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COLLEGE OF ENGINEERING
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Ithaca, New York 14850

Final Report

September 1, 1974 to August 31, 1975

CONTROL ELEMENTS FOR AN UNMANNED MARTIAN ROVING VEHICLE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MRV 75-1

December 31, 1976

Contract NASW-2750

Submitted by

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MARTIAN ROVING VEHICLE PROJECT

CORNELL PROGRAM OBJECTIVES

1. TEST PLATFORM

   An Operating Roving Vehicle

2. NAVIGATION COMPUTER AND CONTROLS

   To Allow Vehicle to Navigate Autonomously to a Designated Target Within 100 Yards.

   a. PDP-8 Computer with Control Algorithm Mounted External to Vehicle But

   b. Up-Link and Down-Link Radio Computer to Simulate On-Board Computer Control.

   c. Direction Sensor

3. OBSTACLE SENSORS

   To Determine Non-Negotiable Obstacles

   a. Microwave Radar to Detect Obstacles Rising Above Terrain Level at Distances Up to Thirty Feet.

   b. Tactile Obstacle Sensor to Sense Discontinuties in the Terrain Below the Terrain Level. Also as a Short Range Detector of Obstacles Rising Above the Terrain as a Back-Up to the Microwave Radar Sensor.

Summary

The roving vehicle simulator has been operated autonomously under control of the simulated on-board computer. With the microwave radar obstacle sensor mounted and operating, it was able to avoid a student placed in its path and to return to the originally assigned direction when that path was clear. The tactile obstacle sensor was able to detect impassible obstacles while allowing the vehicle to negotiate passible obstacles. Analysis of the automatic brake system led to a recommendation that further work did not look promising.

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I. INTRODUCTION

The development of prototypes of candidate obstacle detection systems has been set up with the additional objective of providing a realistic design experience for Master of Engineering students at Cornell University. The project has included students from both the Schools of Electrical and Mechanical Engineering. In addition to the obstacle detection systems, an autonomous roving vehicle has been designed, built and tested under limited conditions.

The unmanned exploration of the planet Mars will probably require an autonomous roving vehicle since the signal transit time is too great for continuous monitored control. For a vehicle to rove autonomously, it must either be able to handle all obstacles encountered or be able to determine which obstacles it encounters can be negotiated and which cannot. The second alternative appears more probable especially in light of the lack of knowledge of the Martian terrain. A main thrust of this project has been obstacle detection from vehicle mounted sensors.

II. SPECIFICATION OF TASKS

A. System Design and Analysis. The roving vehicle simulator controlled by the PDP8 computer through radio links with information gathered from the obstacle sensors and attitude sensors is a complex system with numerous interactions between subsystems. Overall system design and analysis is to be used to define subsystem interactions and to set requirements and performance standards for the subsystems.

B. Microwave Radar Obstacle Sensor. The microwave radar obstacle sensor is designed to detect obstacles protuding above the terrain ahead of the vehicle. The sensor is to determine the direction and distance to all obstacles in time for the vehicle to avoid collision by steering around the obstacles. The output of the sensor is to be sent by the radio link to the computer for use in the navigation algorithm. The objective is an operating sensor mounted on the vehicle. Alternate scanning means, such as a phased-array antenna, will be investigated.

C. Tactile Obstacle Sensor. The extended front cab concept of a tactile sensor is to be developed to provide quantification of obstacles, both positive and negative, with a readout compatible with the radio link and the computer. An algorithm for using the sensor output in the computer is to be developed.

D. Attitude Sensing. The previously develcped attitude sensors are to be tested and incorporated into the autonomous operation of the vehicle.

E. Automatic Brake. A braking system is required to stop the vehicle and to hold the vehicle on slopes. Redesign and test of the brake is proposed. The brake is still not to require external logic to control its action.

F. Vehicle Operability and Motion Control. The rover simulator vehicle is to be maintained fully operational to permit installation and on-board testing of the various sub-systems. It will be operated under control of the computer, through the radio data link.

III. SUMMARY OF RESULTS

A. SYSTEM DESIGN AND ANALYSIS

The operational support vehicle with the microwave radar obstacle Sensor Mounted is shown in Figure 1. The vehicle layout is shown in Figure 2. The system schematic is shown in Figure 3. The vehicle as shown in Figure 1 was operated on level ground on which obstacles (student project members) were placed. The vehicle was given a heading which could not be maintained due to the obstacles. The microwave radar sensor determined that obstacles were present and the computer set up an avoidance procedure which cleared the obstacles and then returned to the assigned heading.

With the microwave radar sensor shut off the vehicle was operated in a mode which simulated failure of the microwave radar sensor. The tactile sensor outputs were compared to the maximum tolerable limits for each sensor in the on-board control section. In this mode the vehicle was stopped when a non-negotiable obstacle was encountered while it was not stopped when negotiable obstacles were encountered. These obstacles were simple steps and ramps of various heights.

The original concept of MRV, its general lay-out, and the need for and the functioning of the various sub-systems has been described at length in previous reports, so will not be repeated in detail here.

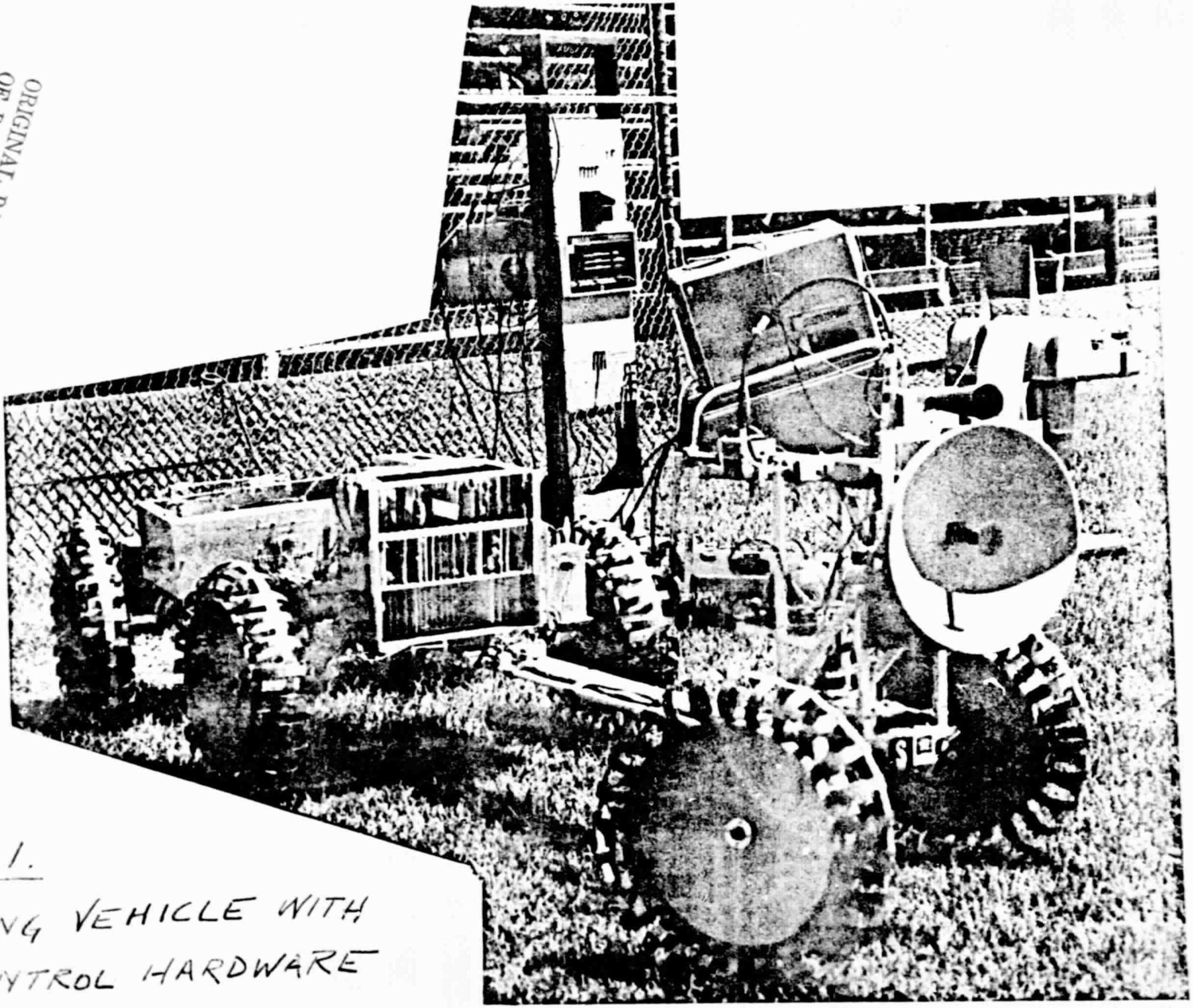


FIG. 1.

ROVING VEHICLE WITH
CONTROL HARDWARE

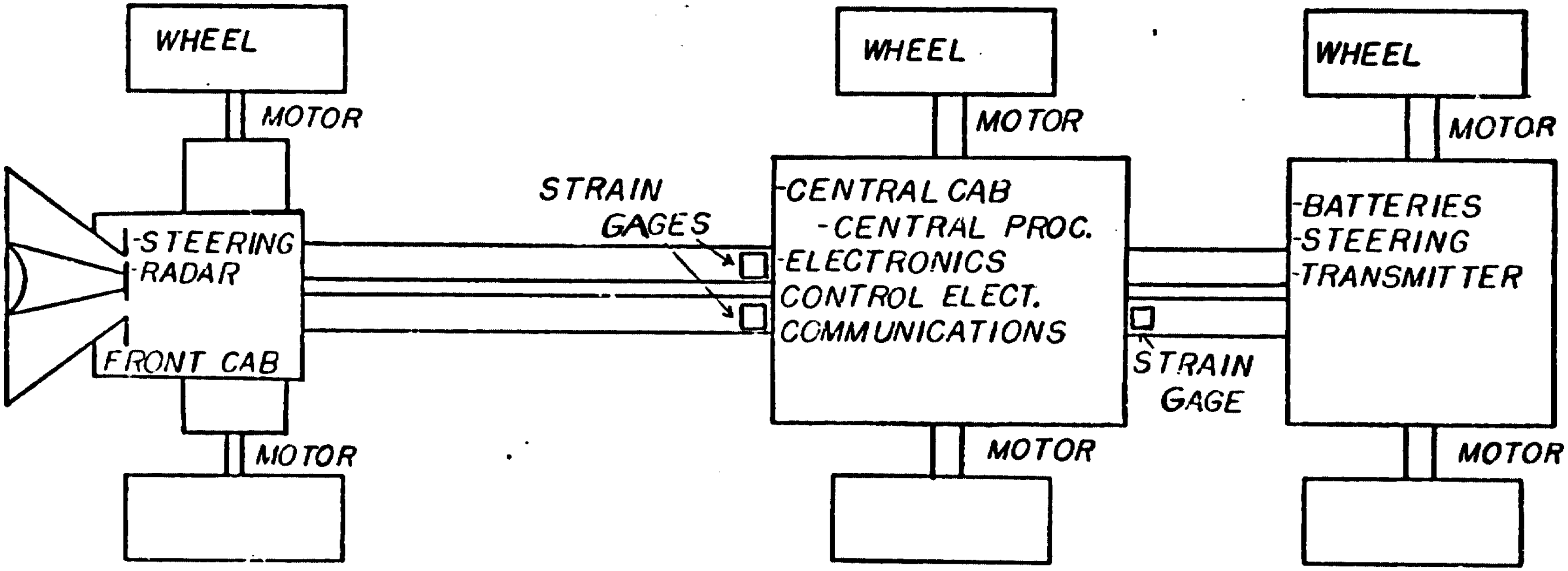
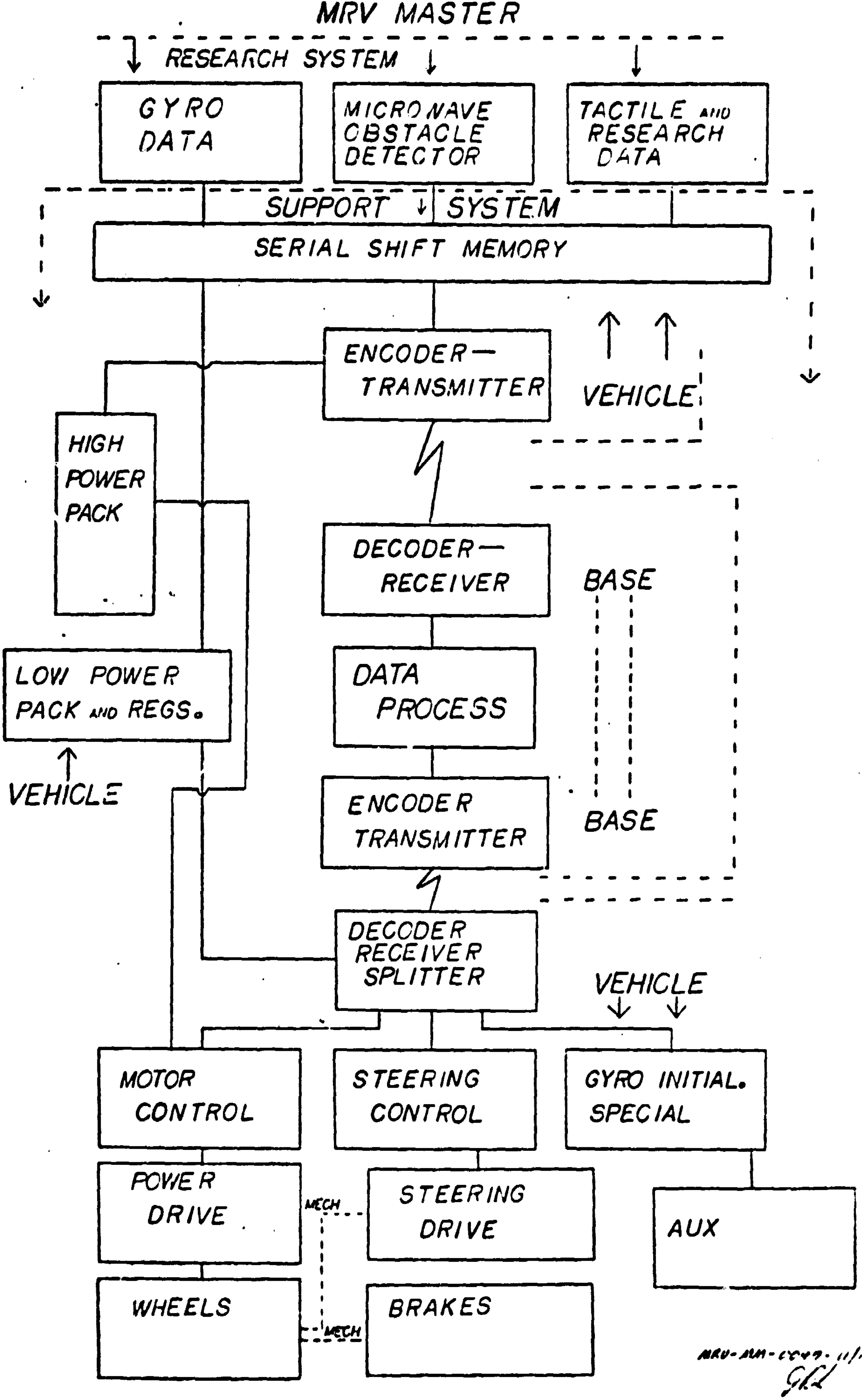


Figure 2 VEHICLE LAYOUT

Figure 3


MRV MASTER
RESEARCH SYSTEM
GYRO DATA
MICROWAVE OBSTACLE DETECTOR
TACTILE AND RESEARCH DATA
SUPPORT SYSTEM
SERIAL SHIFT MEMORY
ENCODER— TRANSMITTER
VEHICLE
HIGH POWER PACK
DECODER— RECEIVER
BASE
LOW POWER PACK AND REGS.
VEHICLE
DATA PROCESS
ENCODER TRANSMITTER
BASE
DECODER RECEIVER SPLITTER
VEHICLE
MOTOR CONTROL
STEERING CONTROL
GYRO INITIAL. SPECIAL
POWER DRIVE
MECH
STEERING DRIVE
AUX
WHEELS
MECH
BRAKES
MRV-MM-CC49-11/6/4

Included in this report are block diagrams of the several principally elecrical sub-systems. The block diagrams, some of which have appeared in previous reports, are largely self-explanatory.

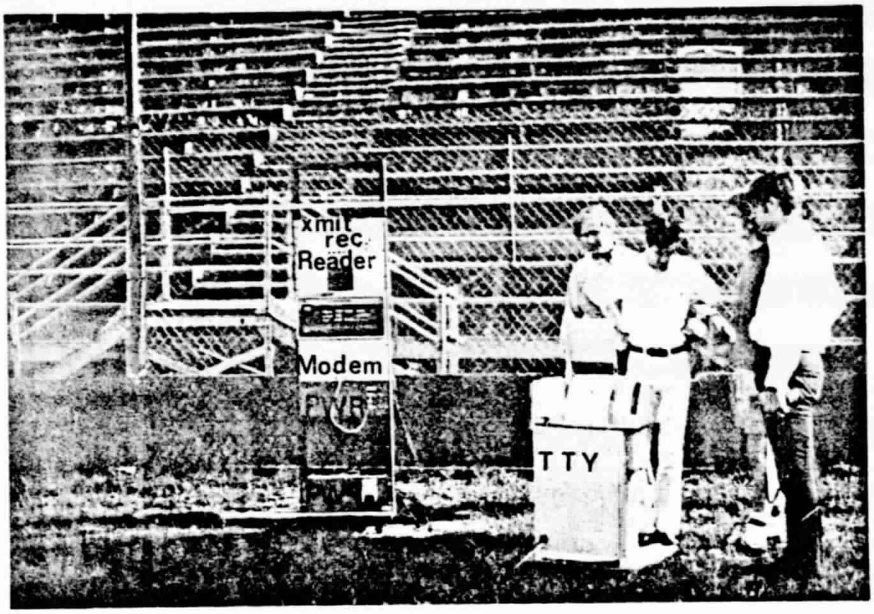
The vehicle lay-out, shown in Figure 2, shows the locations of the principal sub-systems. The layout was dictated by operational restrictions, and by the need to distribute the weight equitably.

Figure 3 shows the entire MRV system, including the radio-linked base station, as well as the MRV itself. It is probable that a lightweight computer could be carried aboard the vehicle, thus avoiding the need for this particular radio link. Currently, mini-computers of sufficient capability were not available to the project, however.

Figure 4(a) and 4(b) shows the data link, through which the signals sensed by the vehicle are transmitted for processing in the computer, and the resulting computer commands returned to the vehicle for execution. The sensed data is from gyros, strain gauges, radar, etc., as suggested in the vehicle software, Figure 5.

Figures 6,7, and 8 depict the gyro, motor control, and steering control systems, respectively. The start-up of the gyro involves starting the spin motor, caging, and uncaging, all in proper sequence. Motor control has to do with the six driving wheels that move the vehicle. The vehicle motion and steering controls have an inherent feed-back through the directional gyro, which senses and reports the vehicle heading.

The vehicle mounted control and processing elements are shown in Figures 9(a), (b), and (c).



BASE PROCESS UNIT

Figure 4(b)

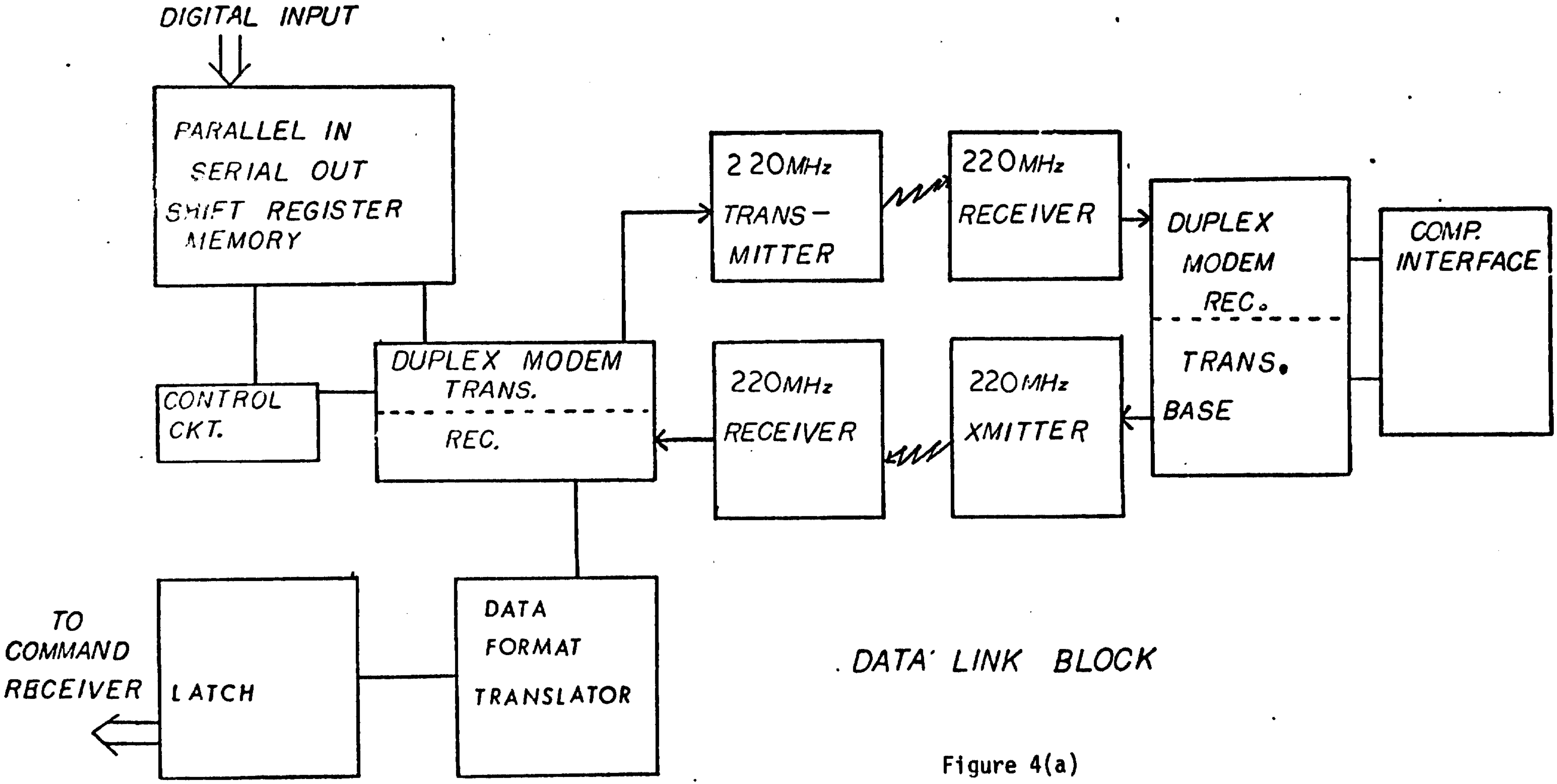
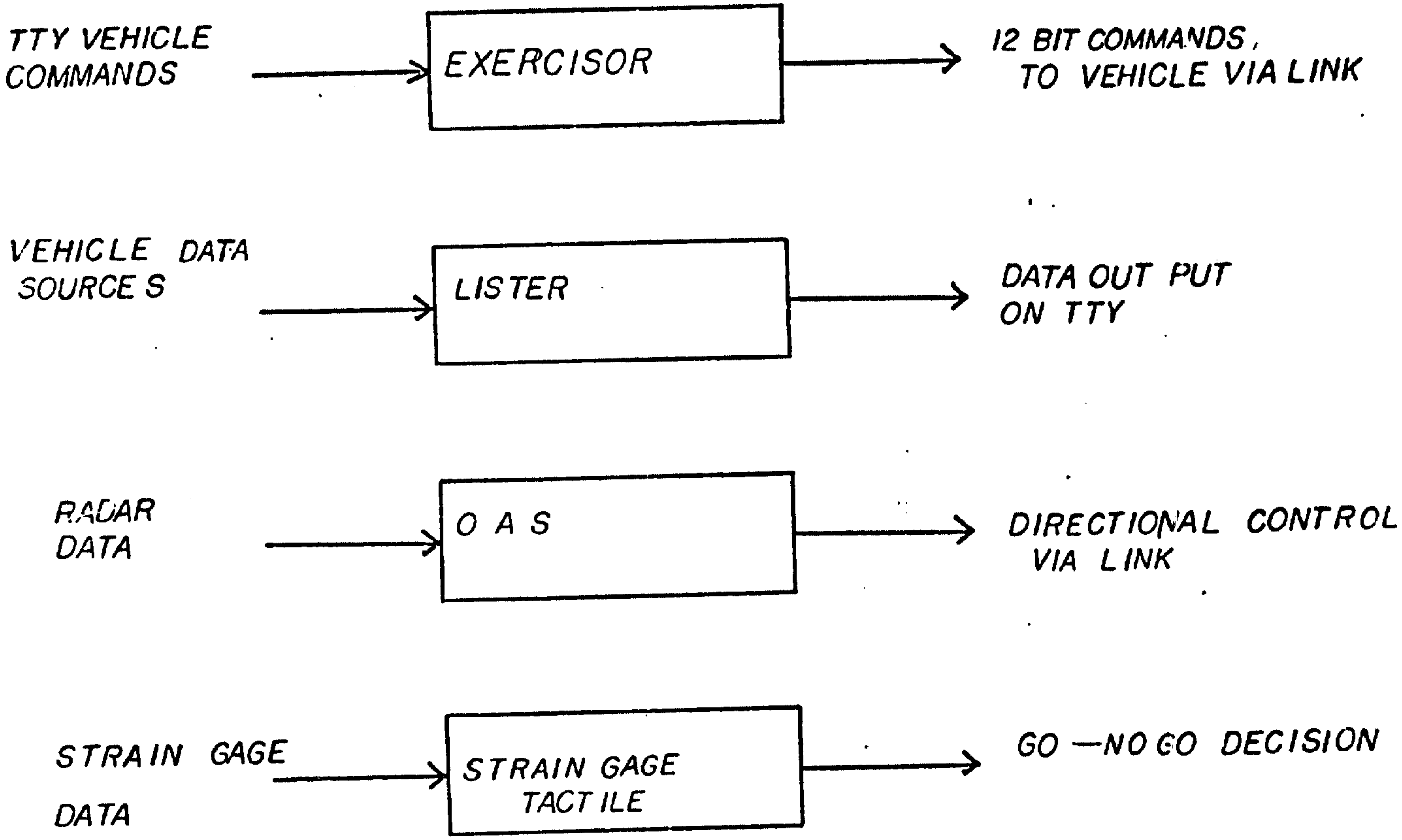
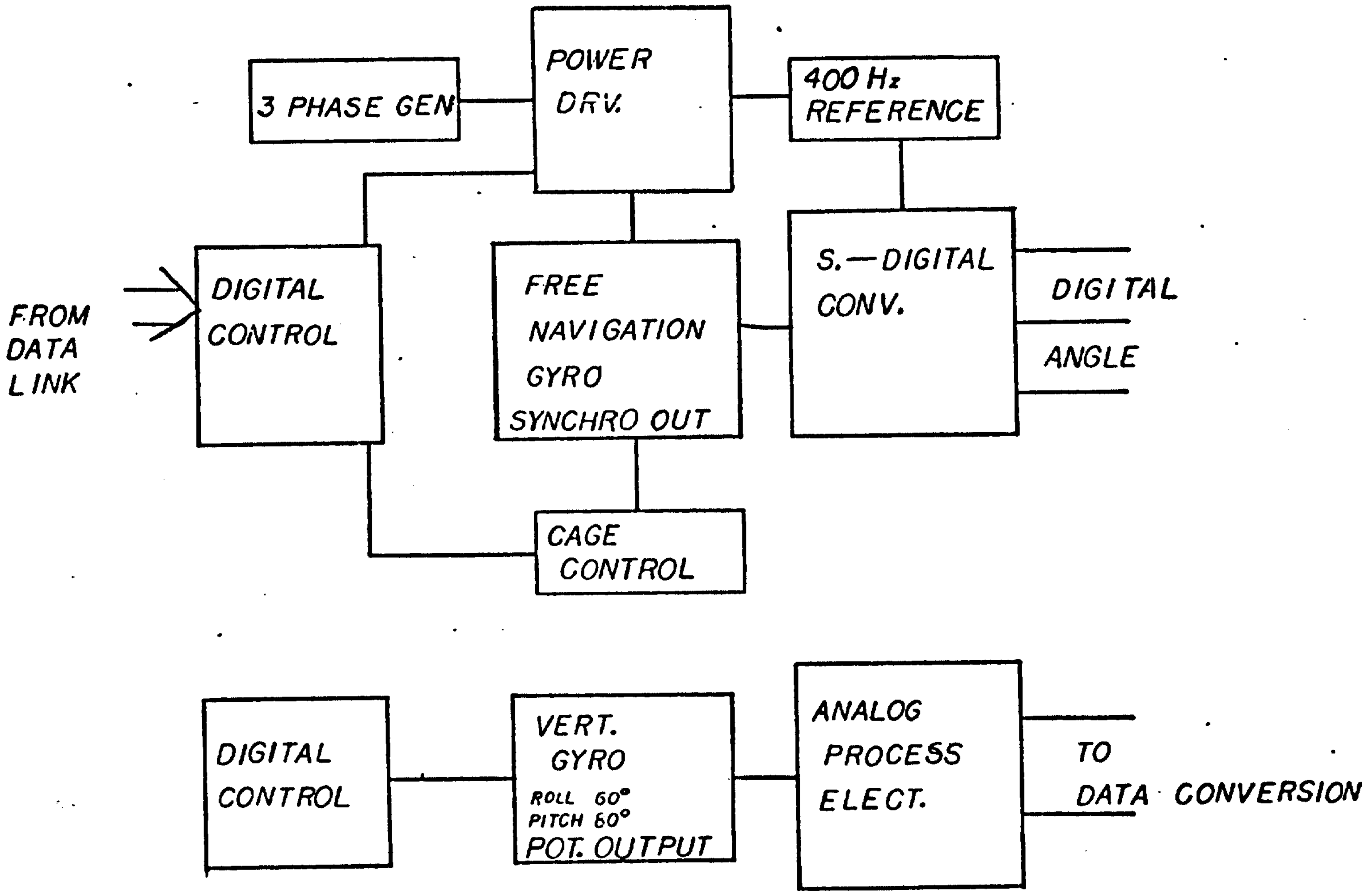

DIGITAL INPUT
PARALLEL IN SERIAL OUT SHIFT REGISTER MEMORY
CONTROL CKT.
DUPLEX MODEM TRANS.
REC.
220MHz TRANS-MITTER
220MHz RECEIVER
220MHz RECEIVER
220MHz XMITTER
DUPLEX MODEM REC.
TRANS. BASE
COMP. INTERFACE
TO COMMAND RECEIVER
LATCH
DATA FORMAT TRANSLATOR
DATA LINK BLOCK

Figure 4(a)



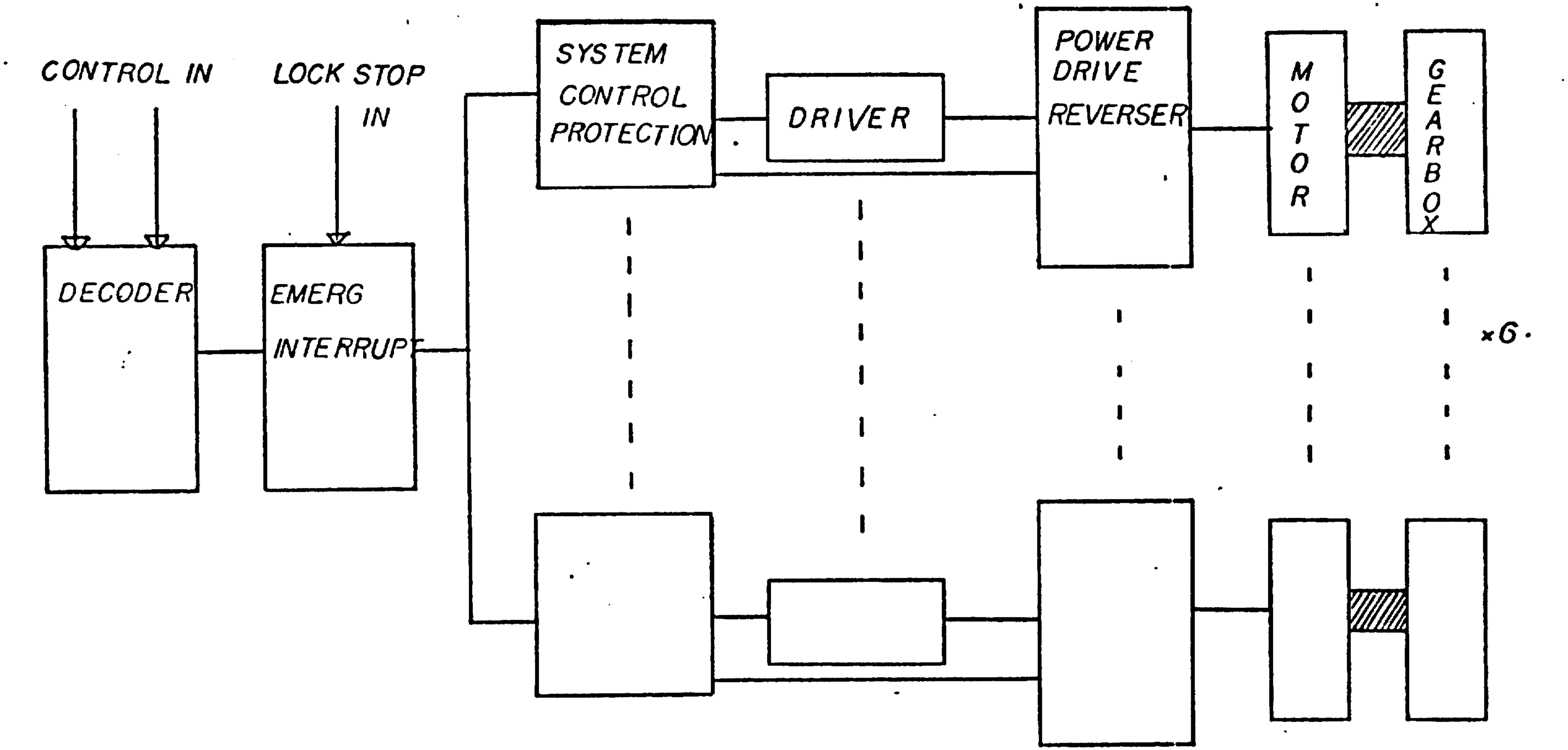
VEHICLE SOFTWARE

Figure 5



GYRO SYSTEM

Figure 6



MOTOR CONTROL

Figure 7

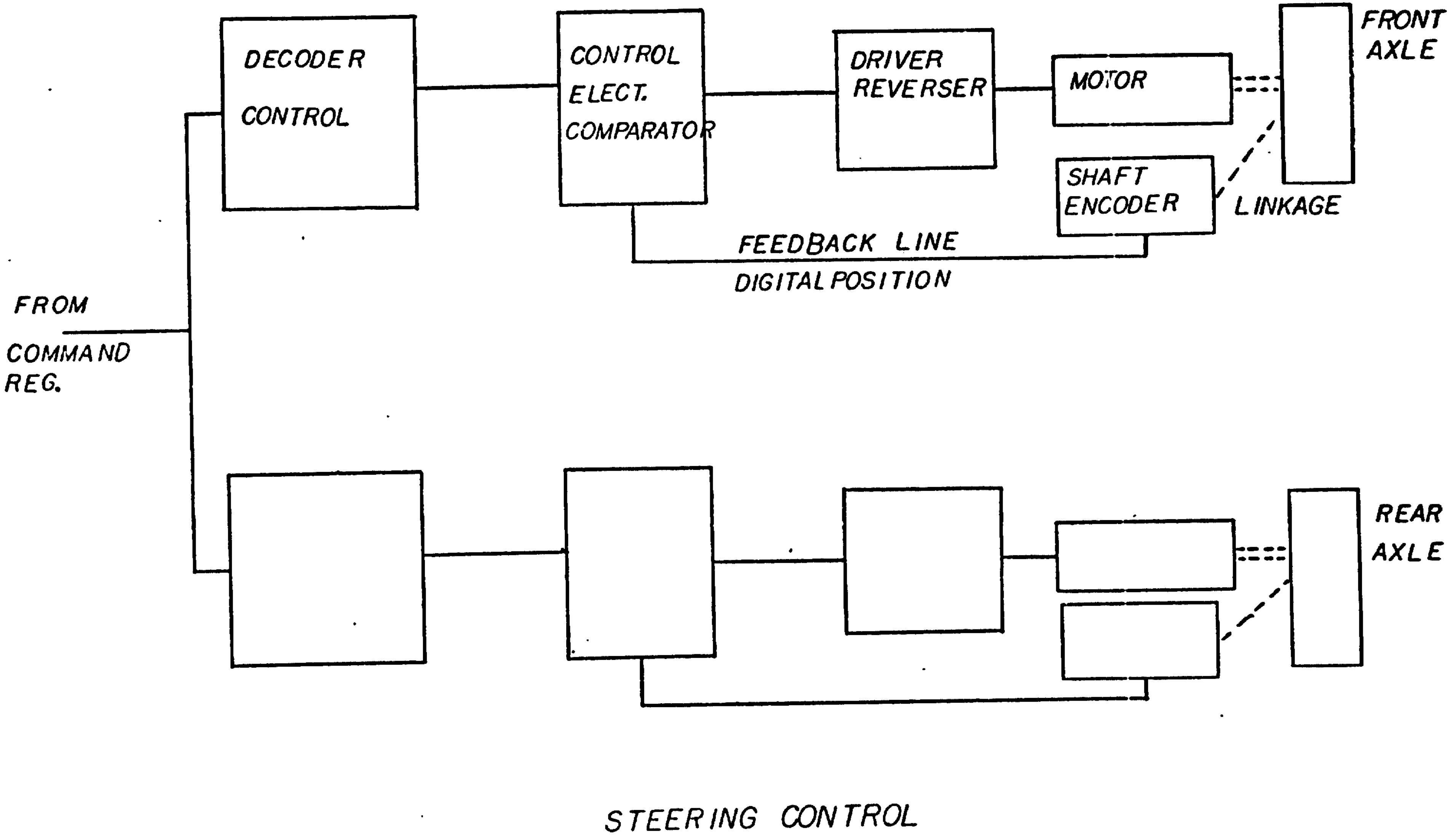

DECODER
CONTROL
CONTROL ELECT. COMPARATOR
DRIVER REVERSER
MOTOR
FRONT AXLE
SHAFT ENCODER
LINKAGE
FEEDBACK LINE
DIGITAL POSITION
FROM COMMAND REG.
REAR AXLE
STEERING CONTROL

Figure 8

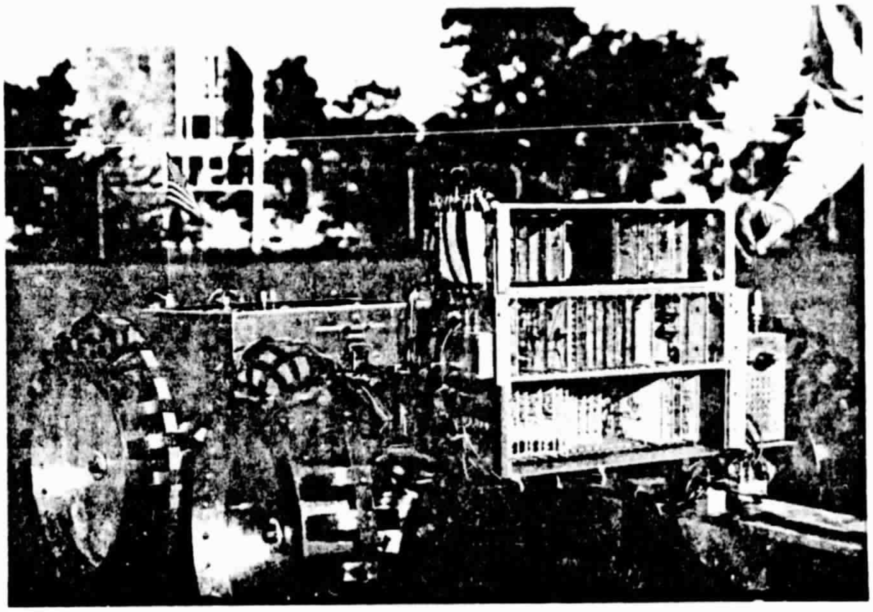
B. MICROWAVE RADAR OBSTACLE SENSOR.

The radar obstacle detector, shown in Figures 10(a), 10(b), and 10(c), Radar Lay-out, is a frequency-scanned microwave unit employing separate transmitting and receiving antennae. The transit time of the frequency-scanned microwave signal results in the received frequency being different from that of the wave then being transmitted. The frequency difference can be obtained from the output of a mixer, and is proportional to the transit time, and so is proportional, also, to the distance to the obstacle which is reflecting the received signal. See Figures 11 and 12. At the heart of the scanned oscillator is a Gunn diode and varactor tuner, shown in Figures 13(a),13(b), and 14. The radar IF amplifier, Figure 15, shows a circuit of operational amplifiers for processing the output of the mixer.

The radar obstacle detector is used to scan some 19 paths fanning out across the area covering nearly 180° ahead of the vehicle. The obstacle avoidance system showing how the radar information is used in the over-all system is shown in Figure 16.

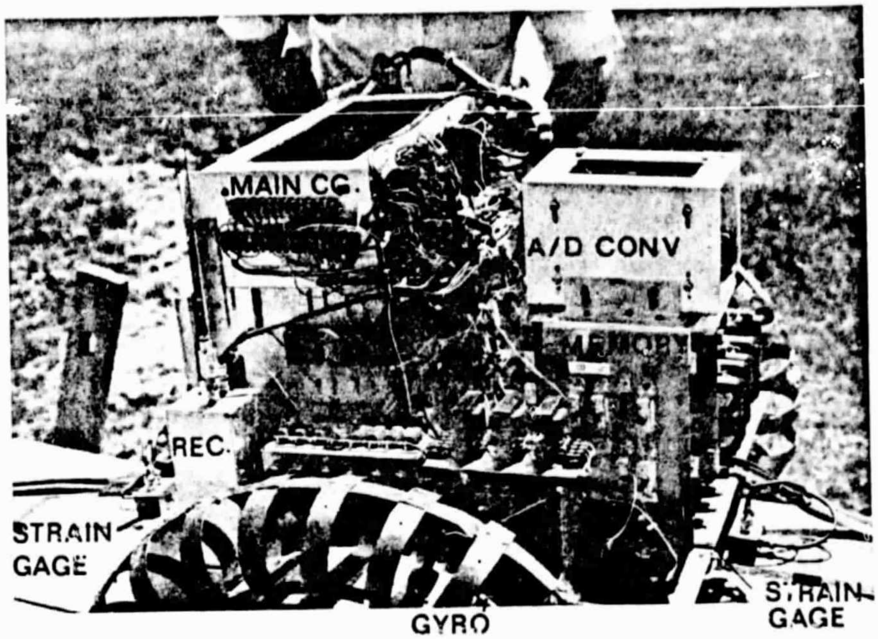
The generalized analog-to-digital conversion scheme is shown in Figure 17 while Figure 18 shows the computer hardware for data processing.

All the sub-section assemblied depicted in the block diagrams and in the circuit diagrams have been designed, constructed, and tested. They have been operated successfully, both as individual units and as parts of the entire MRV.



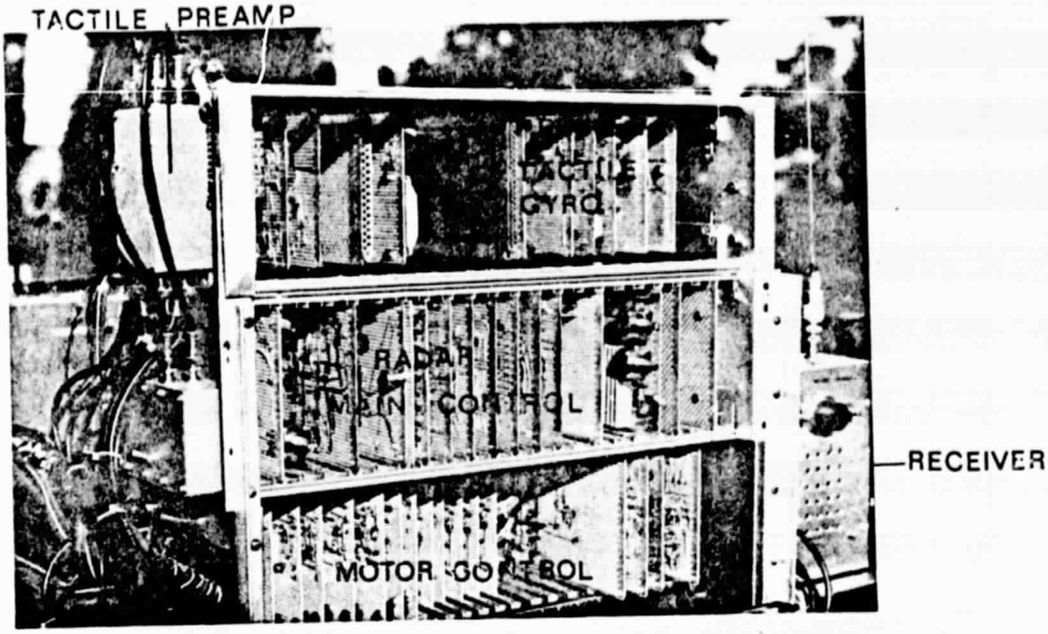
REAR & CENTRAL CABS

Figure 9(a)



CENTRAL CAB—SIDE

Figure 9(b)



MAIN CAGE

Figure 9(c)

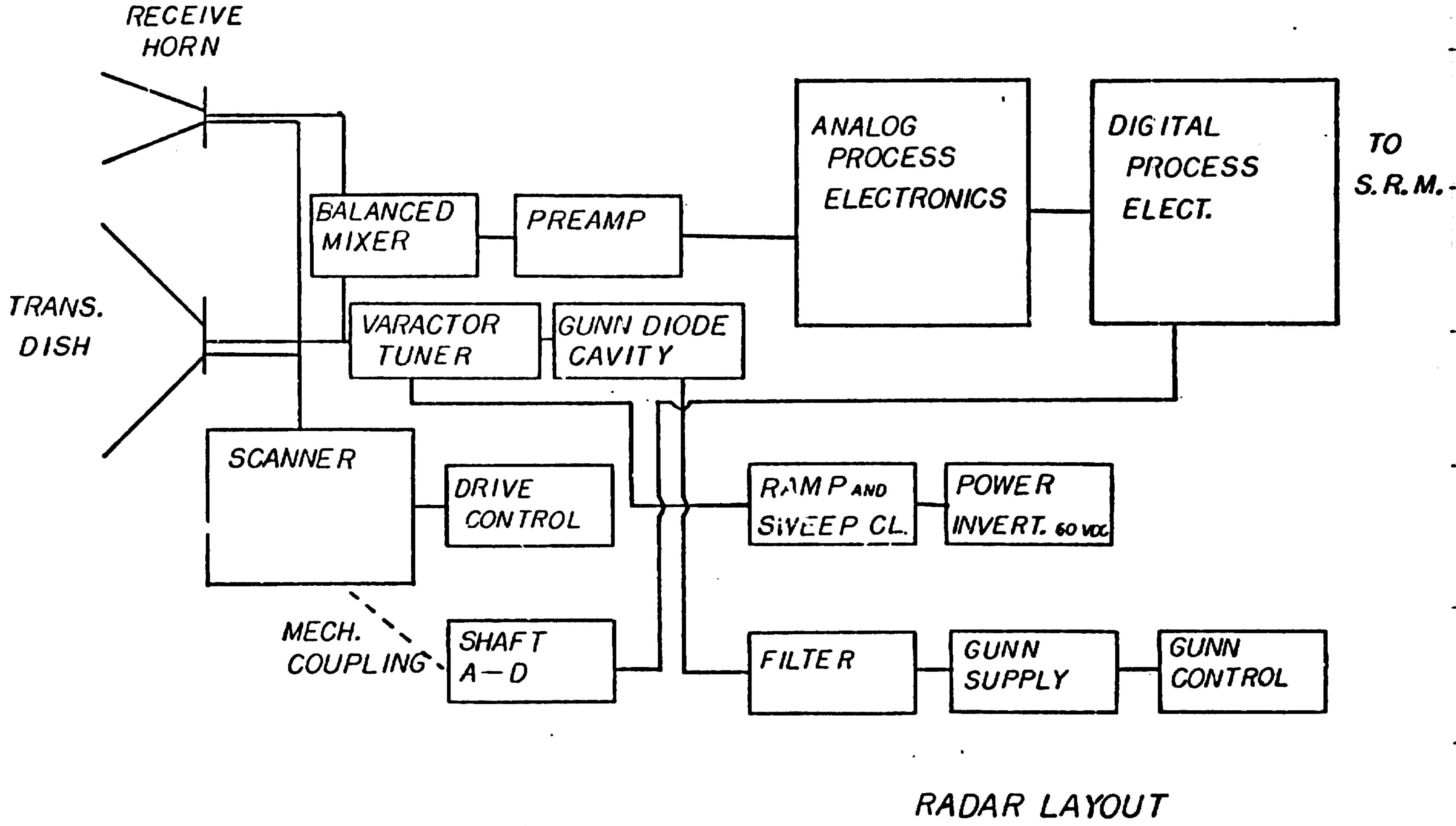
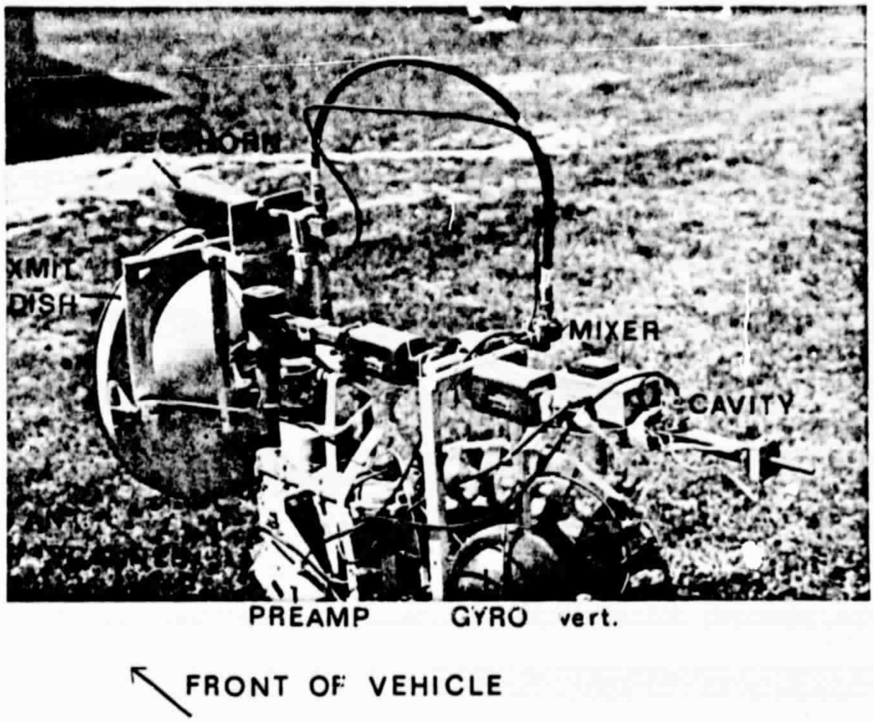

RECEIVE HORN
TRANS. DISH
BALANCED MIXER
PREAMP
ANALOG PROCESS ELECTRONICS
DIGITAL PROCESS ELECT.
TO S.R.M.
VARACTOR TUNER
GUNN DIODE CAVITY
SCANNER
DRIVE CONTROL
RAMP AND SWEEP CL.
POWER INVERT. 60 VDC
MECH. COUPLING
SHAFT A—D
FILTER
GUNN SUPPLY
GUNN CONTROL
RADAR LAYOUT

Figure 10(a)



RADAR LAYOUT

Figure 10(b)

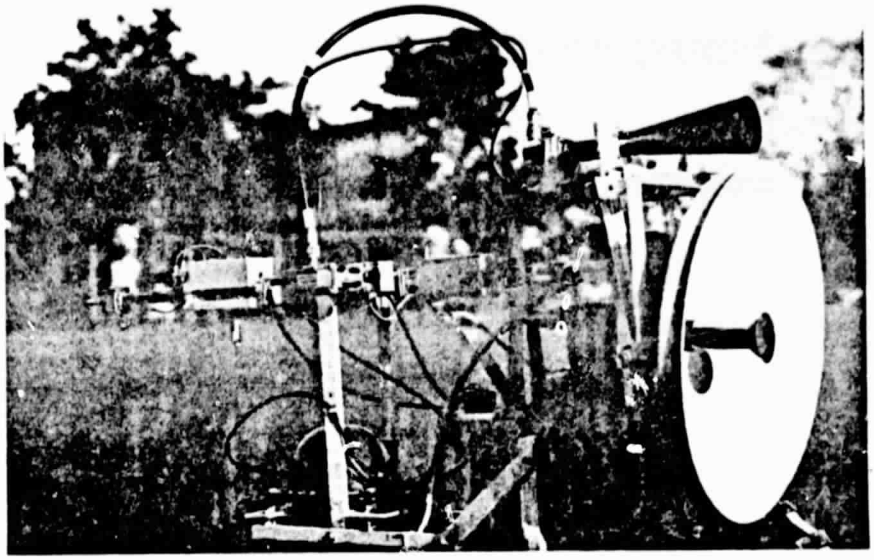
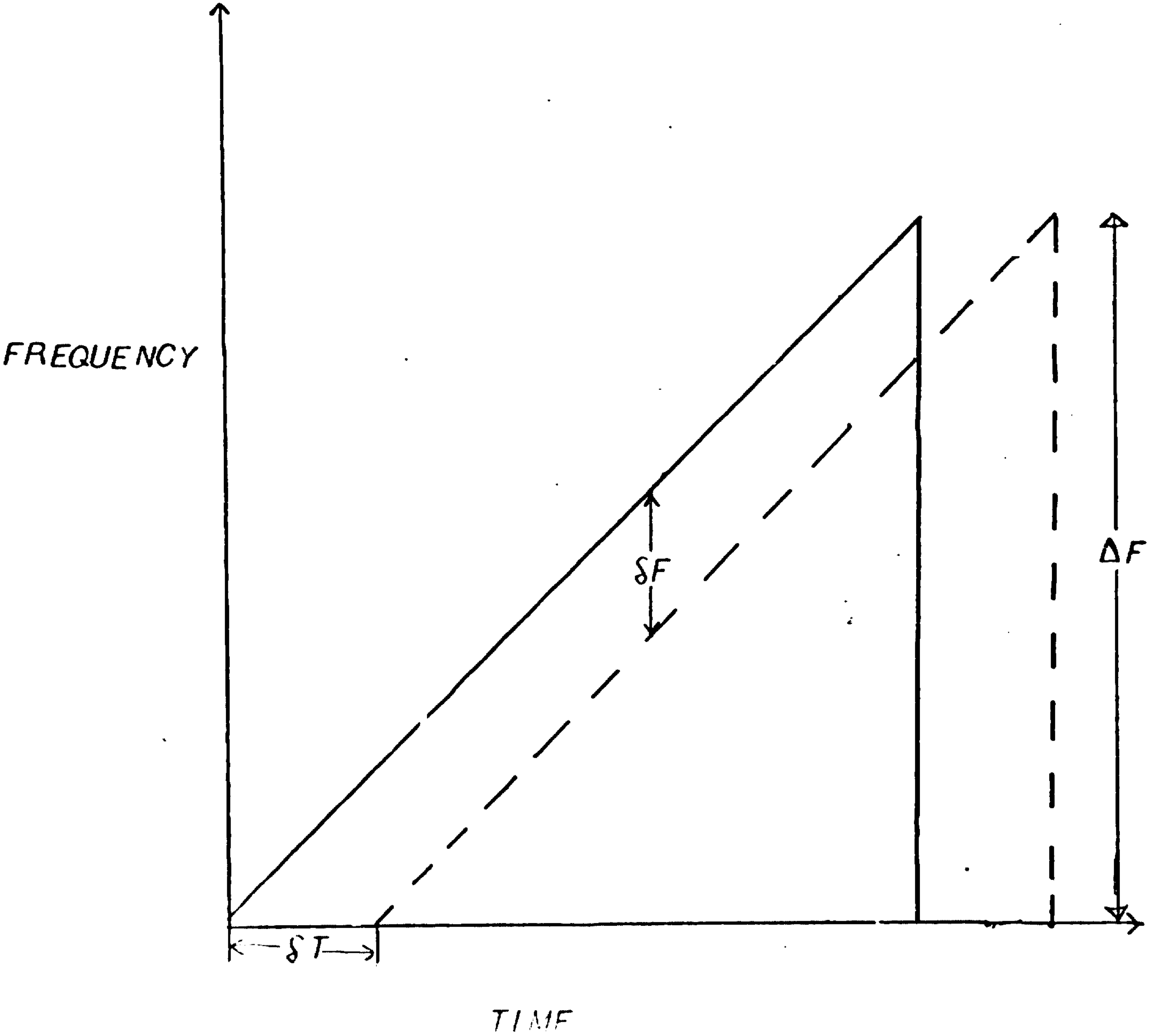


Figure 10(c)



$$\frac{\delta F}{\delta T} = \frac{\Delta F}{\Delta T}$$

Figure 11

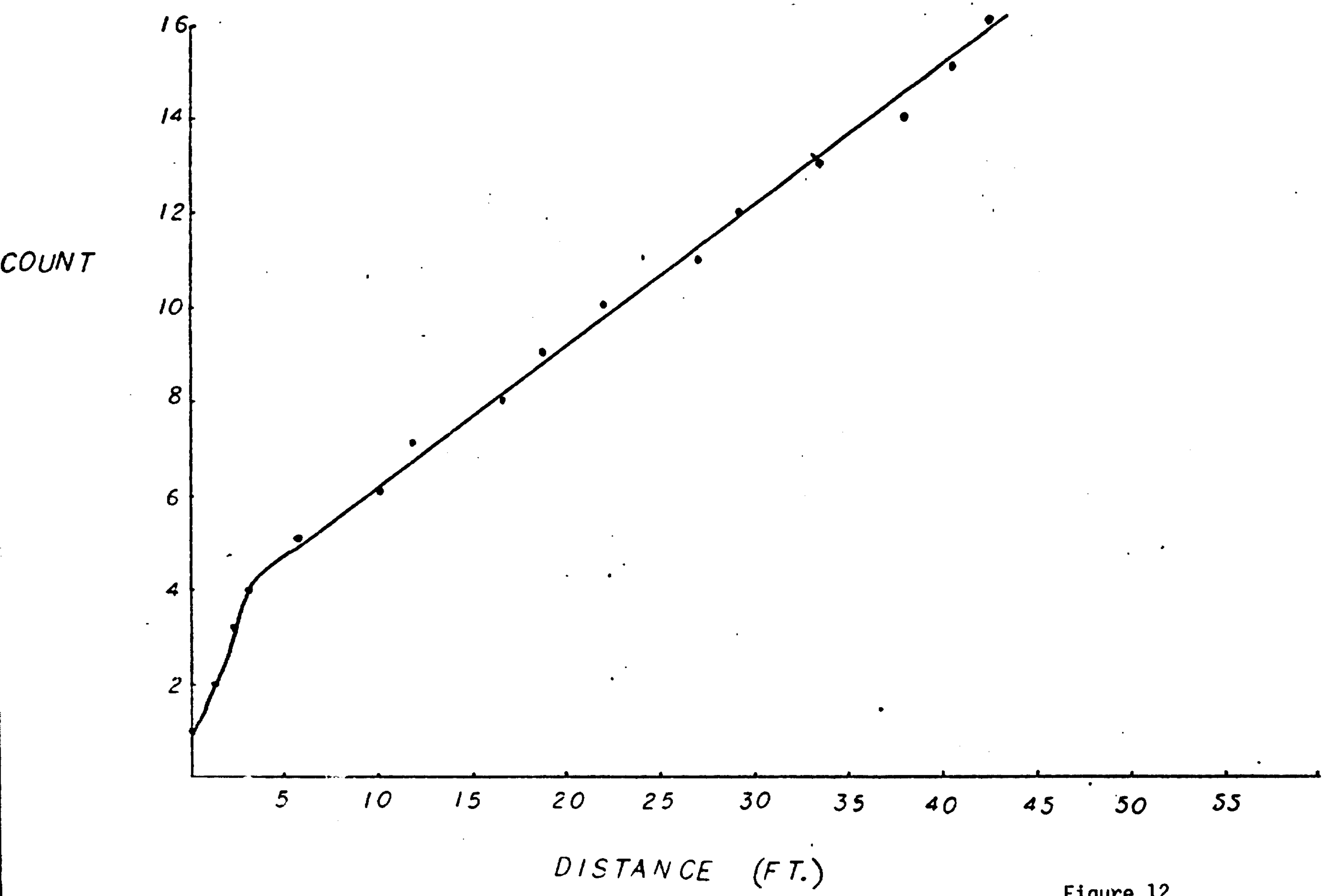


Figure 12

ORIGINAL PAGE IS
OF POOR QUALITY

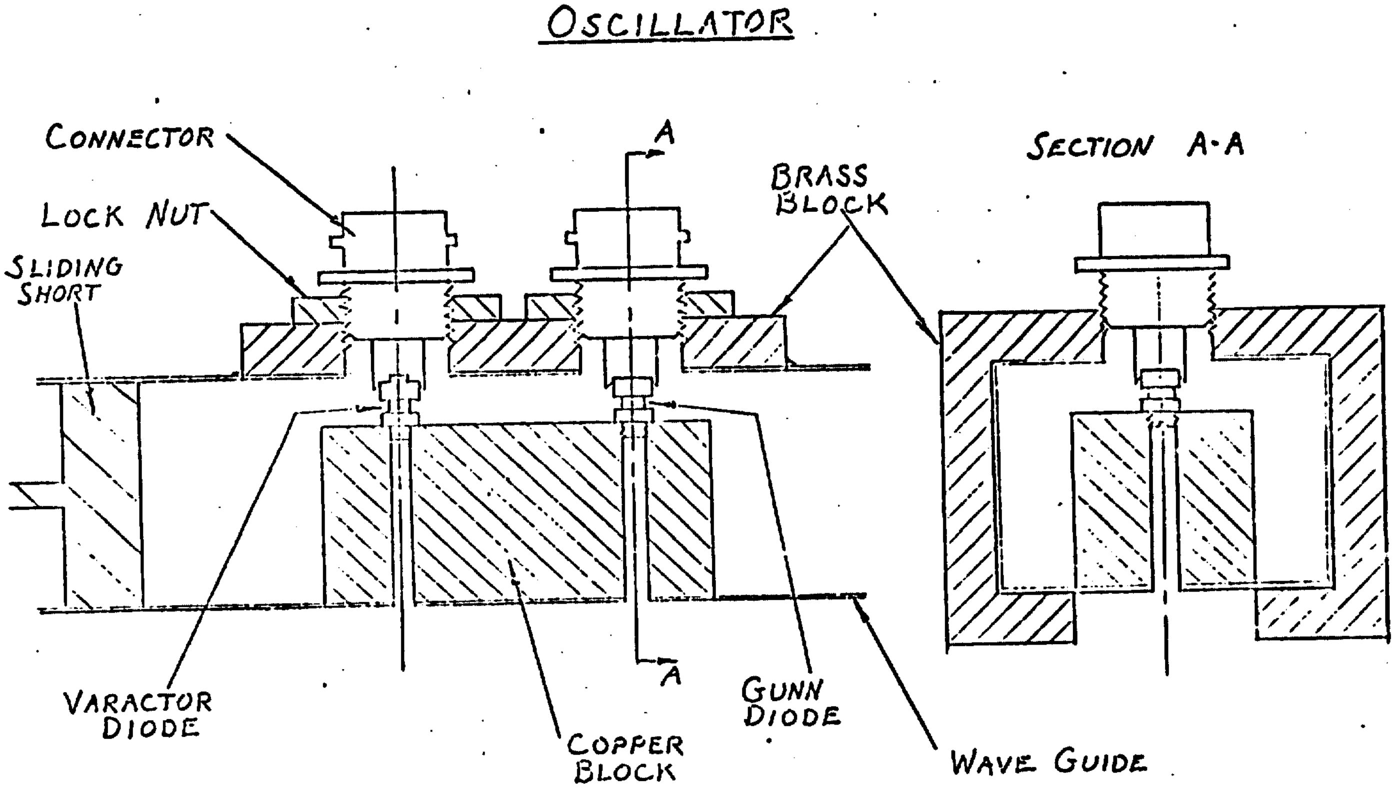
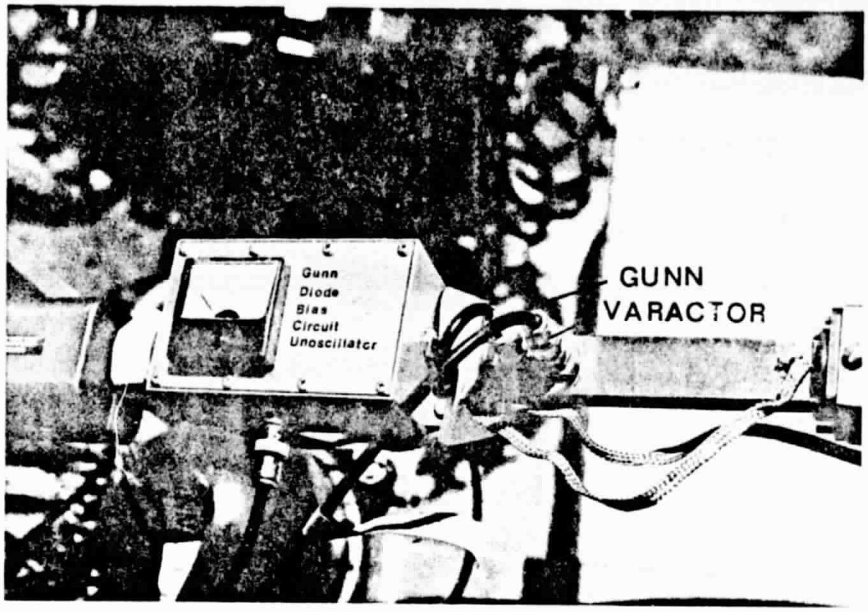


Figure 13 (a)



Gunn/Varactor Diode

Figure 13(b)

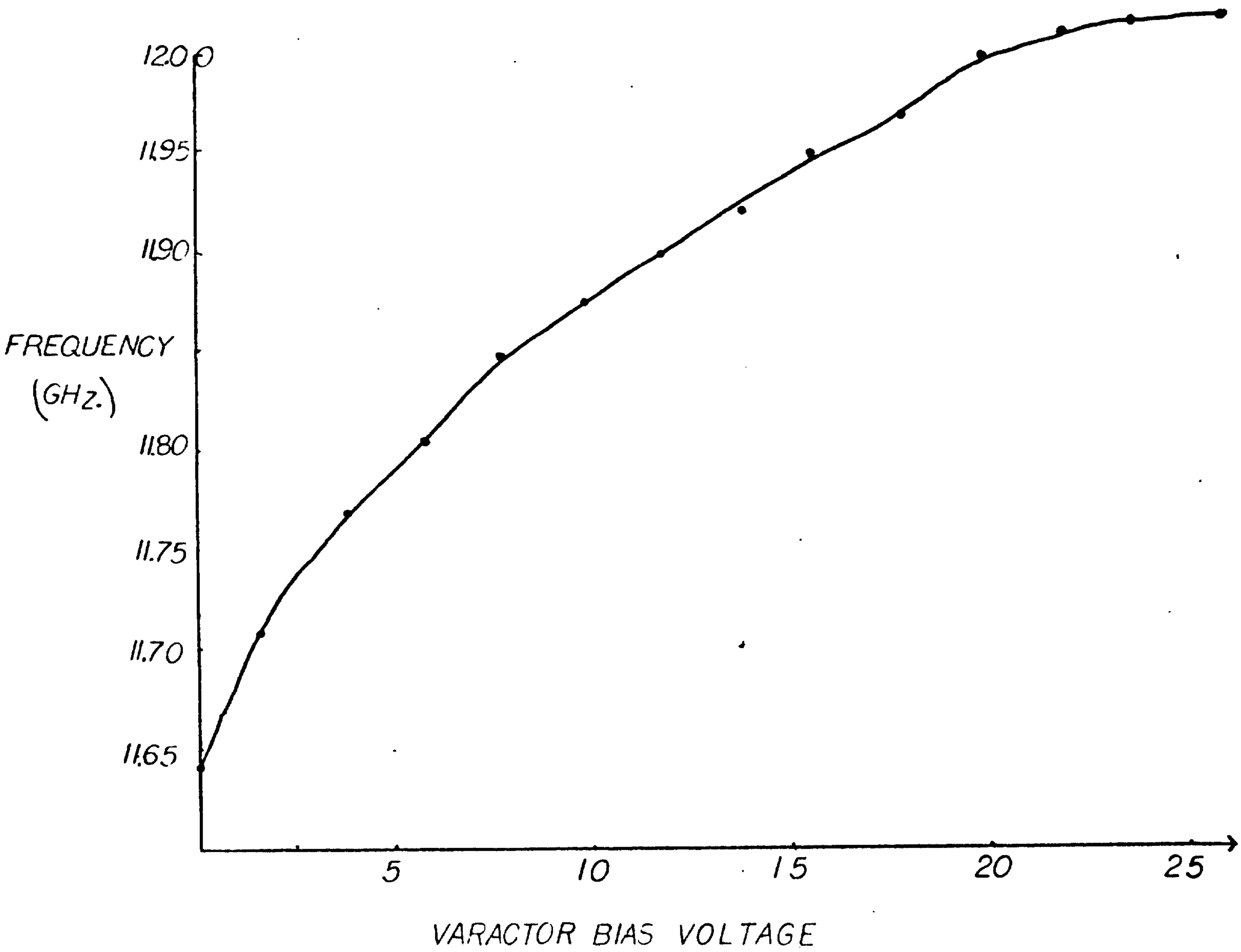

12.00
11.95
11.90
11.80
11.75
11.70
11.65
FREQUENCY (GHz.)
5
10
15
20
25
VARACTOR BIAS VOLTAGE

Figure 14

RADAR IF AMPLIFIER

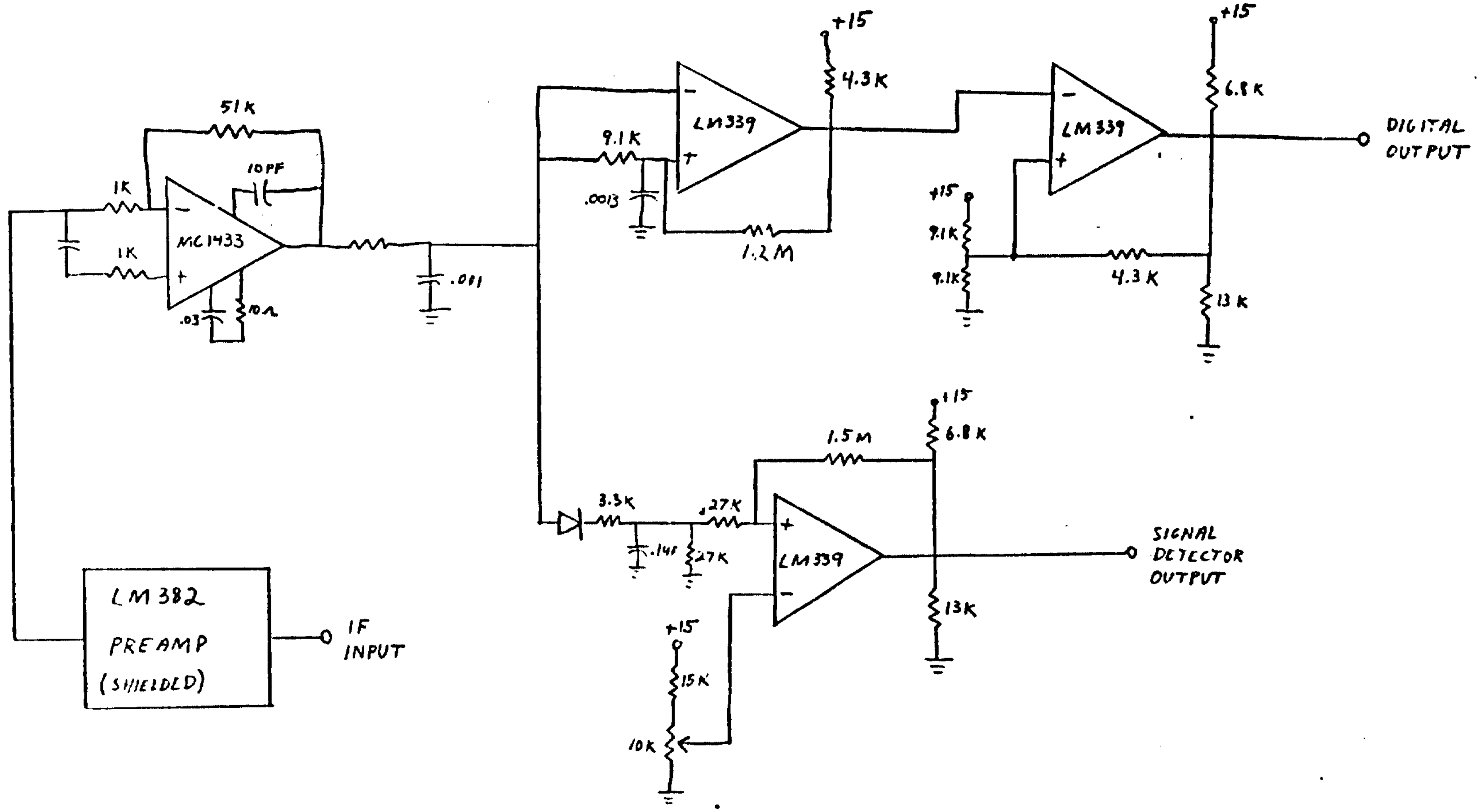
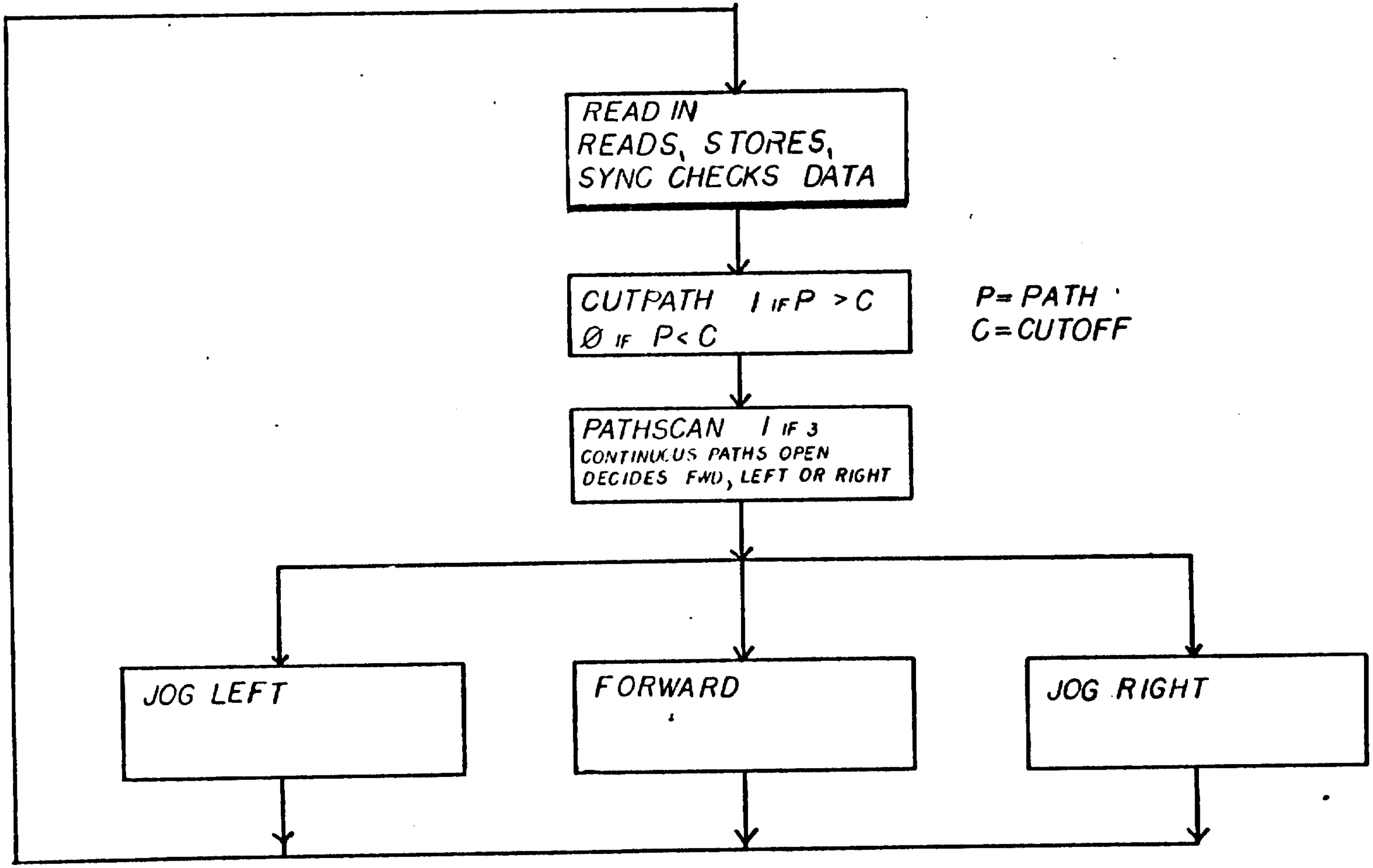
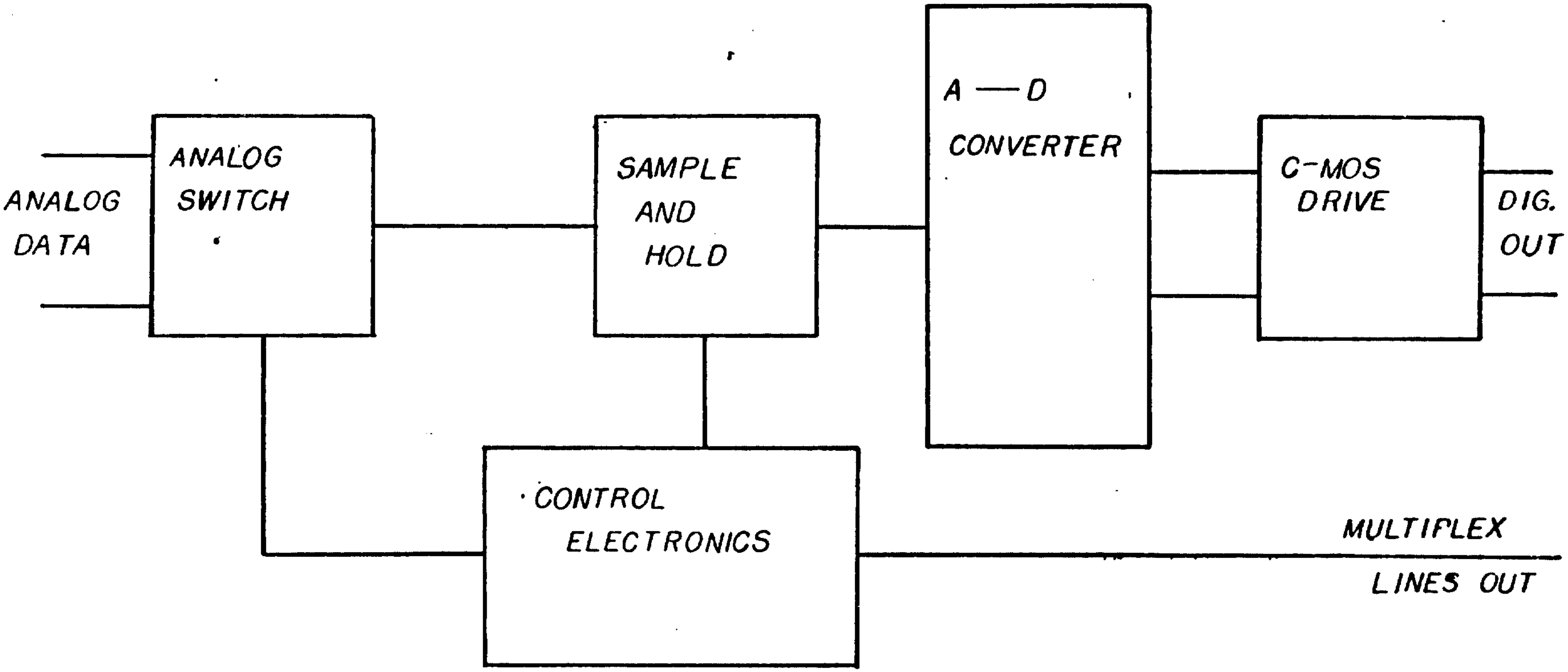


Figure 15

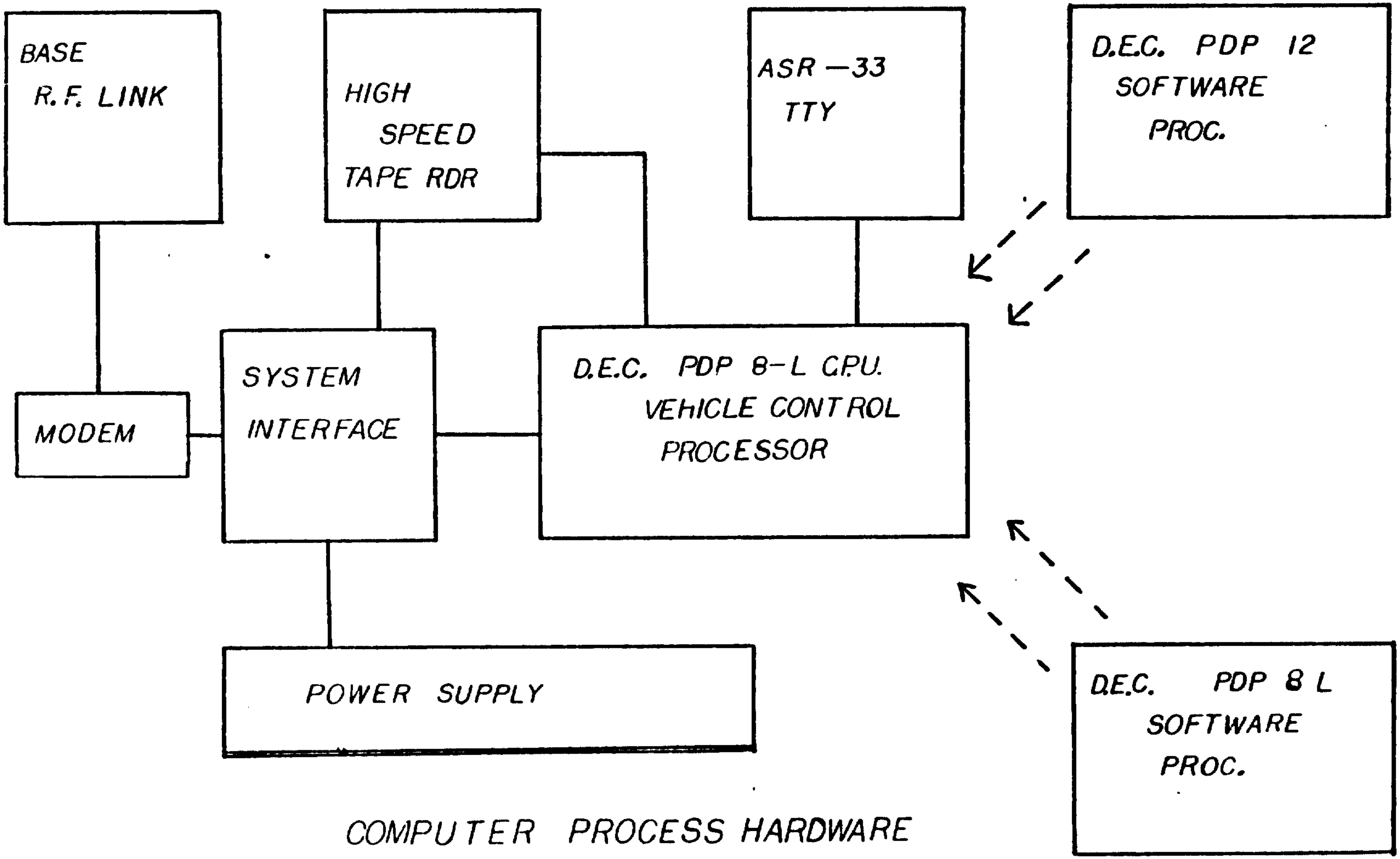


OBSTACLE AVOIDANCE SYSTEM

Figure 16



DATA CONVERSION SYSTEM Figure 17



COMPUTER PROCESS HARDWARE

Figure 18

Some attention was given the problem of pattern recognition involving multiple reflections produced by the radar when several objects were in the scan area at the same time. It appears that a Fourier integral technique could be developed to locate the objects individually, but time did not permit a serious study of the situation.

C. TACTILE OBSTACLE SENSOR.

The tactile obstacle sensor uses the extended front cab, Figure 2, as the sensor. Signals are generated by the strain gage bridges mounted on the main beams of the vehicle fore and aft of the center cab. Two modes of operation are used. The normal update mode interrogates the sensor every wheel revolution. However, obstacles may be encountered between update positions. Therefore limits to each sensor output have been set up and whenever these are exceeded the motor interrupt is activated. Since this operation is "safe", the vehicle may be able to negotiate the obstacle encountered. After the motor is stopped, the algorithm is to be used to check the negotiability of the obstacle. If the obstacle is negotiable the vehicle is to be started. Since the full algorithm was not included in the computer program, this action has not been tested.

The strain gage electronics subsystem is shown in Figure 19. A maximum of flexibility has been included so that the system can be adjusted to function correctly. The overall sensor system electronics is shown in Figure 20.

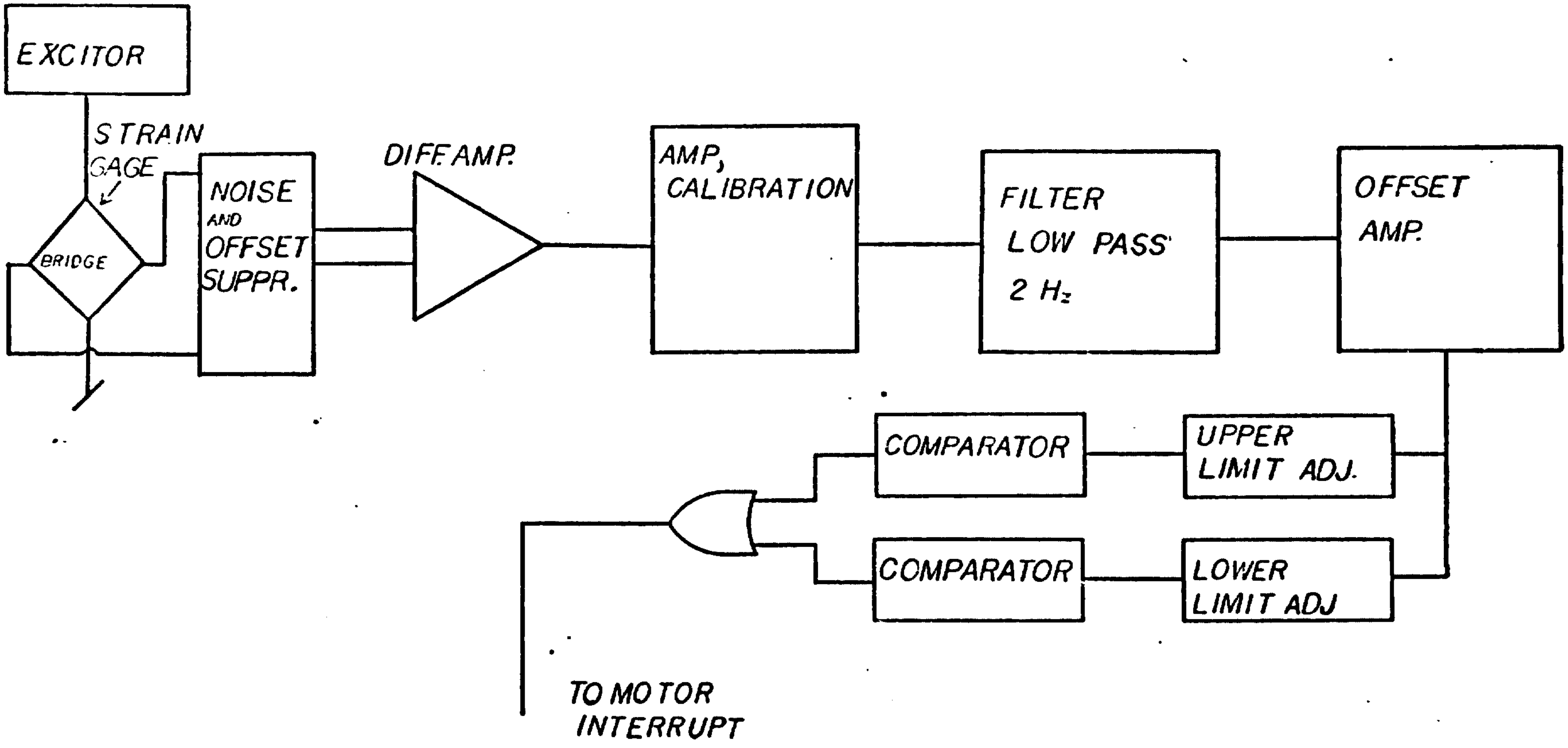
Photographs of the sensor tests are shown in Figures 21,22, and 23.

The tactile sensor algorithm is shown in Figure 24. The algorithm uses inputs of the bending strain in the main beam, tensional strain in the main beam both fore and aft of the center cab, and pitch and roll angles of the front cab. The vehicle parameters of K_b, K_{t_1}, K_{t_2}, A and B must be inserted in the program. These constants are the linear coefficients to convert bending strain to obstacle height, and to convert torsional strains to angles of the front and rear cabs relative to the center cab. The constant A is the distance between the center cab and the rear cab and B is the distance between the front cab and the center cab.

These calculated and measured values are then compared with experimentally determined limits in the sequence shown in Figure 24 to determine the appropriate action to be taken.

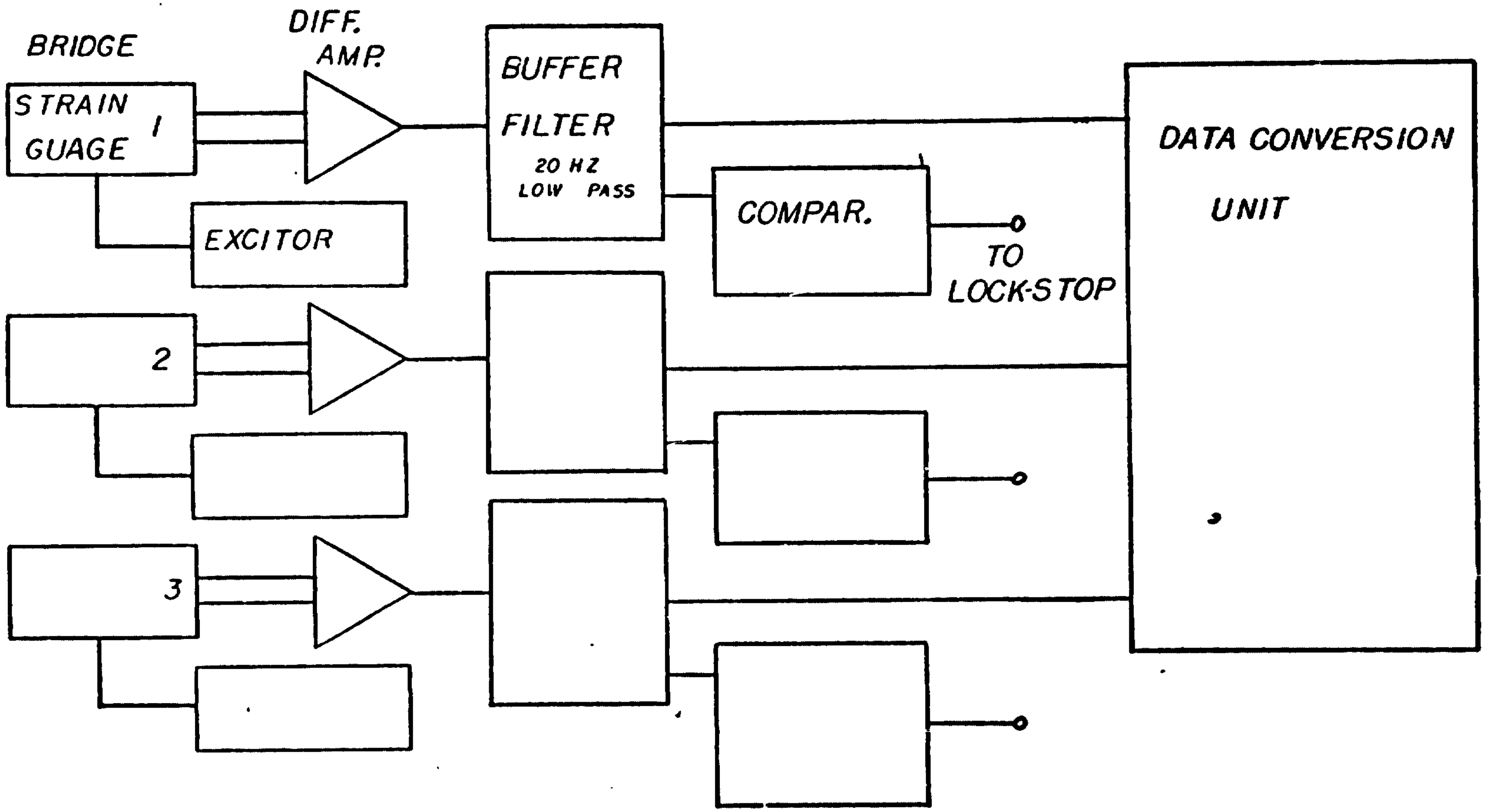
D. Attitude Sensing

All work on attitude and direction sensing was incorporated under the general system development.



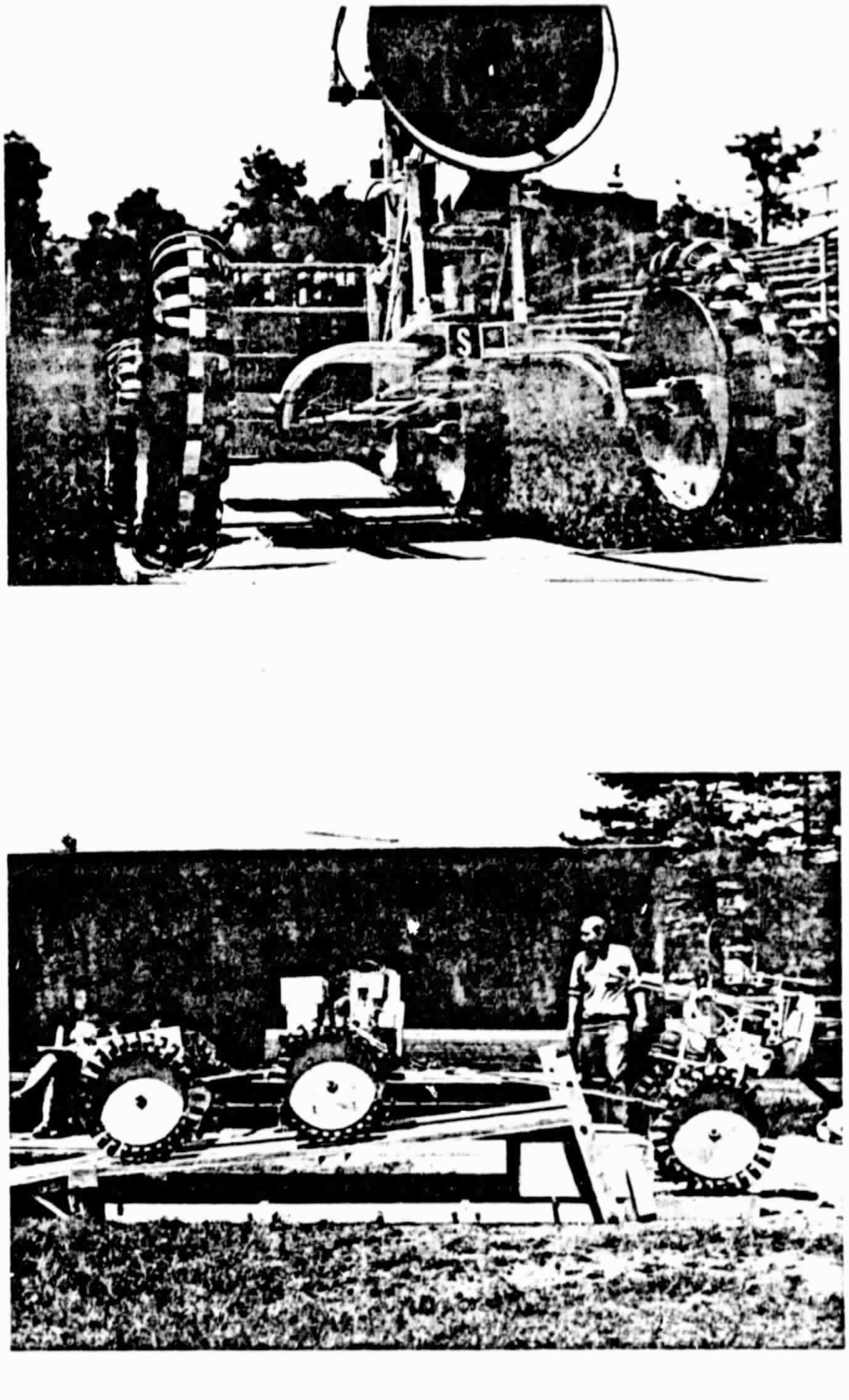
STRAIN GAGE ELECTRONICS

Figure 19



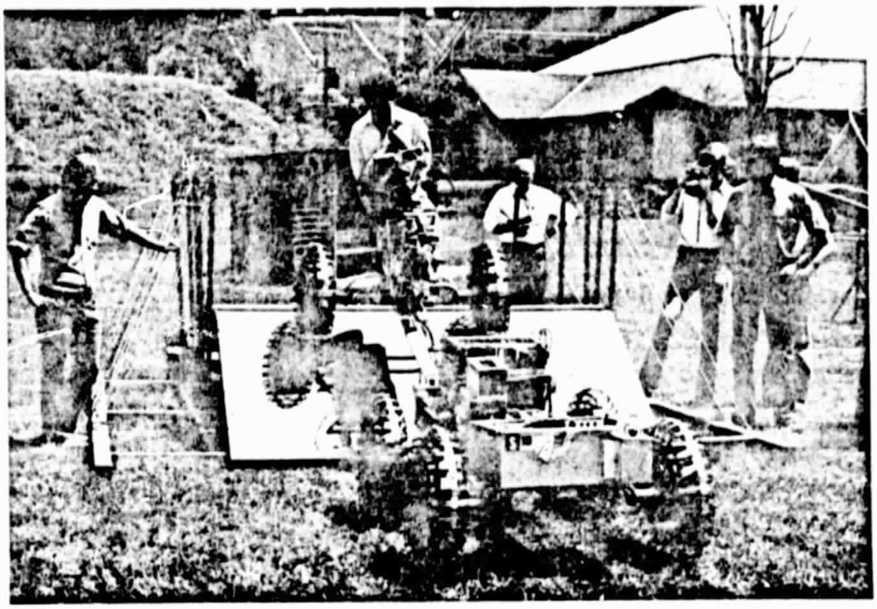
TACTILE SENSOR ELECTRONICS

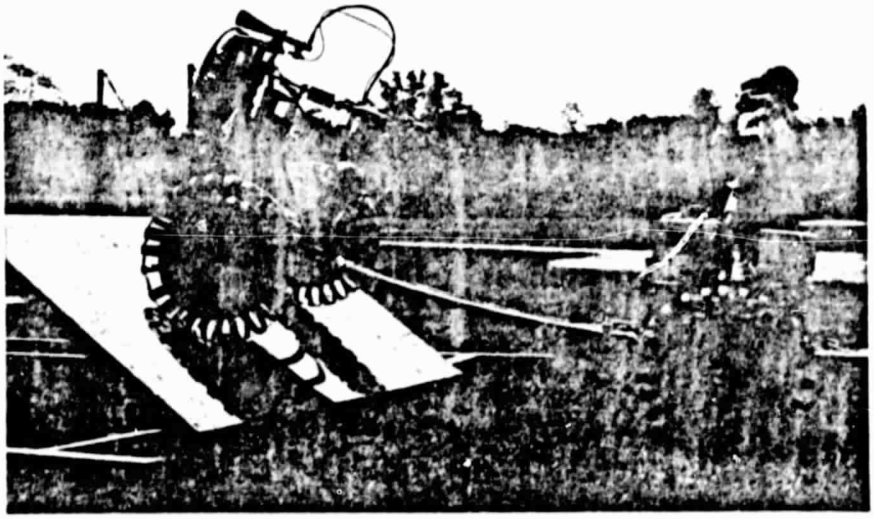
Figure 20



TACTILE DROPOFF TEST

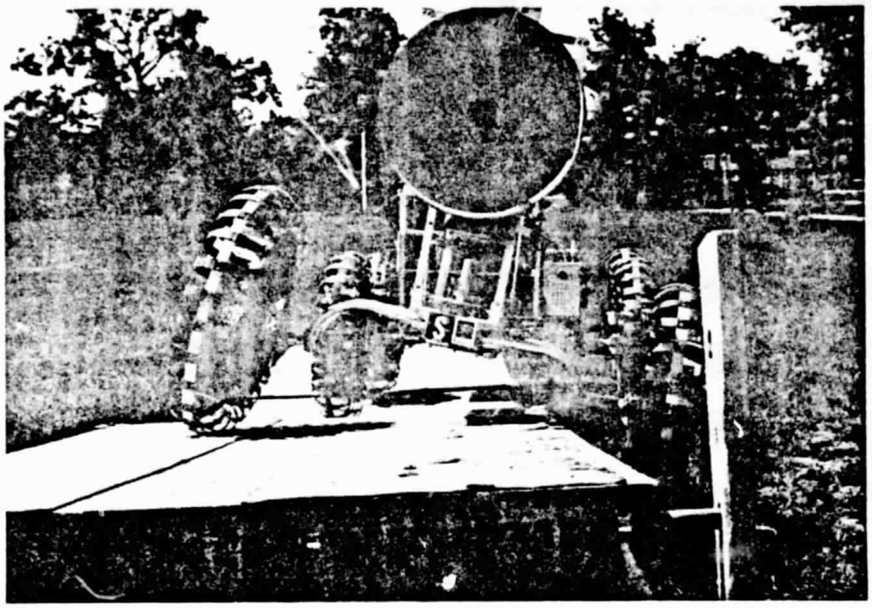
Figure 21





TACTILE OBSTACLE TEST

Figure 22

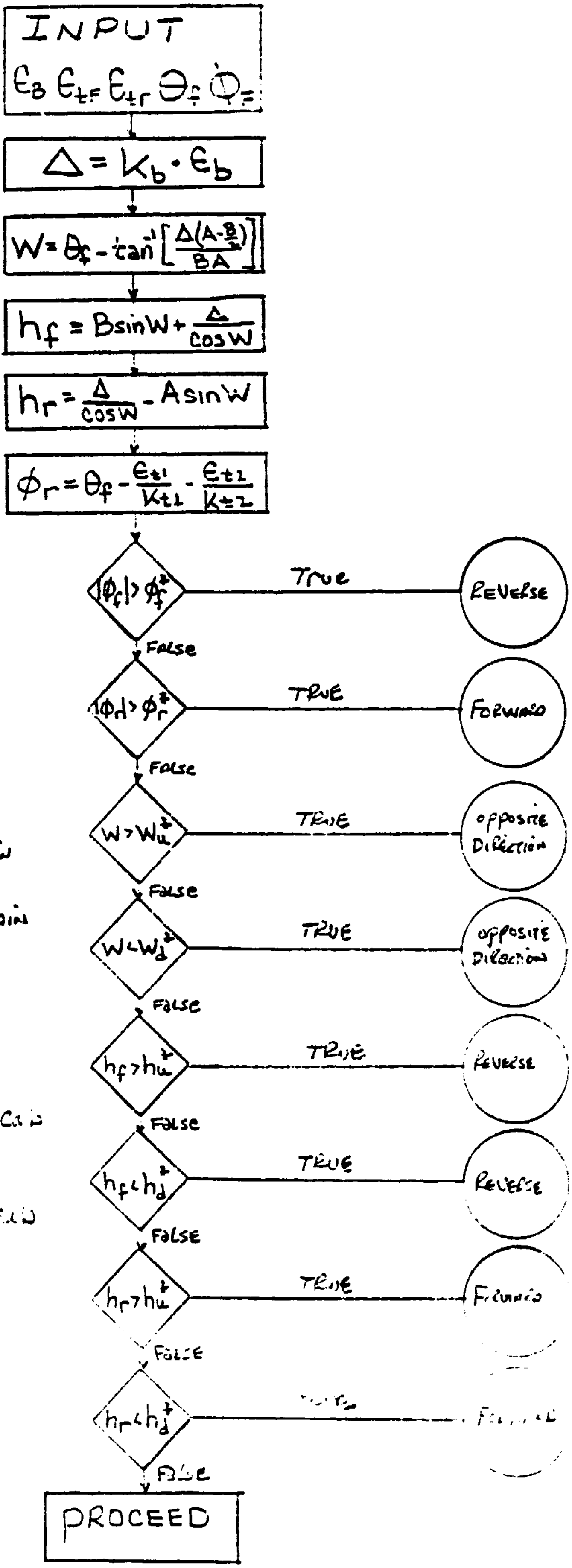


TACTILE TORSION TEST

Figure 23

Figure 24

THE TACTILE SENSOR ALGORITHM



: NOTATION :

ϵ_b = Bending strain

ϵ_{tF} - torsion front strain

ϵ_{tr} = torsion rear strain

θ_F = pitch angle - front

ϕ_F · Roll of front

A = distance, center cab to rear cab

B = distance, front cab to center cab

E. Automatic Brake

For the simple idealized model, Figure 25, descending a hill with the motors operating, an on-off brake characterized by Figure 26(a) resulted in an oscillating motion. Configurations (b) and (c) gave constant speeds somewhat higher than the level terrain speed. This would constitute satisfactory operation if no time lag occurred in the braking operation. Curves of speed vs. time for the vehicle starting on a downhill slope of α degrees are whown in Figure 27. (These are for the curve shown in Figure 26(c).)

A study was then made of a system in which the brake release cam had to rotate a finite amount to release the brake While errors have been found in the program, the conclusion that this condition leads to unstable operation seems to hold. The indexing phenomena may result in the brake being - and remaining - completely disengaged. This concept should not be pursued further unless a different physical system is devised.

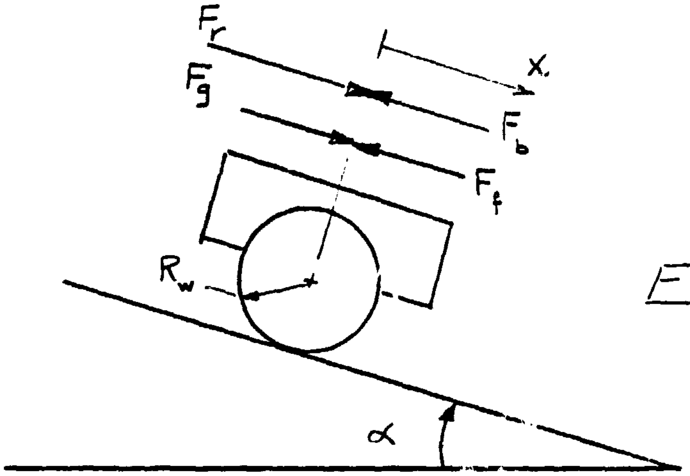
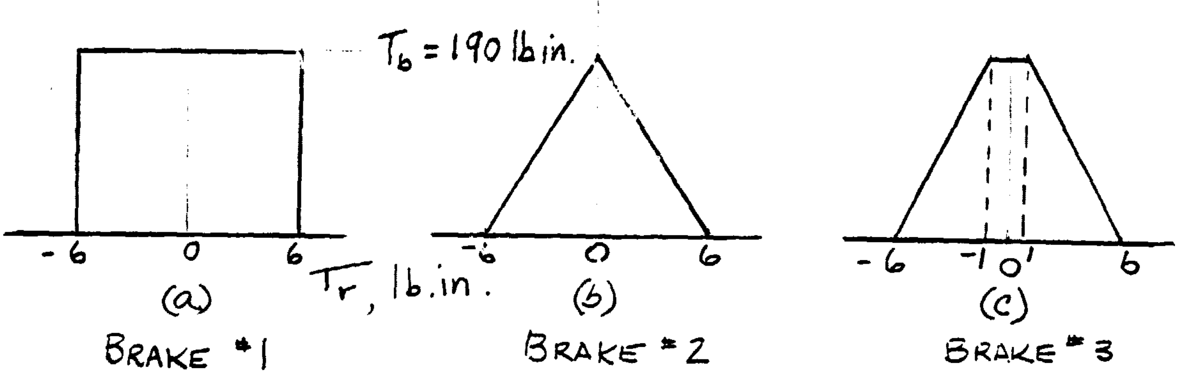


FIG. 25.

$$M\ddot{x} = F_r + F_g - F_f - F_b$$



(a) BRAKE #1

(b) BRAKE #2

(c) BRAKE #3

FIG. 26. IDEALIZED BRAKE TORQUE — REDUCER TORQUE CURVES

$$F_r = \frac{(1.363 - \omega)}{0.001261 R_w} \quad , lb.$$

$$F_f = 0.75 \quad , lb.$$

$$F_b = \frac{T_b}{R_w} \quad , lb.$$

$$F_g = W \sin\alpha \quad , lb.$$

Velocity vs. Time

Brake # 3

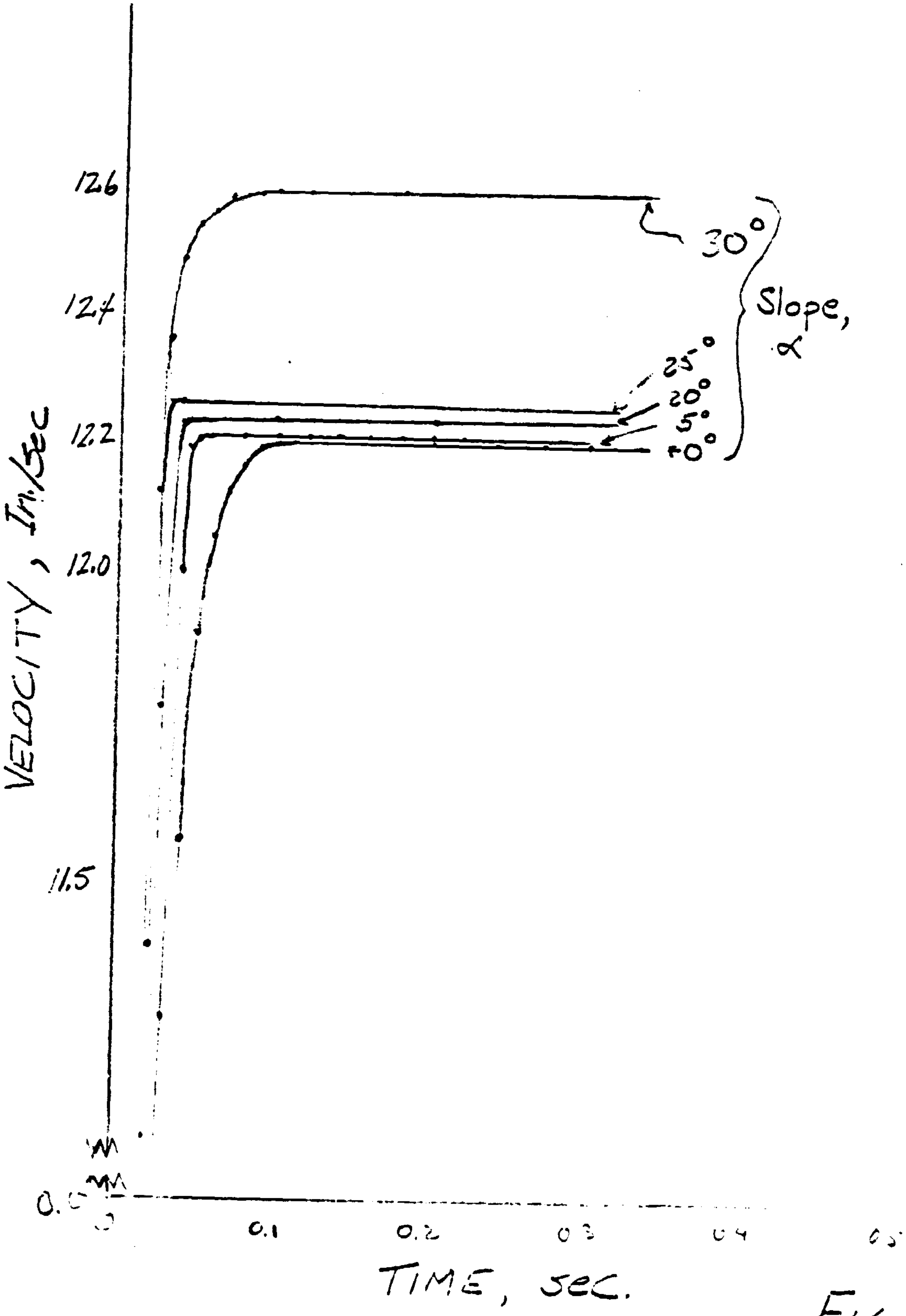


FIG. 27

F. Vehicle Operabiliby and Motion Control.

Most of the aspects of this topic have been covered in Section A. However, one aspect of vehicle operation was changed to avoid problems with excessive vibration of the vehicle. The metallastic wheels used previously were made with a low spring rate to give a large footprint. This resulted in a large amplitude of oscillation whenever the vehicle operated on any surface except a finished flat surface.

To overcome this, a new wheel was designed and built. This wheel is basically a belted radial tire built integrally with the wheel. The design concept used 90 spring steel bands deflected to the shape shown in Figure 28. The inner and outer hoops were to be 0.040 inch thick aluminum sheet. Attachment of the bands to the hoops near the ends of the hoops should reduce pinch point problems to a negligible condition.

The wheels actually built were limited by availability of materials and construction facilities. Twenty-six bands were used and the belt was a 2 inch wide strip. The bands were not as severly deformed in assembly as had been proposed. However, the wheels performed so well that no thought had to be given to limitations from the wheels either in load capacity or vibration.

PROPOSED BELTED RADIAL WHEEL

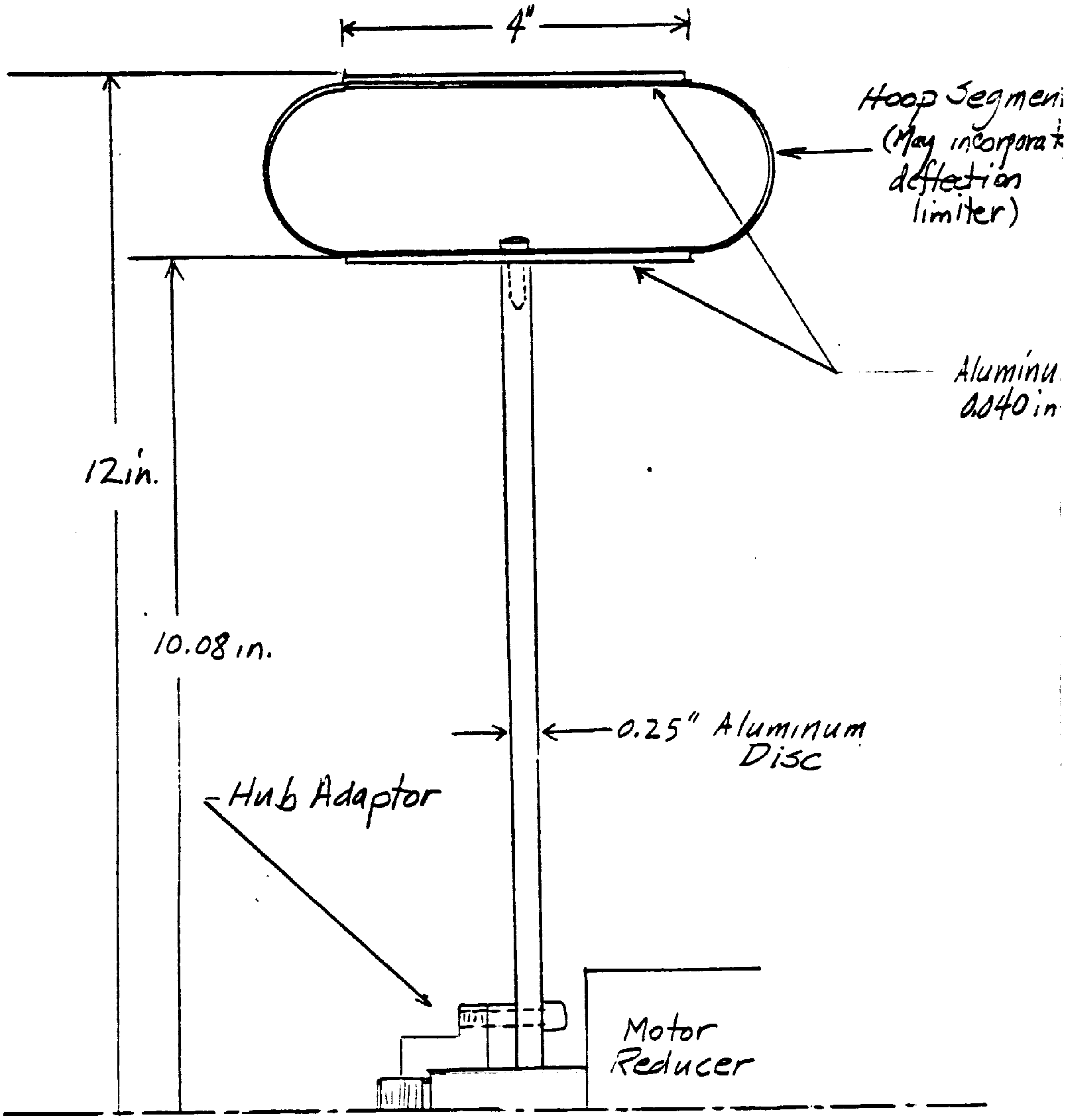


FIGURE 28.

IV. EDUCATIONAL CONSIDERATIONS

This project has inspired considerable enthusiasm and effort among those of our students who are interested more in producing engineering devices that work than in understanding the theory behind engineering devices. The drive of the general student group, inspired and encouraged by student manager Jerome Stockton, to produce an operating vehicle with an operational microwave radar obstacle sensor and a working tactile sensor was well beyond previous groups working on the project. Further, they were able, by reason of much extra effort, to achieve their goals even though they were somewhat short of the totally autonomous vehicle able to navigate to an assigned target through an unknown obstacle field.

The experience of working with other engineers as a team is one somewhat foriegn to our educational system which discourages cooperation to insure that each student has done his own work in order to build his competence. After some hesitation in this new environment, most of the project members enjoyed the priveledge of working together to achieve the project goals. Cooperation between the electrical students and the mechanical students was not as good since they often found themselves attacking the problem in different ways. This was a good experience for both as engineering projects rarely fit just one engineering discipline.

The students have found industry interviewers to be intrigued by their participation in the project. This experience improved their opportunities for employment and will increase their value in their jobs.

The following students worked on the project during the year.

Daniel T. Barry	Undergraduate (Elec.)
Thomas G. Cahill	M. Eng. (Mech.)
David R. Conger	Undergraduate (Elec.)
Shidan Derekshani	Undergraduate (Mech.)
David T. Goodman	Undergraduate (Elec.)
Steven A. Green	M. Eng. (Elec.)
Stanley P. Gross	Undergraduate (Elec.)
Thomas C. Hatch	M. Eng. (Mech.)
Thomas L. Hierl	M. Eng. (Elec.)
William L. Hughes	Undergraduate (Elec.)
John A. Hupcey	M. Eng. (Elec.)
Michael Kornblum	M. Eng. (Mech.)
Rudolph J. Krakes	M. Eng. (Mech.)
Feyyaz M. Kulur	M. Eng. (Mech.)
David P. Lindert	M. Eng. (Elec.)
Robert E. O'Brien	Undergraduate (Elec.)
Douglas G. Pollack	Undergraduate (Elec.)
Ronald L. Quaglia	M. Eng. (Mech.)
Mark D. Riggio	M. Eng. (Mech.)
John Santini	Undergraduate (Elec.)
Michael Spencer	M. Eng. (Elec.)
Kenneth F. Spina	M. Eng. (Elec.)
Jerome R. Stockton	M.S. (Elec.)