THE LUNAR ROVING VEHICLE— HISTORICAL PERSPECTIVE

Saverio F. Morea

Research and Technology Office
NASA Marshall Space Flight Center
Huntsville AL 35812

As NASA proceeds with its studies, planning, and technology efforts in preparing for the early twenty-first century, it seems appropriate to reexamine past programs for potential applicability in meeting future national space science and exploration goals and objectives. Both the National Commission on Space (NCOS) study and NASA's "Sally Ride study" suggest future programs involving returning to the Moon and establishing man's permanent presence there, and/or visiting the planet Mars in both the unmanned and manned mode. Regardless of when and which of these new bold initiatives is selected as our next national space goal, implementing these potentially new national thrusts in space will undoubtedly require the use of both manned and remotely controlled roving vehicles. Therefore, the purpose of this paper is to raise the consciousness level of the current space exploration planners to what, in the early 1970s, was a highly successful roving vehicle. During the Apollo program, the vehicle known as the Lunar Roving Vehicle (LRV) was designed for carrying two astronauts, their tools, and the equipment needed for rudimentary exploration of the Moon. This paper contains a discussion of the vehicle, its characteristics, and its use on the Moon. Conceivably, the LRV has the potential to meet some future requirements, either with relatively low cost modifications or via an evolutionary route. This aspect, however, is left to those who would choose to further study these options.

INTRODUCTION

Dreams of exploring the universe and traveling in space to other worlds and planets probably go back to the days of Copernicus when he pointed out that the Earth was not the center of the universe. With the subsequent technical and mathematical efforts of the early scientists such as Galileo, Kepler, and Newton, man became more aware of the universe and the laws that govern its motions. Thus, from the naive dreams of early man wrapped in legends and myths, modified by better physical and scientific understanding, man came to the realization of the possibility of flight into space. Indeed, the foundation for the investigation of space was laid through this inauspicious beginning.

The history of the LRV may have begun in the world of science fiction that had as its roots this evolving notion that man was only a part of a much larger unvierse. In 1901 for instance, the Polish science fiction writer Jersz Zulawski wrote *NA Srebrnym Globie (On a Silvery Globe)* in which his space travelers, after landing on the Moon, used a roving vehicle to perform a traverse that began at the lunar North Pole and proceeded south through Mare Frigoris and Mare Imbrium, ending near Mare Vaporum and the lunar equator—a very ambitious traverse. It then became a relatively short step from the science fiction writers of the nineteenth and twentieth centuries to the first primitive steps in the accomplishment of man's dream of visiting other worlds.

HISTORY AND BACKGROUND

The evolution of the LRV, from the fiction of these early visionaries to the nonfiction of contemporary engineers and scientists, proceeded via a series of more pragmatic contractor and government studies conducted primarily during the 1950s and 1960s. It was during this period of time when dreams, blended with creativity and technology, sparked with the national objective of "landing a man on the Moon in this decade," gave initial life to what was to become a reality in the 1970s: driving a car on another planet. To discuss all the various concepts and studies performed and how these concepts finally led to the design of an LRV would take far too long and would not be particularly relevant to the objective of this paper. However, it should be mentioned that numerous studies were conducted by organizations such as Boeing, Bendix, Lockheed, General Motors, Northrup, and Grumann, just to name a few. These studies examined configurations of vehicles that included fully automated designs with lunar life times of a year and a range of 1000 km, manned configurations of four and six wheels, tracked vehicles, manned flying platforms, mobile laboratories containing a shirt-sleeve environment for the astronauts, small automated rovers the size of a suitcase, and machines the size of a bus.

The LRV was not initially part of the early Apollo planning by NASA, but rather evolved into the agency's planning during the mid-phases of the program. As the milestone of sending a man to the Moon before the end of the decade of the 1960s became more realistic with each successful Apollo test flight in near-Earth orbit, and the expected safety margins for the subsequent missions began to more clearly emerge, plans that would maximize the scientific return from the Moon began to take on more significance in NASA's planning. In other words, once the task of satisfactorily testing the basic Apollo hardware was demonstrated, NASA's plans for optimizing the return on investment from subsequent missions to the Moon came into clearer focus.

In late May of 1969, the agency planning for an LRV culminated in a decision to proceed with development of a light article two months prior to the first manned lunar landing (Apollo 11). Subsequently, the responsibility for the management of the design and development of the LRV was given to the Marshall Space Flight Center in Huntsville, Alabama, and in turn to this author. After open competition during the summer of 1969, followed by competitive negotiations with the Bendix Corporation and the Boeing Company, NASA awarded a contract to the Boeing

Company on October 29, 1969. The contract, among other things, called for the delivery of a "manned qualified" flight vehicle to Kennedy Space Center (KSC) for installation into the Apollo 15 spacecraft by March 1971. The first flight article delivery was to take place a mere 17 months from contract go-ahead, only 22 months from NASA's decision to proceed with the progam. Because relatively little was known about the conditions on the lunar surface when the LRV program was initiated, a significant technical challenge faced not only engineers who established the technical design requirements, but also the engineers who were to design, test, and build this marvelous "spacecraft on wheels." To accomplish this task with a technically sophisticated and reliable vehicle in such a short period of time and within extremely tight budget constraints, new and innovative approaches to the procurement and management aspects of the program were required. Given the constraints the program was faced with, it is probably correct to say that no other program has replicated or surpassed the track record of this one. However, the procurement and management aspects of this program are another study in itself.

With the benefit of 20/20 hindsight, the justification and need for the LRV may seem unassailable today, but such was not the case at the time that the go-ahead decision had to be made. Remember, the crew of Apollo 11 had not yet landed on the Moon. Reserving 400 to 600 lb of payload to carry a car to the Moon did not find favor among some NASA officials, who would much rather have carried this additional payload as extra "hovering" fuel for the lunar module (LM). The extra fuel would have provided more assurance that a safe place to land on the Moon could be found, thus decreasing the risk that the mission would have to be aborted at a most critical moment and just short of the principal objective. The decision to proceed, therefore, was a brave one to make at that particular time and not, by any means, a unanimous one within NASA.

The other side of the equation, however, dealt with how much more science could be accomplished if the astronauts had a relatively fatigue-free mode of transportation. The use of the LRV not only increased the distance the astronauts could explore away from the LM, but also substantially impacted how long the astronauts would be able to remain outside the LM. For instance, the Apollo 11 crew only traveled about 250 yards during their 21.5 hours on the lunar surface. On the other hand, with the first use of the LRV on Apollo 15, a distance of 17.3 miles was traversed and by Apollo 17 this was further increased to 22.3 miles. At one point astronauts were able to work 4.7 miles radial distance away from the LM through the use of the LRV. All told, an area similar to that of Manhattan Island was explored. This was a far cry from the area of one or two football fields, which represented the limits prior to the LRV. Also, it might be remembered that a combination of high metabolic rates and a lack of navigation aids caused astronauts Alan Shephard and Ed Mitchell on Apollo 14 to fall somewhat short of an important scientific objective. In the interest of safety, the flight director of that mission instructed the astronauts to abandon their attempt to reach the lip of Cone Crater when some difficulty was encountered in locating it. The use of an LRV on that mission would have easily solved their problem since it was designed to transport a relatively fatigue-free astronaut to a selected location through the use of an on-board navigation system. Table 1 compares the LRV performance of the final three Apollo missions with that of Apollo 14, which had no LRV but did have a lunar cart that was pulled by the astronauts and contained their tools and sample collection containers. The use of LRVs on each of the last three Apollo missions enabled the astronauts to cover significantly larger areas, accomplish more scientific physical work, and accumulate much more information about the Moon than what had been previously accumulated in the combined rock samples from the prior three missions that had landed on the Moon (Apollo 11, 12, and 14).

TABLE 1. Lunar Roving Vehicle performance comparison.

	Apollo 14	Apollo 15	Apollo 16	Apollo 17
Driving time (hr:min)	N/A	3:02	3:26	4:26
Surface distance traversed (miles)	3.3 (estimated)	17.3	16.6	22.3
EVA duration (hr:min)	9:23	18:33	21:00	21:30
Average speed (mph)	N/A	5.7	4.8	5.0
Max range from LEM (miles)	Unknown	3.1	2.8	4.7 EVA #2
Longest EVA traverse (miles)	1.5 (estimated)	7.75	7.2	12.5 EVA #2
Rock samples returned (lb)	94	170	213	249

GENERAL REQUIREMENTS

The LRV became affectionately known as a "dune buggy," a "moon buggy," the "moon car," etc. It was compared to a golf cart and a small car. The fact is that none of these characterizations was accurate. Although deceptively simply in appearance, the LRV in reality was a highly specialized and complex sophisticated vehicle more aptly described by using the terminology "manned spacecraft on wheels."

The vehicle was designed to be operated in the harsh vacuum of space and with temperature extremes on the lunar surface of ±250°F. Because of anticipated physiological problems with the astronauts' depth perception on the Moon, landing on the Moon at low sun angles was considered a necessary constraint in mission planning. This consideration, therefore, meant that the LRV needed to be designed with a capability to operate in the deep shadows of the mountain ranges for substantial periods of time when temperatures could still be at -200°F to -250°F during the lunar morning. Although intentional use of LRV operation in the shadows was not planned in the mission time line, given all the unknowns of the lunar environment, it did not seem appropriate to constrain the LRV design to only the warm, sunlit portions of the Moon. Thus, even if low weight considerations would not have eliminated the use of traditional rubber tires, the temperature and vacuum constraints did. Figure 1 shows LRV *1 on the lunar surface.

The LRV had to be designed for maximum static and dynamic stability while simultaneously minimizing weight and volume. The stability and weight design considerations were constrained by the requirement that the LRV be capable of carrying two astronauts, tools, science equipment, cameras, television and audio transmission equipment, as well as the weight of the collected rock and soil samples. All this added up to approximately 1100 lbm, which represented considerably more than twice the empty weight of the LRV itself. (By comparison, the average automobile can only safely carry about half its own weight.) In addition, the vehicle had to remain statically stable on slopes of up to 45°.

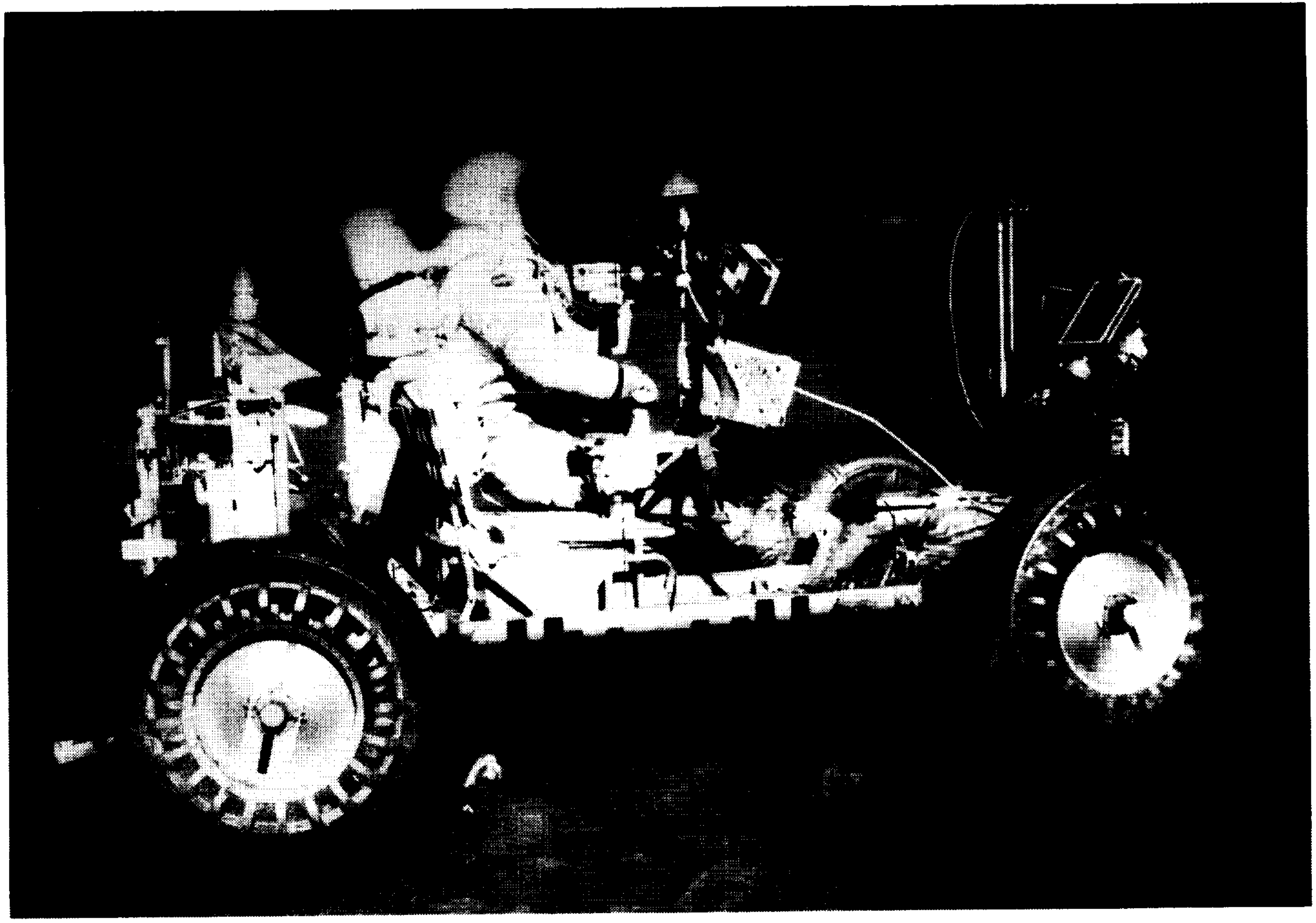


Fig. 1. Lunar Roving Vehicle #1 on the lunar surface during Apollo 15 mission.

Other major design drivers included the requirements that the vehicle be capable of carrying two astronauts in their spacesuits and be operated by either the left- or right-seated astronaut. Because of the extremely limited motions an astronaut had in a pressurized spacesuit, a conventional steering wheel was ruled out in favor of a T-shaped hand controller positioned in front of and between the astronauts. The small limited storage volume of 35 ft^3 available to carry the LRV to the Moon (stowed in a quadrant of the LM descent stage) presented a major design challenge. The solution to the dilemma of the small storage volume available vs. the desire to have a very wide base vehicle for stability purposes resulted in a "folded package" concept for the vehicle (Fig. 2). The final result was like unfolding a vehicle the size of a minicompact car to approximately the dimensions of a full size automobile.

The reliability factors also were a strong design driver. Reliability was attained through a combination of simplicity of design and operations and through redundancy. The redundancy aspect was expressed as a requirement that "no single point failure shall abort the mission and no second failure endanger the crew." This requirement resulted in two independent steering systems (front and rear), two independent battery systems (each

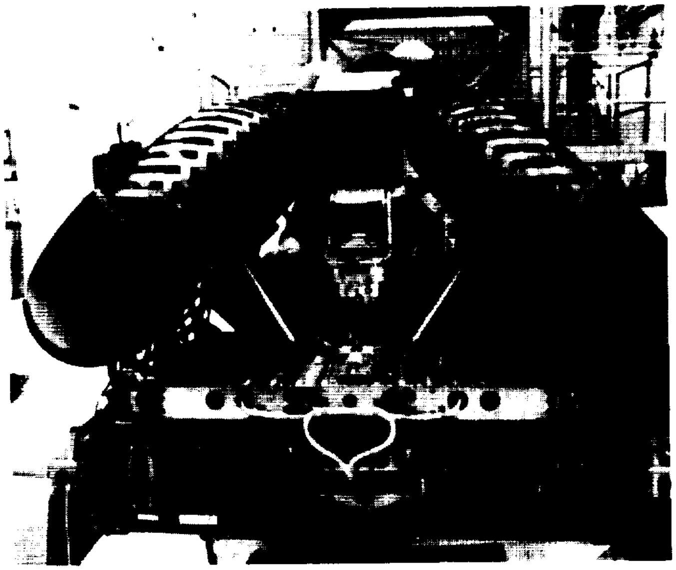


Fig. 2. Lunar Roving Vehicle folded prior to installation in LM.

with sufficient energy to power the vehicle), dual hand controller potentiometers, etc. Circuit and logic protection techniques were also incorporated into the design. These techniques were circuit breakers, velocity limits on changing motor rotation direction, and power interrupt during braking and hand controller return to neutral for steering command. The capability for switching any of the steering or traction drive systems to either, or both, batteries was provided along with independent drive motors for each wheel.

Yet another major design requisite was the consideration that the lunar dust could be a troublesome factor. Remember, very little technical data on the soil characteristics of the Moon were known during the entire development period of the LRV. Attention to the potential dust hazard resulted in designing fenders to prevent the depositing of a "rooster tail" of dust on the vehicle and crew. All moving parts had to be protected against dust, including hermetically sealing the wheel drive motors and traction drive assemblies. Even the slighest coating of dust on thermally radiating surfaces would materially degrade their thermal performance. Thus, during all operations of the LRV, dust covers had to be provided over the radiating surfaces, necessitating storage of the heat until completion of the extravehicular activity (EVA). When the vehicle was parked and the astronauts prepared for their sleep period in the LM, the radiating surfaces of the LRV could then be uncovered and heat rejected to space.

One last major design essential that further confirms the case for the LRV being a "spacecraft on wheels" had to do with the necessity of having a navigation system on board. If EVAs that took the astronauts well out of line of slight of the LM were indeed to be carried out, it would be necessary for the astronauts to know not only where they were at any given moment, but also their most direct route back to the safety of the LM in case of an emergency. Following their tire tracks back to the LM would, of course, have been possible, but would undoubtedly not have been the fastest way to return.

SYSTEMS DESCRIPTION

Figure 3 is a photograph of the flight vehicle LRV #1 prior to final acceptance and shipment to KSC for installation into Apollo 15's LM. It consisted of several major subsystems (Fig. 4) that will be discussed. They are the mobility subsystem, the crew station subsystem, the navigation subsystem, the thermal control subsystem, the electrical power subsystem, and the space support equipment or deployment subsystem.

Mobility Subsystem

The mobility subsystem consisted of a three-piece aluminum chassis, four wheels with wire tread tires and independent traction drive assemblies mounted in each hub, a suspension system, a front and rear steering system, and a hand controller with associated drive control electronics system (DCE). With the exception of the chassis subsystem, the rest of these subsystems were designed, developed, and delivered by the General Motors Delco Electronics Division in Santa Barbara, California, under subcontract to the Boeing Company, who was the prime contractor.

Chassis. The chassis (Fig. 5) provided by the Boeing Company consisted of three separate sections: the forward, center, and aft portions. The forward portion supported the LRV batteries, drive control electronics, and navigation electronics and contained mechanical provisions for mounting a power package and antenna for television transmission. The center chassis provided the support for the two astronauts and their fold-down seats, foot rests, the hand controller, the control and display console, and the omnidirectional antenna for voice communication. The aft chassis was used essentially as a platform with mechanical tie-down points for the astronaut tools and scientific equipment, including storage of the lunar material to be collected. (The power package and antenna on the forward chassis, the voice antenna on the center chassis, and scientific equipment and tools on the aft chassis were equipment that was delivered by the Johnson Space Center and installed on the vehicle by the astronauts after the LRV was deployed on the lunar surface.)

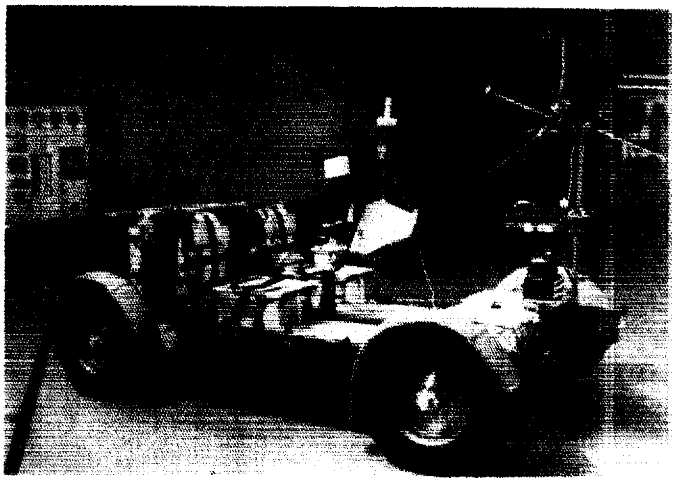


Fig. 3. Lunar Roving Vehicle #1 prior to delivery to KSC for installation on Apollo 15.

All three sections of the chassis were constructed of welded aluminum joined together by hinges. Torsion springs were installed at the forward hinges and were used to assist in unfolding the LRV during deployment on the lunar surface. In a similar manner, torsion bars were used at the aft chassis hinge and served a similar purpose as the torsion springs.

Because minimizing weight was so critical to the design, very careful machining was accomplished on the rectangular tube sections as well as on the chassis fittings in order to remove every unneeded pound of weight. Load testing of the chassis was very critical to confirm the strength of the design, since the analytical techniques alone of these complicated shapes would have necessitated excessive conservatism and, thus, excessive weight.

The floor of the center chasis was made of 2024 beaded aluminum and was capable of supporting the full weight of both astronauts, each wearing a portable life support system in the lunar gravity environment. Here again, with the minimum weight factor being so critical, the LRV overall structure could not have supported the weight of the astronauts in the Earth gravity environment without structural failure. For astronaut training purposes, a special 1-*g* trainer had to be designed and built as part of this program (Fig. 6).

Wheel design. The diameter of the wheel depicted in Fig. 7 was approximately 32 in; it was 9 in wide, and weighed a mere 12 lbm. It was constructed using a spun aluminum hub attached to a traction drive assembly at the inner core and a titanium

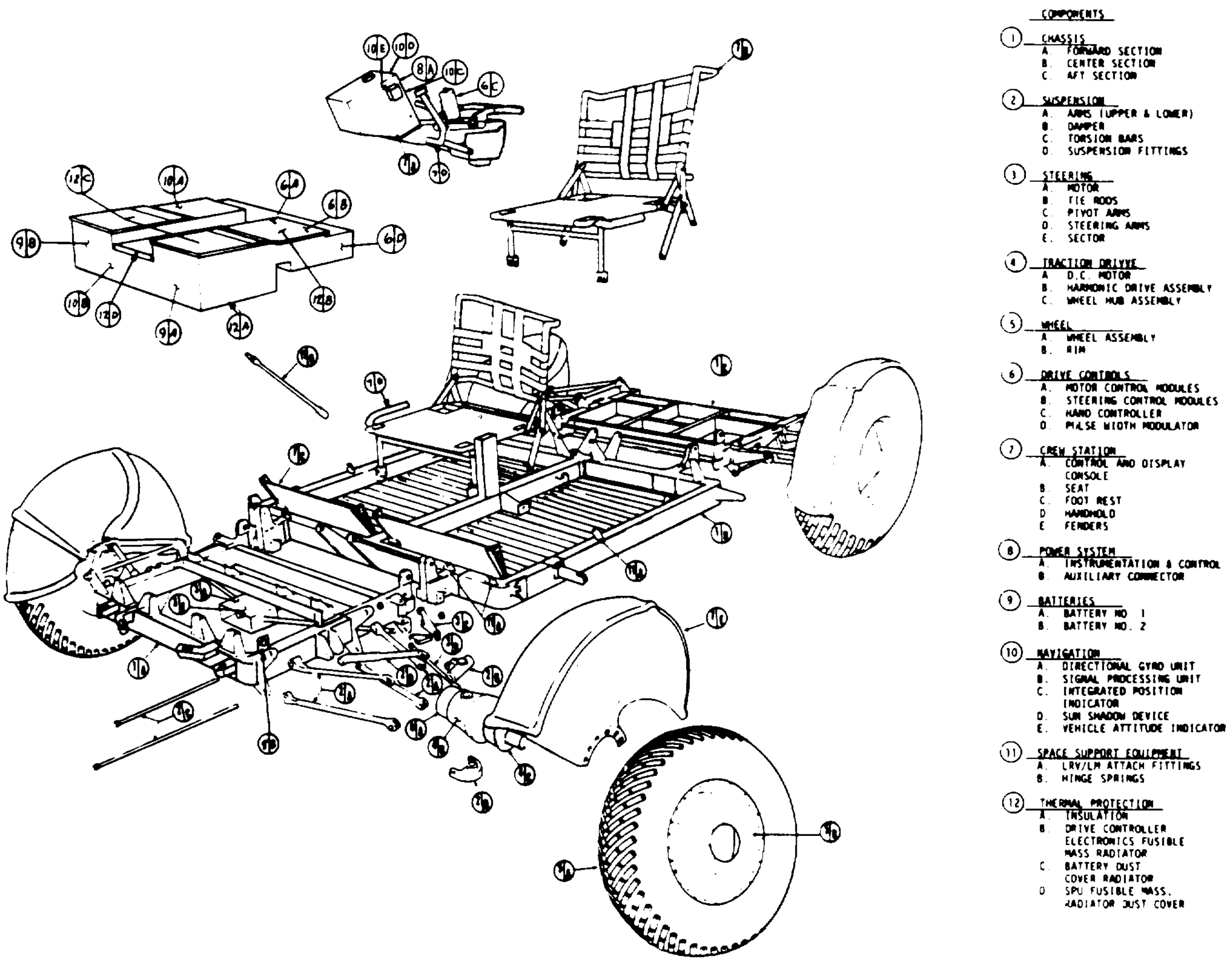


Fig. 4. Lunar Roving Vehicle components.

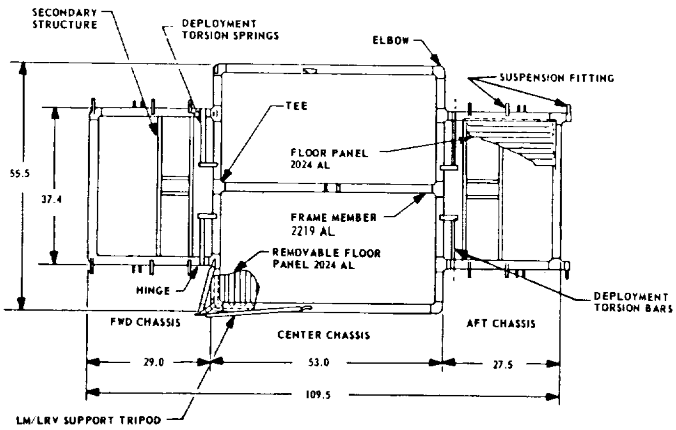


Fig. 5. Lunar Roving Vehicle chassis.

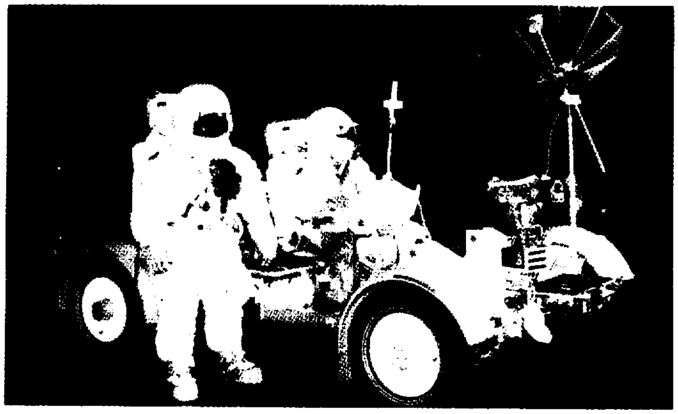


Fig. 6. Earth gravity (1 g) LRV astronaut training vehicle.

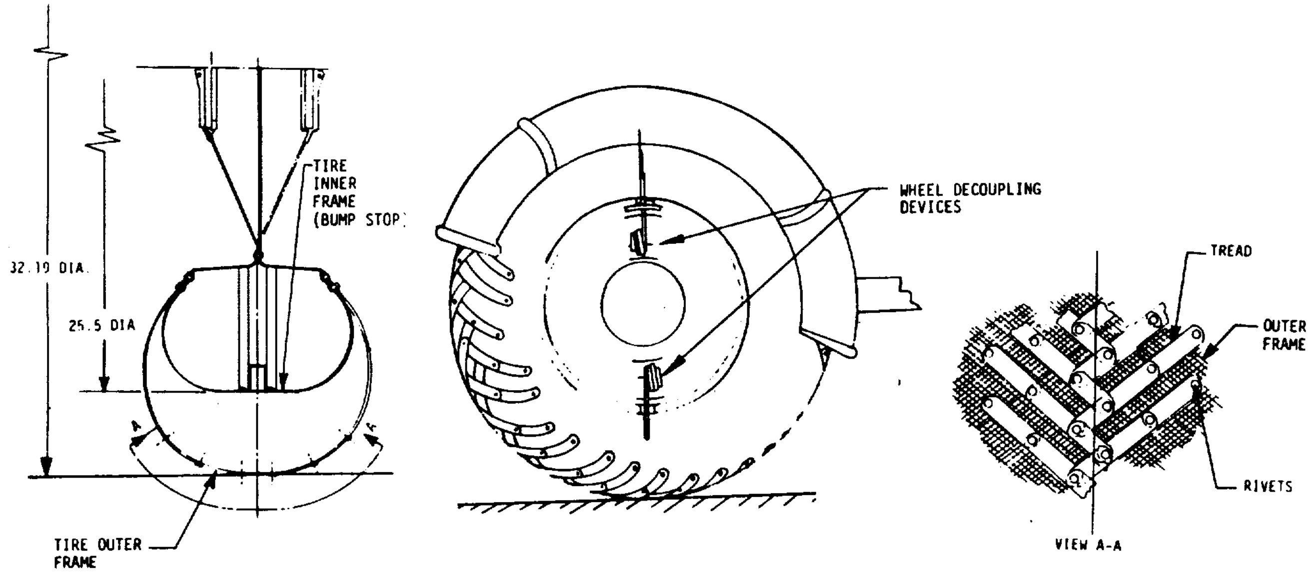


Fig. 7. Lunar Roving Vehicle wheel design.

"bump stop" inside a woven mesh of zinc-coated steel wire (0.033-in diameter) to which a tread made of titanium was riveted in a chevron pattern. Testing with simulated lunar soil at the Government's Waterways Experiment Station at Vicksburg, Mississippi, showed that a chevron pattern that covered 50% of the contact area was optimum and would provide sufficient traction to climb slopes of 20° to 25° without detrimental wheel slip. Endurance testing showed that at vehicle speeds of up to 14 km/hr, rocks with heights as great as 12 in could be struck without wheel or suspension system failure.

Traction drive. The traction drive unit (Fig. 8) attached at the center of the wheel hub consisted of a 1/4 hp series-wound (36 V) dc brush-type drive motor assembly connected directly to a "harmonic drive" assembly with an equivalent of 80:1 gear reduction. The motor and harmonic drive was a totally welded unit, hermetically sealed, and pressurized with nitrogen at 7.5 lb/in^2. Thus, the welded pressurized unit not only provided protection from the lunar dust, but also aided in transferring heat to the hub where it could radiate into space.

The harmonic drive seen in Fig. 9 utilized a unique, yet simple, principle. It converted high speed-low torque to low speed-high torque. The output of the traction drive motor is connected to a wave generator that caused a continuous wave form to be transferred to a flexible spline. A significant gear reduction ratio was developed by having two less teeth on the flexible spline than on the circular spline, thus avoiding the necessity for providing a much heavier conventional gear reduction mechanism. Incorporated into each traction drive assembly was a magnetic reed switch that activated nine times during a single wheel rotation. The pulses generated in this manner were subsequently used in the odometer, speed, and navigation calculations. It might be mentioned here that the use of the harmonic drive principle did not evolve out of the space program, but rather from the shoe machinery business in this country.

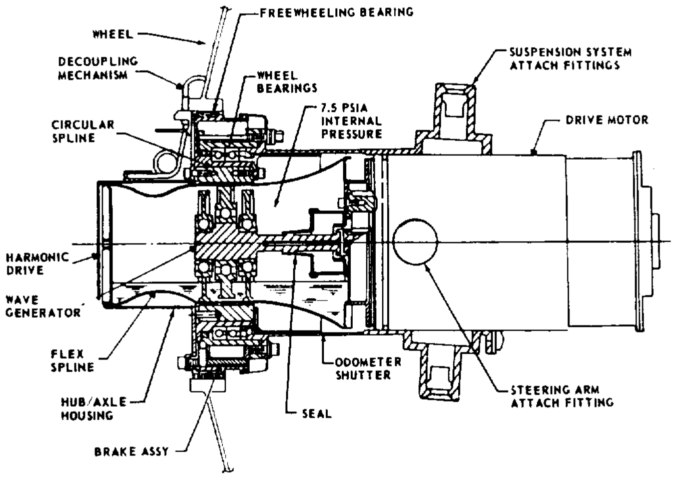


Fig. 8. Traction drive assembly.

To prevent disabling the LRV because of a traction drive assembly failure, design provision was made to enable manual decoupling of the wheel from the traction drive and brake. This was accomplished by pulling the decoupling ring seen in Figs. 7 and 8 with a part from the two tripods left over from the LRV deployment operation. (A portion of one of these tripods doubled as a special tool to accomplish this decoupling.) Once decoupled from the traction drive assembly, the wheel could be left to "free wheel," around the traction drive assembly. The remaining three engaged traction drive assemblies provided the drive power to the operational wheels. Analytically, it was shown that the LRV could be driven in an emergency mode with only one of the four traction drive assemblies engaged (three wheels "free wheeling").

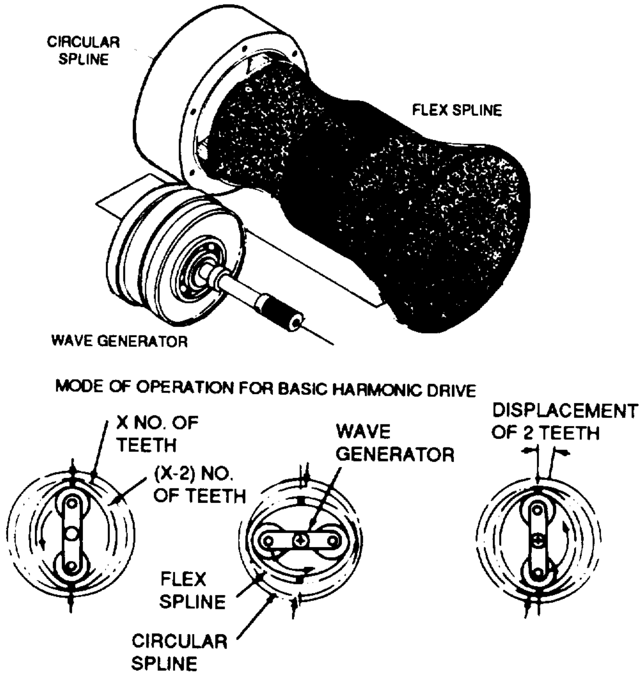


Fig. 9. Harmonic drive.

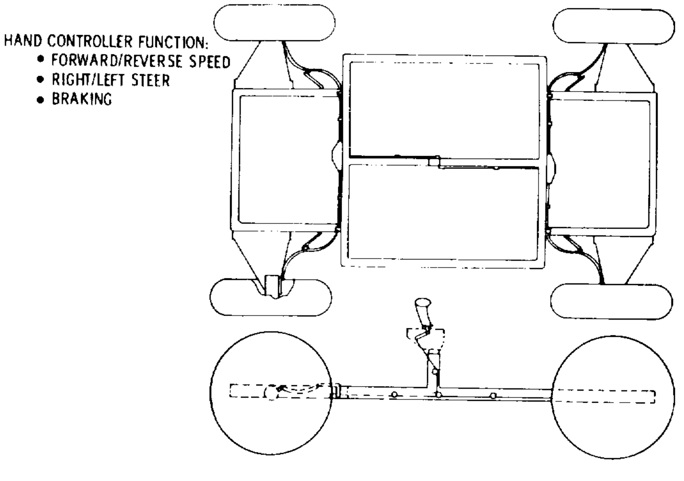
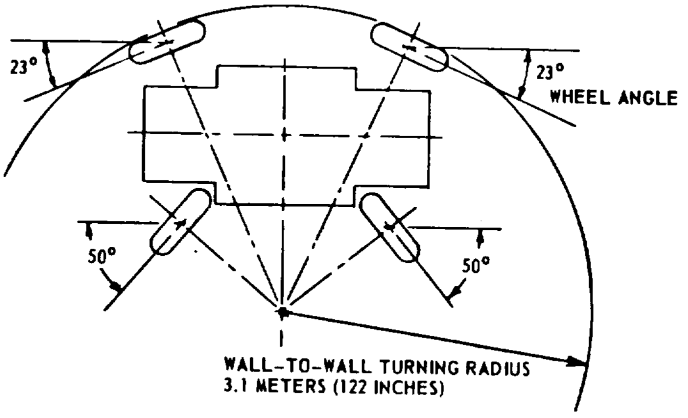


Fig. 10. Hand controller/brake cable system.

DOUBLE ACKERMANN STEERING



CAPABILITY VERIFIED BY ACTUAL MEASUREMENT
ON QUAL AND FLIGHT #1 VEHICLES

Fig. 11. Steering assembly.

Braking was accomplished via a cable connecting the hand controller and the mechanical shoe and drum system on each of the four wheels (Fig. 10). In addition to normal drive braking, the system was also set by the hand controller as a parking brake. In the event of a brake lock-up, possible sag as the result of excessive temperature from extra lengthy parking under adverse solar heat load, or excessive use of brakes during driving, the brakes could be released from the park position by a pull-ring mounted below the hand controller.

Steering. In an effort to reduce total power needs, increase maneuverability, and provide redundancy in all critical systems, the front and rear wheels were designed with independent, modified Ackerman steering subsystems. Each subsystem consisted of a small 0.1-hp, series-wound, split-field, 500-rpm motor driving through a 257:1 gear reduction into a segment gear that connected with each traction drive motor by steering arms and a tie rod. This independent front and rear steering system permitted a vehicle turning radius of 122 in "wall-to-wall," enabling the LRV to turn within its own length (Fig. 11). A steering vane attached between the chassis and the steering arms allowed the extreme steering angles required for the short turning radius. Steering response was rapid, requiring only 5.5 sec from lock to lock, with reversals accomplished by switching field windings through the hand controller subsystem. The beauty of the modified double Ackerman system was that it allowed the rear wheels to always track the front wheels, even in the sharpest of turns, thus providing maximum maneuverability while minimizing the power required for locomotion.

In the event of a steering malfunction, or in the event that the steering would have been overly sensitive, the astronauts had the capability to electrically turn off either the front or rear steering. In addition, the astronauts could mechanically disengage and lock either front or rear steering by pulling a ring on the side of the chassis and mechanically locking the steering system in the center position. If it were necessary to reengage following the disengagement of either steering subsystem, this could have been accomplished through the use of a special tool carried on the LRV. All this redundancy seemed like a large price to pay; however, as the reader may recall, the entire first EVA on Apollo 15 had to be conducted with rear steering only. Although the steering malfunction was resolved during the rest period between EVAs, a significant impact to the mission would have resulted if the LRV had to be dropped from EVA #1 due to lack of steering capability.

Suspension. The remaining suspension elements completing the mobility system consisted of a dual A-frame attached from the hub of each wheel to the chassis via two torsion bars and a shock absorber (Figs. 12 and 13). The torsion bars of different sizes provided ride comfort by reacting the dynamic driving loads into the chassis structure. More than 80% of the load was reacted by the longer of the two torsion bars. The smaller bar served

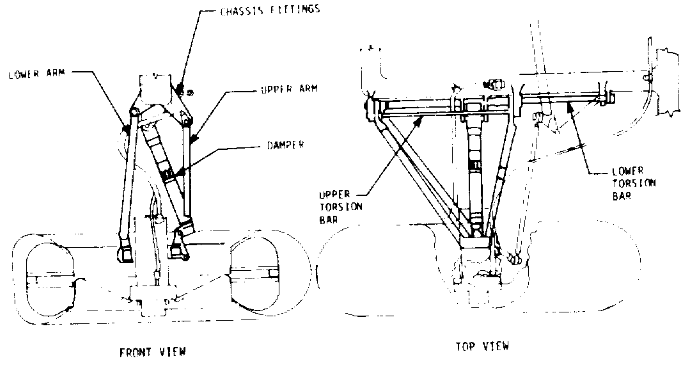


Fig. 12. Lunar Roving Vehicle suspension system.

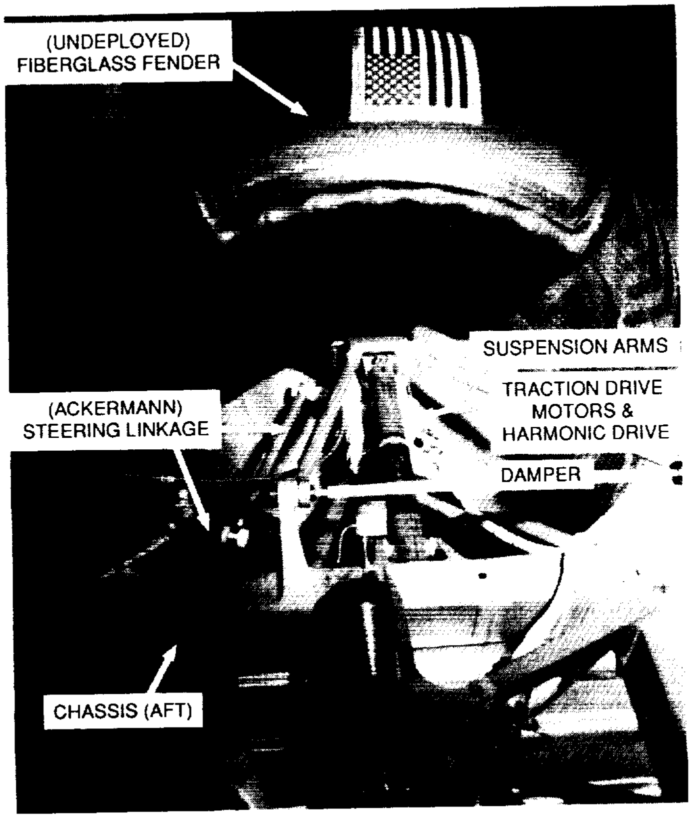


Fig. 13. Lunar Roving Vehicle suspension system.

primarily as a deployment aid during the initial unfolding operations and was the only one of the two bars loaded while in the stowed position. This approach limited any "creep" tendency of the bar material and/or assembly to the secondary (smaller) torsion bar, thus leaving the primary bar unloaded until the vehicle was ready for driving. Each wheel also had a linear piston damper or shock absorber that was somewhat telescoped during storage and then extended upon deployment. The linear piston damper was selected due to its design simplicity, light weight, and efficient loading of the suspension structure.

Drive control electronics (DCE). The DCE package was located on the forward chassis of the vehicle and was the electronic heart of the mobility system. This package accepted forward and reverse speed control signals as well as left or right steering commands through a process called "pulse width modulation" (Figs. 14 and 15). It featured redundant circuitry and dual power supplies. The DCE provided signal processing logic to pulse width modulators that in turn furnished energy to both the traction drive and steering motors. The square-wave pulse, providing power to the traction drive, varied in width, thereby varying applied power as a function of the speed command from the hand controller potentiometers. The traction drive motors pulse rate was 1500 Hz, whereas that of the steering motors was 10,000 Hz. Heat generation from the DCE had to be stored until after the completion of an EVA in order to prevent heat radiation surfaces from being impaired in their function by dust accumulations. More will be said about this in the discussion of the thermal control system.

Crew Station Subsystem

The LRV crew station subsystem (Fig. 16) consisted of two foldable seats, two seat belts, two foldable foot rests, a hand controller, one arm rest behind the hand controller, inboard and outboard hand holds, two toe holds, and the control and display console. In addition, fenders for the wheels and the floor panels of the center chassis were considered as part of the crew station. They were required primarily because the LRV was manned.

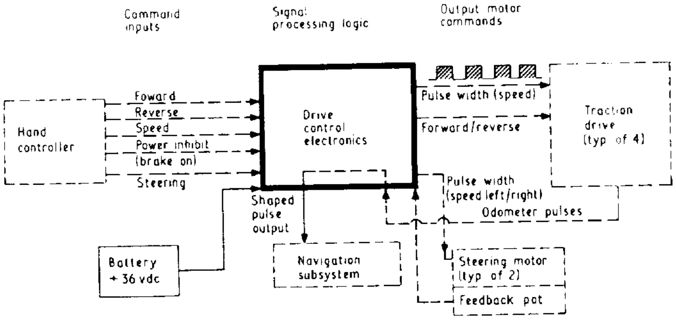


Fig. 14. Drive control electronics operation schematic.

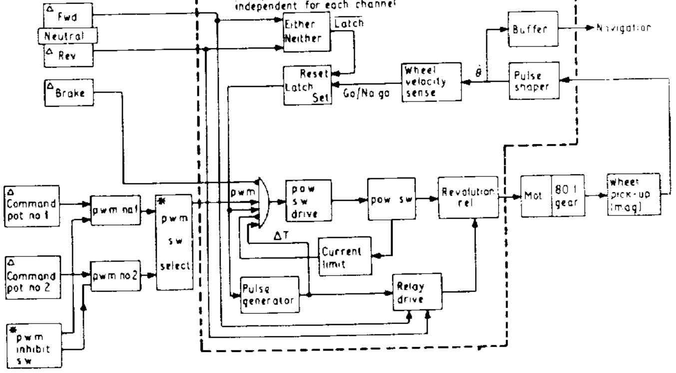


Fig. 15. Drive control circuit block diagram.

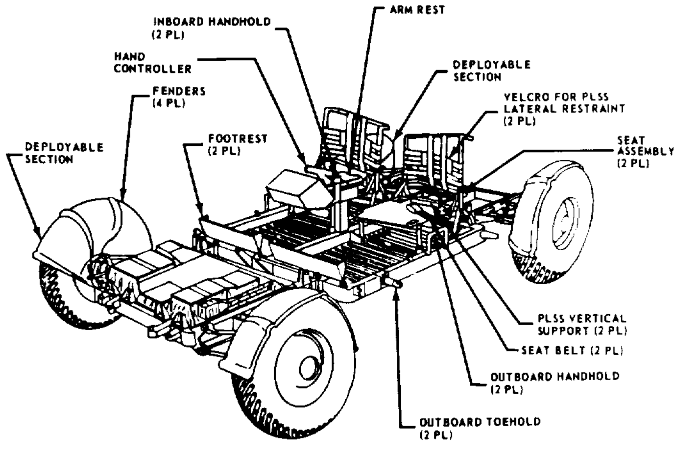
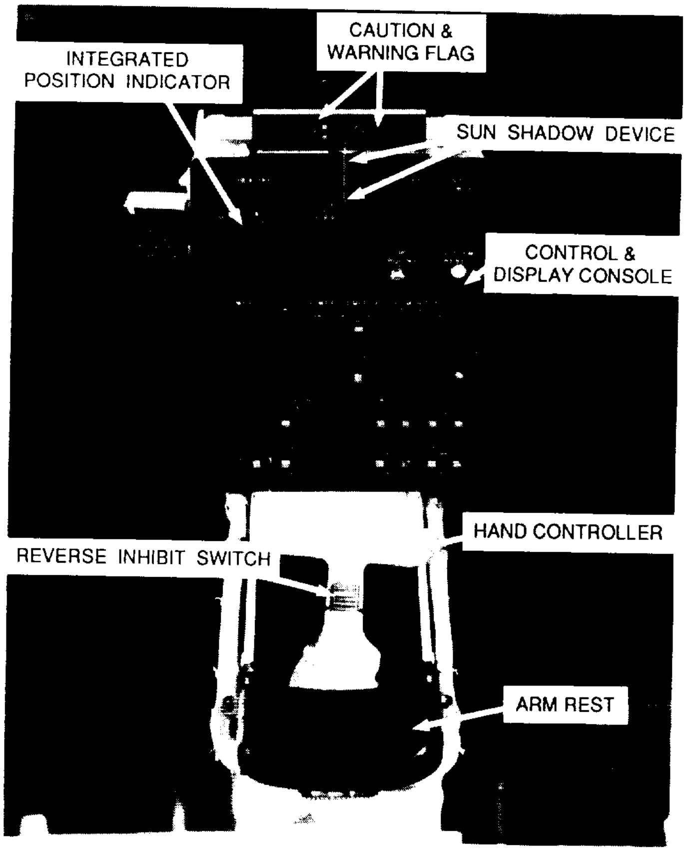


Fig. 16. Crew station subsystem components.

The LRV's seats and foot rests were folded flat onto the chassis during preflight installation and were deployed by the astronauts upon reaching the lunar surface. The seats were of tubular aluminum construction spanned by nylon strips and, together with the back, supported and restrained the astronauts' portable life-support system (PLSS) from sideways and vertical motion while driving. Cutouts were provided in the seat bottoms to enable access to the PLSS flow control valves at all times. Seat belts were made of nylon webbing with an adjustable web section and a metal hood that snapped over the outboard hand hold for quick ingress and egress activity.

A toe hold on each side of the vehicle was used to aid the astronauts in getting in and out of the vehicle. Toe holds were incorporated as the result of early KC-135 flights simulating the 1/6-*g* environment of the Moon. These tests showed rather conclusively that the astronauts required the assistance of a toe hold in order to be able to quickly assume the seated position on the vehicle. The toe hold then could serve as a removable tool in order to activate the wheel decoupling mechanism should circumstances have arisen that required such action. The toe holds themselves were assembled on the lunar surface by dismantling two tripods that connected the LRV to the LM while in the stowed position. These were then inserted into receptacles located on each side of the chassis.

Hand controller. All functions relating to steering, speed control, braking, etc. were handled by a T-shaped hand controller located between the two astronauts and just aft of the control and display console (Fig. 17). Tilting the controller forward of the neutral position proportionally increased forward speed. Reverse power was applied when the controller was tilted backwards past the neutral position after a reverse inhibit switch on the side of the hand controller was activated by the astronaut. With the reverse inhibit switch in the down position, the controller could only be pivoted forward for forward driving. With the switch in the upward position, the LRV could be operated in reverse. Braking was initiated when the controller was pulled backward. At approximately 3 in of aft travel, a spring-loaded catch engaged the handle to lock in the "park" position. Forward and reverse power was cut off when the braking action began. A simple tilting of the hand controller to the left released the parking brake.



Moving the controller left or right caused the vehicle to steer left or right, respectively. As the controller was spring-loaded, it would return to the neutral steering position when released. The hand controller moved a series of redundant potentiometers located in its base, which were used to apply command bias signals to the DCE package for all drive and steering commands. The exception to this electronic drive control was the braking function, which applied tension to the brake control cables mechanically, as previously discussed.

Control and display (C&D) console. The C&D console consisted of an upper portion containing navigation system instruments and a lower portion containing controls for switching and monitoring electrical loads. To enable easy reading of the instruments and switches in shadows, the panel markings were irradiated with promethium 147. Located on the upper left side of the console was an attitude indicator (AI) that provided pitch and roll information within a range of ±25°. In the position shown in Fig. 18, upslope (U) or downslope (D) attitude could be read. Roll angles were obtained by rotating this indicator forward. This action exposed a "roll" scale to the left crewman. This indication was read by the crew and reported to Mission Control Center (MCC) during navigation update where, with ephemeris data, vehicle heading could be determined. The vehicle attitude data were used by MCC to correct the sun shadow device readings if the LRV was not level. This sun shadow device, located in the upper portion of the console, helped determine the LRV heading with respect to the sun and was compared with the directional

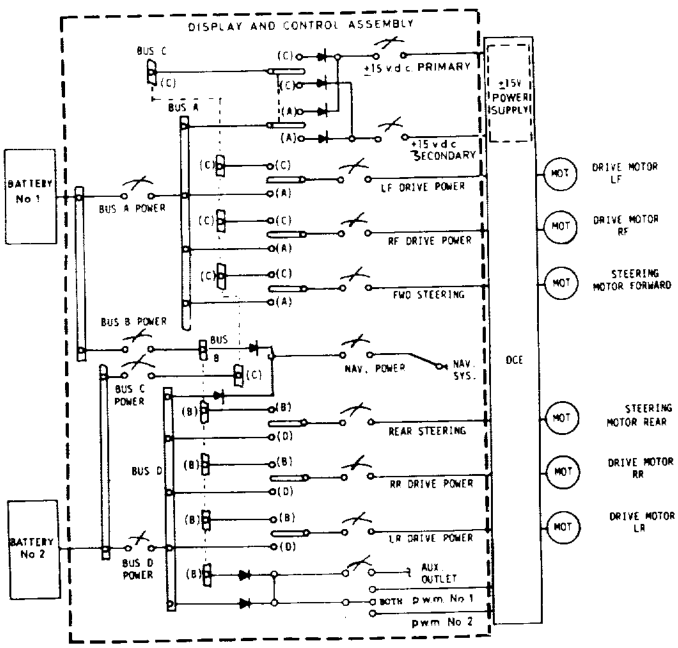


Fig. 18. Electrical power distribution diagram.

gyro as check against gyro drift. When lifted into position, the sun shadow device would cast a shadow on a graduated scale, the value of which was radioed to MCC during navigation updates.

Also located in the upper portion of the C&D console was a heading indicator (HI) that displayed LRV heading with respect to lunar north, a bearing indicator (BI) that always showed a bearing directly back to the LM, a range indicator (RI) that always showed distance directly back to the LM, and a distance indicator (DI) that showed distance traveled in increments of 0.1 km. This information was obtained from the navigation signal processing unit (SPU) located on the forward chassis that in turn received its signal from the third-fastest traction drive odometer. The third fastest odometer value was selected to minimize errors caused by wheel slippage and/or to insure against using the output impulses from a wheel that was decoupled and "free wheeling."

The gryro torquing switch was used to adjust the HI during navigation updates. The NAV power circuit breaker was used to route power from the main buses to the navigation susbsystem. The power distribution was designed in such a way as to enable power for the navigation system to be obtained from both batteries simultaneously. This would prevent a critical failure in the event that one battery failed (see electrical power distribution diagram, Fig. 18).

A speed indicator (SI) depicted LRV speed from 0 to 20 km/hr and utilized pulses only from the right rear wheel. The system reset switch was used to reset the bearing, distance, and range digital displays to zero. Lastly, sitting on top of the console was a caution and warning flag used to give the crewmen a visual warning if either battery or if any traction drive motor were overheating. The spring-loaded flag was held down by an electromagnet whose circuit was designed to open in the event of an overheat problem (exceeding 125°F on either battery or 400°F on any drive motor). Should this have occurred, the flag would have immediately popped into full view of the astronauts.

The lower portion of the console contained a power section, a power/temperature monitor section, a steering section, a drive section, and a drive enable section. The power section consisted of circuit breakers that connected the batteries to the main power buses, the auxiliary outlet circuit breaker for power to the communications relay unit, and the circuit breakers and control switch for the ±15 Vdc power to the pulse-width modulators. With four main power buses, any drive motor, steering motor, etc. could be connected to either battery, thus providing full redundancy.

The power/temperature monitor section provided the status of the vehicle's electrical system and temperature of batteries and motors. Battery voltage and current flow from either battery could be displayed when the crewman used the appropriate volts-amps switch position. Similarly, the position of the drive motor temperature select switch determined whether the rear or front wheel motors were to be displayed. In addition, a battery amp-hour integrator meter was provided, which displayed the remaining battery capacity (set at 121 amp-hours prior to the first LRV use on the EVA).

The steering section contained a switch and a circuit breaker for each of the two steering motors. Similarly, the drive and power section had circuit breakers and switches for each of the four drive motors. The remaining section was for drive enable. This section contained a switch for each drive motor that permitted the astronaut to select either pulse width modulator (PWM 1 or 2). As previously discussed, the PWMs provided speed control signals for each motor. The switch just above this section enabled the astronaut to select PWM 1, 2, or both. Here again, redundancy was the uppermost consideration throughout the design. Any motor could be supplied by any PWM, or all motors could be driven from one PWM.

Navigation Subsystem

The navigation system consisted of three major components. They were the directional gyro (DG), odometers on each traction drive assembly that provided distance and speed information, and a small solid state computer. The navigation subsystem was based on the principle that when starting a sortie from a known point, entering speed, direction, and distance traveled information into an onboard computer, and then computing vehicle position from these data by solving a relatively simple trigonometric problem, would provide bearing and distance back to the LM (Fig. 19). Inputs to the navigation subsystem were changes in the LRV direction with respect to lunar north (obtained from the DG) and odometer pulses that were obtained from the wheel rotation of the third fastest wheel. For each increment of distance measured by the odometer circuitry, the signal processing unit (SPU) would calculate the east-west and north-south distances traveled based on vehicle heading data obtained from the gyro. These distances were summed with related distances already in the registers, and range and bearing to the LM automatically calculated and then displayed on the C&D console (see prior discussion).

The overall accuracy requirements of the navigation system were that the system needed to be capable of determining the bearing to the LM relative to lunar north within ±6° at a radius of 5 km from the LM. In addition, the distance from the LR to the LM had to be within ±600 m, again at a radius of 5 km. The system had to be capable of displaying the distance traveled at

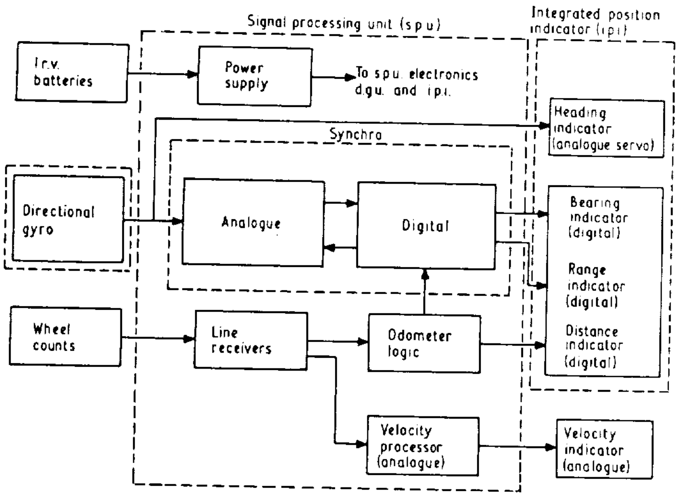


Fig. 19. Navigation system block diagram.

any point in the traverse to an accuracy of ±2%. (These requirements were met on the lunar surface with considerable margin.)

Reverse operation of the vehicle produced some error as the odometer logic could not distinguish forward or reverse wheel rotation. Thus, odometer pulses generated while operating the vehicle in reverse were seen by the SPU as forward motion. Although this would undoubtedly introduce some error, it was determined that the error would be so minor that it was not worth the extra cost, weight, and complexity to design into the SPU a network that would allow such correction.

Thermal Control Subsystem

The LRV made use of a passive and semipassive system of thermal control (Fig. 20). The system included special surface finishes, space radiators, multilayer insulation, thermal straps, and fusible mass heat sinks. At liftoff from the Cape, LRV storage volume temperatures were maintained at 70°F ± 5°F. Insulation and reflective coatings were used to control the heat loss of various critical components during boost, Earth orbit, translunar flight, and lunar landing. It was important for the batteries to be maintained between 40°F and 125°F. Other equipment had wider temperature tolerances between -30°F and 185°F.

The basic concept of thermal control on the lunar surface consisted primarily of storing heat during vehicle operation and rejecting heat to deep space by radiation while the vehicle was parked between EVAs. Thus, during operation, heat generated was stored in heat sinks consisting of two LRV batteries and tanks containing wax-like phase change material. At the completion of an EVA, the astronauts would park the vehicle in a specific orientation with respect to the sun in order to achieve the most favorable cool-down attitude and then lift three dust covers from the forward chassis, exposing fused silica second-surface mirrors that were the heat radiating surfaces. The radiators had to be totally covered during LRV operation to prevent dust accumulations, which would effectively destroy the radiation properties of the mirror. When opened by the astronauts, the dust covers were held open by a throw-over locking mechanism. During the astronauts' rest/sleep period between EVAs, the heat stored by the batteries and the tanks containing the phase change material would be rejected to space. This heat rejection would continue until battery temperatures came down to 45°F (±5°F), at which time a bimetallic spring device would disengage the throw-over latch, allowing the covers to be closed automatically.

During LRV operation, the covers provided dust protection to the DCE, the SPU, the DGU, and the LRV batteries. Passive protection was provided by multilayered aluminized mylar and nylon netting insulation blankets with a "beta cloth" (polished glass) outer layer that was necessary to protect against wear and direct solar impingement.

Instruments on the C&D console were mounted on an aluminum plate that was isolated from the rest of the vehicle through the use of fiberglass mounts. The external surfaces of the console were coated with a heat-resistant paint, with the face plate being black anodized for temperature control while reducing reflections that were annoying to the astronauts. Heat generated by each of the traction drive assemblies and the shock absorber (linear dampers) was radiated to space through the hubcap disk and the casing, respectively. The pressurized gas inside each of the traction drive assemblies aided in this process of heat rejection.

Electrical Power Subsystem

This subsystem consisted of two 36-V silver-zinc batteries, a wire distribution system, connectors, circuit breakers, switches, and meters (Fig. 18). Both LRV batteries were designed for minimum weight and consisted of plexiglass monoblock (common cell wall) construction, 23 cells with silver-zinc plates, potassium hydroxide as the electrolyte, and a magnesium case. The batteries were rated at 121 amp-hours each and were normally operated simultaneously with approximately equal loads. As previously discussed, through selective switching at the control and display console, the total or any part of the electrical load could be carried by either battery alone. The batteries were located on the forward chassis and were enclosed by thermal blankets and dust covers. Each battery was protected from

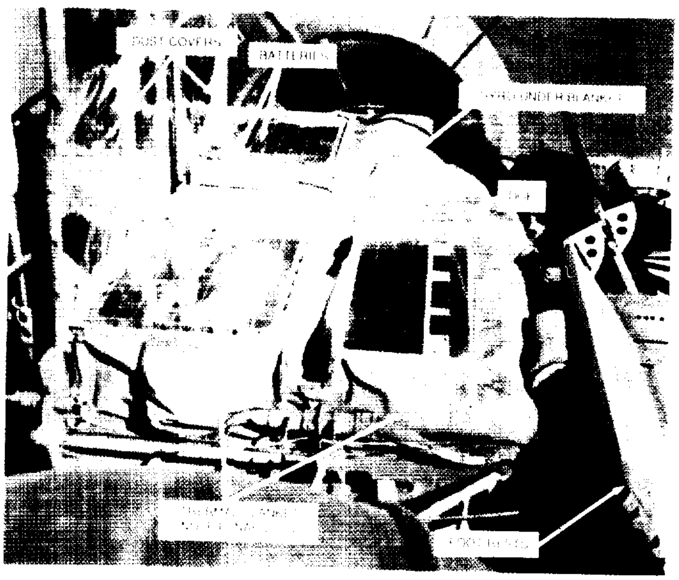


Fig. 20. Portion of thermal control system.

excessive internal pressure by a relief valve and from excessive temperatures by monitoring at the C&D console during operation and radiators exposed between sorties, as previously discussed under the Thermal Control section. Because the batteries were used as heat sinks (battery #1 was connected by thermal straps to the navigation system's SPU and battery #2 to the navigation system's DG), careful monitoring and control of their temperatures was essential.

Stowage and Deployment Subsystem

Because of the stability requirements for a two-man vehicle and the volumetric constraints dictated by the LM and upper-stage fairing, it was necessary that the LRV be transported to the Moon stored in a folded configuration and then deployed after arrival on the lunar surface. Figure 21 shows the LRV in the typical folded position just prior to installation and integration into the LM. In the LM, the folded LRV was supported and secured by space-support equipment that also served to deploy the vehicle once on the Moon.

The space-support and deployment equipment had to be designed with sufficient capability to enable a deployment of the LRV to take place in less than 15 min (worst case) with the LM tilted at any angle up to 14.5° in any direction and with the bottom of the descent stage anywhere from 14 in to 62 in above the lunar surface.

This support and deployment mechanism, shown in Fig. 22, consisted of cables, shock absorbers, pin retraction mechanisms, telescoping tubes, push off rods, and other pieces required to deploy the vehicle. The actual deployment was accomplished by the astronaut pulling on two nylon tapes. While standing on the LM access ladder, the first step by the astronaut was to pull a "D"-handle. This action served to retract three pins holding the LRV to the attach points, thus freeing the LRV for the deployment sequence. A spring-loaded push-off rod, shown in the upper portion of Fig. 22, thus began to move the folded vehicle away from the top of the LM storage bay by some 5 in until it was stopped by two steel deployment cables.

At this point the astronaut descended the LM access ladder, walked around to the LRV's right side, and began to unreel the nylon tape in a hand-over-hand manner, slowly lowering the vehicle to the surface (see sequence in Fig. 23). After approximately 15° of deployment motion, the lower end of the vehicle was rotated onto the two lower points just outside the bay formed by tripods attached to the LRV's center chassis. As the chassis reached approximately 45° in rotation, release pins on the forward and aft chassis were automatically pulled. This action caused the aft wheels to unfold, assisted by torsion bars, until latched and locked. The astronaut continued unwinding the tape until, at approximately 73° of rotation from the LM, the forward chassis and wheels were automatically deployed and locked. At the 73° point in the deployment, a cam released latches on the support arms, which served as the rotation axis allowing the telescoping tubes to extend further, thus holding the LRV away from the LM.

At this point the astronaut pulled the second operating tape located on the left side of the LM quadrant, allowing the forward end of the LRV to be gently lowered to the surface and causing

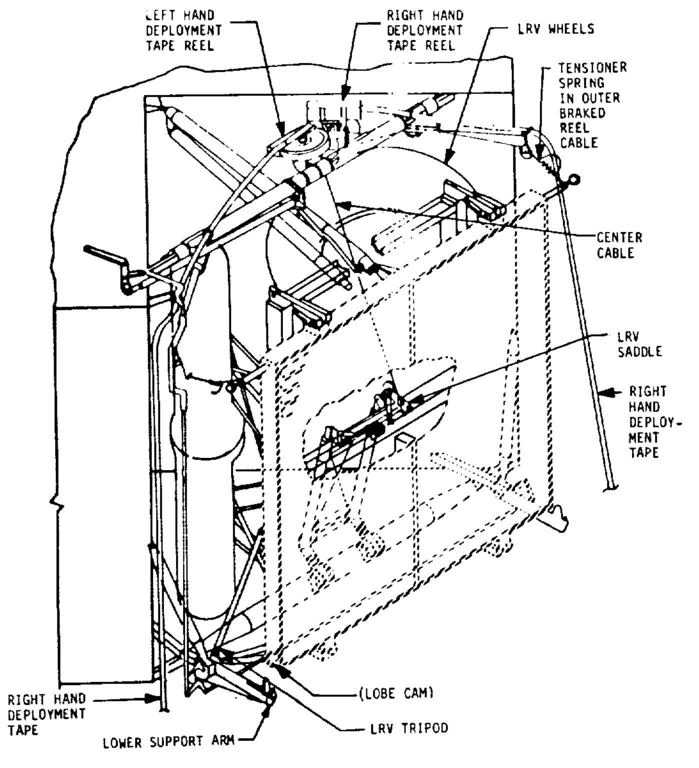


Fig. 21. Lunar module/space-support equipment with LRV installed.

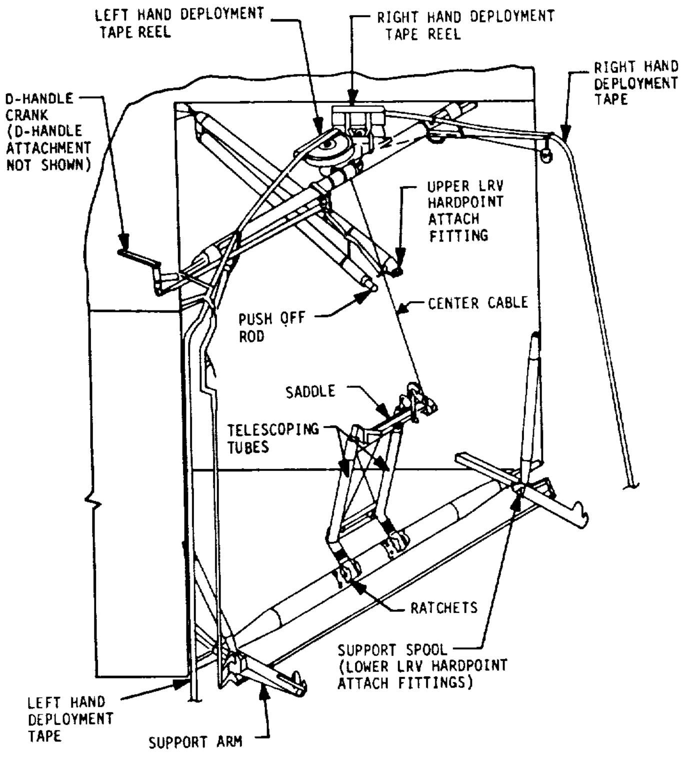


Fig. 22. Space-support equipment.

the telescoping tubes attached between the LRV and the LM to guide the LRV away from the LM. This action was followed by the astronaut pulling a release lanyard at the forward chassis' left side, allowing the telescoping tubes to fall away.

After the LRV was disconnected from the LM and space support and deployment equipment, the astronauts would insert toe holds, erect seats and foot rests, deploy wheel fender extensions, release seat belts, and remove docking pins and latches from several places on the vehicle.

At this point, one astronaut powered up the LRV, confirmed all controls were working properly, and then proceeded to back the vehicle away from the LM and drive it to the side of the LM where the auxiliary equipment was stored. The vehicle was powered down and the auxiliary equipment mounted on the LRV. This included the lunar communications relay unit (LCRU), the ground control television cameras assembly (GCTA), the voice and television antennas, and the aft pallet containing most of the hand tools and science instruments needed for the sorties.

SUMMARY

In summary, there are two salient issues worth re-emphasizing. The first deals with the initial purpose of the paper: to revisit the LRV design and program in some specific detail in order to provide contemporary space exploration planners with an opportunity to become more knowledgable of this "spacecraft on wheels," which operated so successfully on three separate missions to the Moon. Conceivably, by some modifications to this vehicle or by some evolutionary redesign, this vehicle could possibly satisfy requirements for a roving vehicle inferred by the potential new national thrusts in space. It is hoped that this paper might be the catalyst to spark a renaissance for the LRV.

The second point deals with the validity of the terminology "spacecraft on wheels," which was referred to early in the paper. What may have been viewed as a locomotion device truly embodied the sophistication of a spacecraft, as supported by the detail provided in this paper. The astronauts who had the privilege

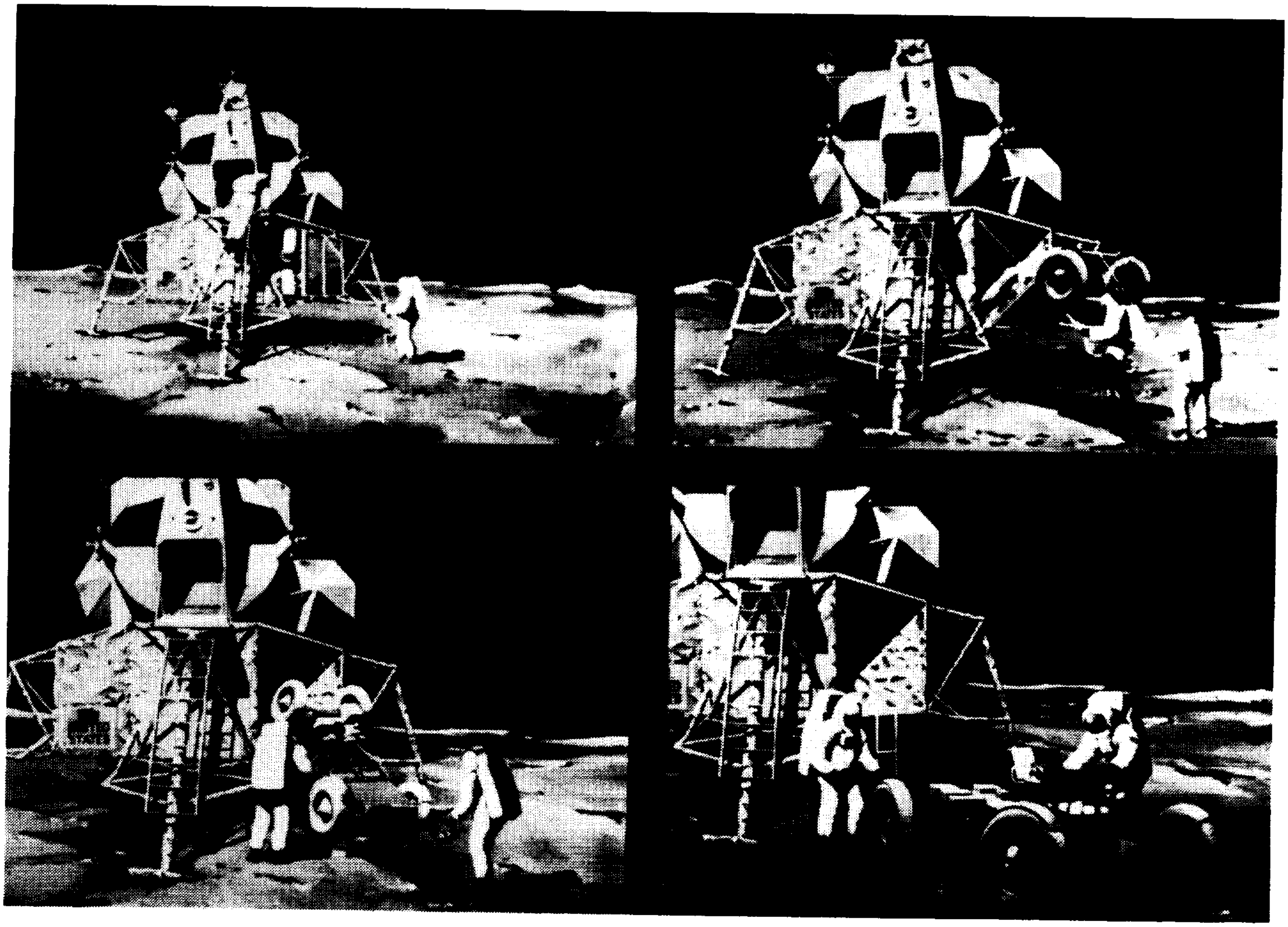


Fig. 23. Deployment sequence.

of driving this machine on the lunar surface [D. Scott, J. Irwin (Fig. 24), C. Duke, J. Young, G. Cernan, and J. Schmitt] all had very positive comments about its handling, performance, reliability, and the sort of machine the LRV was. In fact, the superlatives flowed quite easily in all the mission debriefings. The crew of Apollo 17 (G. Cernan and J. Schmitt), upon their return to Earth, had nothing but praise for the LRV:

> "The Rover performed admirably . . . that vehicle that sits out there at Taurus Littrow—We talked an awful lot about having two good spacecraft, but we told ourselves that we had ***three good spacecraft***. That thing couldn't perform better—and we pushed it in many cases to the limit. But let me tell you that vehicle for a long time was just a little bit better than we were because it's a super performing vehicle. If you take a couple more batteries up there, that thing would just keep going . . ." (emphasis added)

Such glowing testimonials from the men who used the LRV offer more compelling arguments for its merits than this paper could hope to do.

Fig. 24. Astronaut Irwin with rover at Apollo 15 landing site.