the two machines employing the system of interrupt.

To transfer a data byte from the navigational computer to the drive computer, it must write that data byte to its port 80, which also generates a strobe signal at this port. This strobe signal is then used to register the byte into the port F0 of the drive microcomputer, which, in turn, generates an RST6.5 type interrupt.

To transfer a data byte from the drive microcomputer into the navigational computer, it must first write the data into its F0 port which produces an RST0 interrupt signal for the navigational computer. It is the duty of the interrupt handling routine of each of the two computers to read the data from their communication ports.

7. Conclusions

WATSON was designed and built (Fig. 6), during two terms (8 months) and was debugged and documented on a third term. Except for the 2nd term, during which a student was working on a full time basis on it, all other times the work has been on a coursework basis and, therefore, confined to a limited number of hours per week.

Though the machine is now complete and test programs performs semi-intelligent tasks of wandering around while evading objects, the serious task of programming it has just been started by two of our graduate students.

Now, at the completion of the hardware design and construction phase, we can look backward and discuss a few decisions which we feel should have been made differently. The use of self encoding drive wheels instead of friction driven alternators for tight feedback loop is one such decision. Also a digital form of pulse width modulation, capable of a broader duty cycle range as well as more linear behaviour is another such conclusion.

All these, with the added help of experience gained while programming the machine, should prove valuable in the next trial for the construction of

WATSON/II!

8. ACKNOWLEDGEMENTS

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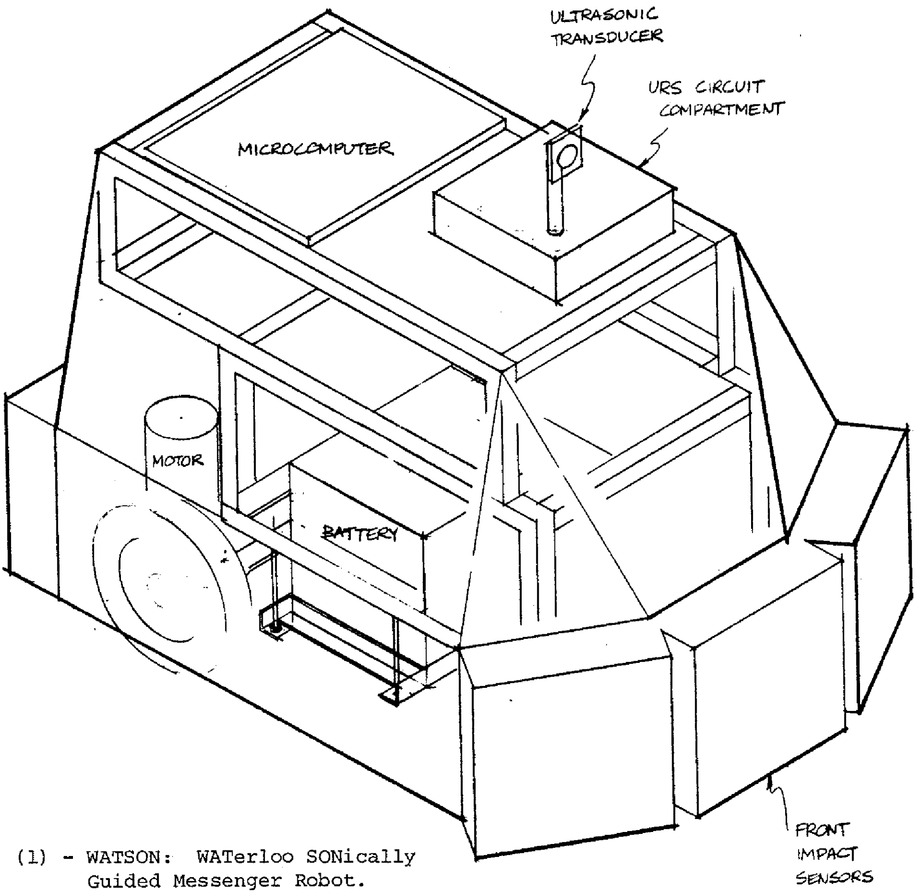


Fig. (1) - WATSON: WATerloo SONically
Guided Messenger Robot.

Fig. (2) - WATSON: Side View

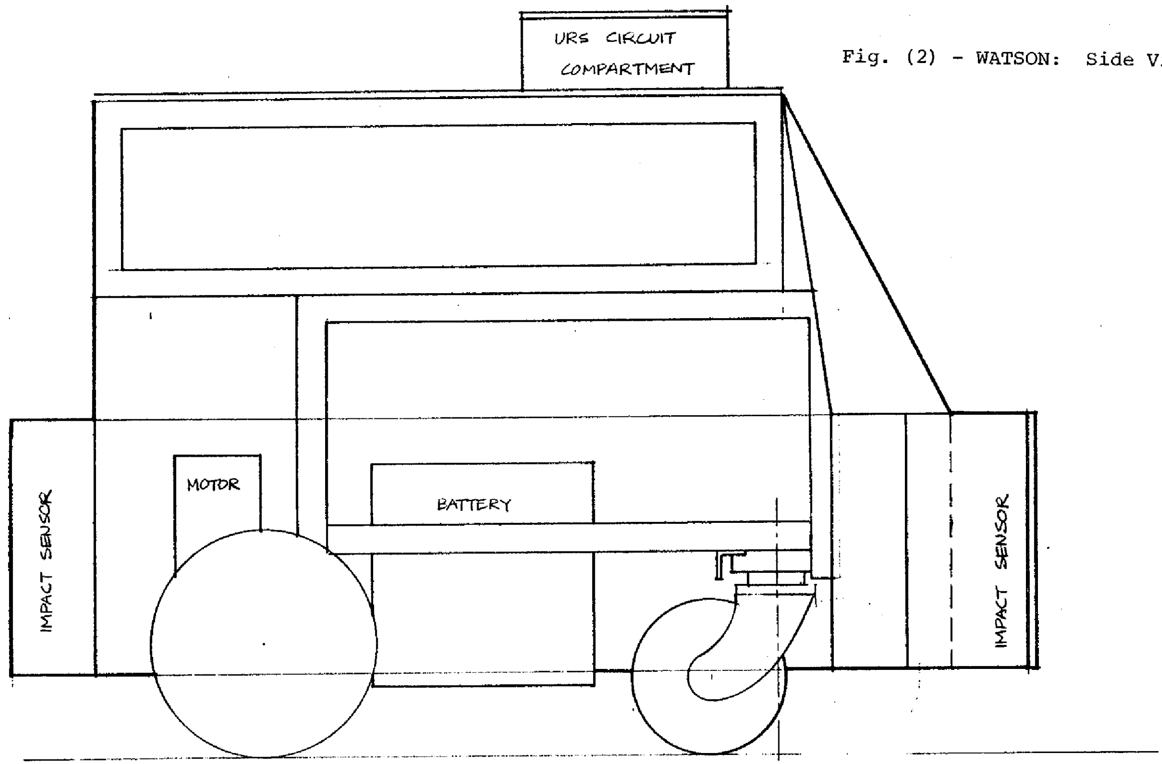
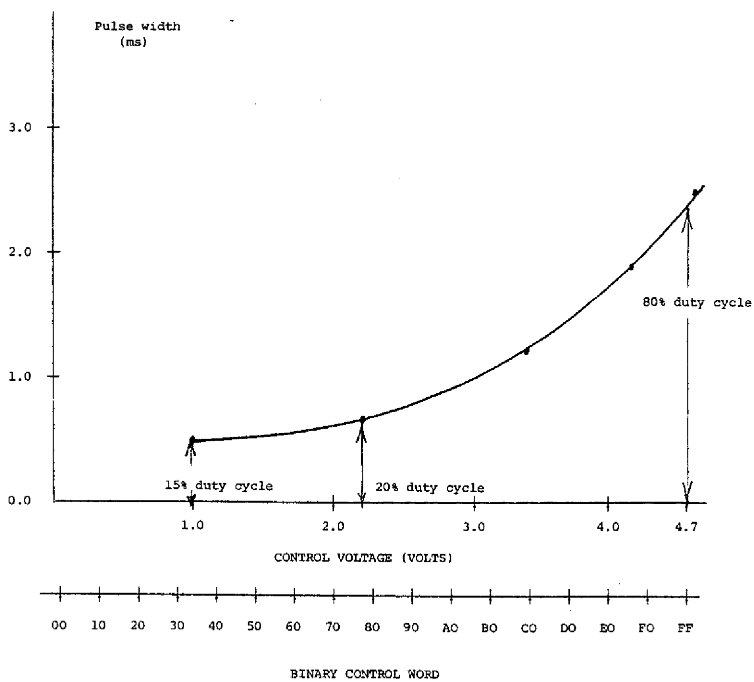


Fig. (3) - The bit assignment for port controlling the relays

Port EO	Signal Name	Enable Logic Level
Bit 0	Select power supply	0
Bit 1	Select left reverse	1
Bit 2	Select left forward	1
Bit 3	Select right reverse	1
Bit 4	Select right forward	1
Bit 5	Select brake relay	0

Fig. (4) - Control characteristics of the pulse width modulator



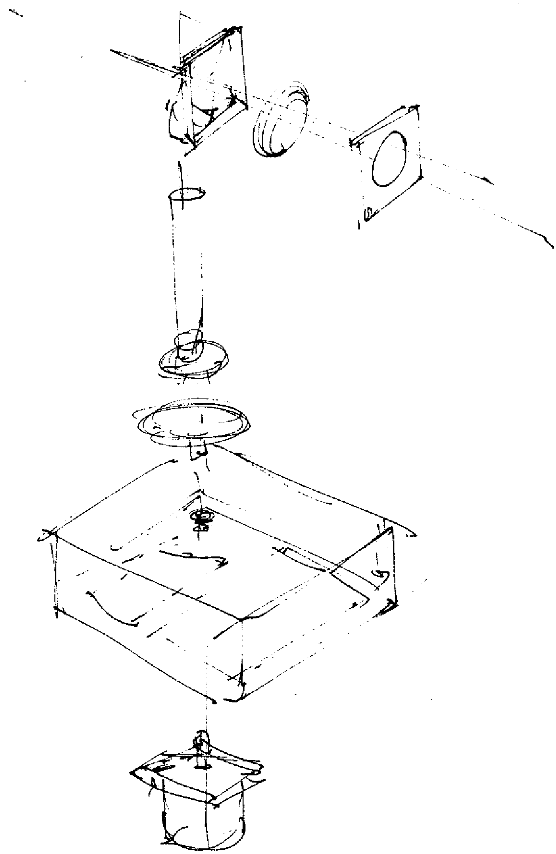


Fig. (5) - Ultrasonic Rangefinding
System

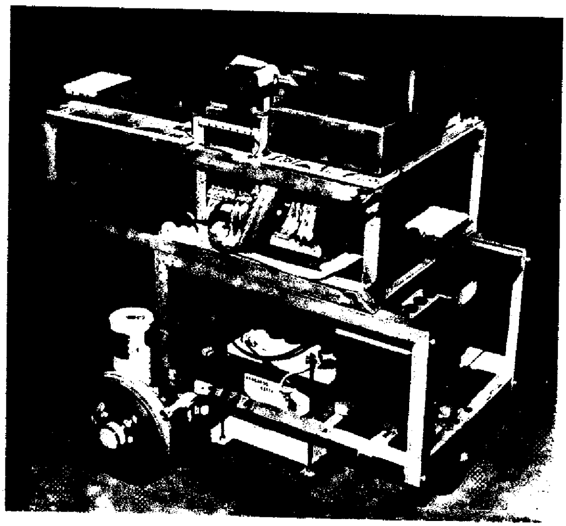


Fig. (6) - WATSON: Almost Complete,
without impact sensors.