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COLLEGE OF ENGINEERING
Cornell University
Ithaca, New York 14850

A Progress Report for
July 1, 1969 to June 30, 1970

CONTROL ELEMENTS FOR AN UNMANNED MARTIAN ROVING VEHICLE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NSR-33-010-055

Submitted by

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February 1, 1971
Revised June 1, 1971

College of Engineering
Cornell University

Abstract

Design development of equipment previously designed and built to perform specified tasks aboard an unmanned roving vehicle was undertaken. These tasks are: obstacle sensing by both a laser sensor and a tactile sensor; obtaining a soil sample and determining the mechanical properties of undisturbed soil; vehicle navigation to enable the vehicle to proceed to a designated destination; and communication links to enable the vehicle to receive commands and transmit data to the controller. The specific objectives accomplished during the period are summarized.

TABLE OF CONTENTS

I. INTRODUCTION

The use of an unmanned roving vehicle to explore portions of the Martian surface appears desirable. A Martian Roving Vehicle (MRV) would allow scientific exploration in areas undisturbed by landing maneuvers and areas unacceptable as landing sites. An autonomous MRV should increase the roving speed since the communications turnaround time is avoided. However, the vehicle must not be allowed to proceed into situations from which it cannot recover.

The primary goals of this project have been to produce a mobile test vehicle which would have properties similar to the most likely MRV, to develop working controls so that this vehicle could be operated remotely, to develop obstacle sensing capability -- both short range and medium range, to develop a navigational ability for the test vehicle to allow autonomous operation of this vehicle, and in addition to develop a soil sampler and tester.

The work of the project is carried out by students in the Master of Engineering program at Cornell under the direction of Professors R. L. Wehe and R. E. Osborne. The students in this interdisciplinary effort are primarily from the mechanical and electrical engineering schools.

II. DEFINITION OF TASKS

A. Obstacle Detectors. Both a short-range tactile obstacle sensor and a medium-range laser rangefinder obstacle detector are being developed. The short-range sensor will back up the medium-range detector for positive obstacles as well as serve as the primary sensor for negative obstacles.

The medium range obstacle detector will allow some evasive action so that positive obstacles will not need to be contacted. This should improve the mobility of the MRV since ideally the rover could proceed through an obstacle field without stopping. A laser rangefinder is being developed to serve this function. The laser beam is scanned by mechanically driven scanning mirrors. The present goal for this device is to detect all objects between 5 and 30 feet (1.5 to 9.1 m) which have a height greater than 30 inches (762 mm).

The short-range tactile obstacle sensor has been conceived as an unpowered wheel pushed ahead of the MRV and rolling in the path to be traversed by the vehicle. The problems with this sensor are those of negotiating obstacles since the sensor must be able to negotiate all obstacles which the vehicle is to negotiate.

B. Soil Sampler-Tester. Samples of soil will be desired at most science stops and in addition tests of soil strength will be desired at many points.

The soil sampler must obtain a sample which is large enough for the soil analysis devices within the MRV. This sample should be free of contamination from the sampler itself and from previous samples. The sampler should provide means for bringing the sample into the cab.

The soil strength tester should provide shear and bearing strength information for study of the planet surface and for possible future rover design.

C. Short-Range Navigation. The short-range navigation task is to design a guidance system to enable the test vehicle to proceed autonomously to a given destination. The present goals of a 200 yard square are to be expanded after a working system has been developed.

D. Communications. A communications system is to be developed to transmit commands to the test vehicle and to return requested data.

III. SUMMARY OF RESULTS

A. OBSTACLE DETECTORS

Both a medium range obstacle detector and a short range obstacle detector are described. The medium range detector uses a laser rangefinder principle with mechanical scanning to locate obstacles over 30 inches (762 mm) in height which lie within 30 feet (9.1m) of the vehicle. The short range detector must contact the obstacle to sense it. The tactile sensor must then be able to negotiate all obstacles which the vehicle can negotiate.

A.1. LASER RANGEFINDER OBSTACLE DETECTOR*

Vertical steps higher than 30 inches, and rising slopes greater than 30° are obstacles that the vehicle is not intended to negotiate. The laser obstacle detector is intended to detect (i.e., locate), such of these obstacles as may lie within a range of from 5 feet to 30 feet away from the vehicle, in a 170-degree sector immediately ahead.

The technique employed involves the use of a laser beam, aimed sequentially across the sector every six degrees, approximately. The transit time of the laser light returned from an obstacle is a measure of the distance to the obstacle. The direction of the beam is determined from a shaft encoder that triggers the emitted laser pulse. The detector is, essentially, a very short-range, low-power radar (see block diagram).

Among the significant accomplishments of the year are:

1. The completion of individual circuits begun earlier.

2. The reduction of rise-times in both the laser-pulser, and the returned-signal detector to levels that do not adversely affect the measurement of the over-all radar-pulse transit time.

3. Reduction of signal noise from dark current, by suitable

selection of circuit parameters; and from the background, by use of a narrow-band optical filter. (See Spectral Response Curves).

4. The improvement of timing circuitry.

5. The testing of the Laser-Receiver sub-system. This was a bench-test including the system housing, but not including the angle-encoder. Responses were obtained from objects having high reflectivity, at close range.

Further work is indicated in several areas:

1. The improvement in alignment of the optics.

2. Laser power increase by use of a more powerful, or a more efficient laser.

3. Increase in the sensitivity of the optical receiver.

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* For a detailed account of activities, see "Electromagnetic Obstacle Detector for Unmanned Extraterrestrial Roving Vehicle" by David R. Dymm, Jim R. Latimer, and Hans-Henrik Sorensen, May 26, 1970.

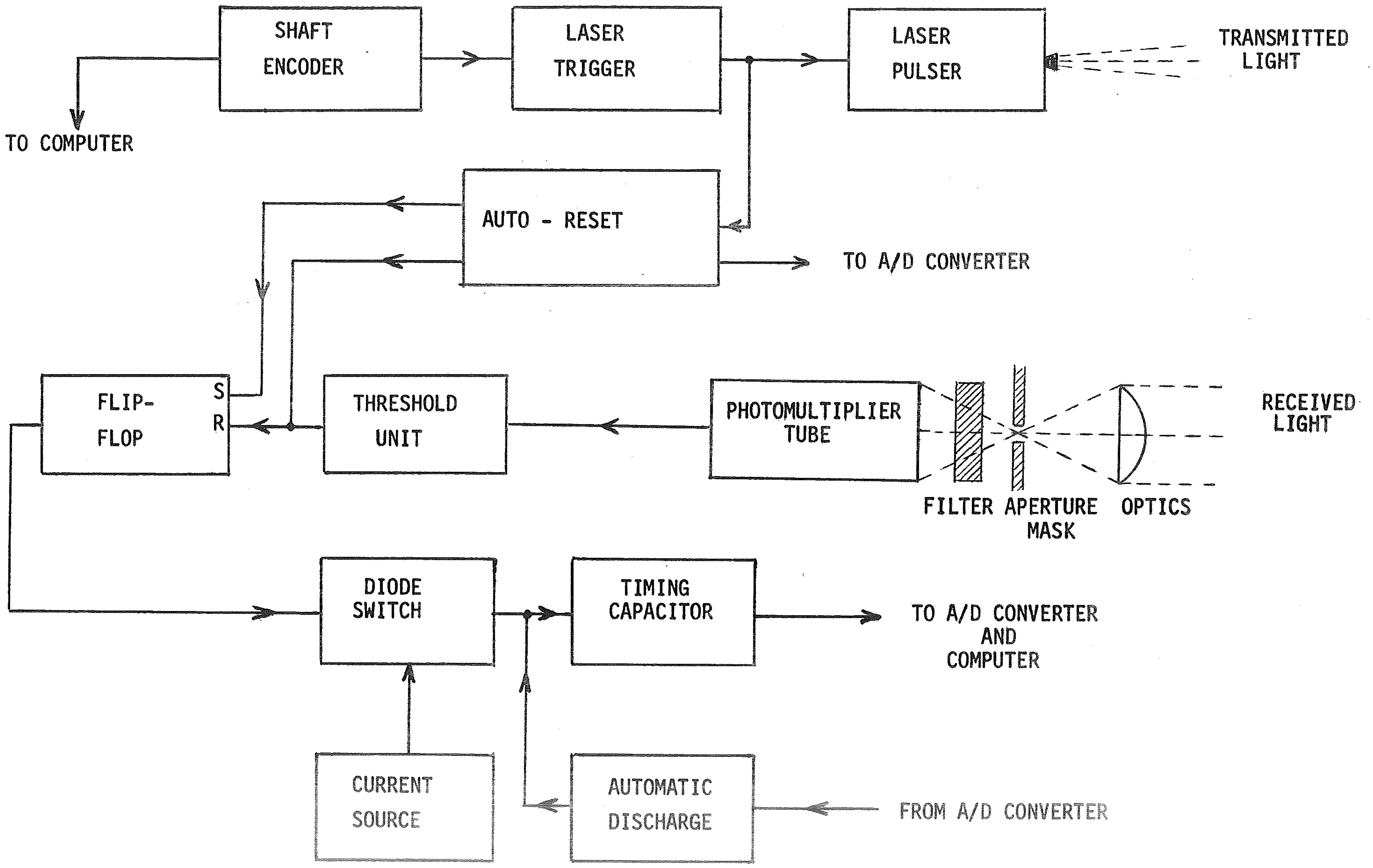

Figure A.1. Block Diagram - Laser Obstacle Detector

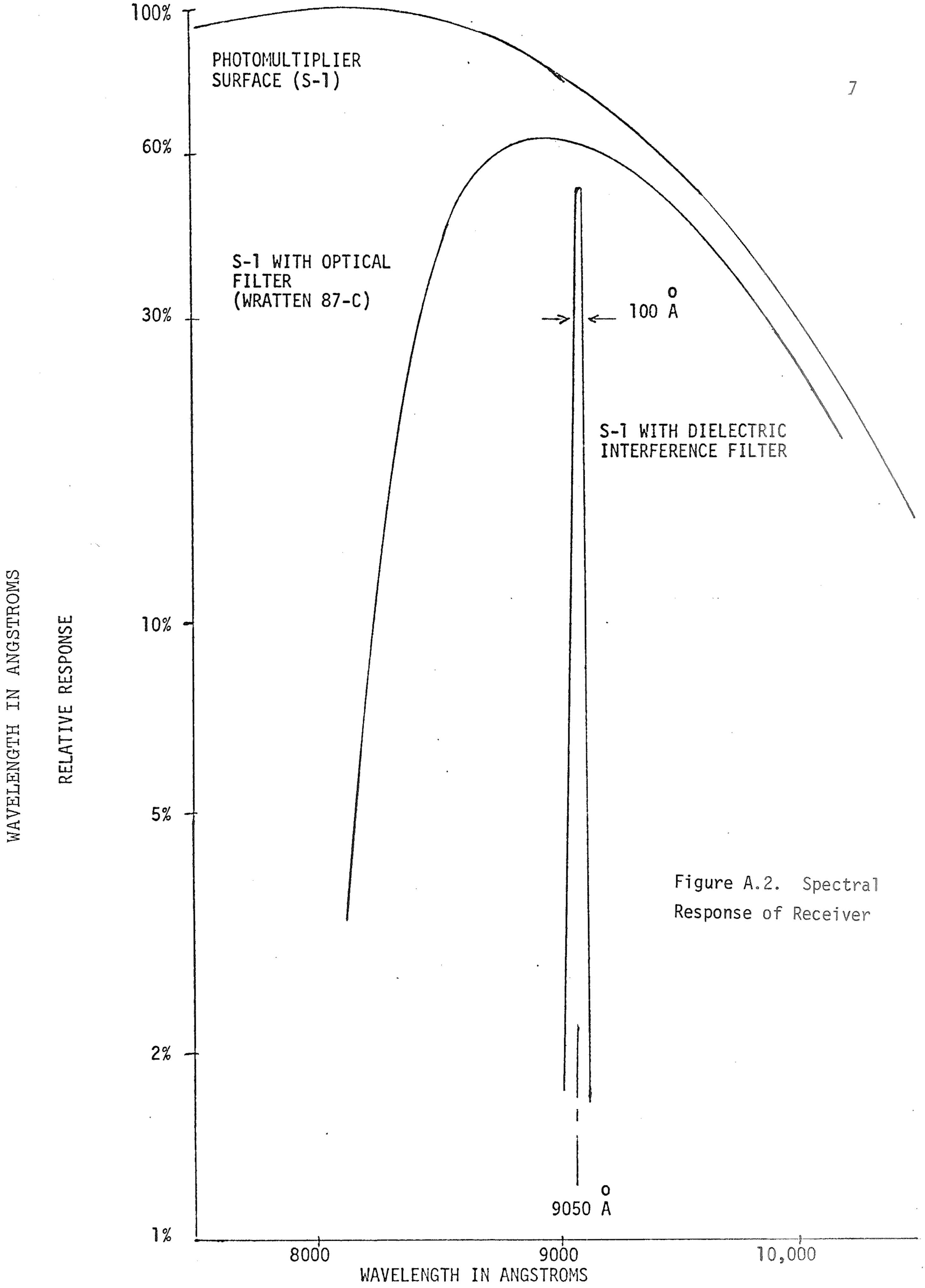

Figure A.2. Spectral Response of Receiver

A.2. Laser Rangefinder Mechanical Scanning Assembly

H.H. Sorensen

The mechanical scanning assembly is shown in Figures A3, A4, and A5. The basic design is of a rotating turret which carries both the laser scanning mirror and the receiver mirror. The driving unit, the laser and the photomultiplier tube are located within the turret support. The laser is off the rotational axis with the beam deflected to the axis by means of two fixed mirrors mounted at the top of the turret. A Fresnel lens is used to increase the received signal at a minimum weight.

In addition to the thin-film filter used to reduce background noise, a mask is inserted at the focal plane which allows only light to pass which is returned from points which the laser beam could hit. The light passing through the mask is then allowed to fall on the photomultiplier tube for sensing.

The current scanner is improved over the previous model in that:

1. Sliding contacts for power and for signal transmission were eliminated by placing the laser on the fixed platform. This was made possible by using mirrors to direct the light path to the turret centerline.

2. The possible scan angle is now 345°.

3. Design simplification resulted in some weight saving. This was done without documentation.

4. The design was made more compact by placing the drive motors inside the turret support.

5. All operating components are inside the turret where they are protected from air-borne dust and sand.

The present mechanical scanning is limited to a single plane relative to the vehicle. Several possibilities exist for scanning over an area in front of the vehicle. Development has not proceeded in this area due to effort being placed on obtaining a dependable single-plane scanning.

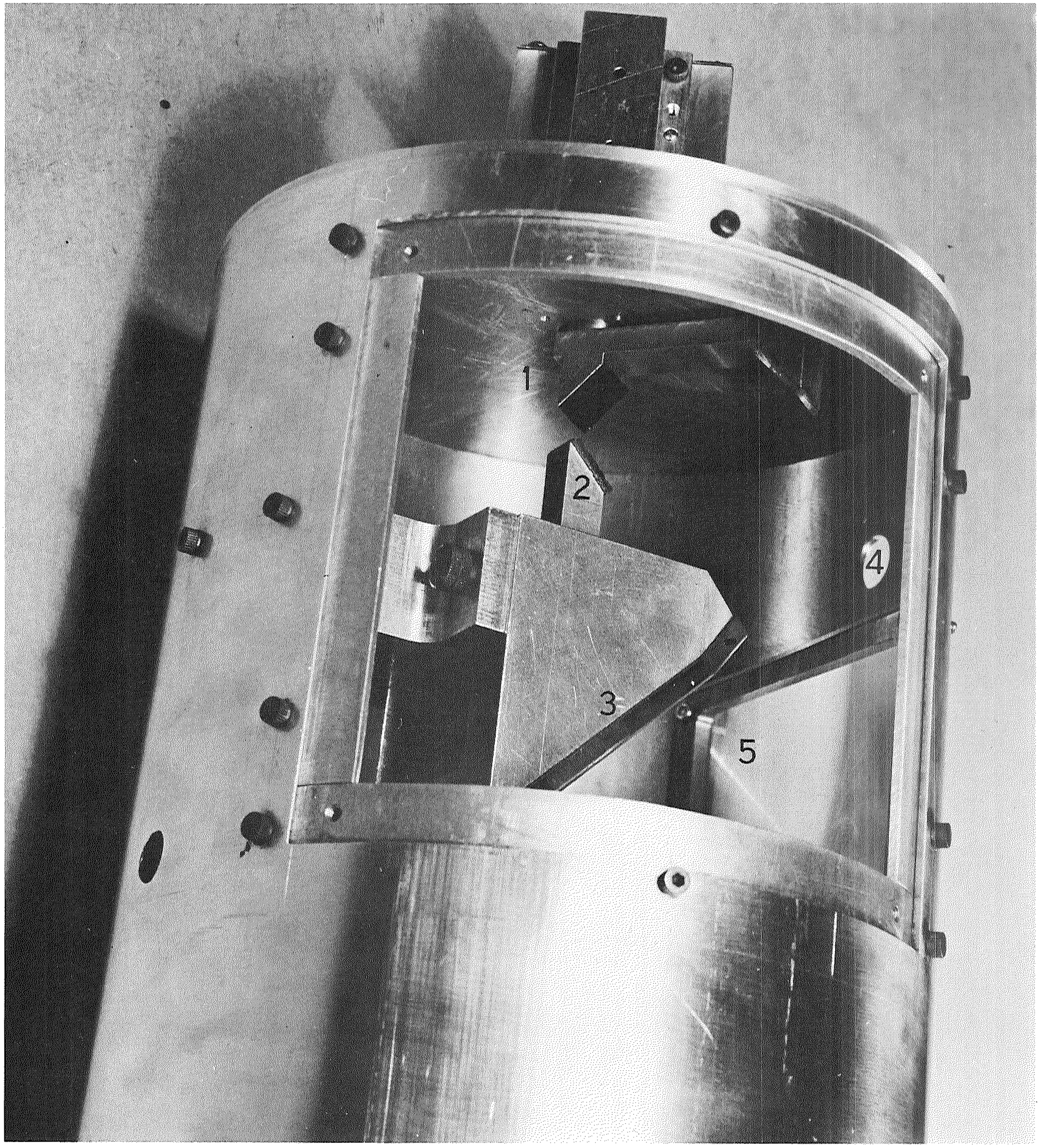

Figure A.3. Laser Mechanical Scanner Interior - (1) Fixed Mirrors, (2),(3) Rotating Mirrors, (4) Laser Beam Exit, (5) Fresnel Receiving Lens.

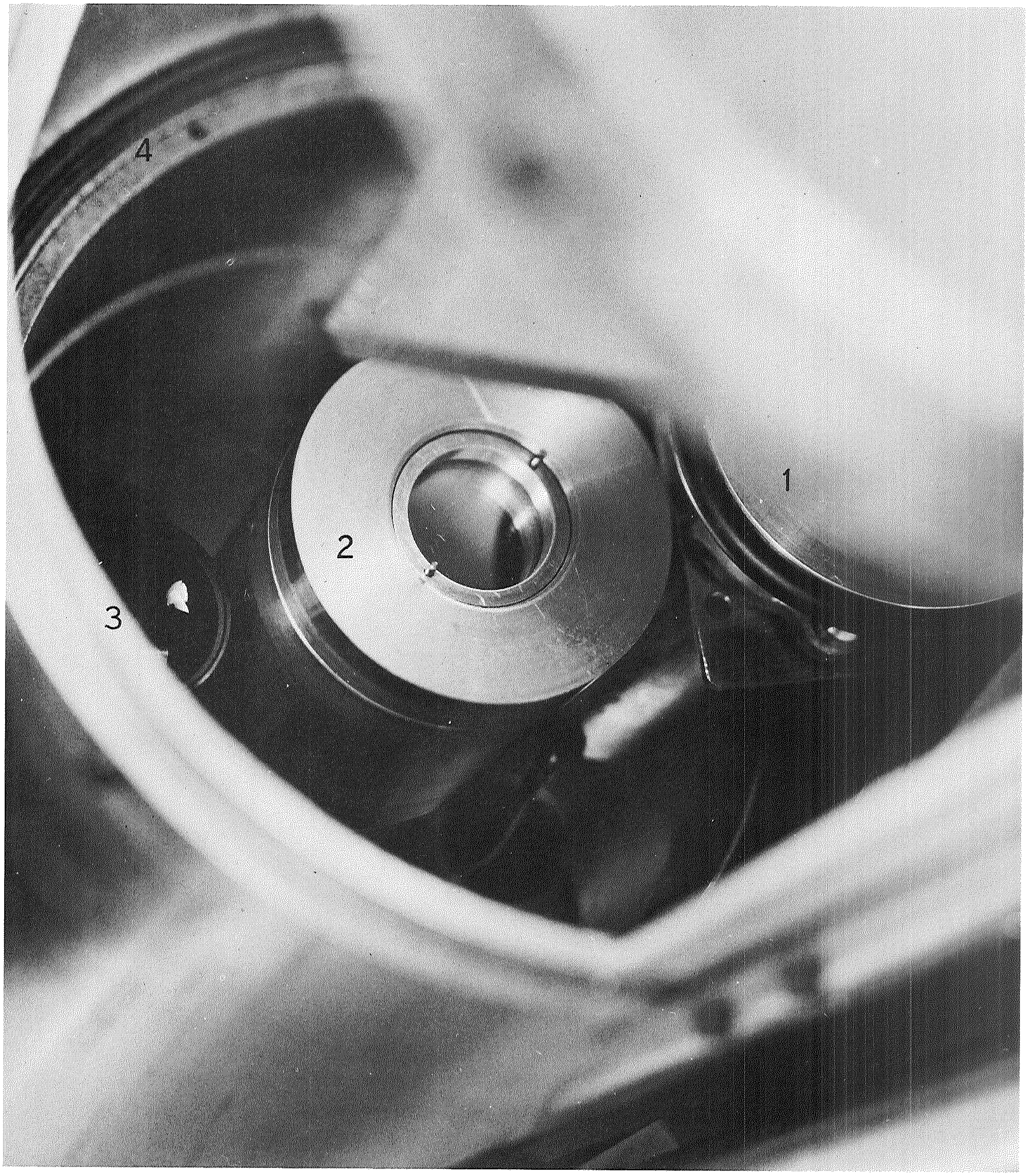

Figure A.4. Laser Mechanical Scanner Interior - (1) Drive, (2) Photomultiplier Assembly, (3) Laser, and (4) Support Bearing.

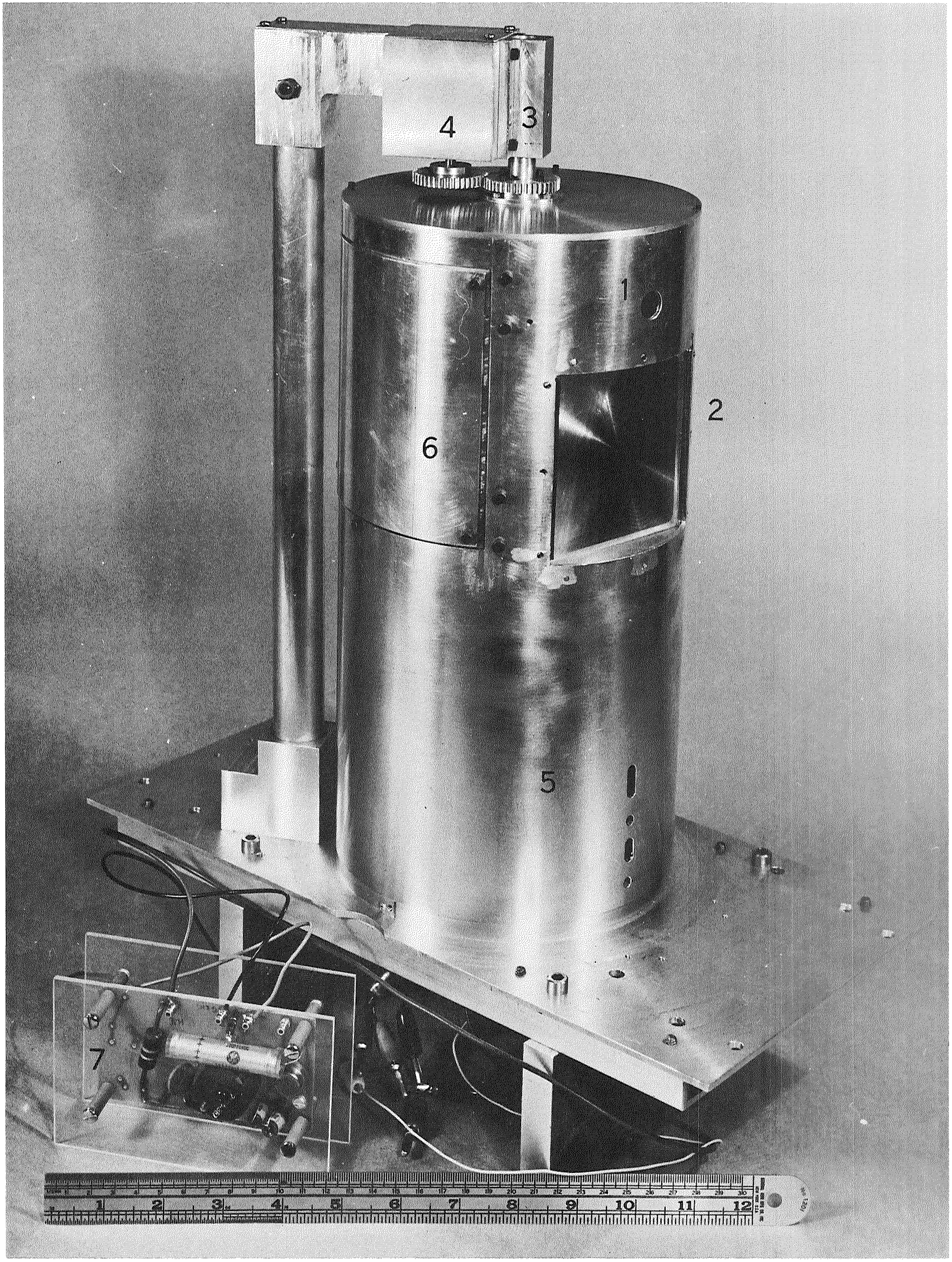

Figure A.5. Laser Mechanical Scanner Exterior - (1) Laser Beam Exit, (2) Fresnel Receiving Lens, (3) Fixed Mirror Support, (4) Encoder Housing, (5) Turret, (6) Access Door, (7) Photomultiplier Power Supply.

A.3. TACTILE OBSTACLE SENSOR*

The tactile obstacle sensor requires no power other than that supplied by the vehicle drive wheels to push it over the terrain. As shown in Figures A.6 and A.7 the sensor consists of an arm mounted on the front carriage by a pivot. The arm is allowed to slide relative to the pivot against a constant force spring. At the outer end are a bumper and a spring pivot assembly. The spring assembly resists deflection of the forearm to which is mounted the sensor wheel.

When the sensor strikes an obstacle greater than 30 inches (762 mm) the arm is forced back against the constant-force springs. When this occurs, a microswitch opens the circuit to the drive motors. The spring will stop the vehicle gradually. One difficulty experienced with this design is that the arm may be moved back by obstacles less than 30 in. (762 mm) thus stopping the vehicle even though the obstacle could be negotiated.

A pictorial sequence of the sensor satisfactorily negotiating a 25 in. (635 mm) obstacle in a straight-on approach is shown in Figure A.7. There are still many obstacles which the sensor cannot handle successfully. Further development of the tactile sensor is planned to improve its performance.

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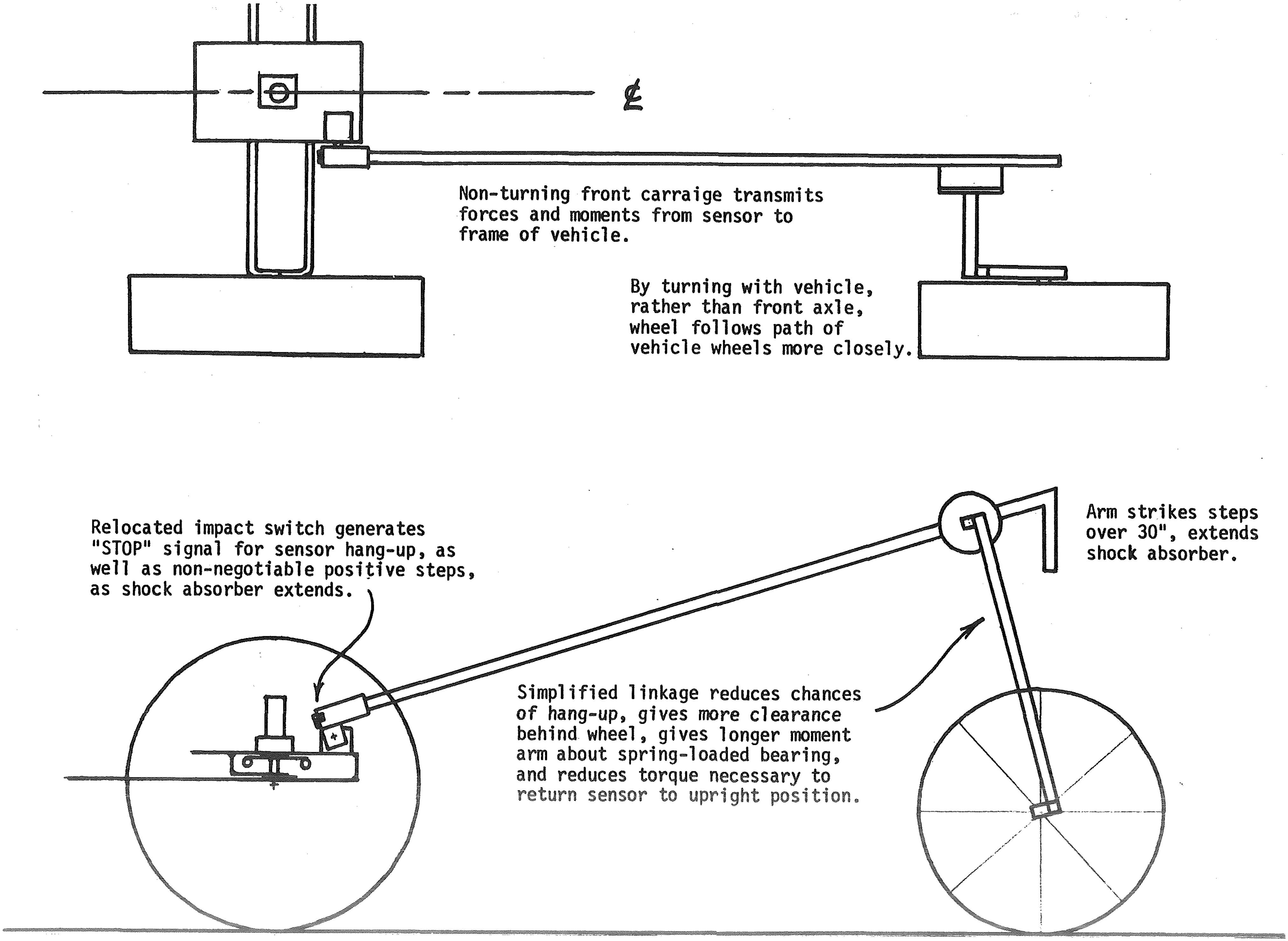
* "A Tactile Obstacle Sensor For An Unmanned Extraterrestrial Roving Vehicle", Ralph Brooks, Jr., June 1, 1970.



Non-turning front carraige transmits forces and moments from sensor to frame of vehicle.

By turning with vehicle, rather than front axle, wheel follows path of vehicle wheels more closely.

Relocated impact switch generates "STOP" signal for sensor hang-up, as well as non-negotiable positive steps, as shock absorber extends.

Arm strikes steps over 30", extends shock absorber.

Simplified linkage reduces chances of hang-up, gives more clearance behind wheel, gives longer moment arm about spring-loaded bearing, and reduces torque necessary to return sensor to upright position.

Figure A.6. Redesigned Electromechanical Obstacle Detector and Non-Turning Front Carriage

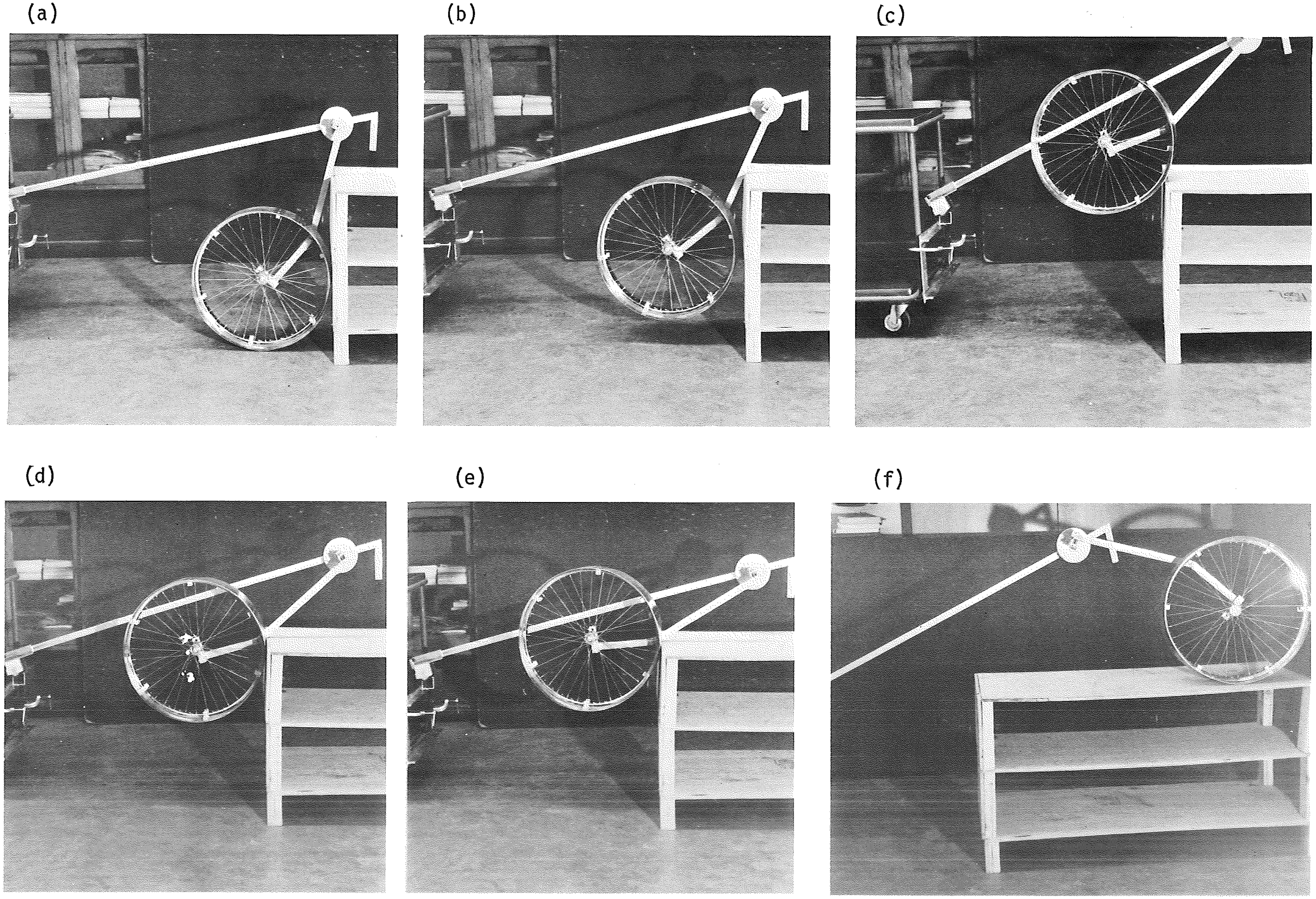


Figure A.7. Tactile Sensor Negotiating a 25 in. (635 mm) Obstacle

B. THE SOIL SAMPLER-TESTER

S.B. TROY

D.R. WAGLE

R.D. POLLAK

The soil sampler-tester has three functions (1) obtaining a soil sample, (2) determination of soil shear strength and, (3) determination of soil bearing strength. The three tasks are carried out by separate devices mounted on the crosshead of the deployment device as shown in Figure B1. The three tasks have been worked on separately by the team members and will be so presented.

The soil sampler head is shown in Figures B2 and B3 . The plate containing the scoop blades is hinged to allow dumping of the sample. Dumping takes place as the deployment device brings the crosshead up to where the pressure lever contacts the pressure plate. This results in compression of the pressure plate spring until the latch is tripped. The pressure lever has previously caused the catcher to open out under the sampler head. Downward motion of the crosshead allows the spring to close the scoop plate. Pictures of the sampler in operation are shown in Figures B4 and B5 . Limited operational tests indicate some success but definite problems remain to be solved such as sample size, intra-sample contamination and fouling of the mechanism by particular soils.

The vane shear tester operates by determining the reaction torque as the vane head, Figure B6, which has been driven into the soil by the crosshead descent, is slowly rotated. The reaction torque is resisted by an extension spring acting on a lever attached to the reaction member. This system results in a non-linear rotation of the reaction ring with

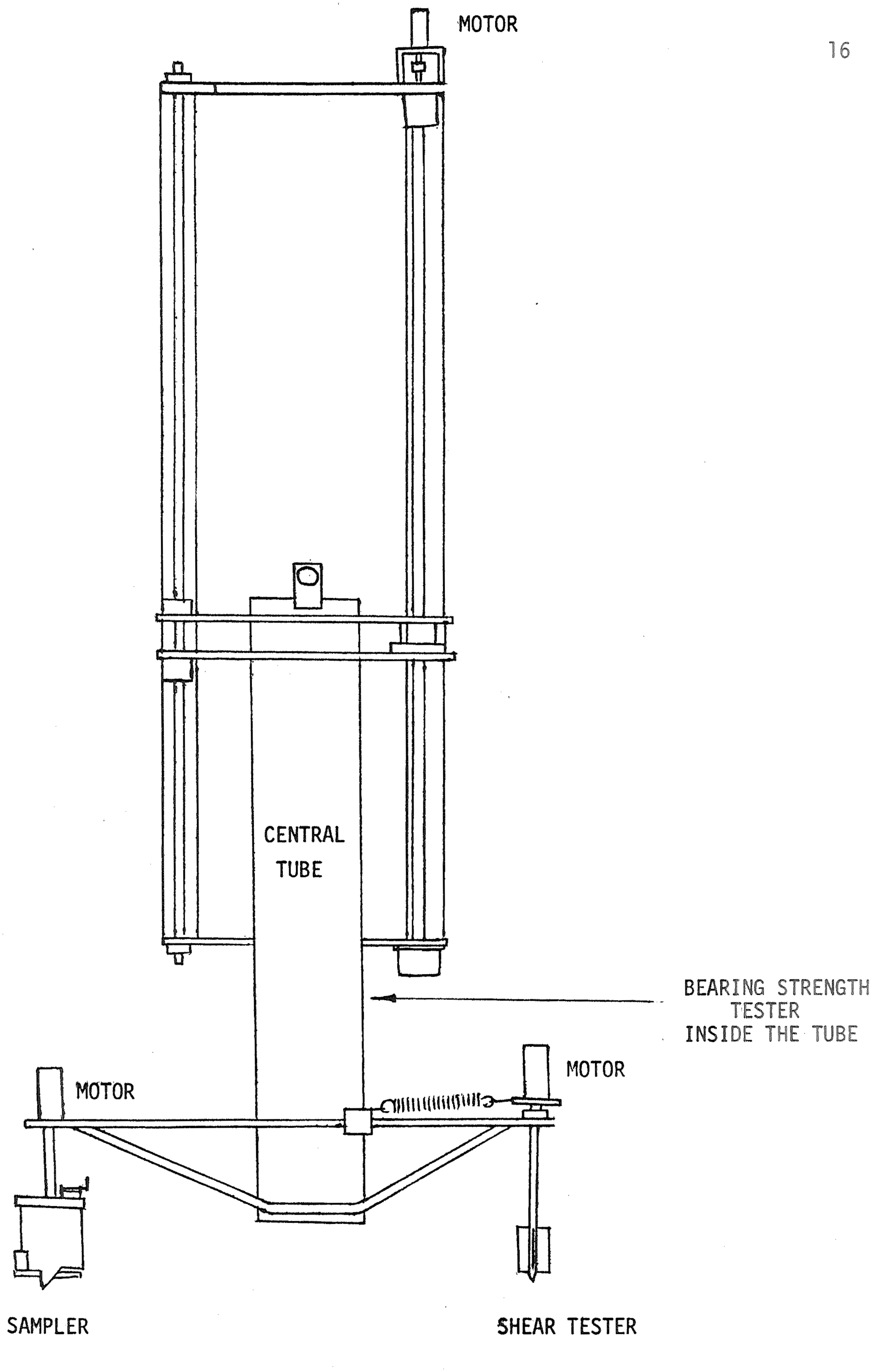


Figure B.1. Soil Sampler Tester

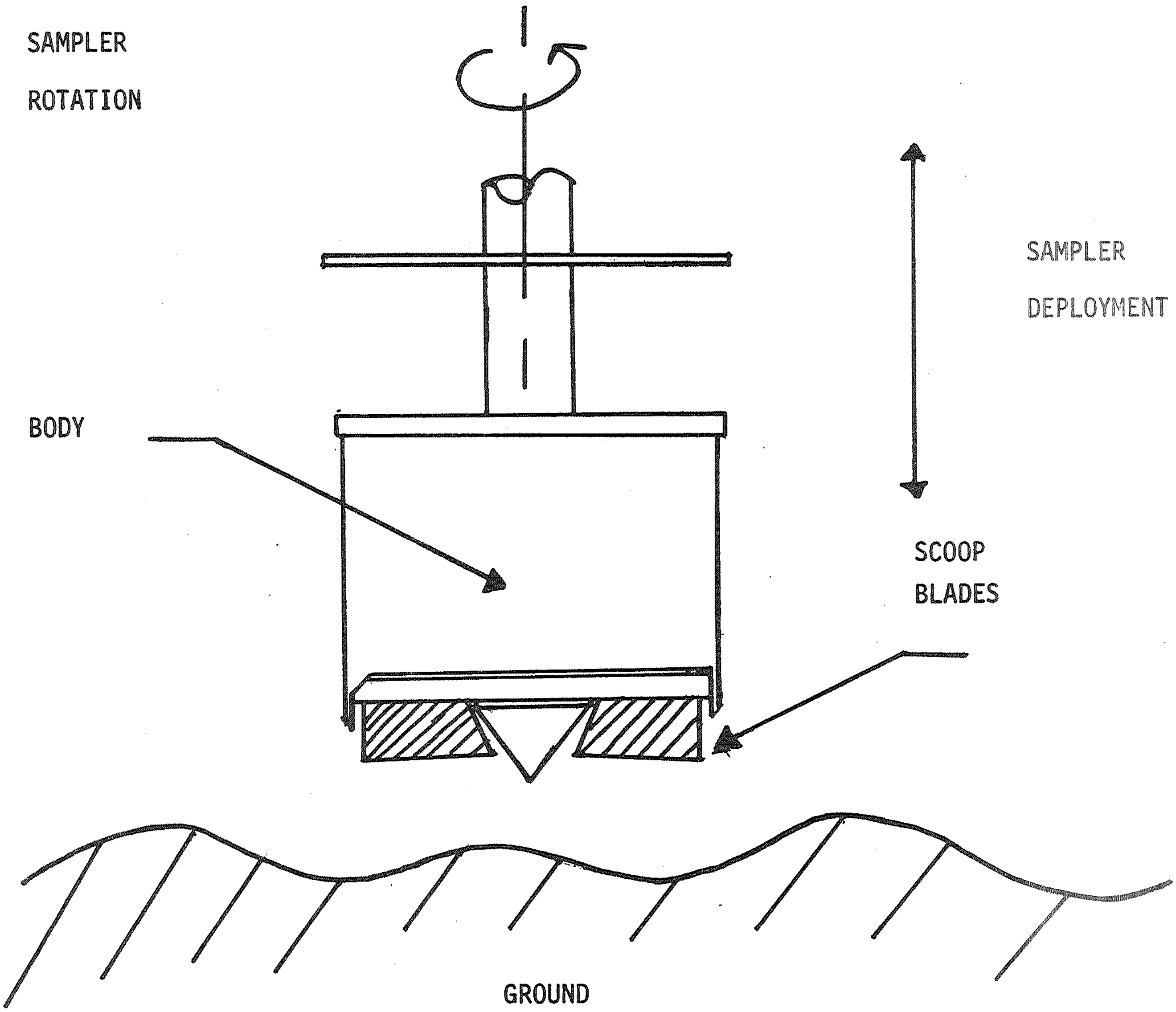


Figure B.2. Soil Sampler

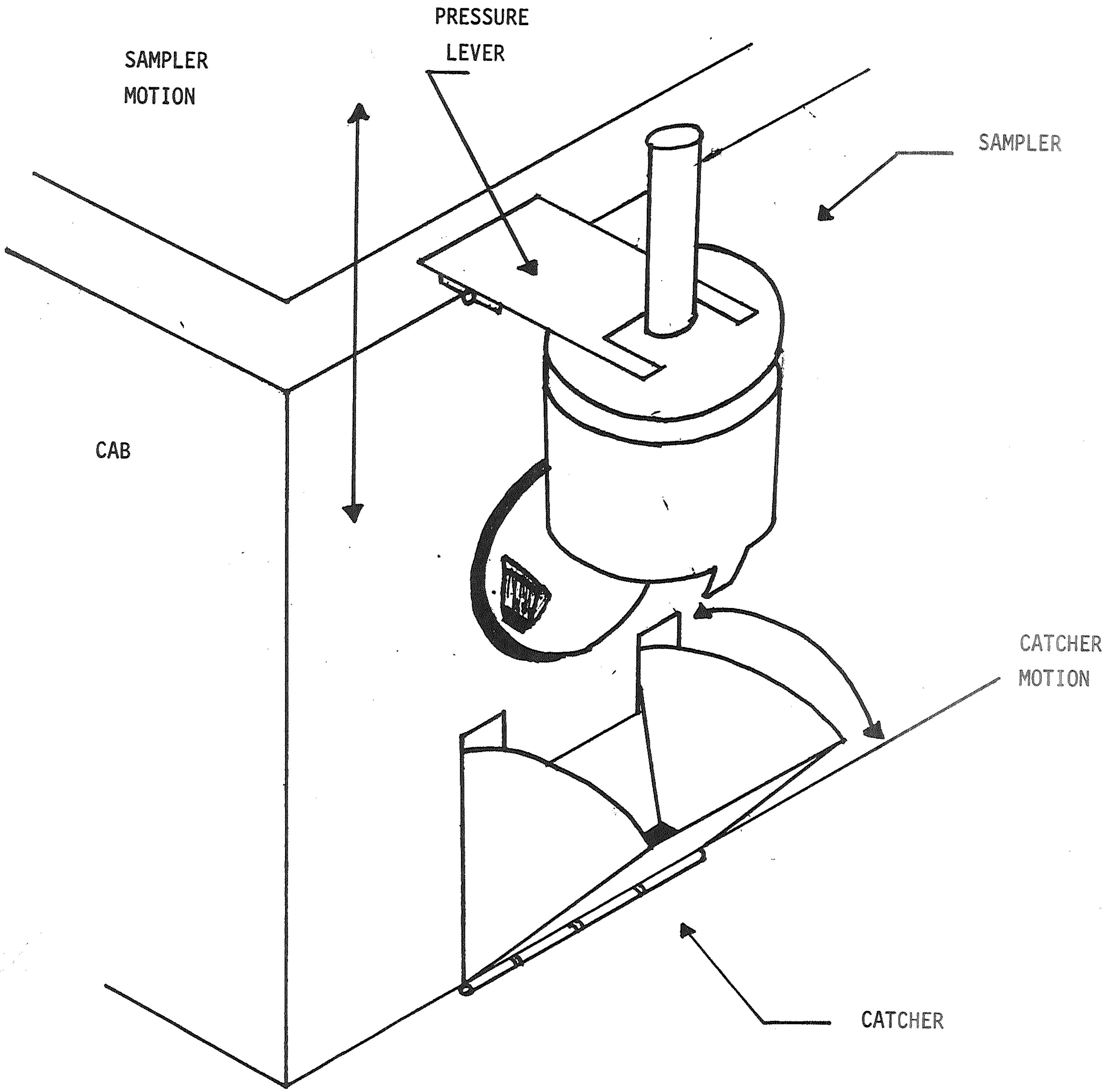


Figure B.3. Catch Sample Volume

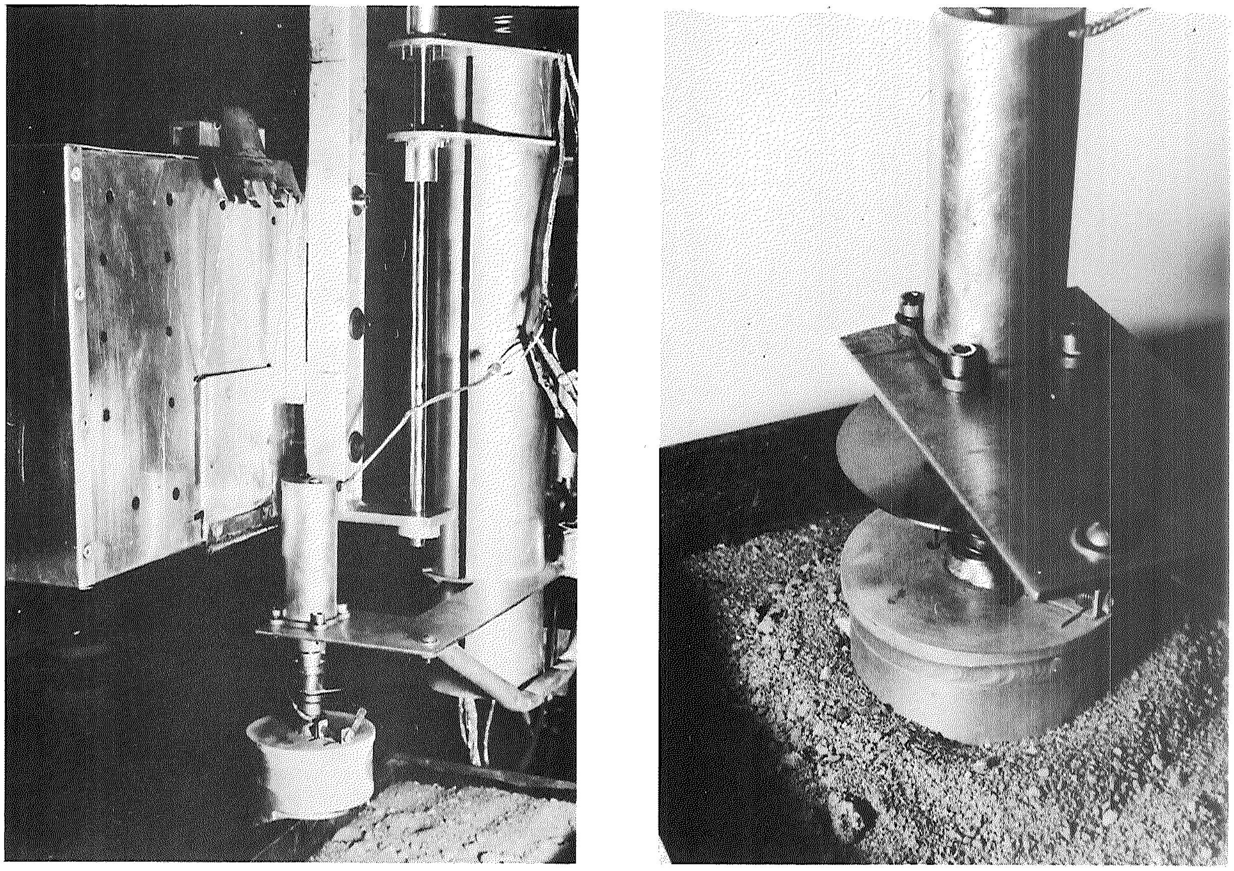


Figure B.4. (a) Sampler being lowered to soil by deployment device.

(b) Picking up Sample.

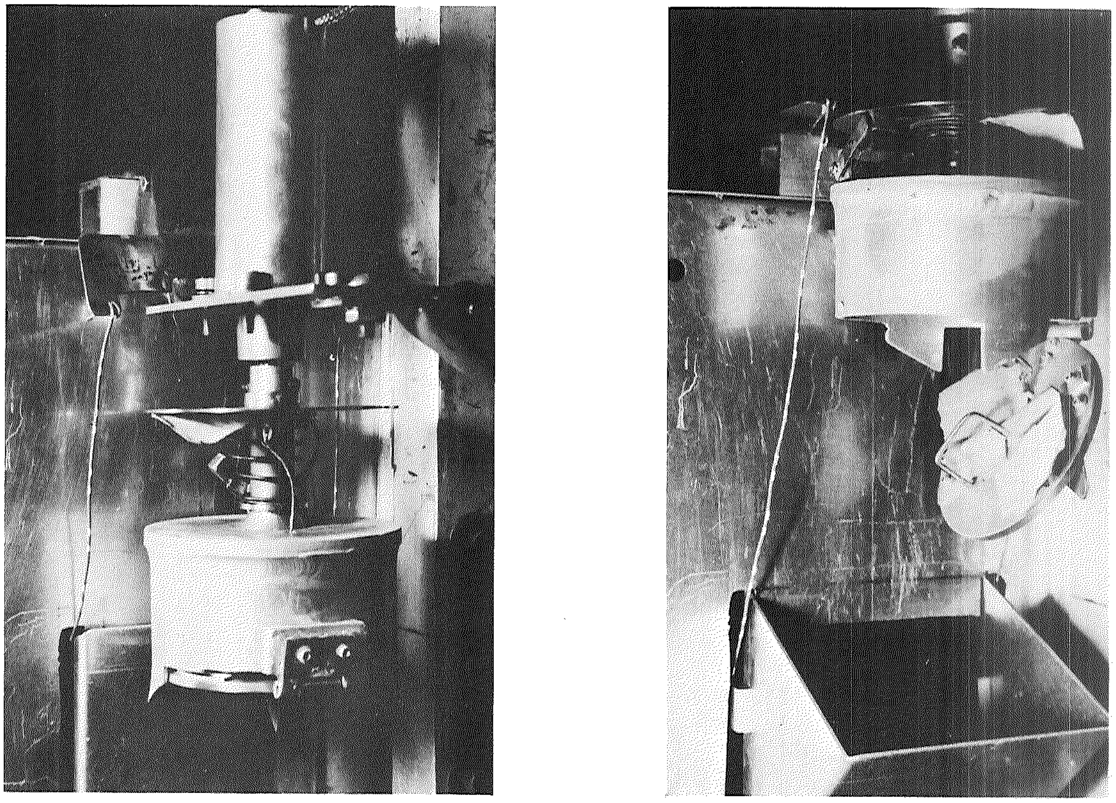


Figure B.5. (a) Sampler intercepting cab opening and dumping device.

(b) Cab collector door open and sampler dumped.

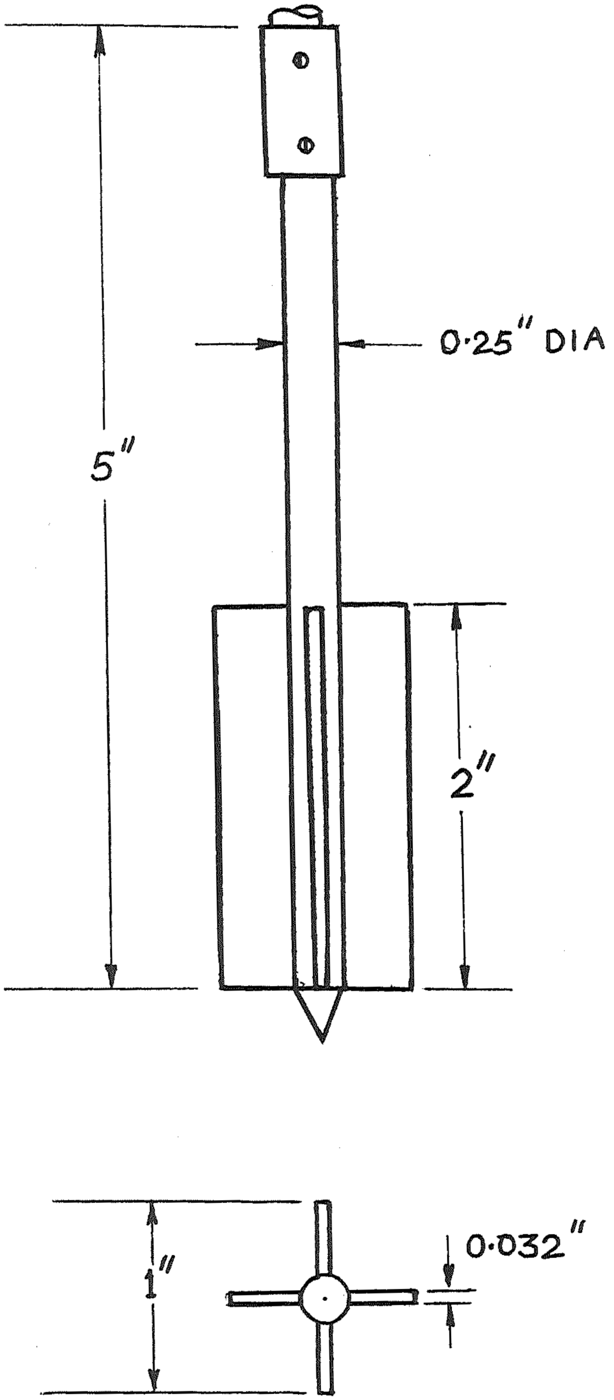


Figure B.6. Vane Borer Shear Tester

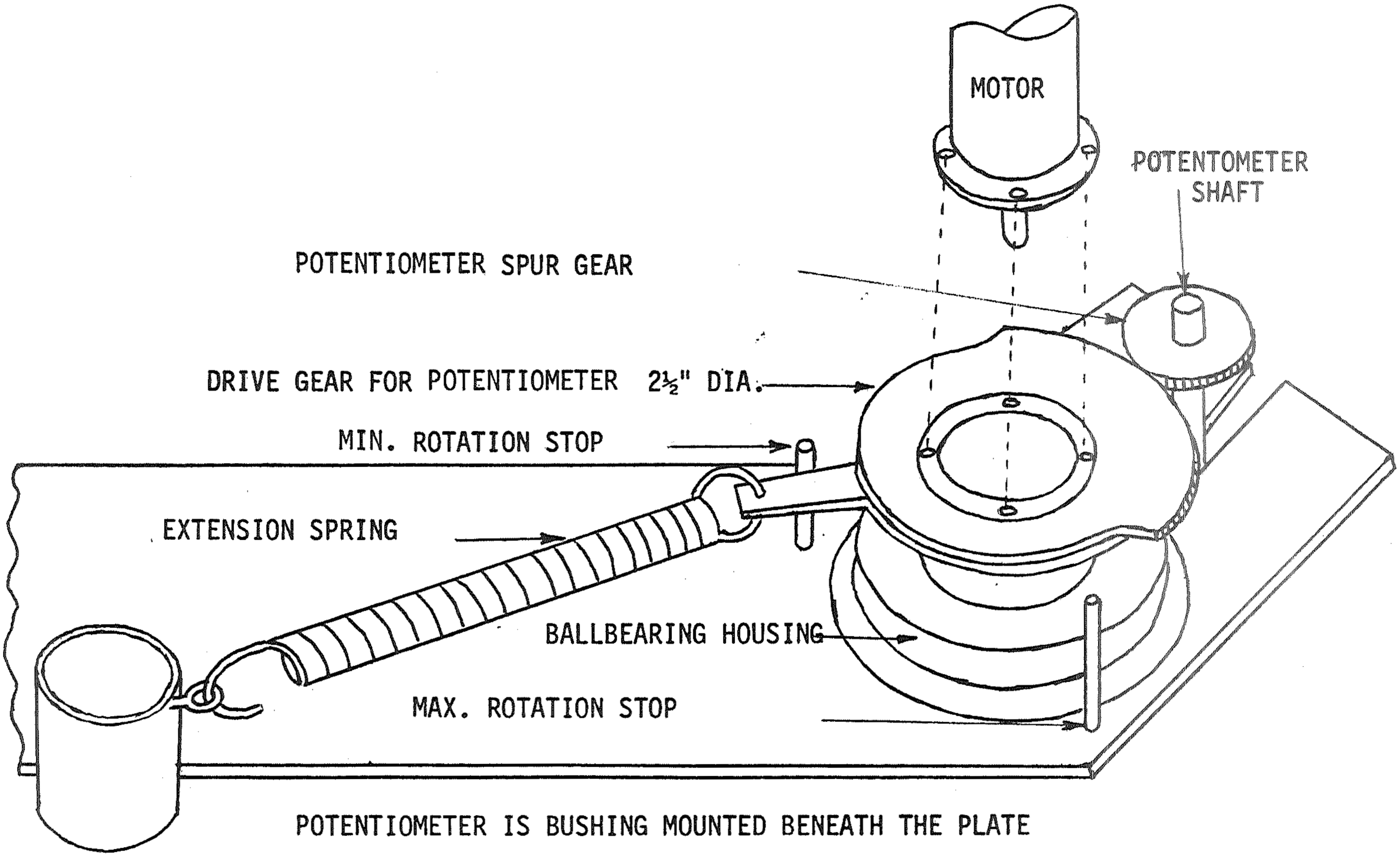


Figure B.7. Vane Borer Shear Tester
Top (Torque) Measuring Section

increasing torque. The ring rotation is carried to a potentiometer by a segment gear and pinion. The non-linear response has been chosen to increase the relative output for low torques at the expense of output for higher torques. The relative sensitivity remains nearly constant with this arrangement. The calibration curve, Figure B8 shows the non-linear response.

The force necessary to drive the vane borer head into the soil is sufficient to cause considerable tipping of the rear cab when the Sampler-Tester is mounted on the back of the rear cab. It will be necessary to alter the design to avoid this problem. Several solutions will be explored including a new vane borer head, and moving the test unit nearer to the cab center of gravity.

Determination of the soil bearing strength presents considerable problems if the device is to be mounted to a flexible vehicle. Even the impacting tester requires a reaction force which will result in tipping motions which will invalidate results. Typical load-penetration curves are shown in Figure B9 . The soil shear diagram under a plunger being forced into the soil is shown in Figure B10. The failure of soil under bearing loads is a shear failure, and it may be possible to predict load-carrying ability without having to drive a plate into the soil - either by steady force or by impacting. This possibility will be further explored.

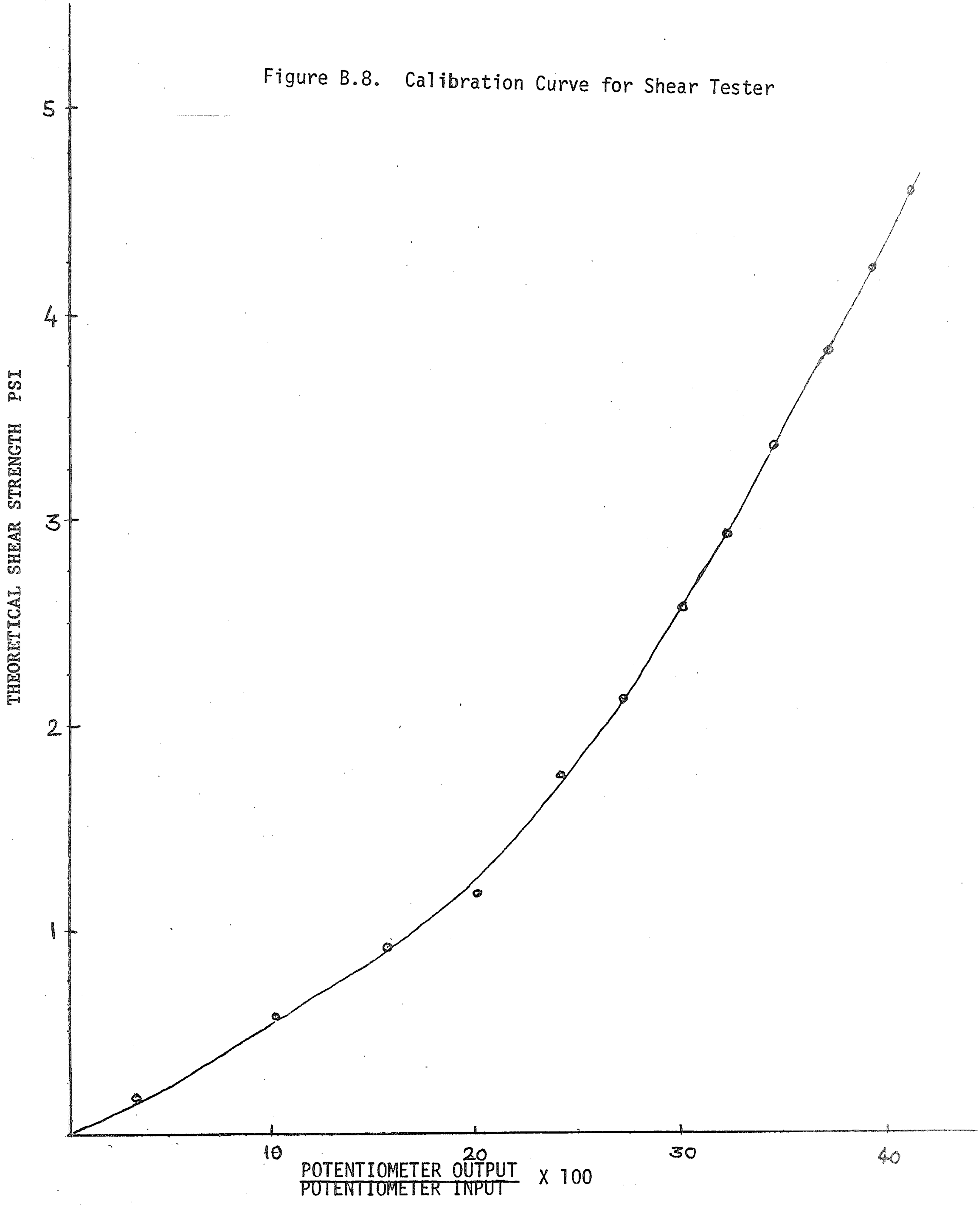


Figure B.8. Calibration Curve for Shear Tester

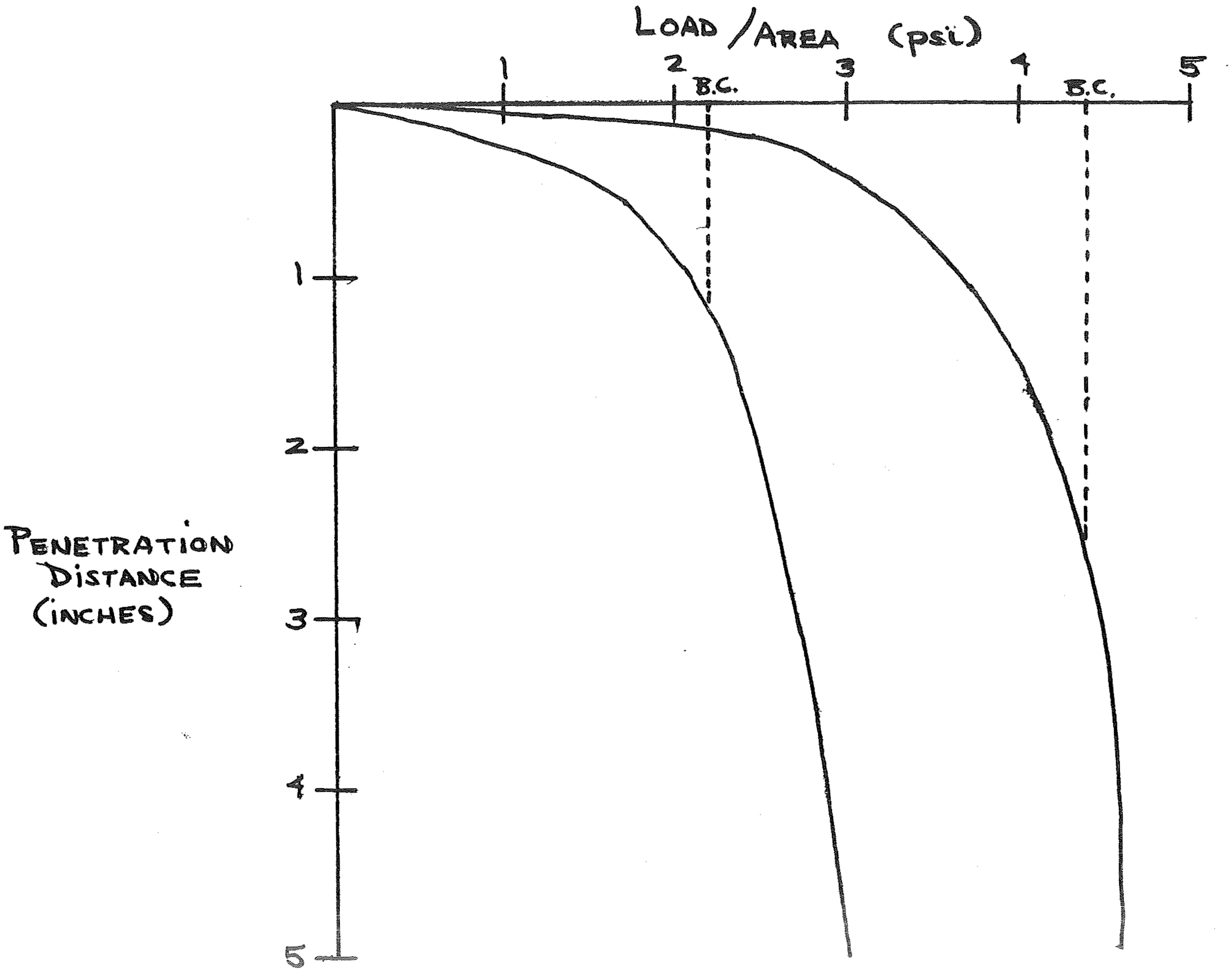


Figure B.9. Penetration Vs. Load

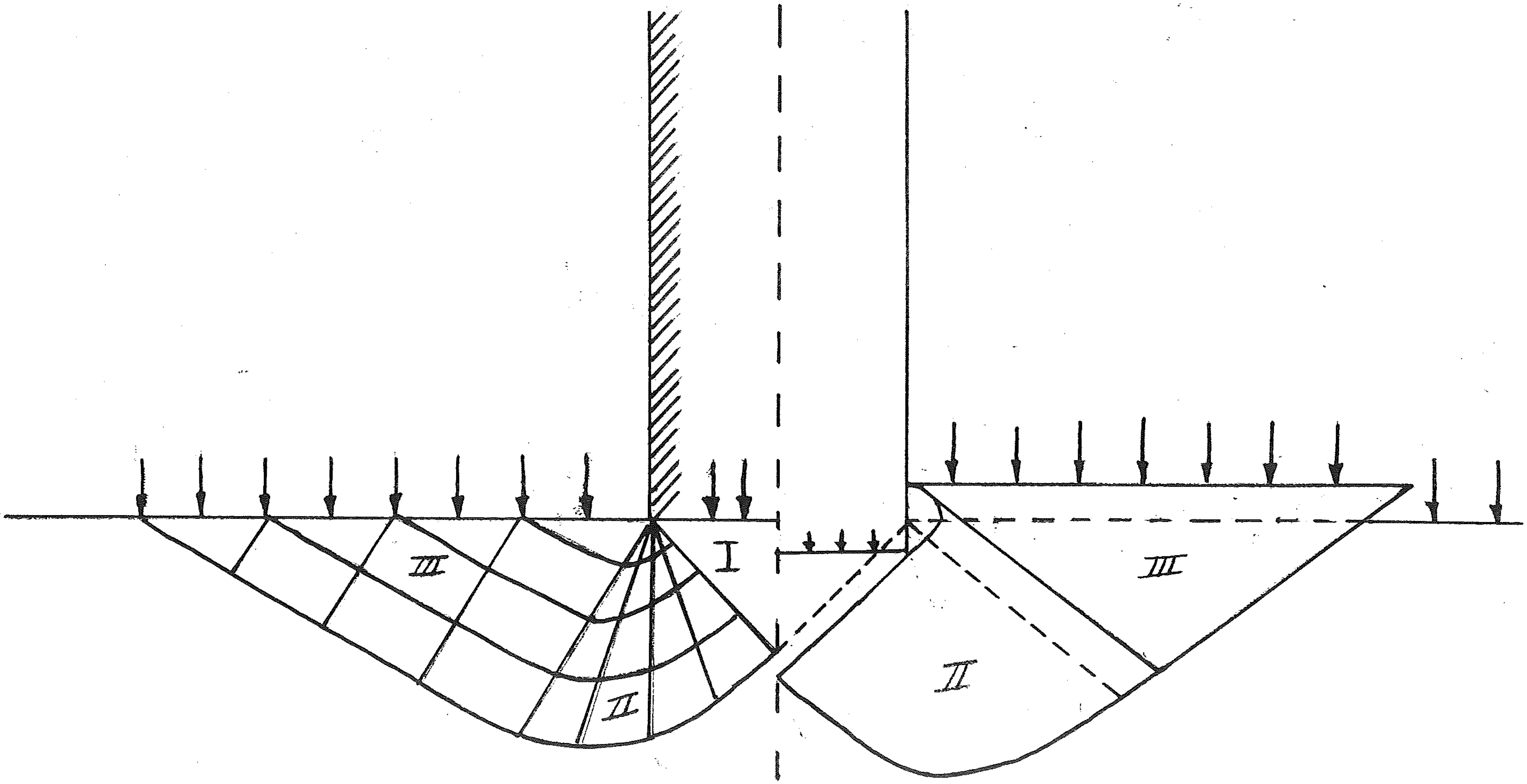


Figure B.10. Soil Shear Diagram Under Bearing Plate

C. NAVIGATION SYSTEM*

The navigational scheme utilizes a Cartesian co-ordinate system, in which the target is located at the origin, and the original position of the vehicle is on the Y-axis, headed directly toward the target. Since direct progress toward the target may be blocked by obstacles, both X and Y components of the motion must be accounted for. Heading direction is determined from the output of a gyroscope; distance travelled is in terms of wheel circumference. Progress is processed and stored in the Navigation section of the computer, and is up-dated with every revolution of the wheel. The computer must determine the best clear path, and issue commands to the motion controls to cause that path to be followed. See the Block Diagrams for Heading Detection and Computer Operation.

During the year, the path-finding algorithm was refined, a vertical attitude warning scheme was developed, and work on the Navigation section of the computer was advanced. Such tests on the computer as were possible in the absence of other computer input sub-systems, were successful.

The use of a strapped-down gyro for directional reference was studied by setting up a terrain modelling computer simulation. The true heading was determined from a relationship derived by H. Shuster.

$$\text{TAN}\ \beta = \text{TAN}\ \alpha\ \text{COS}\ \phi\ \text{SEC}\ \theta - \text{SIN}\ \phi\ \text{TAN}\ \theta$$

β = Indicated Angle

α = True heading angle

ϕ = Roll

θ = Pitch

The work on this phase of the study is continuing.

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* For a detailed account of activities, see "Navigation Computer" by Barry D. Weeks, May 27, 1970; "Heading Detection System for an Unmanned Mars Roving Vehicle" by Walter E. Knapp and Maresh C. Jain, 20 May 1970.

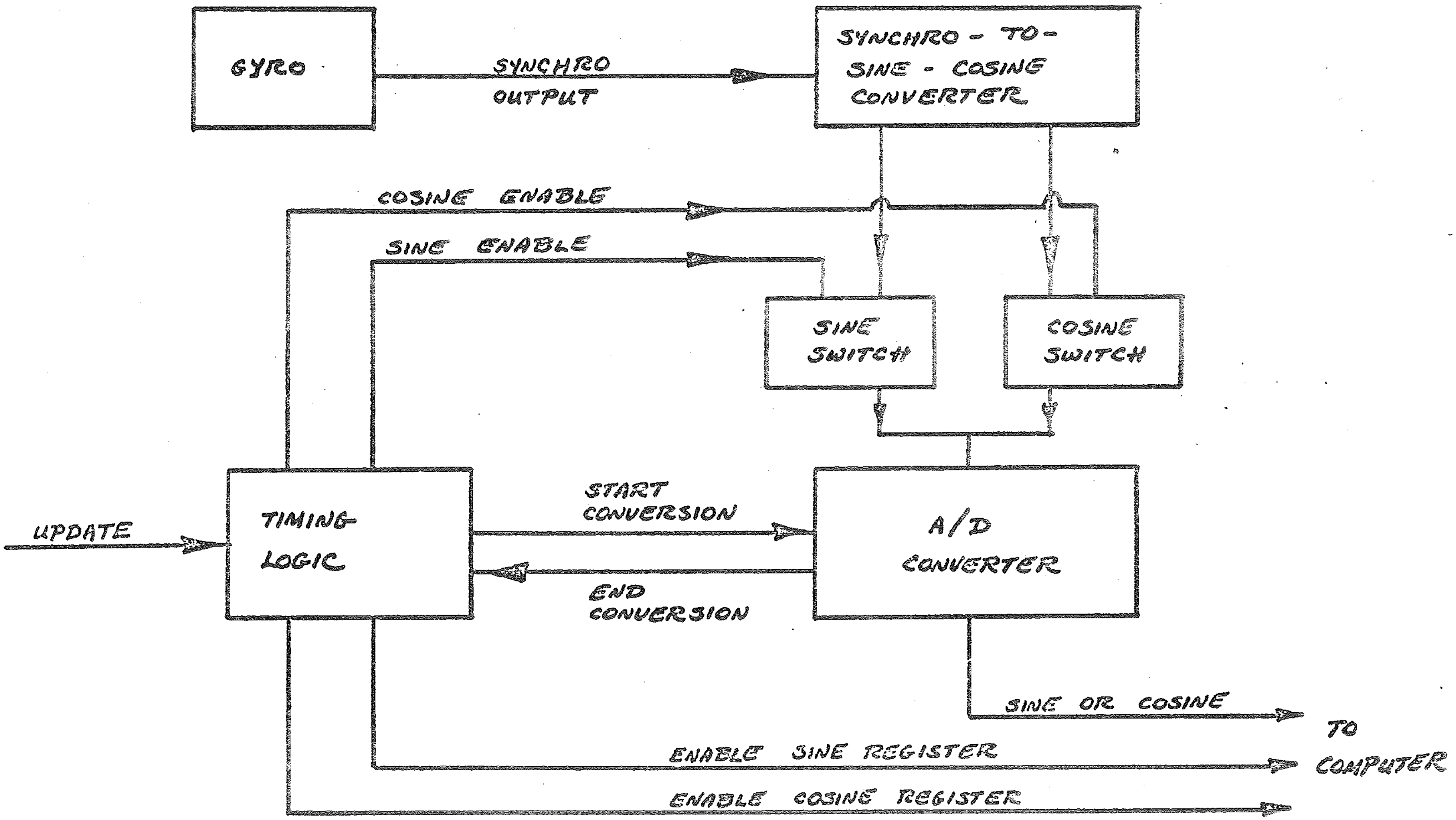


Figure C.1. Heading Detection System

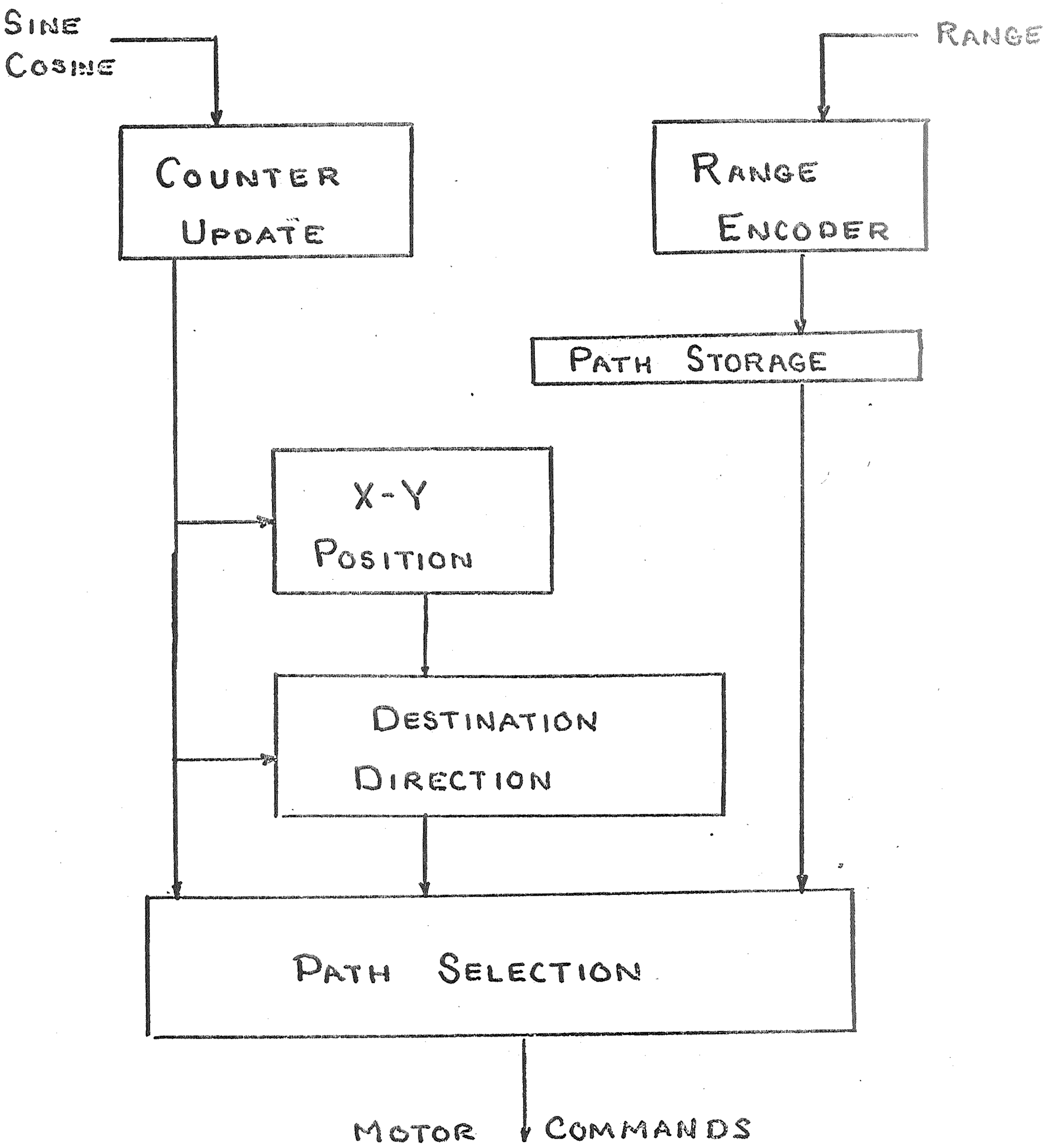


Figure C.2. Computer Operation

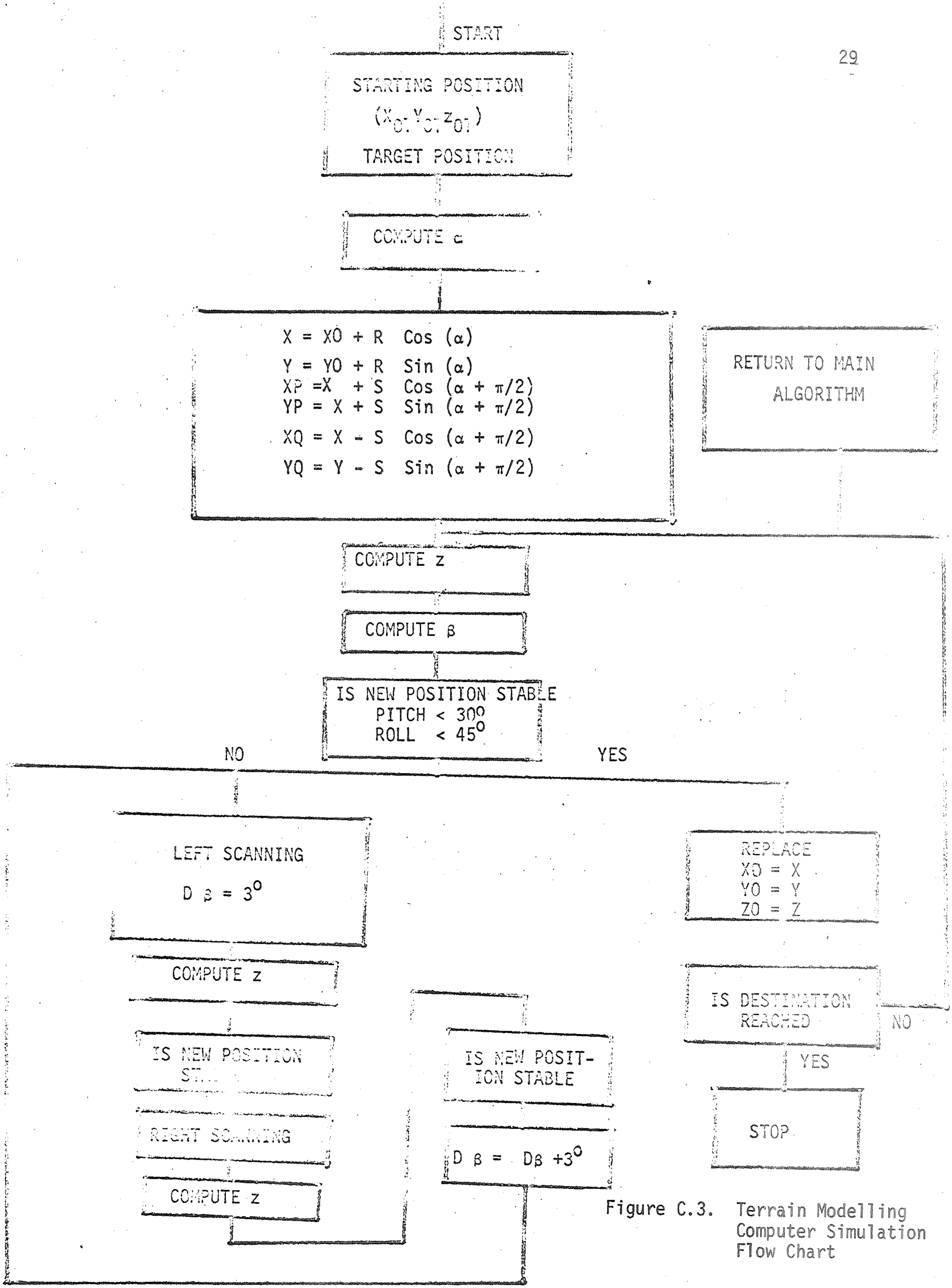
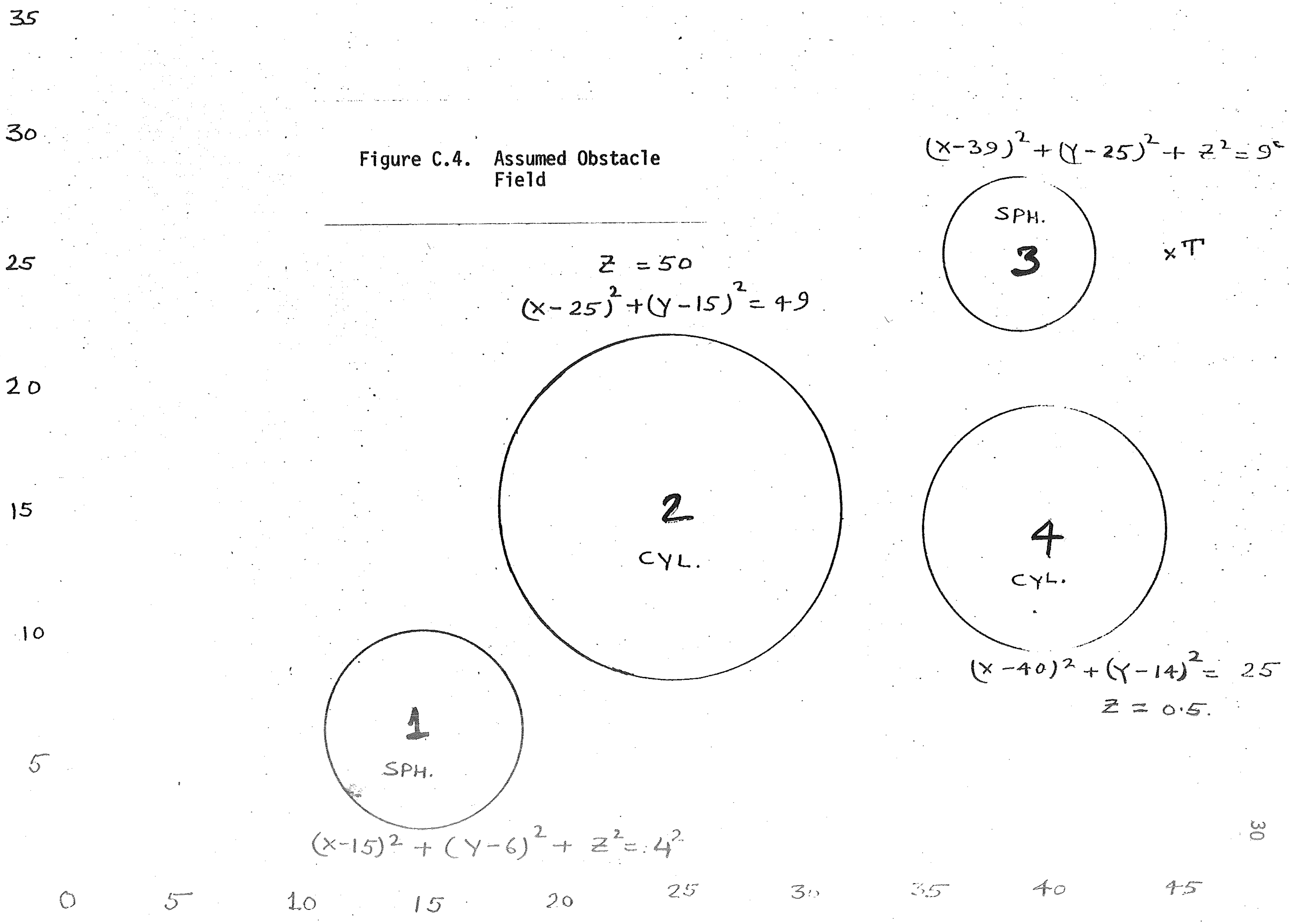


Figure C.3. Terrain Modelling Computer Simulation Flow Chart

Figure C.4. Assumed Obstacle Field



D. COMMUNICATION SYSTEMS

The effort in the communications area was divided into two parts: The up-link, for carrying destination co-ordinates, and initiating-command signals from a base station to the vehicle, and the down-link for returning information determined by the scientific packages, and information pertaining to the vehicle's functioning back to the base.

The up-link(1) utilizes a binary pulse-code-modulation/amplitude modulation, citizen's-band walkie-talkie, in which information bits are transmitted as audio-tone signals. Different modulating frequencies are used for commands, and for co-ordinates. There are 32 possible commands, each encoded as a 9-bit sequence. The transmission and decoding time is 1/2 second. Reliability of transmission under interference conditions is enhanced by use of start-stop synchronization, a parity bit, a 3-bit alert code, and dual sampling of bit intervals. The up-link system, and both transmitter and receiver-decoder were operational and demonstrated at the Spring Review. See Receiver and Transmitter Block Diagrams.

The down-link(2) effort was carried out during the Spring term only, and was directed toward the design, construction, and testing of a cyclic Hamming encoder and decoder. A thorough-going study of coding was made, resulting in the adoption of a cyclic Hamming (7.4) code. The system was built, tested, and displayed at the Spring Review. See Subsystem Organization and Encoder-Decoder block diagrams

(1) "Up-Link Command Telemetry System for a Proto-Type Unmanned Extra-terrestrial Roving Vehicle" by G. Burnell Hohl.

(2) "Down-Link Subsystem" by R. Klein, D. Leeper, and E. Wild, June 1970.

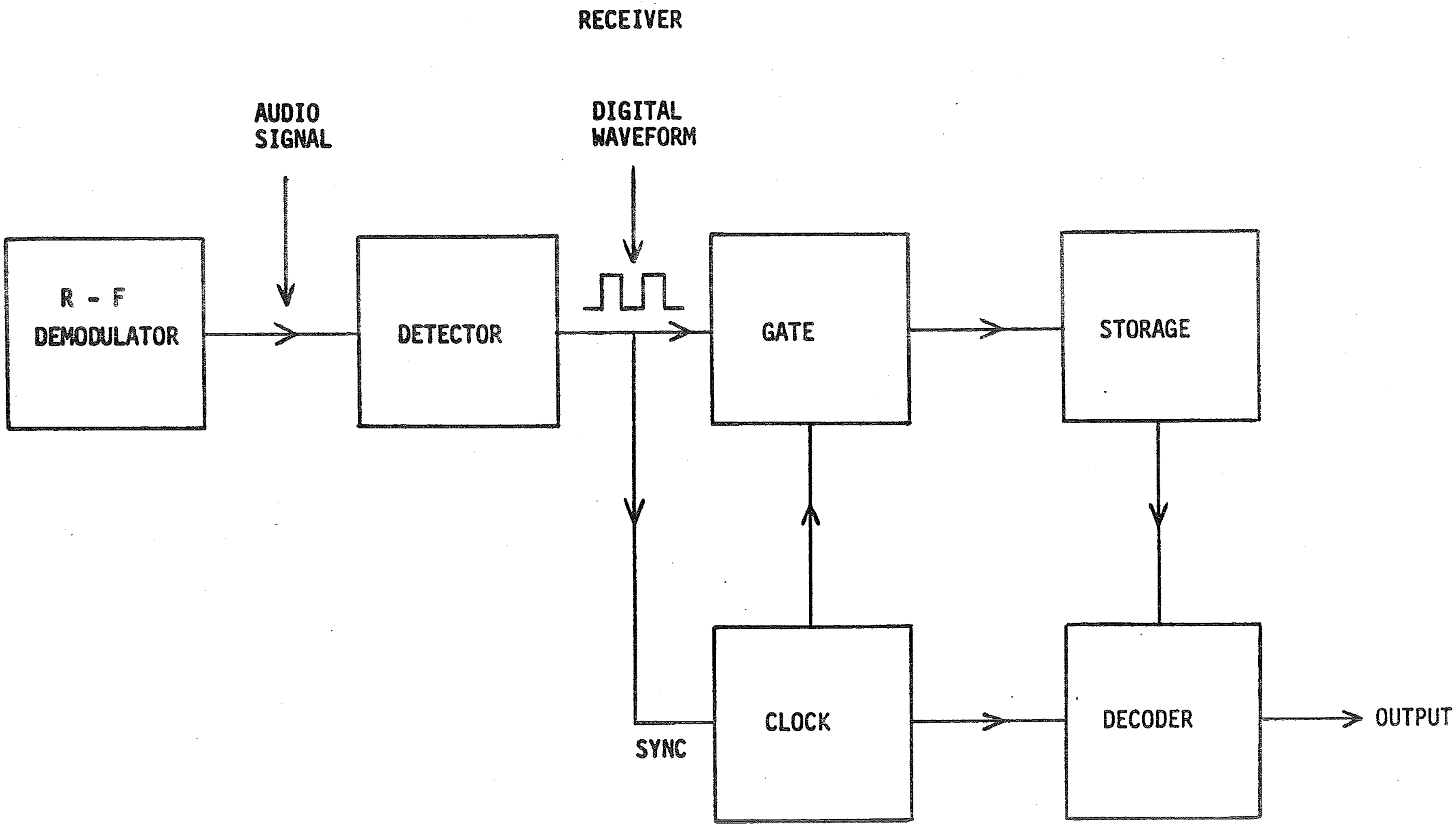


Figure D.1. Uplink Receiver

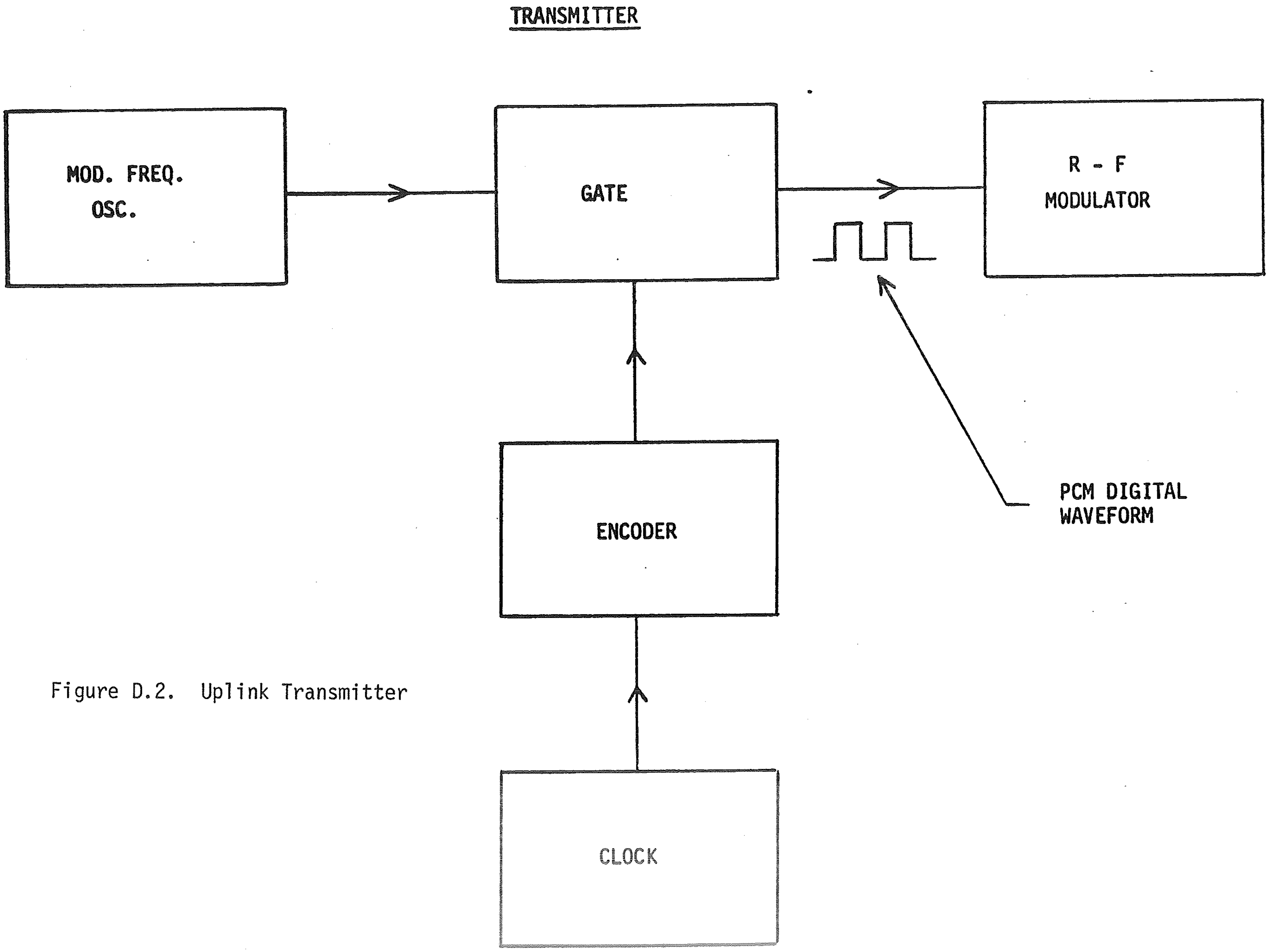


Figure D.2. Uplink Transmitter

SUBSYSTEM ORGANIZATION

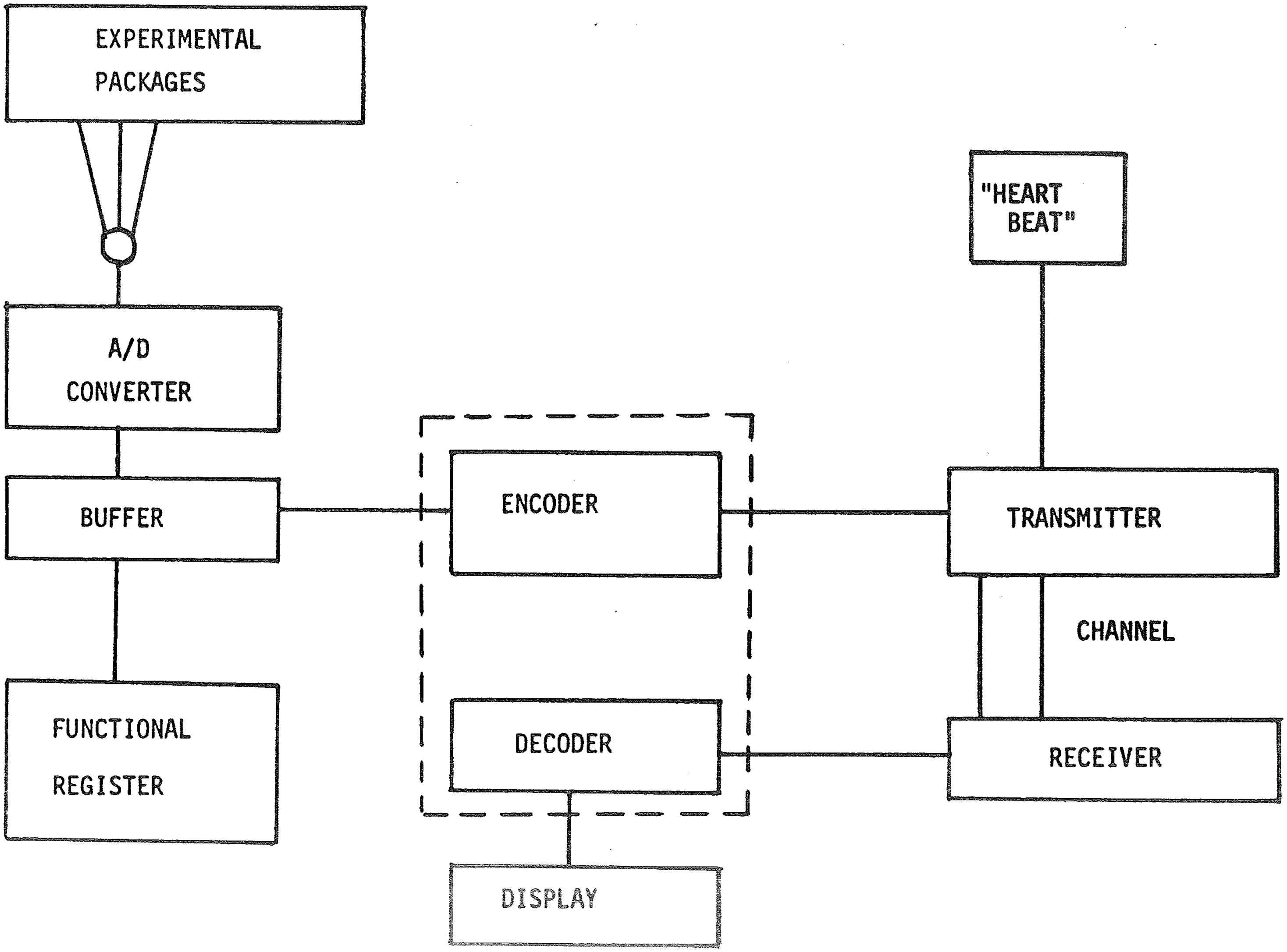


Figure D.3. Downlink Subsystem Organization

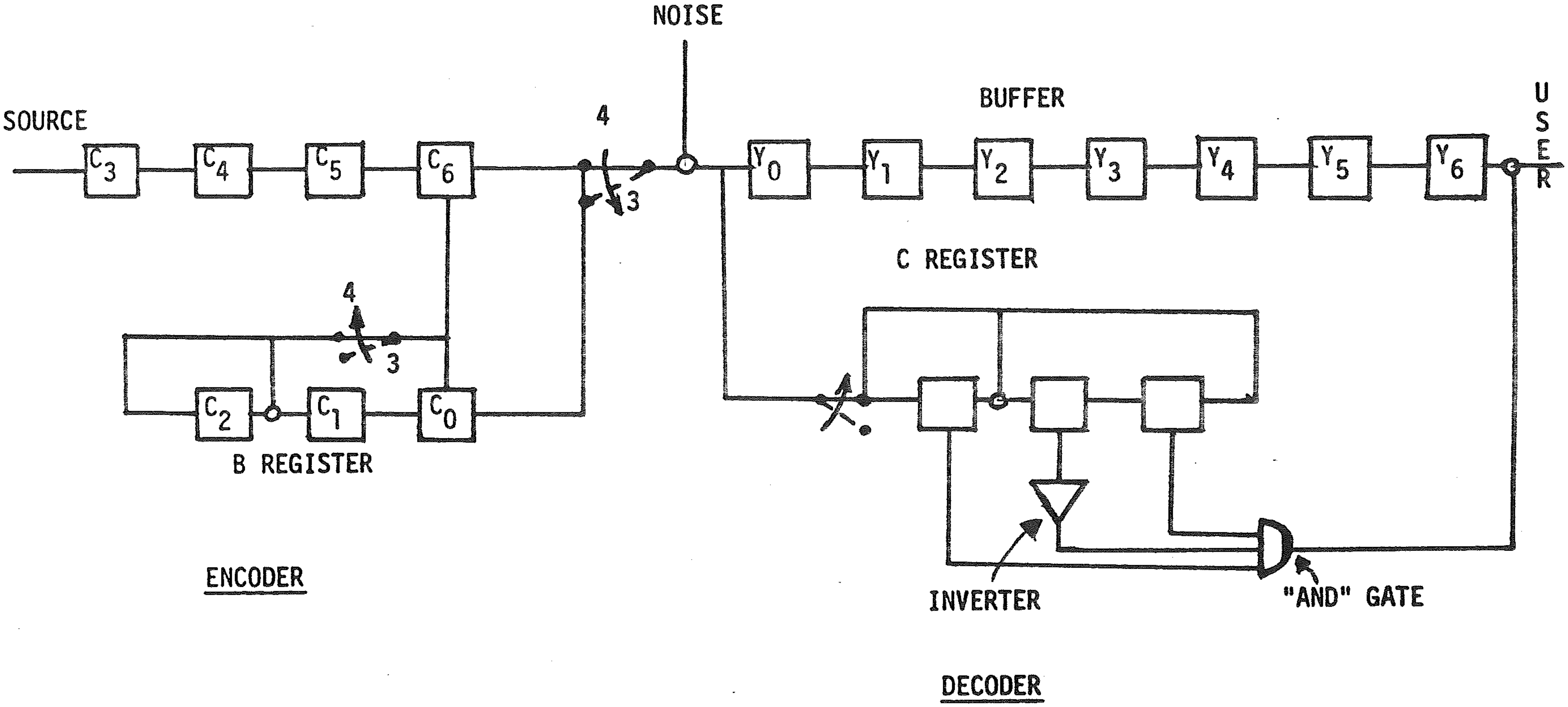


Figure D.4. Downlink System

E. MOTION CONTROL UNITS*

There are two separate units involved in motion control; steering control, and drive-motor control. Before working on refinements to either of these, magnetic relay-contactor systems, with protective inter-locks were installed on the vehicle to render it operative in case it was required to aid in the developments going on in other sub-systems. The relay-contactor systems also can serve as back-up units in case of automatic control failures. Except for size, the drive and steering units are identical. The drive control simply starts, stops, or reverses the six wheel-driving motors; the steering control does the same for the two steering motors. For decelerating the vehicle, dynamic braking of the drive motors is used.

The effort was then turned toward minimizing control power consumption, providing over-current limiters, achieving minimum turn-radius, and providing for optional telemetry-logic or manual control (by umbilical) operating modes. (See the block diagram).

Feed-back control schemes were laid out in block-diagram form, and a solid-state switch was built. Unfortunately, the switch was destroyed during testing, immediately prior to the Spring Review, and was not available at that time.

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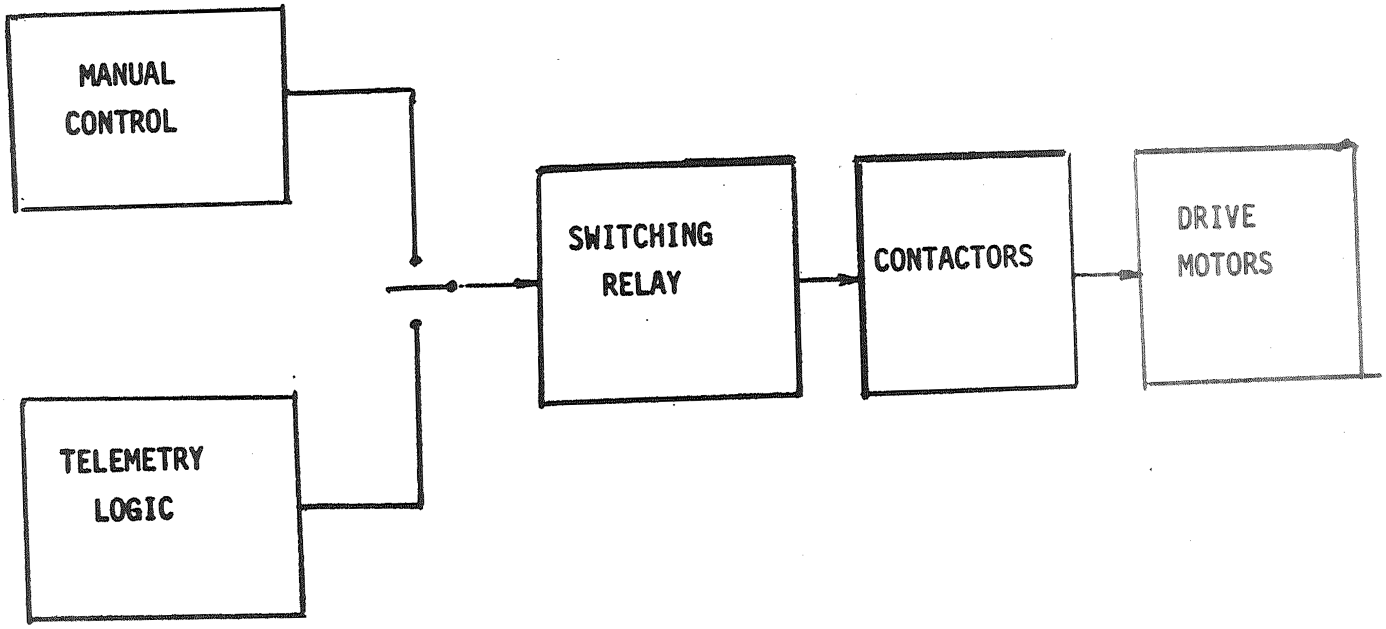
* For detailed description see "Motion Control Unit for Roving Vehicle" by James Suyo.

Figure E.1. Drive Control Unit



IV. PROJECTIONS OF ACTIVITY FOR THE PERIOD JULY 1, 1970 TO JUNE 30, 1971.

A. Obstacle Detectors. Continued work to improve the performance of the laser rangefinder. The timing circuit has worked only in sections in breadboard. Difficulty with excessive noise in the photomultiplier circuit must be overcome. The mechanical scanning unit is assembled but must be checked-out in operation. The tactile sensor has been improved but still fails to recover when negotiating obstacles from two to 12 inches . Removal of weight and use of counterbalancing will be attempted to improve performance.

B. Soil Sampler-Tester. The present model is able to pick up a sample and deposit it in the body of the rover. Problems still exist with intra-sample contamination and interference with operation by soil particles. The vane shear tester operates well after it is inserted in the soil. Problems exist in penetrating it into the soil with a minimum of disturbance of the soil. The use of an impact bearing strength tester will be reconsidered.

C. Short-Range Navigation. Components for the uncorrected gyro system have been acquired and individually operated. The system will be assembled and put in operating condition. The navigation computer will be completed and put in operating condition for bench operation. A study will be made of the alternatives for the next model.

D. Communication. Operating communications links should be completed for both vehicle commands and information return based upon presently existing models.

V. EDUCATIONAL CONSIDERATIONS

This project gives our Professional Master of Engineering candiates a unique opportunity to practice engineering on a scale not otherwise possible. It has also inspired the staff to seek commitments from companies to provide funding for industrial coop projects to allow for the building of prototype equipment. The engineering concepts of interfacing decision making, trade-offs and product development have helped the students become aware of the realities of engineering. They have too often been told that engineering is science and mathematics whereas most of engineering is concerned with problem solution using any means possible including science and mathematics. This project has helped the students understand the importance of theoretical studies as well as their limitations.

The inspiration of the project has not been limited to the graduate students as the staff has been called on to give short courses to a total of 40 freshmen for each of the past two years.

The following students completed the professional degree program since July 1, 1969:

R.H. Brooks	M. Eng. (Mech)
D.R. Dymm	M. Eng. (Elec)
G.B. Hohl	M. Eng. (Elec)
N.C. Jain	M. Eng. (Mech)
R. Klein	M. Eng. (Elec)
W.E. Knapp	M. Eng. (Elec)
J.R. Latimer	M. Eng. (Elec)
D. Leeper	M. Eng. (Elec)
W. Mihalic	B.S.
R.D. Pollak	M. Eng. Aerospace
H.H. Sorensen	M. Eng. (Mech)
J. Suyo	M. Eng. (Elec)
S.B. Troy	M. Eng. (Mech)
D.R. Wagle	M. Eng. (Mech)
B.D. Weeks	M. Eng. (Elec)
E. Wild	M. Eng. (Elec)

The technical review meetings with Mr. Jesse Moore of JPL were of considerable aid in forcing the students to clarify their work and in the review of their work by a technically qualified person outside the university whose pertinent questions uncovered areas needing more effort.