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REMOTE CONTROL AND NAVIGATION TESTS FOR APPLICATION TO LONG-RANGE LUNAR SURFACE EXPLORATION

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16. ABSTRACT

This report is a description of tests conducted with a vehicle system built at the Marshall Space Flight Center to investigate some of the unknown factors associated with remote-controlled teleoperated vehicles on the lunar surface. Test data are summarized and conclusions are drawn from these data which indicate that further testing will be required.

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I. INTRODUCTION

The utility of the Lunar Roving Vehicle (LRV) would be increased if it could be operated remotely from earth. The power reserves required for safe manned operation could then be expended in further unmanned exploration after the astronauts had departed the lunar surface. An investigation was made to determine the additions to the LRV required to give it a remote capability and to determine the operational problems involved. The results of the investigation are applicable to completely unmanned vehicles and to planetary bodies other than the moon.

The round-trip delay time for control and information signals for lunar operation is approximately six seconds. The effects of this delay on the controllability of the vehicle needed to be studied. It was desired to determine the energy requirements for the added remote control equipment and for remote operation.

Because a television camera would be used for remote viewing, the best camera position (fore, aft, high, and low) and camera type (stereo versus mono, frame rate, etc.) needed to be determined.

Other unknown factors were investigated to determine whether antenna orientation could be maintained, the most satisfactory onboard navigation system, the most favorable driving method (stop-and-go versus continuous), and safe driving speeds.

A remotely controlled vehicle (Figs. 1 through 4) with viewing and navigation systems was fabricated and tested at the George C. Marshall Space Flight Center to investigate these factors. A remote control station was also developed as part of the system.

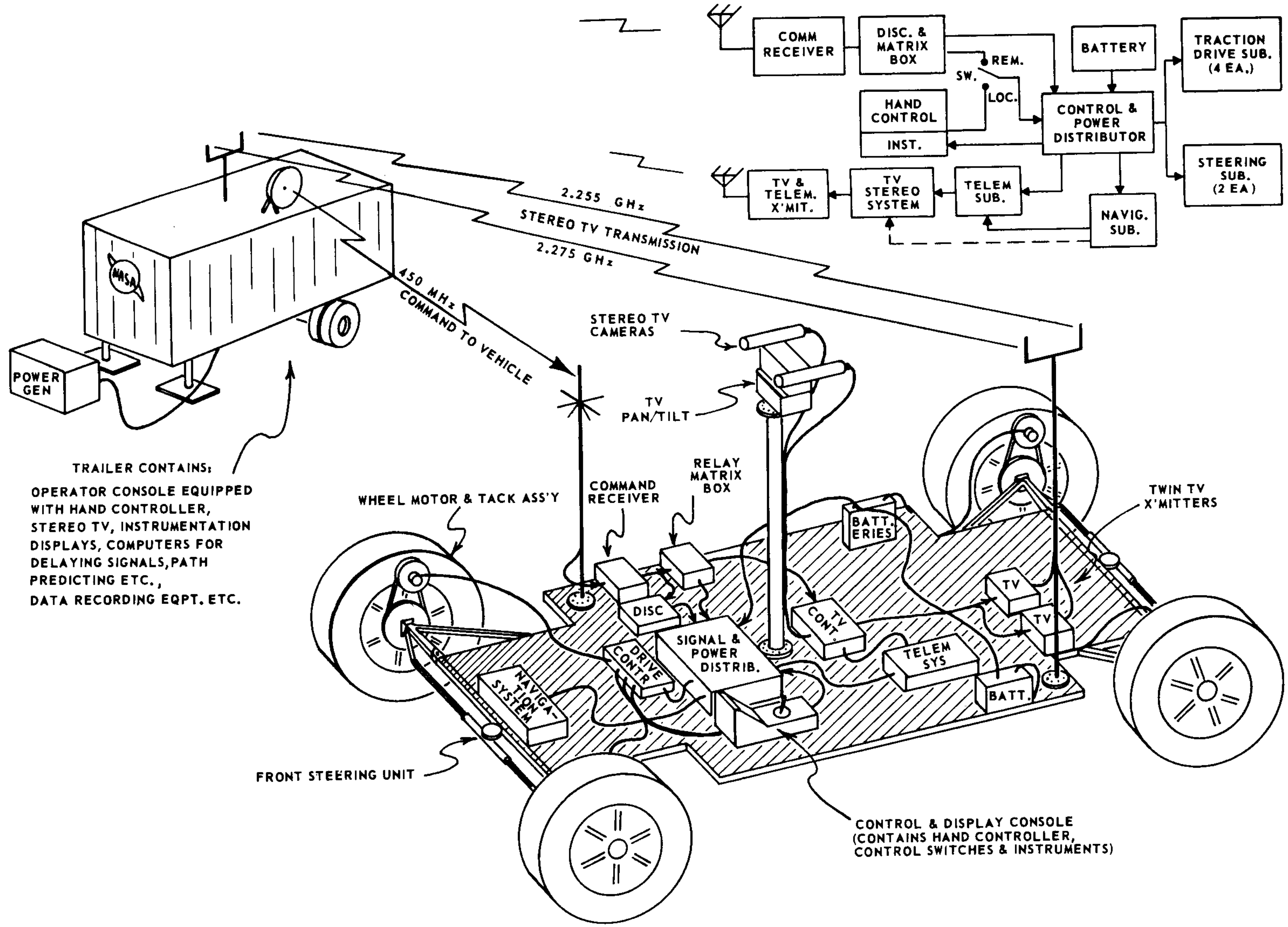


Figure 1. Remote drive vehicle system.

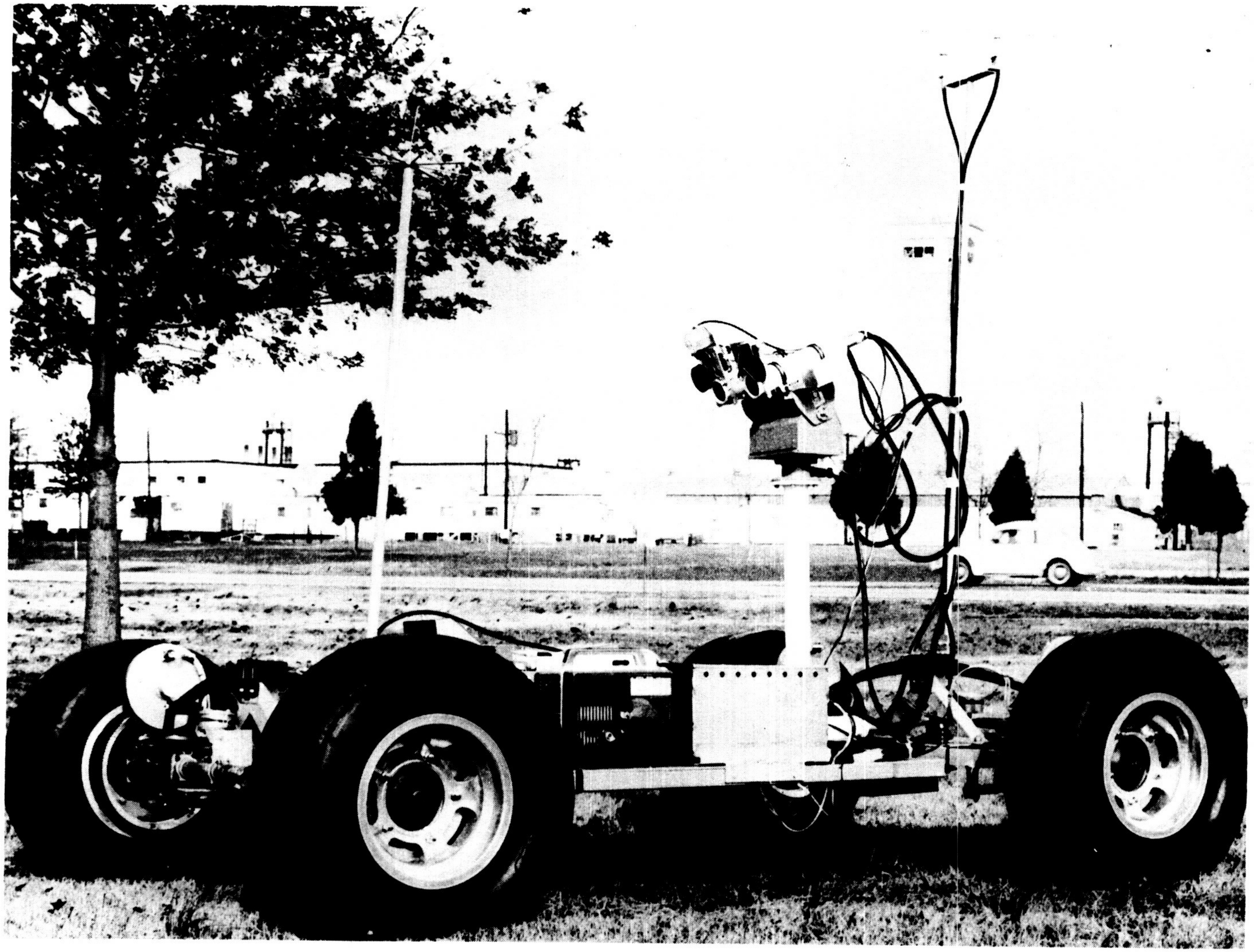


Figure 2. Remote-controlled vehicle.

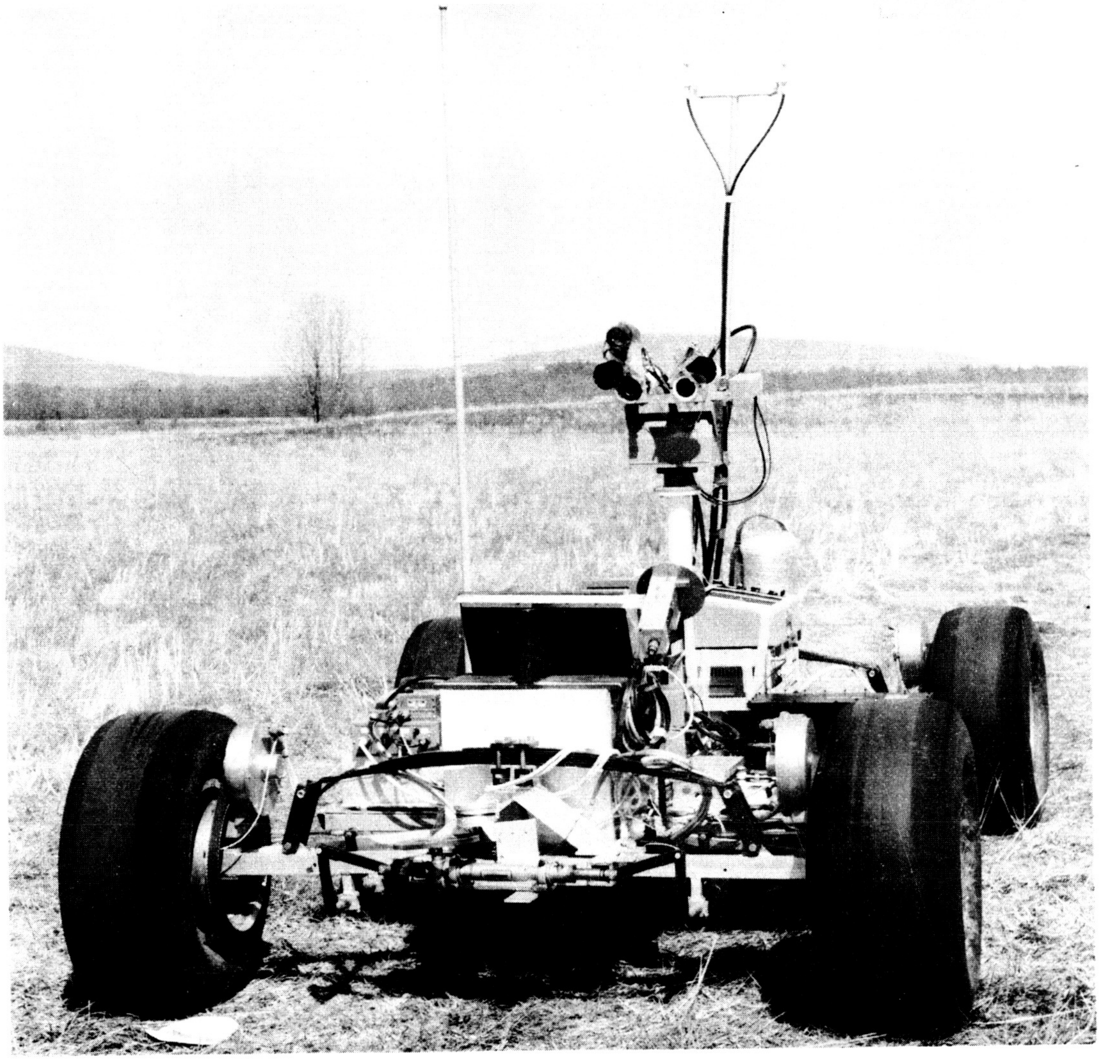


Figure 3. Remote drive vehicle shown at test site.

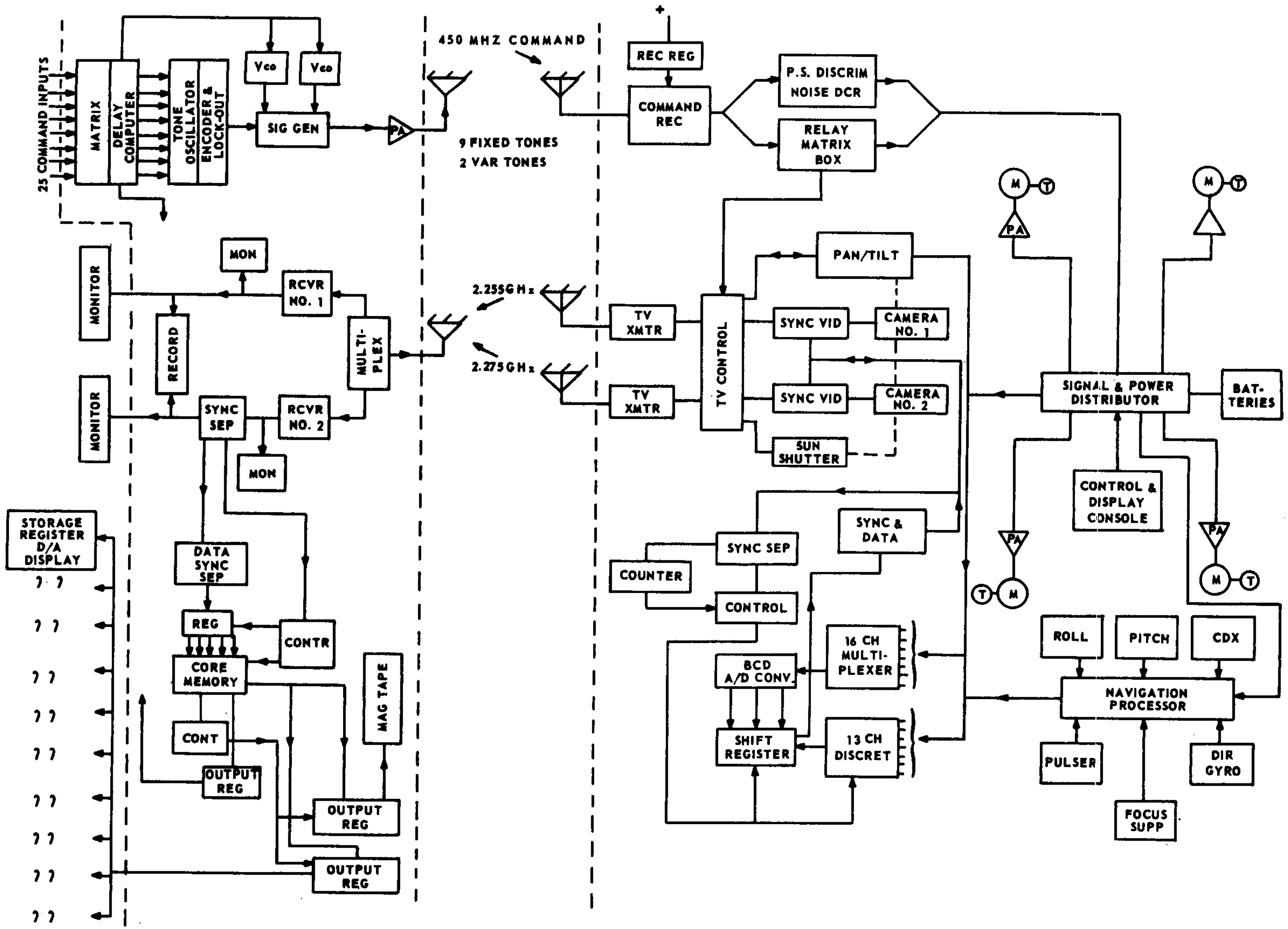


Figure 4. Schematic of remote drive system.

II. VEHICLE SYSTEM DESCRIPTION (Fig. 4)

To investigate the problems of this task, it was believed that a functional, yet simple, electric-drive vehicle with dimensions similar to the present LRV was needed. By proper circuit design considerations, the vehicle could be remotely operated by the addition of a command receive subsystem, a television (TV) and telemetry subsystem, and a navigation subsystem. With this in mind, the subsequent paragraphs describe the system pursued to completion.

Figure 1 is a block diagram of the basic system to be described. Command signals are sent from the base station and processed on the vehicle by the command receiver, a command discriminator, and a signal matrix box. This output is then sent via the LOCAL-REMOTE switch through the control and power distributor to the wheel drive subsystem for mobility, to the steering subsystem for directional control, to the TV subsystem for viewing, and to the navigation subsystem for location. Signals are sent back to the base station by the TV subsystem and TV transmitter. Telemetry signals are multiplexed onto the TV carrier for transmitting back.

To study the remote driving and navigation problems, a vehicle that possesses many of the same basic mechanical and electrical specifications of the present LRV was built. For example, the vehicle is battery-powered and has four independent traction drive systems, double Ackerman steering, and as many of the other basic characteristics as are economically practical under a low budget. Because of an austere budget, much of the mechanical equipment was purchased as stock parts from local automobile parts dealers and the electronic and electromechanical equipment necessary to implement the system was surplus equipment previously used by the Astrionics Laboratory.

The complete vehicle and remote driving system (hereafter called the system) consists of five subsystems of engineering importance. These subsystems are as follows:

(1) Mechanical

(2) Mobility drive and control

(3) Command and receiving

(4) Telemetry and TV

(5) Navigation.

A description of each of the subsystems utilized in the design and development of this vehicle follows in the succeeding paragraphs.

A. Mechanical Subsystem

The mechanical subsystem (Figs. 5 and 6) consists of a flat, rectangular frame on which are mounted four independently suspended and steerable wheel assemblies. Tie rods connect from the steering arms of the front wheels to a rack and pinion motor-driven gear box. The same is also true of the back wheels. This gives simultaneous steering on both ends of the vehicle and is termed double Ackerman steering. Each wheel assembly contains a motor with a tachometer and a belt reduction assembly similar to that used on automobiles for timing belts. Linear feedback potentiometers are located between the frame and the movable steering rack on each end of the vehicle for independent position control steering. The vehicle was designed to be as light and functional as possible and compatible with stock parts, some of which are cast iron. The system was designed exclusively for electronic drive and steering control; consequently, no provisions were made for mechanical steering or braking. A summary of vital statistics of the vehicle's mechanical subsystem is listed below.

(1) Frame — The frame is fabricated from 5-cm square aluminum tubing welded to form a flat rectangular frame. The tread dimension is 178 cm (6 ft, 3 in.). The base dimension is 229 cm (7 ft, 6 in.).

(2) Steering — The steering is double Ackerman with independently controlled rack and pinion units on front and rear. The steering ratio is 22 turns of the motor shaft for lock-to-lock of the wheels. The maximum lock angle is 30 deg, the maximum turning diameter is 8 m (curb-to-curb), and the steering motor torque is 16.3 kg-cm (1.2 ft-lb) derived from permanent magnet torquers on each rack-and-pinion unit.

(3) Suspension — The suspension is independent on all four wheels from modified stock leaf springs.

(4) Braking — Braking is performed dynamically by the control system.

(5) Wheels — The wheels are stock aluminum and equipped with stock 11.00-15 racing slicks. The footprint for each tread is 28 cm (11 in.). The wheel hub assemblies are stock Volkswagen parts.

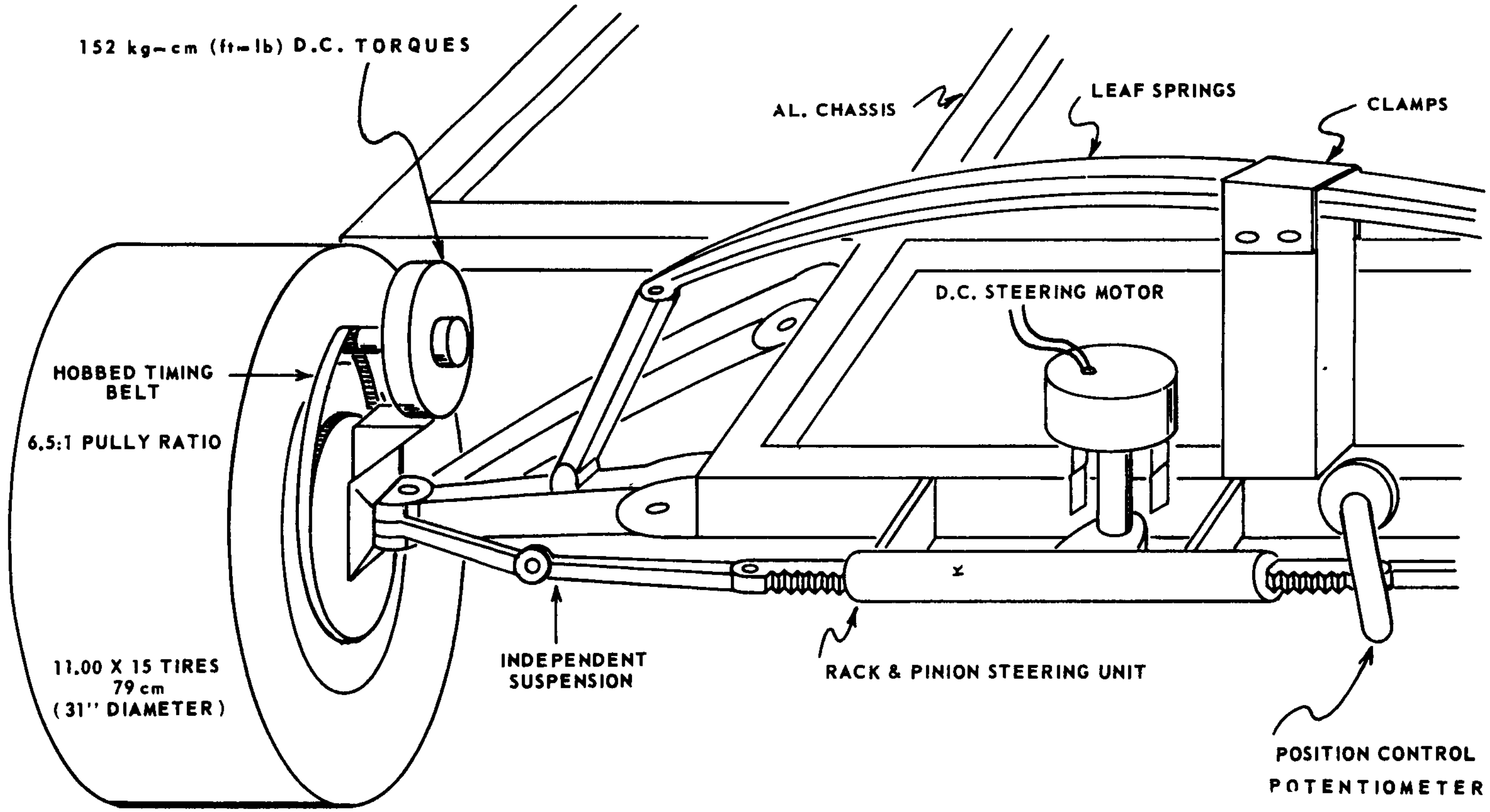


Figure 5. Mechanical subsystem.

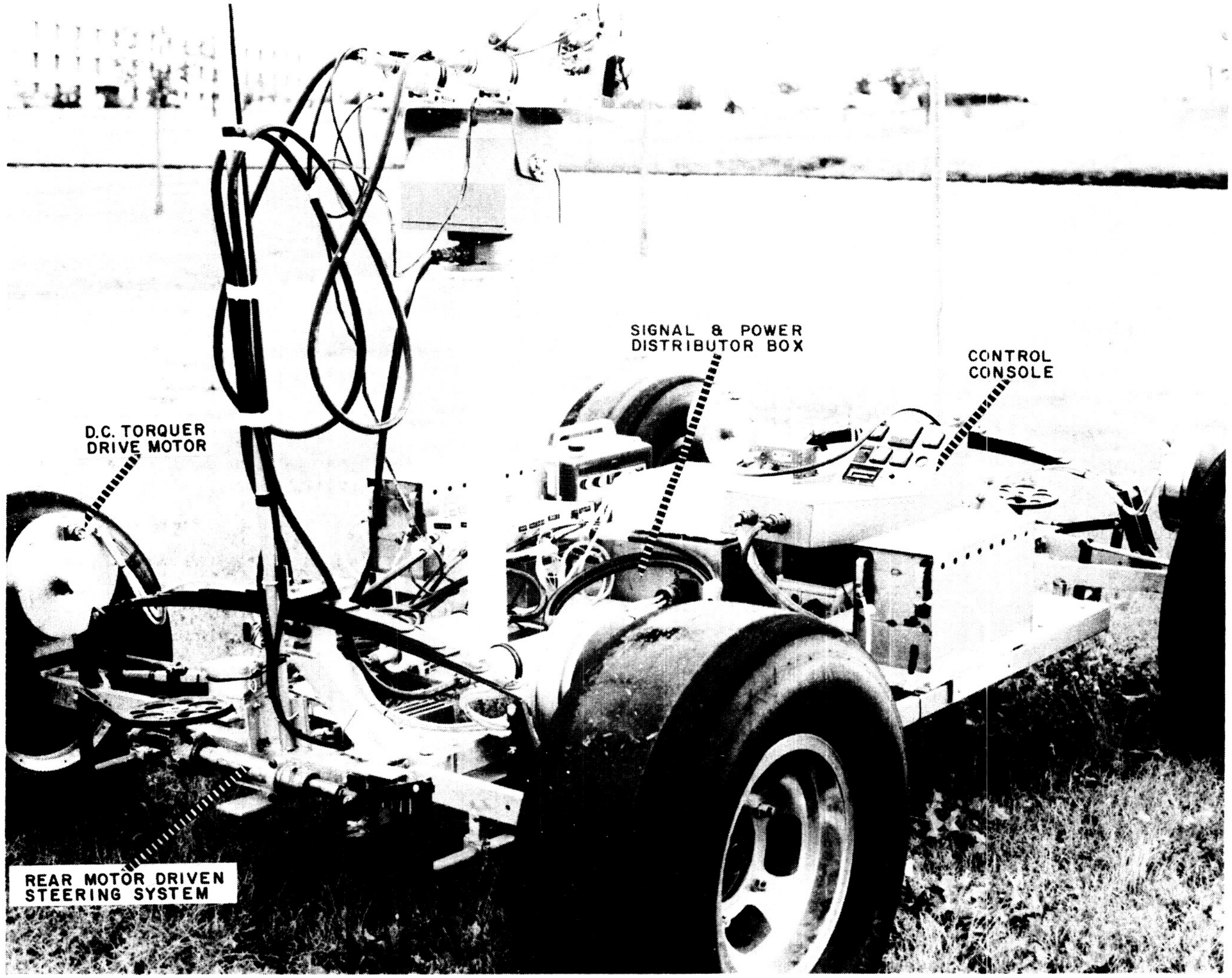


Figure 6. Remote drive vehicle (rear view).

(6) Controls — The vehicle has no mechanical steering or braking controls.

(7) Instrumentation — The console has continuous displays of speed (mph), battery voltage, current, power used (watt-hour), percentage of battery charge used, and vehicle roll and pitch (deg).

(8) Torque — The vehicle has a 980-kg-cm (71-ft-lb) torque available at each wheel. This is derived from 152-kg-cm (11-ft-lb) torque motors operating through a 6.5:1 speed reduction ratio on each wheel.

(9) Other

Weight — The weight is 454 kg (1000 lb) instrumented.

Speed — The speed is 5.6 km/hr (3.4 mph) with 152-kg-cm (11-ft-lb) torquers.

B. Mobility Subsystem

The mobility subsystem (Figs. 7 and 8) consists of two basic parts, wheel drive and steering. Each subsystem receives signals from a common hand controller (local) or discriminator (remote) and power from an onboard distributor and battery supply. The hand controller is a simple spring-loaded potentiometer (all-position) "joy-stick" and is part of the control console. The control console is detachable and contains all the instruments needed for monitoring the mobility subsystem. This detachable console is used for operating in a manned mode on hazardous terrain from alongside the vehicle.

When used in the manned mode, the system is designed so that all vehicle movements such as steering, acceleration, and velocity are functions of the direction and amount of movement of the hand controller; that is, a movement from a center position to front or back results in vehicle movement forward or backward. If reverse is commanded by the operating of a toggle switch (either onboard or remote) the vehicle will move in reverse for backward movements of the hand and brake for forward movements of the hand. A hand movement in a side direction to the vehicle will steer in that direction and will maintain that angle until the stick is moved back to the vertical plane. A side and forward or backward movement of the hand controller merely sets the speed with which the vehicle rounds a curve of that radius. To round a curve without scuffing, differential speed steering is used. This means that when effecting a turn, the wheels on the outer circumference will always

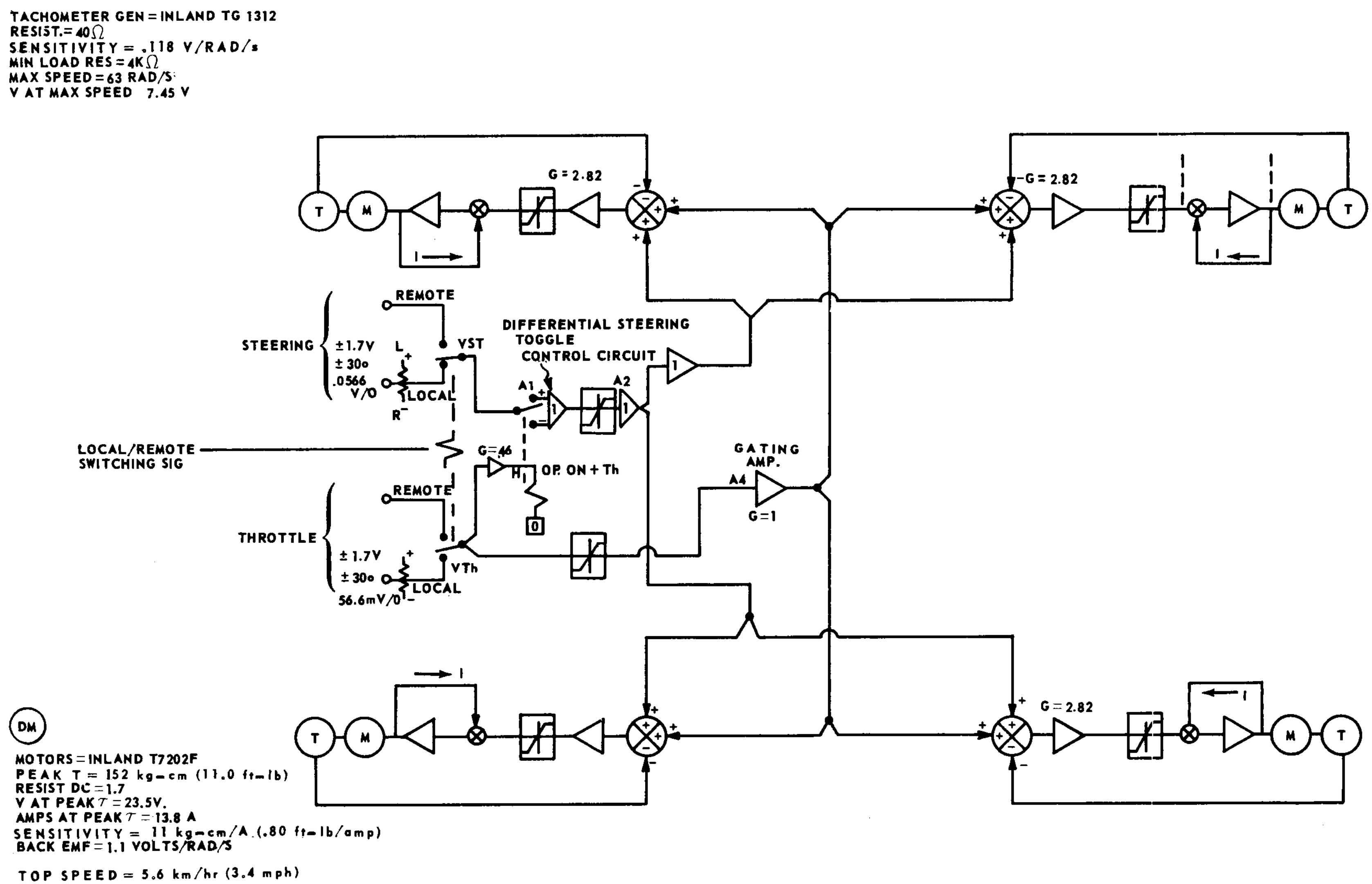


Figure 7. Traction drive control system (with differential steering).

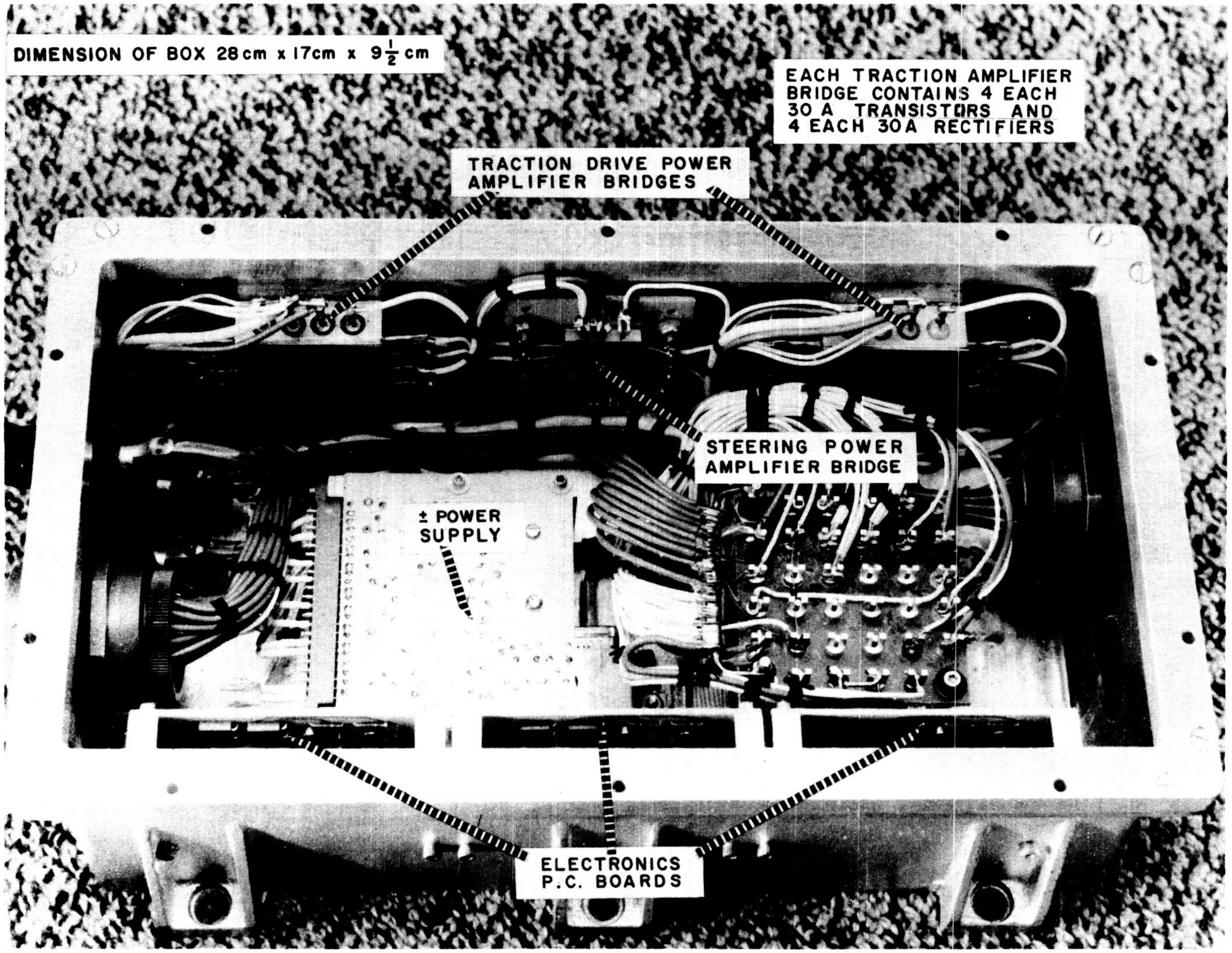


Figure 8. Mobility drive electronics box (containing 2 traction drive and 1 steering power amplifiers).

receive a proportionally larger drive, while the inside wheels receive a proportionally smaller drive than that required for straight motion. This compensation is effective on a curve in any direction and at any speed, either forward or reverse, and greatly aids the turning of the steering motors.

In the paragraphs to follow, a technical description of the hand controller will be discussed as part of the wheel drive and steering system; the control console, signal and power distributor, and battery system will be discussed separately.

1. Wheel Drive Subsystem

This subsystem (Figs. 7 and 8) consists of four identical rate servoloops; a typical one is depicted in Figure 9. Each servoloop is fed in parallel

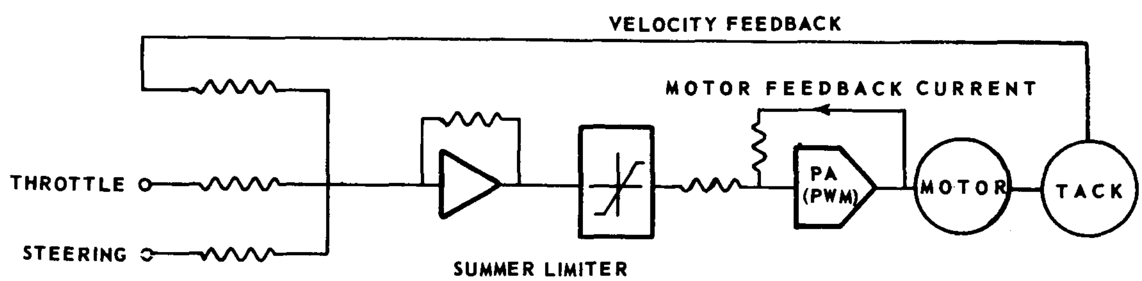


Figure 9. Wheel drive rate loop.

from a common center-tapped potentiometer (to attain plus and minus) on the hand controller or from a discriminator on the command receive system. A tachometer generator located on the shaft of each drive torque motor provides feedback to that wheel to produce the speed required by the controller. All four wheel drive loops are calibrated to give the same speed for a given amount of controller signal. The logic behind the vehicle movement is based on the most logical movement of the hand to give these responses. Since the drive electronics and motors are responsive to the logic of the hand controller signals, the direction and rate that the vehicle moves or the amount of braking is a function of these polarities and amplitudes, respectively.

The hand controller uses potentiometers energized from a plus-minus power supply with zero V being the center tap of the potentiometer and arranged so that the wiper is on zero with the stick in the vertical position. The output is a linear plus-and-minus signal for front-to-back throttle or side-to-side steering movements. This type of signal creates good system control logic, and gains are set so that smooth accelerations result. All the drive stages are analog type and accept either polarity signal. On the remote control position, these signals for driving and steering are obtained from the discriminators on board the vehicle. By using a switching bridge type power amplifier, the direction and rate of the dc motors are controlled simultaneously; therefore, no relay bridges are needed.

A FORWARD-REVERSE switch on the control console (and also on the remote console) is used in conjunction with the local and remote hand controller. This switch assures the operator that the vehicle will respond only in the mode desired (a forward-brake mode or reverse-brake mode but not in both). A discrete command from this switch or its remote counterpart operates a latching relay which in turn provides the gating of the signals of proper polarity into the power stage to effect these operations. Thus, with this switch in the forward position the vehicle will move forward for forward motion of the hand control and brake for backward movements of the stick. If the switch is in the reverse position, the vehicle will move in reverse for backward movements of the stick and will brake for forward movements.

In each case, the braking signal is created by taking the throttle signal to zero and summing this with the already reverse tachometer signal. On this brake command, the reverse polarity and amplitude of the tachometer's feedback signals will brake the vehicle to a stop and hold it to zero velocity until commanded to move. The vehicle relies totally on this dynamic braking even though a parking brake command is transmitted from the remote station. The parking brake command provides the chase vehicle with the information (light or horn) to scotch the vehicle when it is desired to turn off drive power.

To negotiate small turns without scuffing, a differential signal from the steering potentiometer is summed into the vehicle's left-side drive control circuitry with one polarity and to the vehicle's right-side drive control circuitry with the opposite polarity. This creates a left- and right-side differential drive as a function of the steering potentiometer. These analog signals are continuously variable and automatically toggle in polarity for braking and/or for reverse commands. The amount and direction of conduction of this signal into the summing point is adjusted so that it will always add and subtract from the main throttle with the right polarity and amplitude in order to round any curve at any throttle speed in either direction (forward, reverse, or braking) without scuffing. For straightforward and reverse movements, the contribution of this signal to the drive system is zero.

The electrical and electronic components associated with the wheel drive are listed below.

(a) Wheel drive motors — Inland dc torquers type T-7202F

Peak torque rating τ_p = 152 kg-cm (11 ft-lb)

Volts at peak torque V_p = 23.5 V

Amperes at peak torque I_p = 13.8 A

Torque sensitivity K_T = 11 kg-cm/A (0.80 lb-ft/A)

Back EMF constant K_B = 1.1 V/rad/s

Tachometer generators — Inland type TG-1312D

Voltage sensitivity = 0.118 V/rad/s

Voltage maximum output = 7.45 V

Dc resistance = 40 Ω

Minimum load = 4 kΩ

(b) Electronic control circuits — Figures 7 and 8 show the electronic control circuits.

The power output stage in each loop of the traction drive system is a switching-type, push-pull power amplifier. This amplifier operates as a current source by current feedback sampled from the motor circuit. It is a pulse-width modulated amplifier that switches from a self-contained, 4800-Hz oscillator. This oscillator also excites the power supplies that produce the plus-minus low-level voltages used by the differential amplifiers. The electronic components used in the circuitry are state-of-the-art types and resulted in a compact, efficient package. For example, the output bridge consists of four 25-A transistors (400-W dissipation capability) and four 30-A rectifiers all in one 5-cm^3 (0.75-$in.^3$) package. Integrated circuit operational amplifiers are used extensively for summers, function generators, etc.

Signal conditioning from the hand controller, discriminator, etc., to the traction drive system takes place on a printed circuit board located in the distributor. It is on this board that the differential drive steering signals are generated. Thus, the distributor serves as a combination signal and power distributor.

2. Steering Subsystem

The dual steering system (Fig. 10) of the vehicle is electric and is composed of two separate and identical position control loops. Each of the loops consists of a summing amplifier stage, a power amplifier stage, a dc torque motor and gear box, a wheel position potentiometer, and mechanical linkages. Both systems are operated by a common hand controller. The error signals into the power amplifiers are derived from a voltage difference between the hand controller and the wheel angle potentiometers. The two dc torque motors drive to reduce these error voltages to zero; thus, the wheels follow the side-to-side movement of the onboard or remote hand controller. The remote steering analog signal is obtained from an onboard discriminator.

A trade-off for the steering system was made in the selection of the gear ratio and torquer capacity to optimize the response time for the anticipated speeds of this special test bed, since the amount of torque required to steer a vehicle is a function of its speed, weight, tire footprint, ratio of the gear box, etc. A 16.3-kg-cm (1.2-ft-lb) torquer acting through an 11:1 gear pass coupled to the shaft of a stock steering gear box was chosen. This combination resulted in 22 turns of the motor shaft for the lock-to-lock wheel movement.

The components of the steering system include the following items.

(a) Motor — Inland type T-2950E

Peak torque τ_p = 16.3 kg-cm (1.2 ft-lb)

Volts at peak torque V_p = 30.2 V

Amperes at peak torque I_p = 2.6 A

Torque sensitivity K_T = 2.5 kg-cm/A (0.46 lb-ft/A)

Motor gear set ratio 11:1

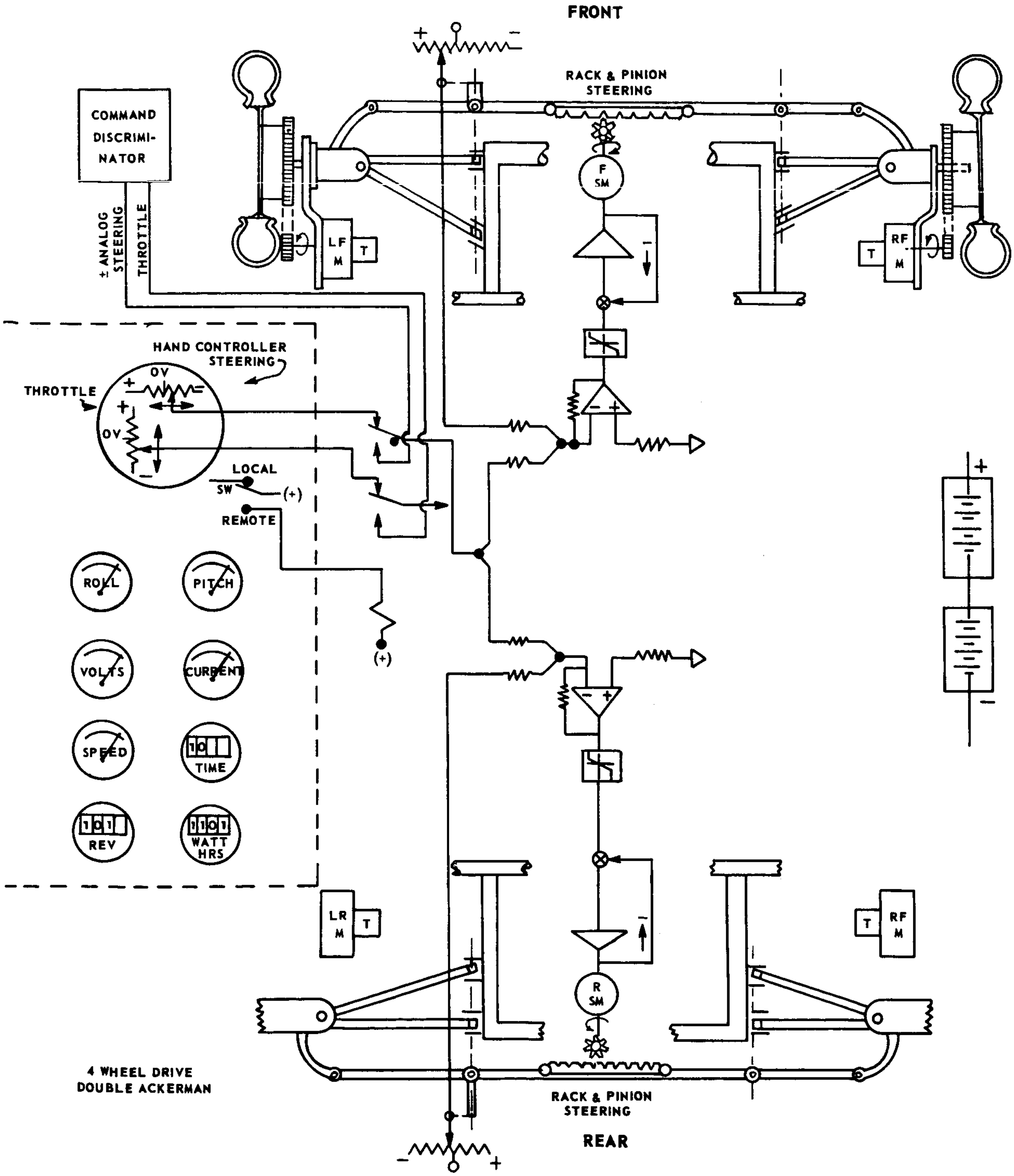


Figure 10. Vehicle steering control subsystem.

(b) Gear box — stock rack and pinion unit from Sprite automobile

(c) Electronic control circuits — Electronics for the steering subsystem are the same as for the traction drive subsystem, except the output power amplifiers use 5-A bridges instead of 25-A bridges.

3. Power System

The onboard power system consists of a set of batteries, a power distributor, and a set of monitoring instruments. Each is discussed below.

a. Batteries. Most of the electrical and electronic equipment on the vehicle was designed to operate from 28-V supplies; since batteries with this voltage rating were available, this was the natural choice for use on this vehicle. Some of the criteria for choosing a suitable battery are as follows:

(1) Watt-hour capacity between charges

(2) Amplifier drainage rate (average discharge current = 50 A)

(3) Stability of voltage over discharge (use) cycle (no regulators are used)

(4) Rechargeability

(5) Weight

(6) Size.

Nickel-cadmium, silver-zinc, and lead-acid batteries have all been used for testing. The nickel-cadmium batteries were found to be very satisfactory since they have a low internal impedance and a reasonably constant voltage and can tolerate many recharges at a high recharge rate. The silver-zinc batteries were used during part of the test; but because they could not be easily recharged and were costly, they were not economically suitable for this particular application. This type of battery has a high energy-to-weight ratio and will be used on the Manned Lunar Roving Vehicle (MLRV) this year.

The lead-acid battery has a high weight-per-cell ratio and a drooping voltage curve over its useful discharge cycle. This tended to make it unsatisfactory for supplying all the voltage-critical systems aboard the vehicle. The very low impedance of this battery did give good results as a source for the vehicle traction drive system alone, since it is not voltage sensitive.

b. Distributor. The distributor is a signal, power control, and distribution point for all the subsystems of the vehicle. It contains power and signal control relays, control and conditioning electronics boards, plus-and-minus power supplies, and power measuring electronics.

4. Control Console

The control console is a detachable package (by cable) (Fig. 11) housing a control stick, system control switches, and monitoring instruments. It has a

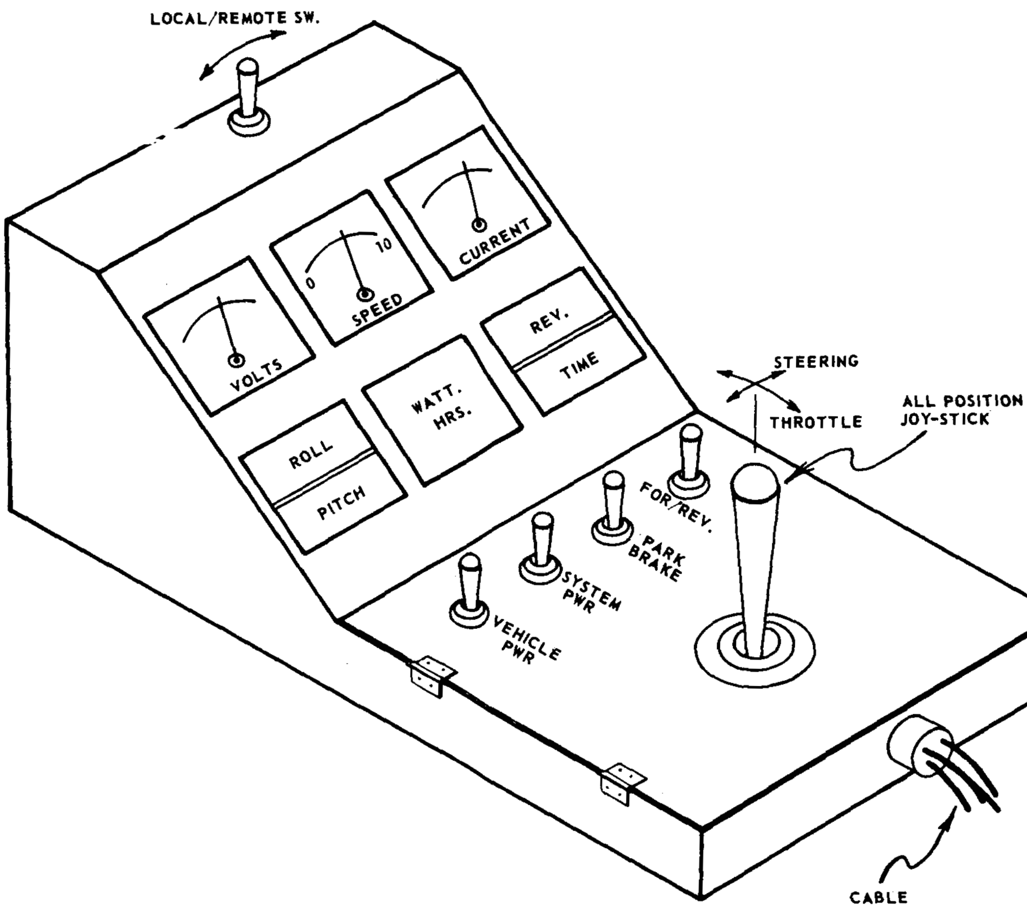


Figure 11. Detachable control console.

single toggle switch for shifting from local to remote control. The control stick (for steering/throttle) is composed of two center-tapped potentiometers arranged in a gimbal such that a fore-and-aft motion actuates one potentiometer and a side-to-side motion actuates the other potentiometer. When the stick is released, it will return to a vertical position. Toggle control switches on the console (except the vehicle POWER-ON switch) operate latching relays in the distributor and thus are commanded remotely from counterpart switches on the remote console.

The control console contains switches and instruments for the following functions:

Switches

(1) LOCAL/REMOTE

(2) FORWARD/REVERSE

(3) Vehicle Power ON/OFF

(4) Systems Power ON/OFF

(5) Constant Speed Travel ON/OFF

(6) Parking Brake ON/OFF

Meters

(1) Speed (mph)

(2) Volts

(3) Current

(4) Watt-Hours

(5) Roll (deg)

(6) Pitch (deg)

(7) Wheel Revolution Counter

(8) Running Time Meter (in 0. 1 hr)

C. Command Subsystem

The command subsystem (Fig. 12) consists of a 450-MHz FM/FM radio-link subsystem by which up to 36 channels of discrete and 2 channels of plus-or-minus analog information are matrixed, multiplexed, transmitted, received, decoded, and fed into the numerous control inputs of the vehicle's subsystems.

This system operates as follows: The 36 discrete commands are matrixed so that each of these commands will key two of nine fixed-tone oscillators. The steering and throttle commands are continuously variable (analog) and control the frequency shift of two separate voltage controlled oscillators (VCO). These nine fixed- and two variable-tone oscillators are then encoded into eleven frequency-modulated subcarriers which FM-modulate the main 450-MHz carrier. This carrier is then amplified and fed into the antenna.

This 450-MHz signal is received on the vehicle by an omnidirectional (5.8-dB gain) antenna and FM receiver (type ANDRW-13). The receiver output consists of nine normally open relay contacts (one for each fixed tone received) and two discriminator outputs, the latter outputs being the two variable frequency subcarrier tones. The subcarrier frequencies are then fed to another dual discriminator which derives the original plus-or-minus analog throttle and steering signals. The nine received relay outputs are dematrixed into 36 two-input NOR gates (54 series TTL) whose outputs operate relay driver transistors stages etc. The tones operate with a short duration (momentary) and, therefore, much use is made of latching-type relays for the vehicle's subsystem. The latching-type relays allow the vehicle to receive a single pulse to begin a command and another pulse to stop the command. Since some commands may be for long periods of time, it would be impractical to have a signal being transmitted constantly; thus, latching relays were the solution. (Example: Tones 1 and 2 latch the motor power on relay, and tones 1 and 3 unlatch this relay.) These relays operate on very short pulses and are used in the system in OR logic arrangement; that is, their coils are pulsed from the normally open momentary contact control switches or from the normally off remote control pulses. Both pulse sources are hard-wired common to the relay coils and either pulse can override the other.

By using the momentary contact (MC) control switches and latching-type relays, the relay coils can be pulsed by either the remote or the local pulse with neither affecting the other. This eliminates the requirements of individually switching all the signal inputs from the local to a remote control condition. Therefore, the single LOCAL/REMOTE switch on the console is used to switch the two analog signals, i.e., the throttle and steering signal,

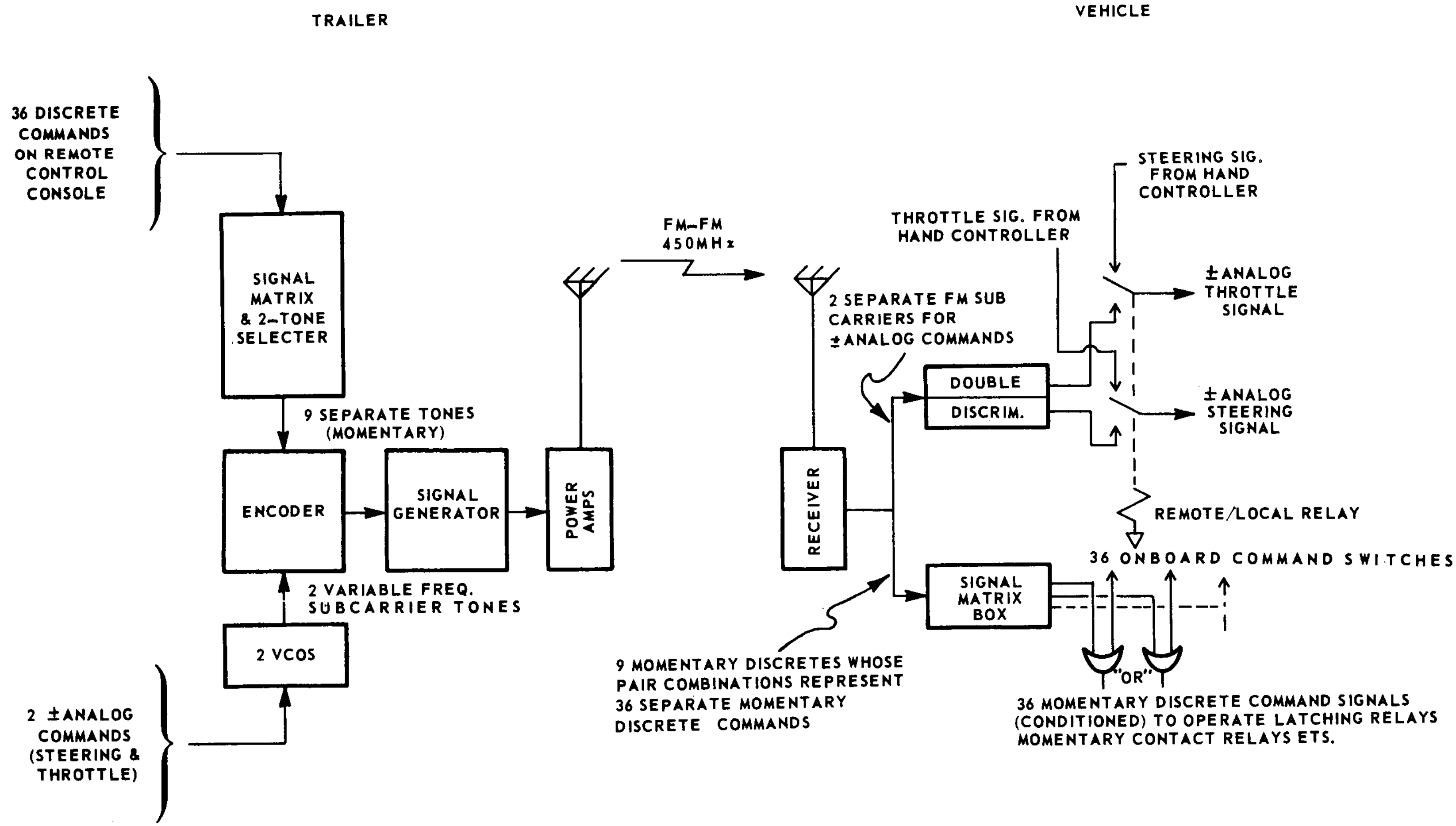


Figure 12. Remote command system.

from the hand controller to the discriminator output. The discriminator outputs are adjustable and, therefore, are compatible with the hand controller. Following is a list of the commands used for the vehicle subsystems:

Vehicle Control

Channel No.	Command	Relay Function
1-2	Motor Power On	(L)
1-3	Motor Power Off	(UL)
1-4	Parking Brake on	(L)
1-5	Parking Brake Off	(UL)
1-6	Vehicle Forward	(L)
1-7	Vehicle Reverse	(UL)
1-9	Steer-to-Center Position	(L)
2-9	Steer-to-Center Position	(UL)
Analog	Throttle (±V)	
Analog	Steering (±V)	

Navigation System

Channel No.	Command	Relay Function
1-8	CDX Drive Positive	(M)
2-3	CDX Drive Negative	(M)

TV Camera Control

Channel No.	Command	Relay Function
2-6	TV Mode Left	(UL)
2-7	TV Mode Both	(L)
2-4	TV Tilt Up	(M)
2-5	TV Tilt Down	(M)
2-8	TV Sun Sensor Reset	(M)
3-5	TV Zoom Out	(M)
3-6	TV Zoom In	(M)
4-5	TV Iris Open	(M)
4-6	TV Iris Closed	(M)
5-6	TV Pan Left	(M)
5-7	TV Pan Right	(M)
6-7	TV Focus Far	(M)
6-8	TV Focus Near	(M)

D. Television and Telemetry Subsystem

1. Television

The TV subsystem consists of two 525 scan-line cameras and two FM video transmitters. Camera focus, iris, and zoom are controlled either from a camera control console on the vehicle or from the remote console. To protect the camera vidicons from damage by direct sunlight, they are equipped with automatic shutters that close whenever the cameras are pointed to within ±30 deg of the sun. The cameras are equipped with a 4:1 zoom lens (35- to 8.75-deg horizontal field of view), and they are normally mounted parallel to each other for stereo effects. The cameras are installed on a remote-controlled pan-tilt unit that is positioned atop a post whose height and location aboard the vehicles can be varied. The camera pan-tilt angles, relative to the vehicle axis, are instrumented for telemetering. Video signals are transmitted by the two transmitters operating at 2.255 and 2.275 GHz. Two quarter-wave stub antennas transmit 10 W to the remote driving station.

2. Telemetry

The telemetry system accommodates 13 channels of discretes and 15 channels of analog information for transmission from the vehicle to the base station. A technique of using the "back porch" of the television horizontal sync pulse for transmitting the telemetry information to the base station is used.

This information is then displayed by various types of readouts located so as to make the driving problem as easy as possible. A block diagram of the telemetry system is shown in Figure 13.

The analog part of the telemetry system consists of a 16-channel multiplexer and an analog-to-digital (A/D) converter. A 13-bit receiving register is used for formating the words from a discrete signal register and the A/D converter so that the total information frame can be transmitted sequentially. The system takes the vertical frame and horizontal sync pulses from one of the TV sync generators and modifies it by adding the binary coded words in sequence to the composite video waveform, 1 bit per horizontal line sync pulse. This pulse train is then reinjected into the TV system for transmitting. The vertical frame pulse begins the first word of the format and 16 horizontal sync pulses are allotted for each binary word.

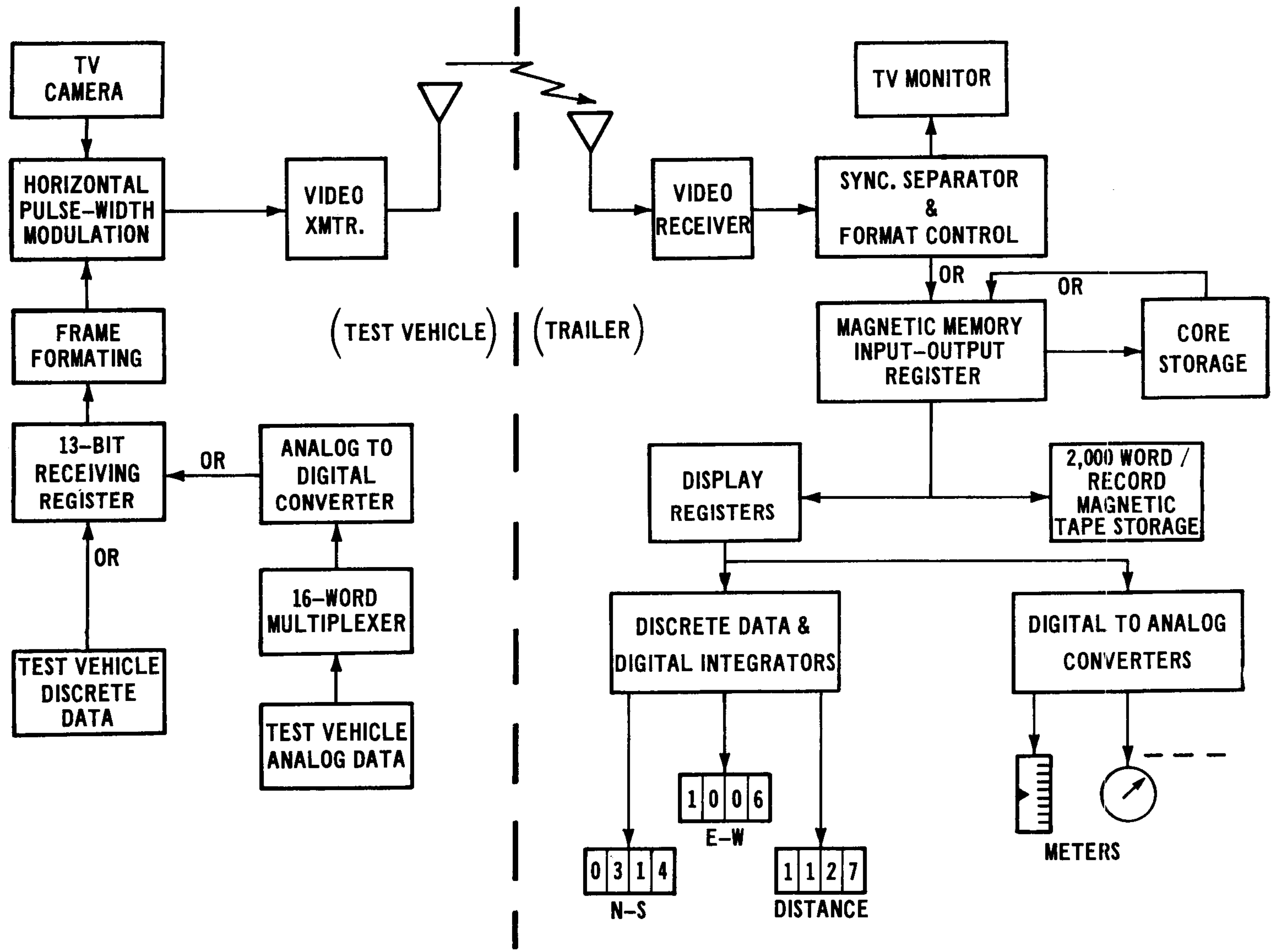


Figure 13. Data transmission system.

Following is a list of the signals telemetered to the base station:

Vehicle

Vehicle Speed
Vehicle Odometer
Vehicle Wheel Angles (Front and Rear)
Vehicle Battery Voltage
Vehicle Battery Current

Navigation

Vehicle Direction Sine
Vehicle Direction Cosine
Vehicle Position North-South
Vehicle Position East-West
Vehicle Pitch
Vehicle Roll

TV Camera

Pan Angle
Tilt Angle

E. Navigation Subsystem

The navigation subsystem (Figs. 14 and 15) is a coordinate system whereby the vehicle's location is continually calculated and referenced against known reference inputs established by a directional gyro system. A processor, with inputs from the wheel pulser, calculates the deviation in meters and/or angle that the vehicle is away from the reference. Since the system operates on an x-y coordinate basis and the locations of the coordinates of the vehicle and the target object are known, the vehicle can be made to move in a direction to reduce these coordinates to zero and thus arrive at the target. Readouts from the system are telemetered to the base station. These registers plus a directional angular readout instrument are located on the front of the vehicle's chassis so that they can be continually seen by the TV camera and thus aid the driving scheme. Details of the system's operation are as follows:

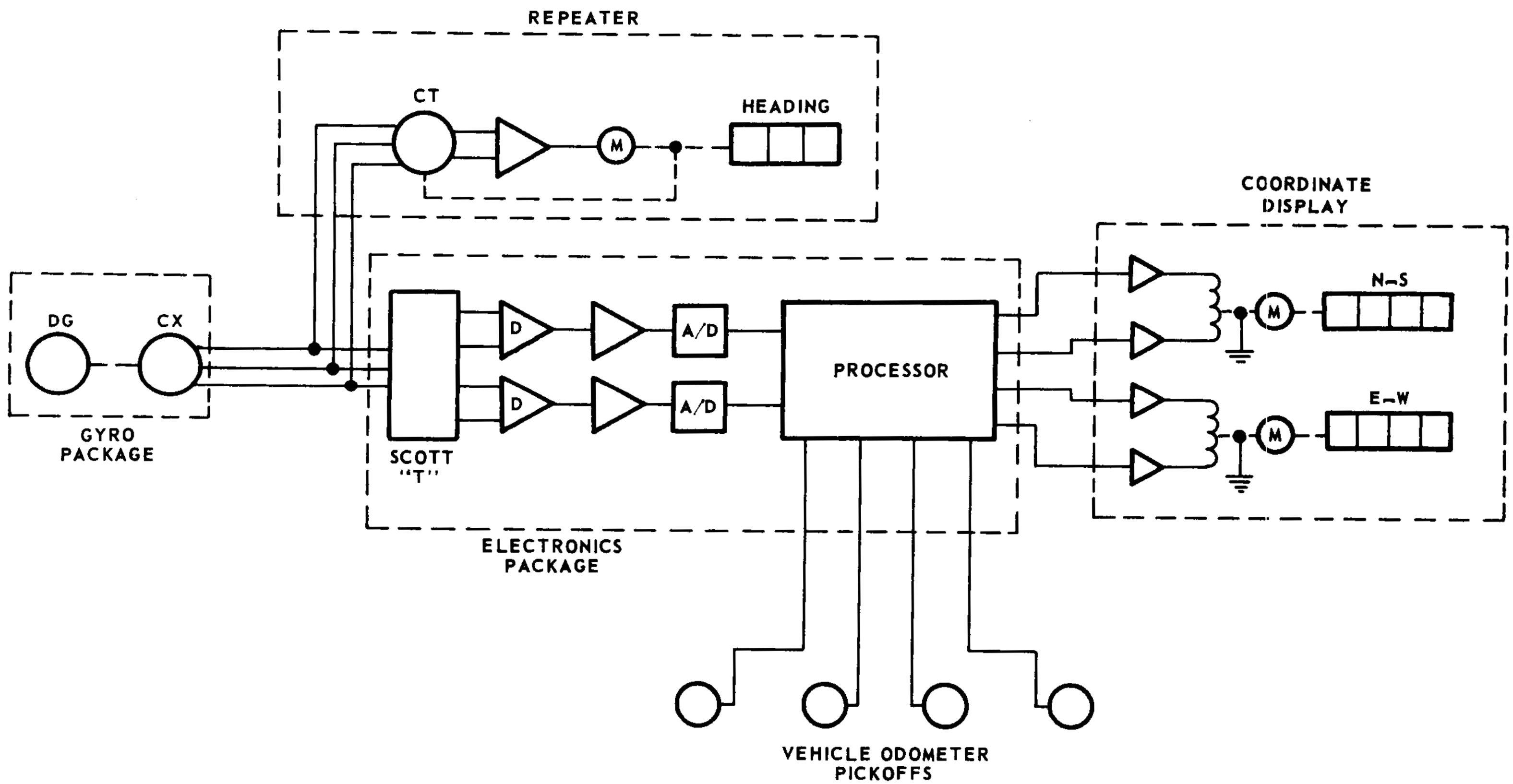


Figure 14. Navigation subsystem.

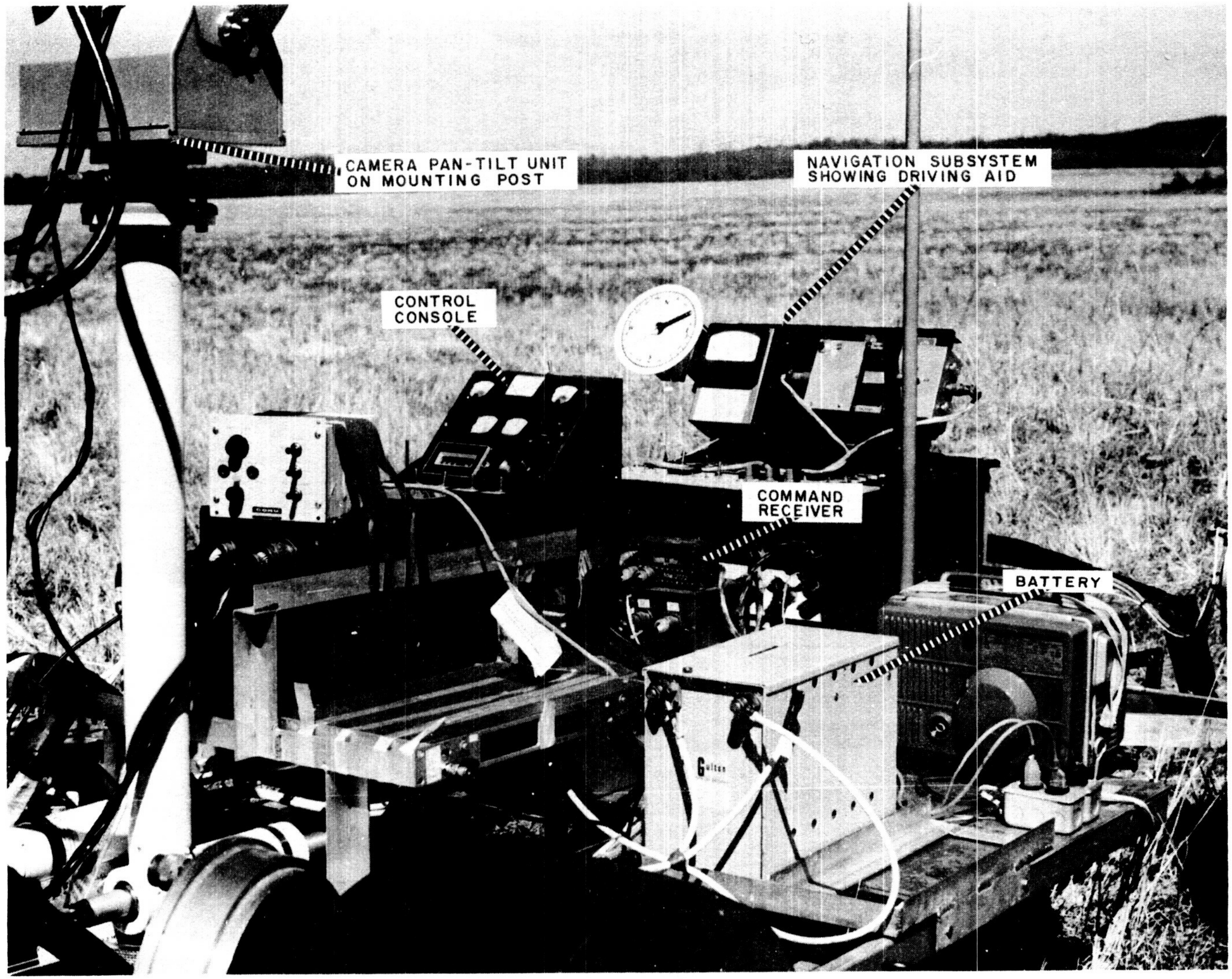


Figure 15. Remote-controlled vehicle equipment.

The dead-reckoning navigation system for the vehicle consists of a directional gyro for establishing an inertial direction, an odometer system for measurements of distance, a signal processor for combining the measured distance and direction, and a sun compass for determining initial vehicle heading information.

The directional gyro output is from a three-wire, 400-Hz synchro transmitter (CX) illustrated in Figure 14. There is provision for torquing the gyro for alignment to the initial reference heading and for updating. A simple servoed synchro repeater provides the vehicle heading display after proper alignment.

The sun is used as the azimuth reference. Sun sensors mounted on a theodolite and driving null meters are used to measure the angle between vehicle heading and the solar subpoint, θ, to within 1 min of arc. The angle between the sun and north, ϕ, is determined from the ephemeris charts. The vehicle heading was then $\gamma = (\phi - \theta)$. The control differential transformer (CDX) shaft is rotated until this angle is registered on the heading display.

The output of the CDX excites a Scott-T transformer that converts the three-wire synchro output to the sine and consine of γ. These two signals are then demodulated, filtered, and scaled so that a sine or cosine value of one (90 or 0 deg) is represented by a 10-Vdc level. The signals are then changed to digital form by an A/D converter for processing. The functions performed by the processor are $\Delta x = \Delta s \cos \gamma$ and $\Delta y = \Delta s \sin \gamma$, and with proper scaling, northings $= \Sigma \Delta x$ and eastings $= \Sigma \Delta y$, where Δs is an increment of distance.

The Δs increment is produced when the third fastest wheel of an odometer produces a signal. This method permits two wheels to spin without introducing an error. The system would also operate with the loss of the odometer signal from one wheel. The vehicle motion is measured more accurately and simply than with arithmetical averaging of the odometer pulse.

III. REMOTE CONTROL DRIVING STATION

The configuration of the remote control driving station was designed to meet the needs of a developmental-type test program. Provisions were made in the equipment to allow for a variety of remote driving conditions such as different delay times, stereo or mono TV viewing, variable TV frame rates, and separate or integrated steering and throttle controls. Because of a constrained budget and limited time, much of the equipment used was obtained as surplus parts or built in-house.

Major elements of the remote control driving station include a driving console, a small digital computer, a command transmitter system, and a telemetry receiving system. A block diagram of the complete system, i. e., both test vehicle and driving station, is shown in Figure 16. The right half of the diagram consists of the system elements included in the remote driving station. These were mounted in a 2.4- by 10.6-m (8- by 35-ft) van-type trailer. A photograph of this trailer is shown in Figure 17. The trailer provided the flexibility and mobility deemed necessary for the remote driving tests. It could be taken to several different test locations where the driving conditions correspond somewhat to that of the lunar surface. By locating the trailer on a suitable hilltop, the test vehicle could be remotely driven over terrain 10 to 15 km distant. A gasoline-driven electrical generator is also shown in Figure 17. It provided all power requirements for the trailer so that the remote control station could be operated at locations not having electric power service.

A. Antenna System

The antennas provided for the remote driving station were installed on top of the trailer and can be seen in Figure 17. Two directional antennas were mounted to an elevation and azimuth positioner. A 1.2-m (4-ft) parabolic dish having an 8-deg beam width was used for simultaneous reception of two video signals. This antenna operated at 2.2 to 2.3 GHz and was vertically polarized. Mounted above the parabolic dish was a corner-reflector antenna that transmitted to a 450-MHz command signal. A fixed antenna was also mounted on the trailer roof, which was omnidirectional and was also used for the command system. Provisions were made inside the trailer for manual switching between the two command antennas. The antenna positioner was remotely controlled from within the trailer. Manual tracking of the test vehicle was done by remotely positioning the directional antennas until the incoming video signal was maximum. Little difficulty was experienced with manual tracking because of the very slow speeds of the test vehicle and the large distances between the test vehicle and the trailer.

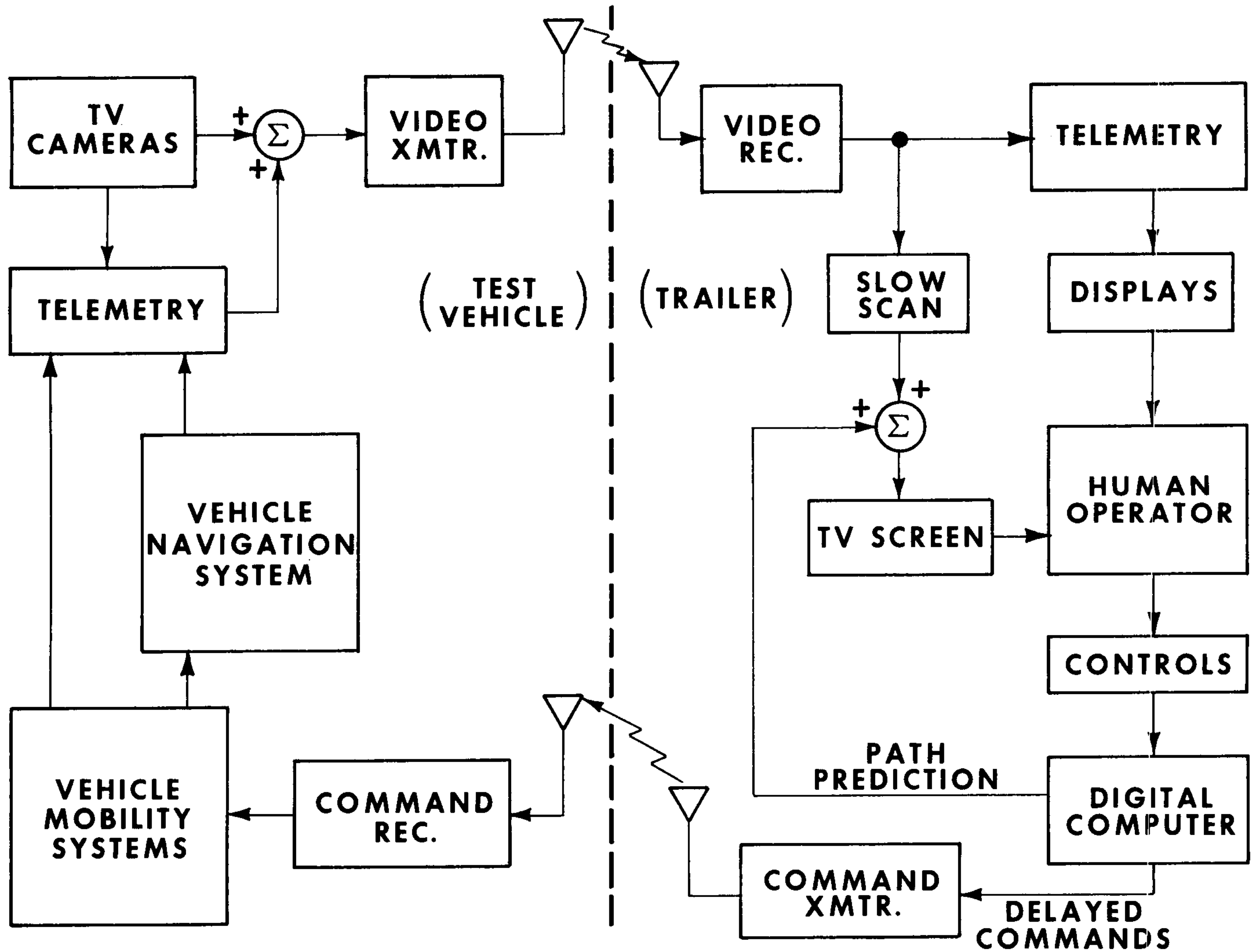


Figure 16. Remote driving tests.

Figure 17. Photograph of van-type trailer (with mounted antennas).

B. Driving Console

The driving console consisted of a video display system, an instrument panel with telemetry displays and discrete command actuators, a data panel, and steering and throttle controls. The driving console was located in the aft portion of the trailer and can be seen in Figures 18 and 19.

1. Video Display System

Two video scenes were available for displaying to the remote control driver. These could be used to generate a stereo view by mounting the two TV cameras aboard the test vehicle in a side-by-side and parallel-axes orientation. A three-dimensional image was presented to the driving console operator by use of a stereo viewer shown in Figure 18. The viewer consisted of four front-surface mirrors which caused the operator's right eye to view the video scene from the right TV camera and the left eye to view the left TV camera scene. To assist the operator in acquiring a three-dimensional image, manual adjustments were provided with the stereo viewer mirrors so that relative horizontal and vertical positioning of the two TV pictures was possible. Two rack-mounted, 43-cm (17-in.) TV monitors were used to display the 525 scan-line signals received from the TV cameras. The stereo viewer was attached on the front of the driving console; however, it could be easily removed when test conditions required monoviewing. The driver looked straight ahead into the viewer to see the TV scene and, without moving his head, could glance down and view the complete instrument panel.

2. Instrument and Control Panel

The instrument and control panel consisted of round dial meters, edge-wise meters, digital readouts, and control switches for operating the vehicle systems remotely. A sketch of this panel is shown in Figure 20, where it can be seen that the panel is divided into three sections. The left section contained video-related displays and controls. Guidance and navigation functions were grouped in the center portion, and vehicle operation displays and controls were located on the right side of the panel. All command signals initiated from this panel were discrete, i.e., on-off, controls. The characteristics of the command system provided for actuation of only one discrete command at a time. All pushbutton switches were back lighted; they controlled two separate functions such as forward and reverse, and they were momentary/ratchet action switches that were polarized with latching relays on the vehicle. Table 1 provides more detailed information of the panel.

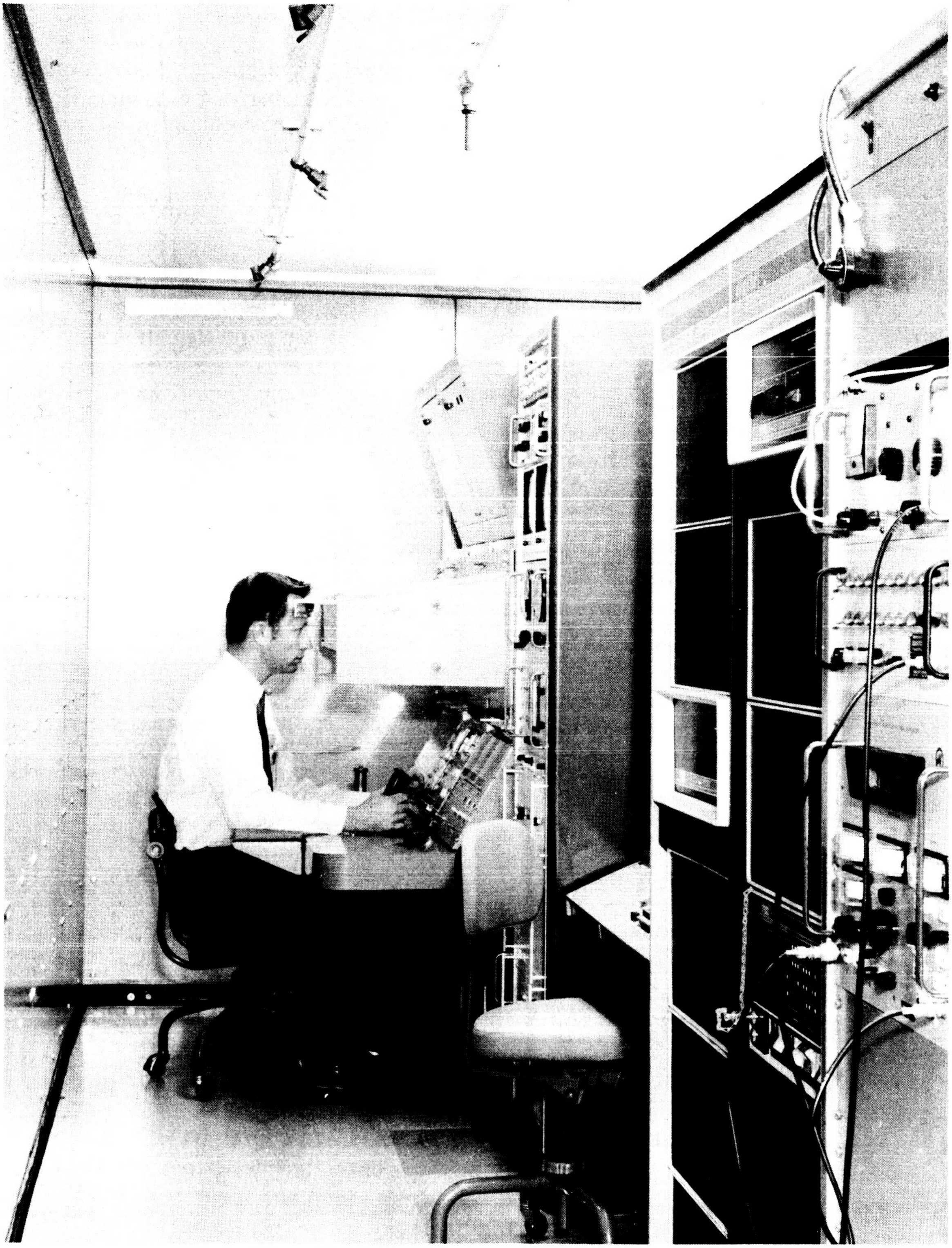


Figure 18. Driving console located in aft portion of trailer.

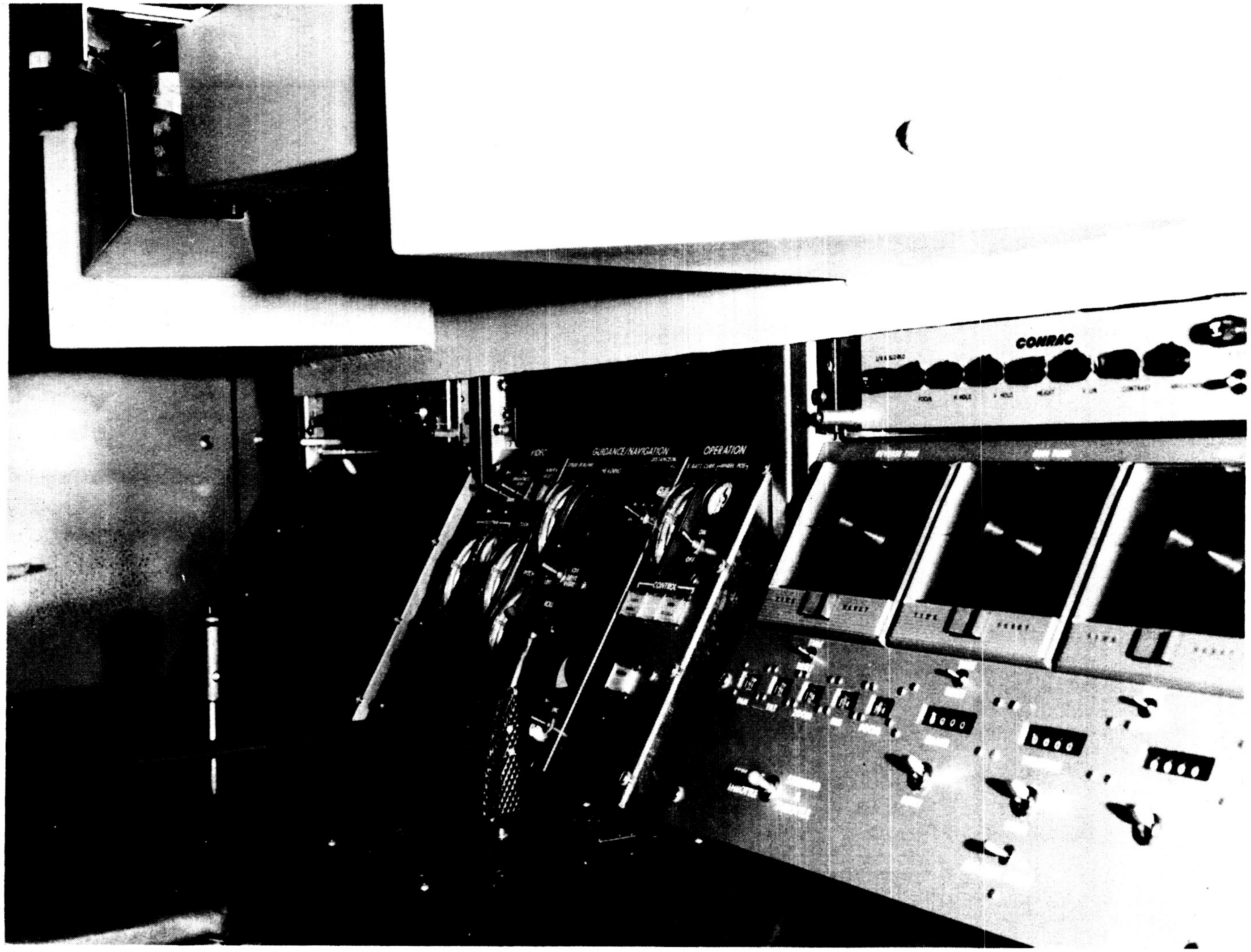


Figure 19. Data panel.

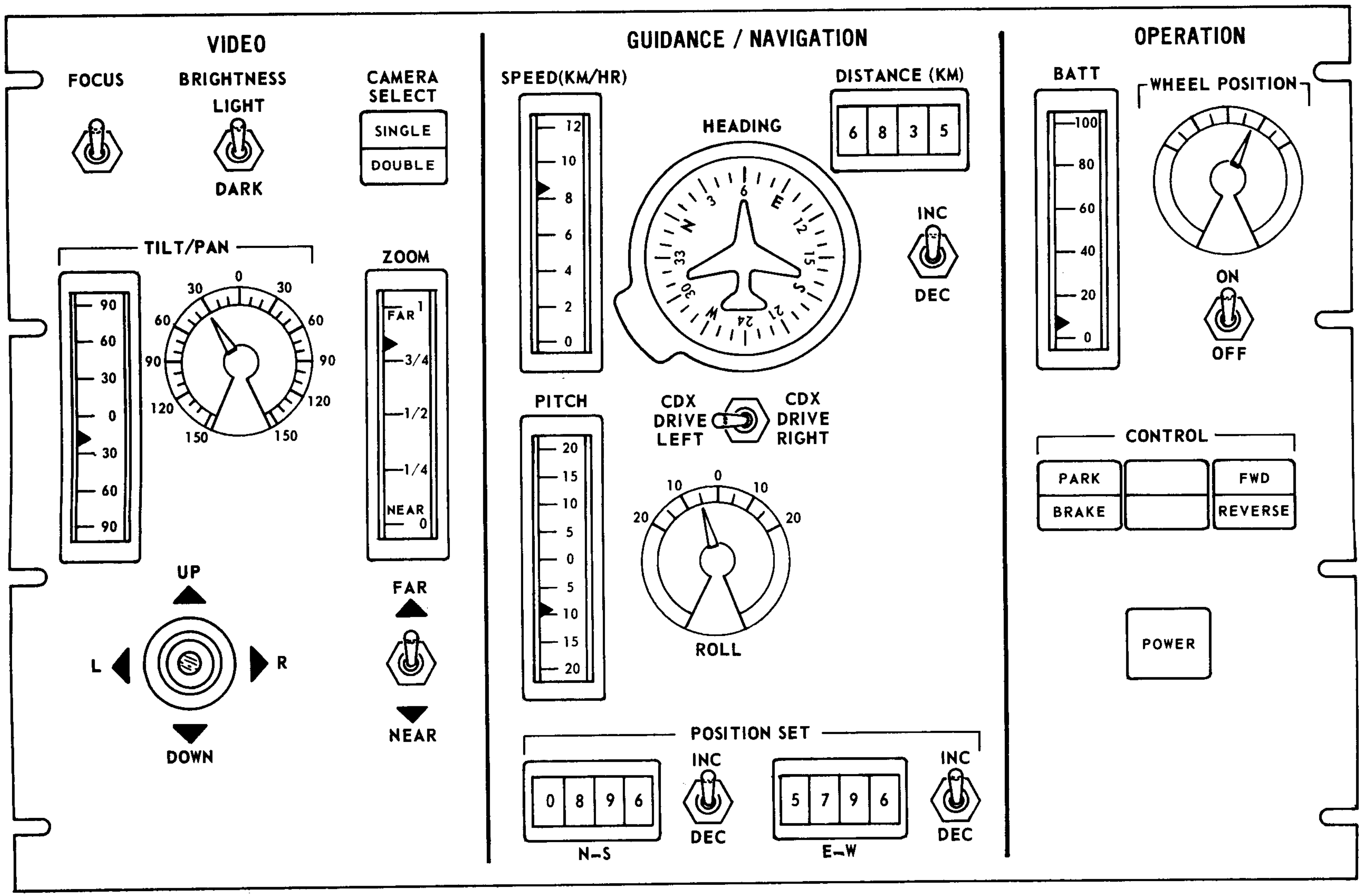


Figure 20. Instrument and control panel.

TABLE 1. INSTRUMENT AND CONTROL PANEL FUNCTIONS

Display	Command	Type
Camera tilt		Edgewise voltmeter (-90, 0, +90 deg)
Camera pan		Round voltmeter (-180, 0, +180 deg)
Camera zoom		Edgewise voltmeter (0 to 1)
	Camera pan and tilt	Miniature x-y controller
	Camera zoom	Toggle switch, three-position, spring return
	Camera focus	Toggle switch, three-position, spring return
	Camera iris	Toggle switch, three-position, spring return
	Camera select	Pushbutton, mode control of either one or both cameras
Speed		Edgewise voltmeter (0 to 12 km/hr)
Heading		Synchro meter, continuous heading
Pitch		Edgewise voltmeter, vehicle attitude
Roll		Round voltmeter, vehicle attitude
Distance		4-digit readout (m), scaled
North-south		4-digit readout (m), scaled
East-west		4-digit readout (m), scaled
	Increment-decrement	Toggle switch, updates digital readouts
Battery		Edgewise voltmeter, vehicle battery current
Wheel position		Round voltmeter, vehicle turn
	Park brake	Pushbutton, ON-OFF
	Forward/reverse	Pushbutton, vehicle direction
	Power	Pushbutton, vehicle power

3. Data Panel

A data panel was located beside the instrument and control panel and is shown in the foreground of Figure 19. This panel, consisting of counters, stop clocks, and reset controls, was used primarily for collection of test data. Counters were used to total the number of times during a test run that the following controls were used: pan, tilt, zoom, iris, focus, brake, throttle, and steering. A steering mode select switch was also included on the data panel.

4. Steering and Throttle Controls

Two modes of controlling vehicle speed and direction were provided on the driving console. In one driving mode combined steering and throttle commands were made with a two-axis side-arm controller. Fore-and-aft rotations of this controller resulted in throttle and brake commands, while left-and-right motions initiated steering commands. This controller was spring loaded so that it would return to neutral in both axes whenever no forces were applied.

A throttle-type, single-axis controller was provided for the second driving mode. In this mode, the left hand was used for throttle and brake motions and the right hand for steering control. The single-axis controller had a friction-type action so that it would remain in the position that it was left in. A detent at the neutral position served to distinguish between throttle and brake positions.

Both controllers provided analog inputs to the command system so that continuous control of the test vehicle speed and steering was effected. In Figure 19 both control sticks can be seen on the desk-top portion of the driving console.

C. Time Delay Simulation

An important consideration in the design of the remote control driving system was the representation of time delays. It was realized that the time delay was one of the most difficult elements with which the remote control driver had to cope. In the actual situation of remotely controlling a lunar surface vehicle from the earth, signal delay is caused by time required to transmit the commands and time required to receive video and telemetry information. Equipment for simulating command delay and a video recorder for simulating the return delay were redundant for the purposes of this study.

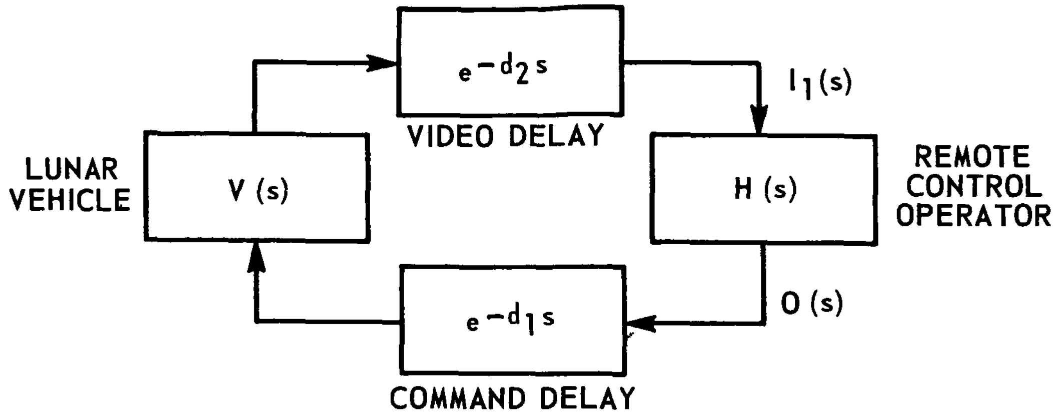
Figure 21 illustrates the equivalence of a system with two separate time delays and a system with the two time delays combined. This equivalence can be proven using convolution integrals or Laplace transforms. The remote control operator sees the same input in both systems and should therefore respond the same with either case. Likewise, it can be reasoned that the test vehicle would have an identical response with either method of representing time delay.

A choice was then made regarding the equipment to be used for simulating time delay. A small-scale digital computer could be used to delay commands or a video recorder could be used to delay the TV presentation. A decision was made to use the computer because it could also provide for other functions in the remote driving station, such as path prediction, signal conditioning, and data handling.

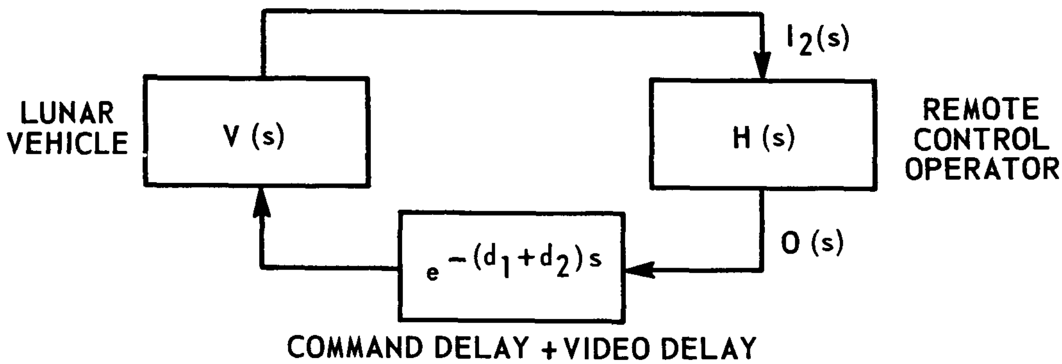
A PDP-8 computer was installed in the trailer and can be seen on the right side of Figure 17. All command signals were sampled by the computer five times per second, delayed by the computer program, and then sent to the command transmitter. The PDP-8 was configured to have 16 A/D and 16 D/A single buffered channels, 8K memory, hardware multiply/divide, and a digital clock. Program input was by means of a paper tape reader.

D. Slow-Scan Representation

A technique was employed with the TV presentation to simulate frame rates of 30, 10, 4, 2, 1, 1/2, or 1/4 frames/s. The purpose of this was to determine acceptable frame rates in order to make reductions in video power or bandwidth requirements for transmission. The video signal received from the test vehicle had a standard format of 30 frames/s and 525 scan lines. A magnetic disk video recorder was rotated at a synchronous speed equal to the field rate of the video signal received. The video recorder simulated slow-scan TV by recording a frame and outputting that frame at a standard rate of 30 frames/s until the next slow scan interval occurred. As an example, a slow-scan rate of 1 frame/s was represented by recording an incoming frame and outputting that frame 30 consecutive times. The disk recording system was capable of recording two channels so that stereo TV could be viewed in a slow-scan mode.



$$I_1(s) = O(s)\left[e^{-d_1 s}\right]\left[V(s)\right]\left[e^{-d_2 s}\right]$$



$$I_2(s) = O(s)\left[e^{-(d_1+d_2)s}\right] V(s) = I_1(s)$$

Figure 21. Time delay simulation.

E. Path Prediction

Provisions were made to assist the operator in contending with the difficulties of remotely driving a vehicle with time delays of several seconds. This was considered a potential benefit whenever maneuvering accuracy was required such as in obstacle avoidance. Equations were formulated which determine the effects of throttle and steering commands on the vehicle location. Assumptions in the equations included a flat plane representation of the terrain surface. Because the command signals were immediately available for the prediction calculations and since the video scene was the result of the system time delay, the predicted vehicle location could be superimposed on the TV picture of the terrain. Inputs to the equations were steering and throttle commands, time, camera pan angle, and camera tilt angle. The PDP-8 digital computer was used to calculate the path prediction in addition to time delay simulation. A path prediction display was added to the TV scene of the terrain by use of an additional TV camera in the trailer which viewed a cathode ray tube (CRT). This prediction display was a small circle which moved vertically because of throttle commands and horizontally because of steering commands.

IV. TEST RESULTS

Initial testing of the vehicle and remote driving station was made in March and April of 1971, at the Marshall Space Flight Center near Huntsville, Alabama. The remote driving station was located on top of Madkin Mountain, which was 200 m above the surrounding terrain. Six kilometers from the mountain top and having a direct line-of-sight with it was a large open field in which the test vehicle was operated. Testing consisted of a remote navigation sortie and a remote driving investigation.

A. Navigation Sortie

The controller/navigators were provided with a 1:10,000-scale photograph of the sortie area with seven target sites marked on the photograph and described by coordinates from a grid overlay. They were unfamiliar with the area and had their first view of it on the TV monitors. The remotely controlled vehicle was delivered to the sortie origin, the directional gyro was aligned, the navigation system zeroed, and control was turned over to the remote control driving station.

The vehicle was navigated to the most distant site and returned to the origin, a total of 3.7 km. All seven points were located successfully on the outward leg of the sortie. On the return leg a tree 45 m from target 2 and almost identical to it in appearance was selected. The navigation system indicated the true site was between the two points.

Because of the vehicle's suspension a certain amount of "crabbing" was present in its movement. This led to errors in the navigation output of 10 to 40 m. However, as seen by the success in driving to and locating the targets, this proved to be sufficient except for the one case mentioned.

The total time for the sortie was 5 hr with the average speed of 0.68 km/hr. Maximum speed driven was 4.8 km/hr. Thus, about 15 percent of the time was spent driving with 85 percent spent studying the terrain with the camera, comparing it with the photographs, determining required headings, etc.

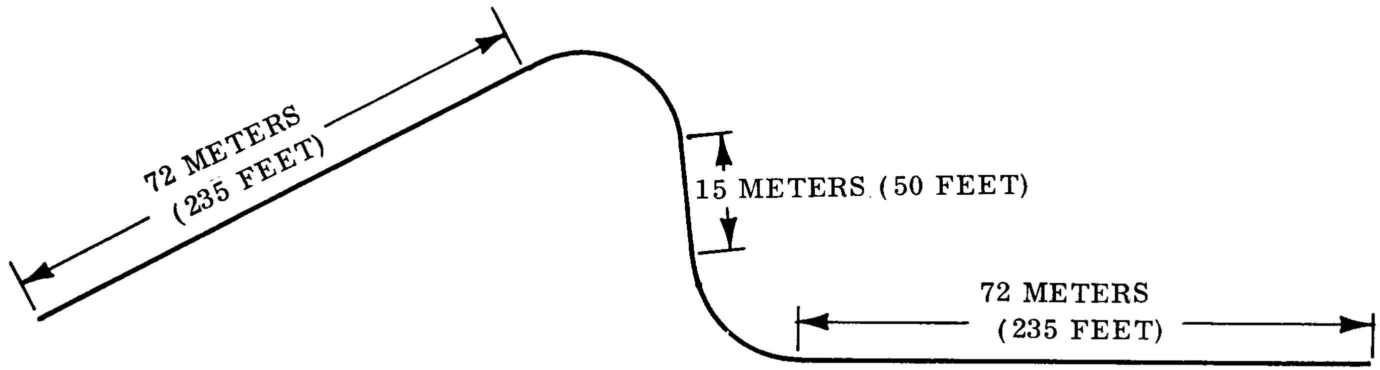
B. Remote Driving Tests

A series of tests was made to obtain preliminary data on an operator's equipment requirements and his capability for accurately driving a lunar vehicle by remote control from earth. All features of the remote driving system described herein have not been investigated because of time limitations. Those features considered most crucial were addressed in this initial test program.

Driving conditions investigated consisted of time delay, TV field of view, separate and integrated controls for throttle and steering, and operator driving mode. Total time delay of signal propagation from earth to moon and back is on the order of 3 s. However, additional time delay may result because of the operational system characteristics such as verification of command reception, slow scan TV, and buffering of signal processing equipment. Time delays of 4, 6, and 8 s were used in the driving tests so that a range of possibilities was considered. Two different TV lenses were provided which had horizontal fields of view of 28 and 53 deg. A self-paced driving mode and a stop-and-go mode were also compared. In the self-paced mode the driver was allowed to go as fast and for as long a time as he chose, but, at the same time, he was constrained to drive accurately on a marked course. In this mode the drivers usually drove at a relatively constant speed and stopped only when they had excessive course departures. Stop-and-go driving consisted of giving a short-duration throttle and steering command and then waiting to observe the resultant vehicle movement before initiating the next iterative command. Timing of the duration of the command inputs in the stop-and-go mode was not measured but was left to the driver's judgment instead. The drivers became fairly consistent in making the duration of the command about equal to the amount of the time delay.

A test course with terrain features similar to the lunar surface was not available at the time the initial driving tests were conducted. As a substitute, a course with two 15 m (50-ft) radius turns and a total length of 214 m (700 ft) was marked on an open field (Fig. 22). The test vehicle was positioned at either end of the course and astraddle the markings before each test run.

Data recorded at the test vehicle consisted of an x-y plot, total power consumption, run time, and battery voltage. Data were also recorded at the remote control station and included the total actuations of the steering, brake, and throttle controls. As a backup for the x-y plotter, field notes were also taken on the vehicle track deviations. Deviations were noted when all four wheels were on the same side of the marked course. Since the



ALL TURNS 15 METER (50-FOOT) CONSTANT RADIUS
TOTAL LENGTH OF COURSE: 214 METERS (700 FEET)

Figure 22. Test course.

vehicle was about 2.4 m (8 ft) wide, this ground rule allowed a track tolerance of ± 1.2 m (4 ft).

Three test subjects were used as remote control drivers. The driving tests were separated into two phases. The first phase consisted of 52 runs for driver training. This was followed by 74 data runs in which each test subject drove four times at each test condition. A test matrix is shown in Figure 23 which illustrates the four variables and the driving conditions investigated. During the driver familiarization, it was concluded that the wide-angle field of view was much preferred since both front wheels could be observed while driving. This was considered such a necessity for accurate driving that only the wide-angle field of view was used in Phase 2.

Preliminary analysis of the data is presented in frequency distribution form in Figures 24, 25, and 26. Average driving error for each data run was obtained from the X-Y plots and is used in Figure 24 to depict results of time delay, driving mode, and type of hand controller. Test results showed little difference in driving error caused by driving mode when the time delay was 4 s. However, stop-and-go driving resulted in more consistent driving and reduced error with 8-s time delay. Separate and integrated controllers were compared at the 4-s time delay condition. The frequency distributions in Figure 24 show slightly smaller driver errors with the separated controller.

Another measure of driving performance was obtained from the data by constructing frequency distributions of driving deviations. The maximum deviation from the marked course was plotted for each course departure that occurred. Because several course departures were usually experienced on each data run, a larger data sample was available for use. These data are presented in Figures 25 and 26 for comparison of driving modes. Figure 25 shows test results for 8-s time delay and tends to favor the stop-and-go driving over self-pace in two ways:

1. About 25 percent more course departures occurred with the self-pace mode.

2. Maximum driving deviation for each course departure averaged 3.6 m (12 ft) for the self-pace mode and 2.7 m (9 ft) for the stop-and-go mode.

Test results for 4-s time delay are depicted in Figure 26. Again, stop-and-go driving showed an advantage. Although the average maximum deviation for each course departure was about the same for both driving modes, approximately 60 percent more departures resulted from self-pace driving.

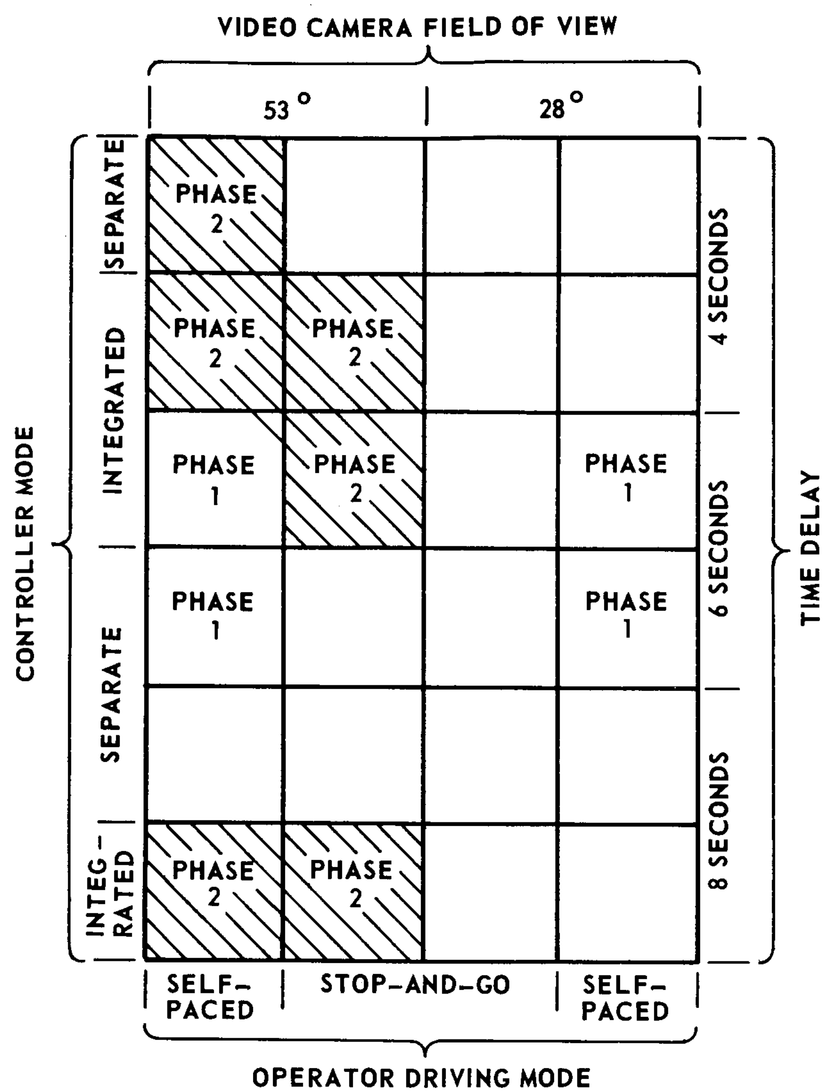


Figure 23. Test matrix for remote driving.

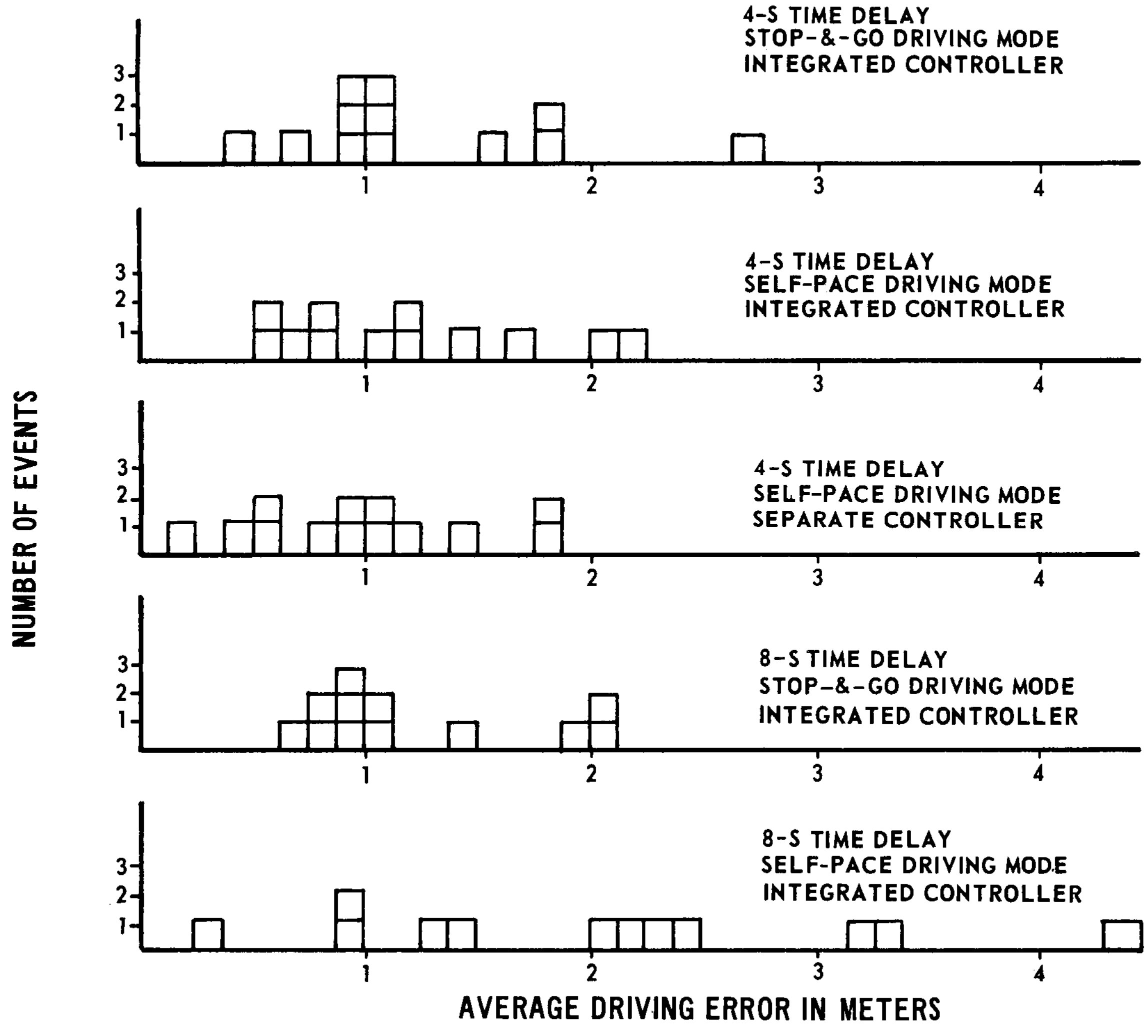


Figure 24. Average driving error for self-pace and stop-and-go driving modes.

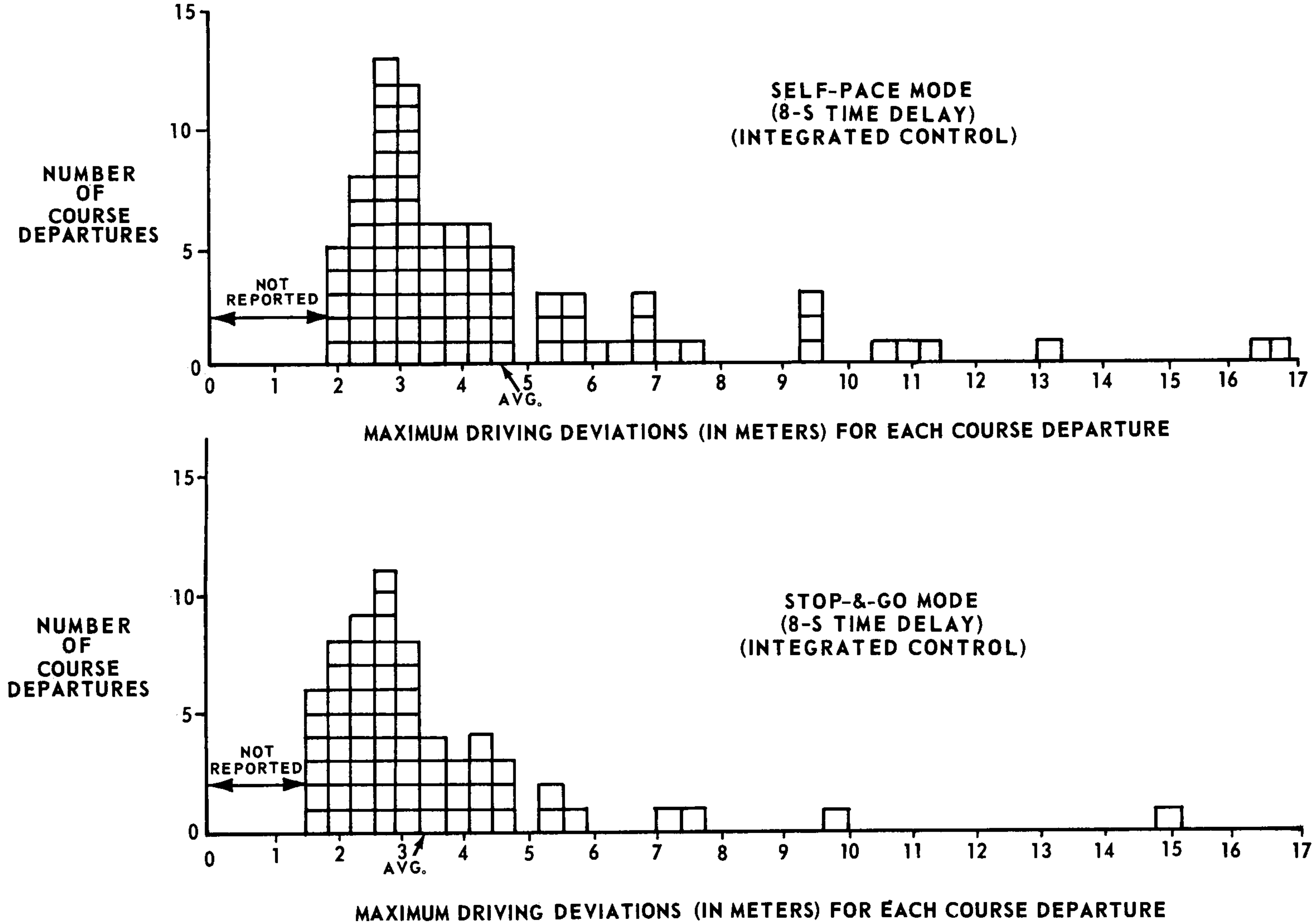


Figure 25. Driving deviations with 8-s time delay.

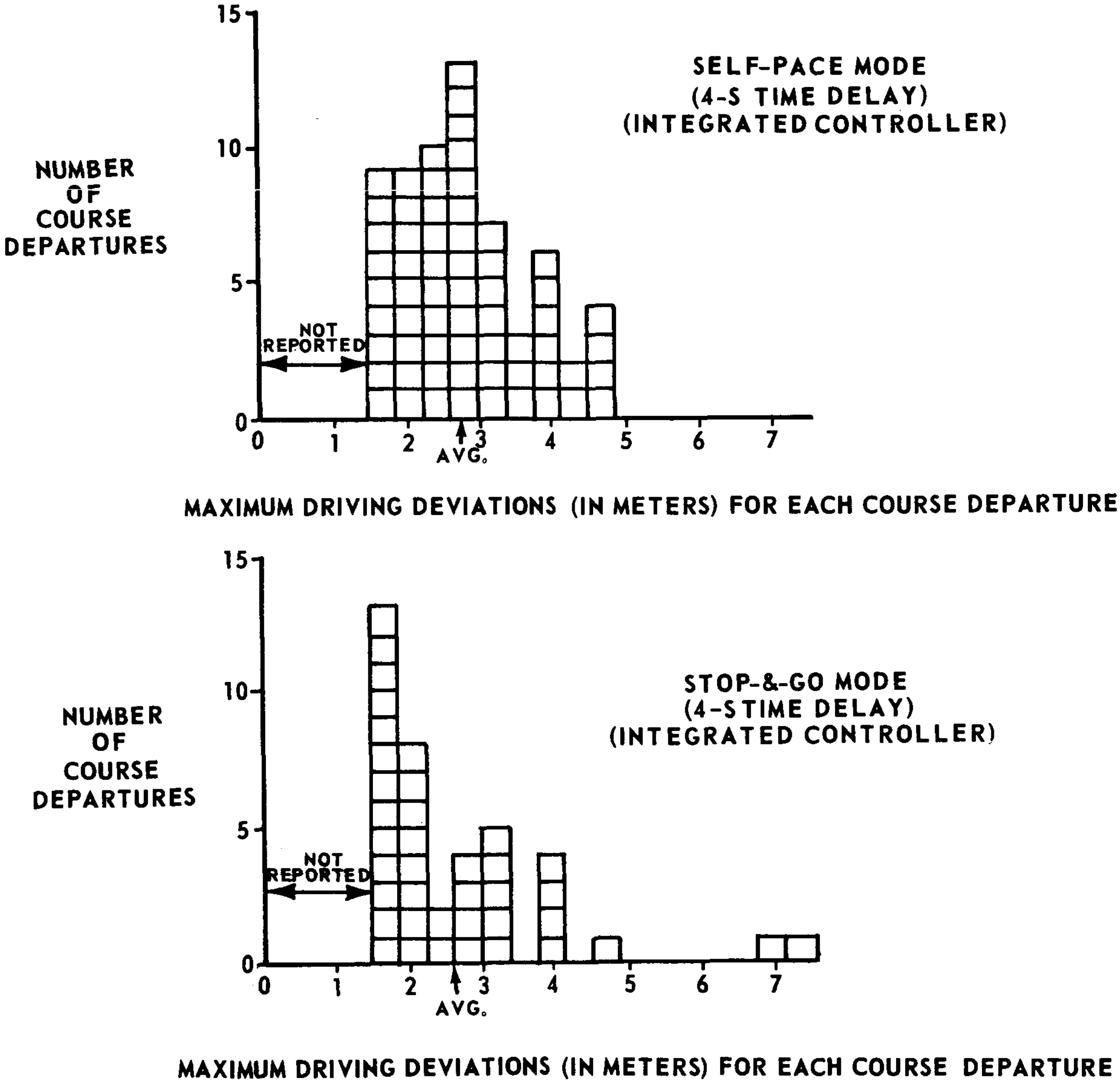


Figure 26. Driving deviations with 4-s time delay.

The test results are summarized as follows:

1. Stop-and-go driving gives better accuracy than self-pace driving. (However, tests with a predictive display may negate this result.)

2. Separate throttle and steering controls provided a slight improvement in driving accuracy. (Drivers also liked the separate controls because less hand fatigue resulted.)

Conclusions based on the experience of building and operating a remote control facility and test vehicle include the following:

1. Additional testing should be made to provide quantitative results on features of the remote driving system, such as predictive display, stereo TV, TV frame rate requirements, and data transmission requirements.

2. Testing should include some operation in terrain more similar to that of the lunar surface.

3. Test results with a predictive display to aid the driver in coping with time delay should improve vehicle capability by extending the range or else reducing power requirements and by increasing controllability for avoiding obstacles.

4. TV field of view should allow simultaneous viewing of both front wheels and the horizon.

5. Apparent terrain motion on the TV monitor caused by the test vehicle's bouncing on the surface was objectionable to the drivers. They preferred to view the TV image with a 20-cm (8-in.) monitor rather than a 43-cm (17-in.) monitor so that the relative effect of the bouncing was reduced.

6. Maximum speed requirements/capabilities for remote control should be investigated.

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