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MOBILITY SYSTEMS ACTIVITY FOR LUNAR ROVERS AT MSFC

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16. ABSTRACT

The Apollo Lunar Roving Vehicle (LRV) mobility system is described. Special emphasis is given to the redundancy aspects and to the selection of the drive motors. A summary chart of the performance on the lunar surface during the Apollo 15 flight is included. An appendix gives details on some MSFC development work on high efficiency drive systems and compares these systems to the selected system.

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MOBILITY SYSTEMS ACTIVITY FOR LUNAR ROVERS AT MSFC

INTRODUCTION

The Marshall Space Flight Center (MSFC) has been active in lunar vehicle technology for a number of years. Early work was done in study programs of vehicles such as the Mobile Laboratory (MOLAB) and later the Dual Mode Lunar Roving Vehicle (DLRV). At least three different Mobility Test Articles (MTA) were built by different contractors involved in the program to test various mobility concepts, especially in the wheel area. These programs were carried only through the NASA Phase B contractual stage; partially because of funding but ultimately because of the accelerated need for a Manned Lunar Roving Vehicle (MLRV) for the Apollo 15 mission. The MOLAB and DLRV programs looked toward large vehicles with a broad range of operational modes and capabilities and survival for long periods of time in a very hostile environment. The advent of the MLRV and its accelerated program allowed these capabilities and modes of operation to be reduced in the severity of their requirements to compress the delivery schedule. For example, the temperature environment was reduced from the $\pm 120^\circ$ C required for a complete lunar cycle to only 0° to 100° C for a partial lunar day, and the operational time was reduced from as much as two years to only a few hours. One aspect of the problem that somewhat increased in complexity was a weight restriction of approximately 181 kg. The actual final weight of the MLRV was somewhat higher (227 kg), but considering that the payload requirement is about 450 kg, this weight is still reasonably ambitious.

During the MLRV contractual cycle, some parallel development of hardware has been pursued at MSFC to support the MLRV design and to investigate the possible future or extended use of the rover for teleoperator-type programs. Figure 1 shows an austere breadboard vehicle which was used by the Astrionics Laboratory to study mobility systems in general and the steering system of the MLRV in particular. Figure 2 shows another simple and economical vehicle fabricated in-house and instrumented for remote control operations. This vehicle has been successfully operated from a mountain about 4.8 km distant with a communications delay time in the command link to simulate lunar operation. This program has been quite successful and leads to the belief that teleoperation of vehicles of this type can be successfully accomplished within the present technology.

MOBILITY SYSTEMS

In all the systems that have been considered at MSFC, the electric motor has been proposed as the basic device for locomotion. Figure 3 is a block diagram of the fundamental components which normally make up the mobility system.

A battery is the customary energy source, although in the DLRV and MOLAB type vehicles supplementary sources such as radio-isotope thermoelectric generator (RTG) or solar array were considered. The device used for throttle and steering control is a hand controller which usually consists of a potentiometer or other device that produces an electrical signal proportional to hand-controller movement. The hand-controller voltage is processed by control electronics that vary the amount of battery power applied to the motor. Both wheel and steering motors are usually matched to the load via a transmission of appropriate ratio. The selection of the motor and transmission is probably one of the most difficult trade-offs and is discussed in some depth in the appendix. The parts of the mobility system not considered here are the suspension and brake system.

MLRV MOBILITY SYSTEM

The MLRV mobility system was designed and built by the Delco Electronics Division, General Motors Corp., Goleta, California, under a subcontract to The Boeing Co. Basic specifications furnished by MSFC which dictated the design constraints are as follows:

1. Performance capabilities.

    a. Climbing a 25-deg slope fully loaded.

    b. Speed of 16 km/hr.

    c. Negotiating a 30-cm high obstacle with both wheels in contact at zero velocity and a 70-cm wide crevasse for both wheels at zero velocity.

2. Four wheels of appropriate size and design to produce the above performance.

3. A range of 120 km.

4. A life of 78 hr during the lunar morning.

5. A design such that no-single-point failure will abort the mission and no-second failure will endanger the crew.

The specifications resulted in a design with the following hardware and performance parameters:

1. An 81-cm-diameter wire mesh wheel with chevrons attached to improve traction.

2. A series-wound brush-type motor mated to an 80:1 harmonic drive transmission forms the wheel drive unit. This unit is hermetically sealed and the two run in a nitrogen atmosphere at approximately 5.17 N/cm^2. The transmission is lubricated with Krytox 143AZ oil.

3. To meet the no-single-point-failure specification, a system of redundancy was conceived and is discussed in more detail in the following paragraphs.

REDUNDANCY

Almost every element of the MLRV has some measure of redundancy. As shown in Figure 4, the energy source was made redundant by using two silver-zinc batteries of nominal 36-V, 120-A-hr capacity to excite the four power buses (A through D). All loads can select one bus from each battery via switches on the control and display console (Fig. 5). The low-level (±15-V) power supplies for the drive control electronics (DCE) box are fed in parallel from both batteries such that the loss of either battery during dynamic operation would not affect its output. This is done because only one supply is operating (the other is in standby), and the loss of this supply will eliminate all vehicle control.

The wheel drive system redundancy is a result of the four-wheel drive aspect. There are four motor-transmission units and, within the DCE box, four power amplifiers, each of which can be turned on or off from the console via the DRIVE POWER switches (Fig. 5). The hand controller has only two throttle potentiometers and two pulse width modulators (PWM) to drive the four power amplifiers. These two PWM modules are fed through four DRIVE ENABLE switches on the console allowing the astronaut to select either PWM to drive any of the four wheel drives.

Steering redundancy is obtained by having identical front and rear steering systems. This double Ackerman steering not only gives redundancy but results in a very short turning radius. Either steering unit can be both electrically and mechanically decoupled. The rear unit can be mechanically recoupled, but the front system cannot.

In addition, the low-level power supply is standby redundant as mentioned earlier.

POSSIBLE IMPROVEMENTS IN REDUNDANCY

The redundancy scheme described, although meeting the specified criteria of no-single-point-failure, could be improved upon at no cost in weight and possibly provide a cost savings. A more natural, simpler scheme would be to make the drive systems completely independent, i.e., the throttle potentiometer, PWM, low-level power supply, and power amplifier. This quadruple redundant scheme eliminates much of the switching on the console, thereby reducing astronaut workload. The DRIVE ENABLE, PWM SELECT, and ±15-V switches could be eliminated completely. Although it would appear to increase electronic parts count, this is not the case. The present low-level power supplies must each be capable of supplying power for all electronics and only one is active. An in-house redesign consisting of six active small supplies for individual drive systems was found to require less parts and to weigh significantly less. Although four PWM modules are needed instead of two, these units require so few parts as to be insignificant. Two component failures in the present system can cause loss of all wheel drives (e. g. , a potentiometer feeding PWM No. 1 and a component in PWM No. 2), but this is not the case with the modified scheme. The advantage in the existing system is that a single failure in circuitry prior to the DRIVE ENABLE switches can be compensated for by the switching scheme. However, the number of components involved is only about 15 as compared to approximately 90 in the power amplifier circuitry; therefore, the probability of a failure in this area is remote.

MLRV MOBILITY SYSTEM OPERATION

Figure 6 is a block diagram of the DCE showing one complete drive scheme. For throttle operation a signal is fed from the hand-controller potentiometers into each PWM module. This is a dc voltage input proportional to hand-controller position and the output is a constant-amplitude pulse whose width is proportional to the voltage input. The outputs from the two PWM's are fed to the control console where one is selected by the DRIVE ENABLE switch to excite the wheel-drive power amplifier. The signal is applied to the power-inhibit gate (G_1) where it is passed on to the drive-power amplifier provided none of the three inhibit signals is present. These inhibit signals are derived as follows:

1. When the current exceeds a prescribed level (about 25 A), the current-level detector triggers a one-shot multivibrator which produces an inhibit signal for a preset time.

2. When the forward or reverse switch on the hand control is changed, the reversing-relay control gate (G_2) is enabled provided the wheel speed is below 1 km/hr determined by the wheel-speed circuitry. The output of this gate triggers a one-shot multivibrator which drives the reversing relay and at the same time inhibits G_1 for 60 ms so that no current will be present in the motor when the relay switches.

3. When the brake handle on the hand controller is pulled back more than 13 deg, G_1 will be inhibited so that no power can be applied. Notice that this inhibit is set such that both brakes and power can be present at the same time to allow the astronaut to start off on hills without rolling backward.

The signal from G_1 is then impressed on the power-amplifier circuitry which drives the motor. The motor speed is a function of the dc voltage input from the hand controller.

STEERING

The steering system on the MLRV consists of Ackerman-type linkage on the front and rear, giving a turning radius of 3 m. Steering is powered by a position-control servo drive with a split-field-series motor driving through a geared transmission for actuation. The split field allows for direction reversal without the need for relays. The steering will go from stop to stop in approximately 6 s for an average rate of about 15 deg/s.

Figure 7 is a block diagram of the steering system used on the MLRV. The steering-command potentiometer on the hand controller feeds a voltage into the control electronics proportional to the desired wheel position. This voltage is compared with a voltage from the feedback potentiometer, and the output is an error voltage which is fed to a voltage-limiter circuit. The output voltage of the limiter is compared with a voltage which is derived from resistors that sample the motor current in the two fields of the motor. The difference in the two voltages is the error signal which is then amplified through one of two channels, depending on polarity, and this drives the motor in such a direction as to reduce the error in the command and feedback potentiometers to zero.

PERFORMANCE

The overall performance of the MLRV on the Apollo 15 mission was very good. The astronauts were pleased with the performance and felt that the basic design did not need improvement. At least two minor anomalies were associated with the mobility system, but these caused no degradation in performance.

When power was first applied to MLRV on the lunar surface, it was noted that no voltage indication was present on battery number two. A quick check of equipment being fed from this battery indicated that the problem was a faulty meter. This caused no performance problems but caused a loss of data feedback for performance evaluation.

When the front steering was tested prior to embarking on the first lunar traverse, it was found to be inoperative. A quick recycling of switches and circuit breakers and some simple tests produced no solution. The front steering was subsequently powered down and the vehicle was operated using rear steering only. The astronauts found this steering very responsive and were reluctant to make any further tests on the front steering during the first traverse to determine the status. At the beginning of the second traverse, the front steering switches and circuit breakers were cycled a few times, and when power was applied, the front steering was found to be operational. Information as to what caused this anomaly is unavailable, and the conclusion was that a number of things could have caused the observed results. When the second traverse began, the astronauts felt that the steering was too sensitive and turned off the rear steering. However, because of a tendency for the wheels to drift, it was turned back on, and after a few minutes of experience no further steering difficulties were reported.

A summary of mobility system performance obtained from data sent back during vehicle operation on the moon is shown in Table 1. Although the distance traveled was about 8 km less than planned for this mission, the speed was 25 percent higher than expected. Energy rates were also lower than had been expected because of much lower frictional forces from the lunar soil than had been predicted. The astronauts stated that the vehicle handled quite well and negotiated slopes with ease. Probably the steepest slope encountered was between 10 and 15 deg, but they were of the opinion that traction and vehicle performance were such that much steeper slopes could have been covered.

APPENDIX

The propulsion system for the Lunar Roving Vehicle (LRV) is an application for electric motors which must meet a large combination of stringent requirements. Among these requirements are variable torque, variable speed, light weight, high efficiency, high torque for obstacle climbing, and high speed for maximum scientific exploration time. Dynamic braking, though not a firm requirement, is a desirable feature. In addition, the system must operate in the thermal vacuum of the lunar environment.

Despite the advantages of the simpler brush-type motor system for the short three-day life of the LRV, it was felt that the short delivery schedule would not allow sufficient time for qualification of this type of motor to operate in the lunar environment. Brushless motors had the advantage that no new technology and no extensive test program would be required to qualify their use in a thermal vacuum. Experience gained from in-house and contractor-supported research on candidate motor systems led to the conclusion that the permanent magnet (PM) brushless dc motor had the best potential for satisfying these requirements [1].

In the preliminary specifications for the mobility subsystem of the LRV, the PM brushless motor was indicated as being the choice candidate. However, the contractor was allowed to select the motor of his choice (termed baseline), but was contractually obligated to carry along the development of an alternate system until it could be shown that the baseline system could perform satisfactorily under simulated lunar conditions.

The baseline propulsion motor, developed by the Garrett Corp. for the LRV, is a four-pole brush-type series motor coupled to a transmission with an 80:1 speed reduction. This transmission, developed by the United Shoe Machinery Co., is known as a harmonic drive. The motor and the wave generator of the harmonic drive are hermetically sealed and operate in 5.17 N/cm^2 of dry nitrogen. The alternate motor, developed by General Electric Co., is a six-pole PM brushless motor coupled to a planetary-spur gear combination with an 80:1 speed reduction. The entire system is open to vacuum. The two motors are shown in Figure 8.

The LRV is a four-wheel vehicle weighing 227 kg (earth). The fully loaded weight with two astronauts plus scientific equipment and payload is 726 kg (earth). A motor at each wheel is driven by an electronic controller which responds to commands from potentiometers mounted on the pivot of a hand controller. All driving functions including forward and reverse driving, speed control, braking, and steering are initiated by the hand controller. The power source for the vehicle is two silver-zinc batteries nominally rated at 36 V with a total weight of 64 kg. The batteries can be operated individually or in parallel and have a combined capacity of 240 A-hr.

The maximum specified speed when operating on a smooth mare is 16 km/hr corresponding to a wheel speed of 116 rpm. The predicted smooth mare torque required at the wheel is 5.76 N-m. The torque required for obstacle climbing and for spanning crevasses is 106 N-m at 3 rpm. Two other torque-speed points specified are for climbing a 6- and a 25-deg slope. These are, respectively, 20 N-m at 60 rpm and 52 N-m at 25 rpm. With reference to the motor shaft and allowances for gear efficiency, the specified torque speed requirements of the motor are 0.1 N-m at 9280 rpm, 0.27 N-m at 4800 rpm, 0.68 N-m at 2000 rpm, and 1.56 N-m at 240 rpm. Since the requirements of the propulsion system are established, a comparison of the baseline series motor and the alternate PM brushless motor is given. The comparison is divided into the following topics: torque versus speed capability, weight and efficiency, braking, electronic controller, and growth capability. Also included is a brief discussion of gear reducer transmissions and other motor systems which have been proposed for lunar vehicles.

Torque Versus Speed Capability

A plot of the above specified performance points is typical of the torque versus speed characteristics of a series motor. Since the speed of a dc motor is limited mainly by the counter electromotive force (emf) generated by the armature, it can be seen that by controlling a single current, the series motor can cover a broad torque speed range. For low-speed operation a large armature and field current creates two strong magnetic fields which couple to produce a high-output torque. For high-speed operation at low-output torque, the armature and field current is reduced. The weakened field now generates less counter emf in the armature and allows the motor to develop high speed.

Ideally, the series motor torque varies as the square of the current. The torque versus current curve for the LRV motor shown in Figure 9 reveals a near linear relationship. The linearity is the result of bearing and brush friction at the low-torque end and of core saturation at the high end. The specified maximum torque of 1.56 N-m is reached at a current level of 22 A and is limited to this value by the electronic controller.

The maximum torque versus speed capability of the series motor when powered from the specified 36-V source is shown in Figure 10. The motor has a significantly higher than required speed capability at high-torque levels. At low-torque levels, however, where most of the driving is done, the speed capability is minimal. The motor has a top speed of 8400 rpm at the initially predicted smooth mare torque of 0.1 N-m. Information gained from recent lunar explorations indicates that the smooth mare torque may be more than twice the initially specified value. Under these conditions, the maximum motor capability is approximately 6000 rpm corresponding to a vehicle speed of 10 km/hr.

A disadvantage of the PM brushless motor in the LRV application is the high armature current required to cover the specified torque speed range. Unlike the variable field series motor the field strength of the PM brushless motor is constant and, in general, is high to minimize weight.

If the armature is wound with a large number of turns to produce high torque at a reasonable current level, the generated counter emf will be high and will limit the motor to low speed. Reducing the number of turns for high-speed operation correspondingly reduces the torque constant and must be compensated by proportionately increasing the armature current to establish the ampere-turn product required for high torque. For a given torque-speed range, the exact maximum current requirement for a PM brushless motor can easily be calculated by equating the mechanical output power of the motor to its electrical output power. This is given by the following equation.

$$I \cdot V = T \cdot S \quad , \qquad I = \frac{T \cdot S}{V} \quad ,$$

where T is the maximum output torque required in N-m, S is the maximum speed in rad/s, V is the counter emf in volts developed at maximum speed, and I is the maximum armature current in amperes. The voltage available for counter emf is the battery voltage less the voltage dropped in the electronic controller and in the armature resistance. Assuming about a 2-volt drop, V in the above equation becomes 34 volts for the LRV application. Substituting the other known requirements and applying proper conversion factors gives the following maximum current:

$$I = \frac{1.15 \times (1.36) \times 9280 \times (0.105)}{34} = 45 \text{ A} \quad .$$

In addition to making the controller design difficult, this amount of current would produce high losses in the controller and in the cabling and would result in a motor with a power output capability several times greater than would ever be required by the vehicle.

The alternate PM brushless motor developed for the LRV employs a technique which eliminates the above problem and results in a low-current system which covers the entire torque-speed range with relatively high efficiency. The stator winding is tapped at one-fourth of its full number of turns. At low speeds, where high torques may be required, the full winding is connected across the electronic controller. When the motor speed reaches approximately 2300 rpm, a speed sense winding in the motor initiates a command to a relay which disconnects the full winding and switches to the one-fourth turn tap. The reduced counter emf now allows the motor to run up to its maximum specified speed while developing torque up to one-fourth of maximum value. This technique reduces the maximum current requirement to 11.3 A or to about one-half of that required for the series motor. The entire switching process is performed automatically by the controller and is analogous to automatic gear shifting in an automobile. The tap changing occurs in less than 10 ms. The motor current is inhibited for 15 ms during the tap changing process to eliminate the possibility of any inductive voltages which may appear across the windings.

The torque versus current curve for the PM brushless motor shown in Figure 9 indicates a linear relationship to 200 percent of rated torque. Since the torque is normally limited to 1.56 N-m by the controller, the motor has at least a 100-percent safety margin for demagnetization. The ultimate torque capability of the motor has not been determined because of power limitations in the electronic controller.

The maximum torque versus speed capability of the brushless motor is compared with the series motor in Figure 10. Although the series motor can develop higher speeds at the higher torque levels, the predicted driving conditions indicate the vehicle will operate less than 5 percent of the time in this range.[1] The PM brushless motor has far superior performance in the anticipated maximum driving range and can propel the vehicle at 18 km/hr at the initially predicted smooth mare torque compared to 14 km/hr for the series motor. Note also that the PM brushless motor can maintain the specified 16-km/hr speed at torque levels almost four times the minimum required value. This is equivalent to climbing a 12-deg slope. The overspeed capability of the PM brushless motor is inherent in the system because the developed counter emf is sinusoidal. Current can be forced into the windings during that portion of the cycle when the counter emf is less than the saturation

1. Results from the flight indicate almost all operations at less than 27 N-m of torque.

limits of the electronic controller. This characteristic could have been used to reduce the maximum motor current 10 percent but was designed in as reserve capability.

Weight and Efficiency

Weight and efficiency of an electric motor are directly related. Since most of the inefficiency of a motor is caused by copper loss, it is apparent that increasing the diameter of a motor increases the available slot area and allows the use of larger wire. The series motor for the LRV weighs 2.7 kg compared to 1.6 kg for the PM brushless motor. Both motors have a copper loss (I^2R) of approximately 100 W at peak rated torque of 1.56 N-m. This brings to light several outstanding advantages of the PM brushless motor over a variable field brush-type motor. First, to approach the efficiency of the PM brushless motor, the series motor must be made almost twice as heavy. The primary reason for this is that the I^2R loss inherent in generating field flux in the series motor is significant; whereas, the PM field is essentially free of losses. Even if efficiency were not a prime consideration, the series motor must be large because of the difficulty associated with removing heat from the rotor. Since the motor was initially designed to operate in a vacuum, the primary source for heat removal is by radiation to the stator. With the PM brushless motor, no heat is generated in the rotor. The heat generating element, the stator, is in contact with the vehicle, and the heat is easily removed by conduction as well as by radiation.

A family of curves relating efficiency and speed as a function of torque for the PM brushless motor and the series motor systems are shown in Figures 11 and 12. These curves include the losses in the electronic controller for both systems. Although the series motor efficiency approaches that of the PM brushless motor at several points on the curve, these occur at torque levels which are seldom encountered and contribute little to the overall mission efficiency. In the anticipated maximum duty torque-speed range, the PM brushless motor system is 20 to 30 percent more efficient than the series motor system. The significance of this is best shown by the curves in Figure 13. For a given battery life, these curves depict the percent increase in driving range realized with the PM brushless motor system over the series motor system at various torque levels. On a smooth mare and at speeds above 4 km/hr, the PM brushless motor consumes 30 percent less energy than the series motor, resulting in an increased driving range of about 40 percent. Note also at speeds below 3 km/hr, when the PM brushless motor is in the low-speed winding configuration, and at low-torque levels, the energy consumed by the series motor system is almost twice that of the PM brushless motor system. It should be indicated here that if the winding turns of the PM brushless motor were increased so that its top speed is reduced to be comparable to the series motor, the current for a given torque would be reduced by 20 percent. This reduces the power loss in the electronic controller and, although it will not significantly increase the peak efficiency of the motor, it will raise the efficiency at lower speeds and result in an even greater increase in driving range.

Braking

The performance of a series motor when used as a generator is unpredictable. Hence, the motors cannot conveniently be used for braking and, in the LRV, mechanical drum-type brakes had to be added to each wheel. The PM brushless motor serves equally well as a motor or as a generator. Simply by reversing the input command, the motor provides controlled regenerative braking to zero speed. The controlled braking feature is inherent in the design of the controller and requires essentially no increase in electronic complexity. Experience gained on two experimental vehicles built at MSFC indicates that the average energy returned to the source under normal driving and braking conditions is less than 2 percent of the total energy consumed. Primary battery systems, such as those used on the LRV, can easily accept this amount of recharge energy with no detrimental effects.

Electronic Controller

The outstanding advantage of the series motor over the PM brushless motor is the simplicity of the electronic controller. The armature current is controlled by a single power transistor plus four power contacts of a double-pole, double-throw relay used for reversing action. Although no relays are required to reverse the PM brushless motor, eight power transistors are required for controlling the two-phase sinusoidal stator currents. These transistors, however, also provide reversing and regenerative braking. Since these functions are performed electronically, a comparison with a mechanical system is difficult and may be meaningless.

Much of the simplicity advantage of the series motor controller was lost because of a requirement to control braking and reversing by pivoting the hand controller. Considerable logic circuitry has been added to prevent inadvertent reversal of the motors while the vehicle is in motion, to prevent drive power from being applied while braking, and to inhibit motor current during switching of the reversing relay. Also, circuitry had to be added to prevent plugging[2] of the motors which could occur if the vehicle were allowed to roll in a direction opposite to that in which the directional relay is set.

In actual parts count, the series motor controller has approximately 30 percent fewer piece parts than the PM brushless motor controller. The parts count for the PM brushless motor controller is based on an MSFC design, which is being furnished along with two LRV motors to the Lockheed Co. to be used as the propulsion system for an experimental vehicle program in which they are engaged under contract to MSFC. The controller provides all the functions relative to the PM brushless motors described in this report and weighs approximately 1.27 kg. Figure 14 shows the PM brushless motor electronics.

Growth Capability

Considerable thought has been given to the possibility of an add-on kit which would convert the LRV to a remotely controlled vehicle that would be teleoperated from earth. The kit would be installed by the astronauts at the end of the final LRV mission. The use of the series motor in this application is questionable. The motors are qualified only for the short life of the LRV and for the relatively narrow temperature range expected to be encountered during the lunar morning. The life and lower temperature range of the motor is limited by oil vapor which may penetrate the seal between the harmonic gear and the motor. At cold temperatures, the motors may fail to start because of contamination of the brushes. The temperature at which oil contamination affects the brushes is well below the range anticipated for the manned missions. A remotely operated vehicle would be subjected to a much greater temperature range. Hence, requalification of the motors would be required.

Other problems of teleoperation are created by the mechanical brakes in controlling the speed of the vehicle while descending slopes. This would require an electromechanical servo in addition to the drive-control servo. The PM brushless motor has the advantage that speed control, direction control, and braking are all performed by a single input command. Remote driving and

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2. Uncontrolled dynamic braking

navigation have been demonstrated at MSFC with an experimental vehicle equipped with PM (brush-type) motors [2].

Transmissions

As previously stated, the baseline and alternate gear reducers developed for the LRV are the harmonic drive and the planetary-spur gear combination. The units were both developed by United Shoe Machinery Corp. The harmonic drive has the advantage of a high-gear ratio in a lightweight package and, in addition, allows for a sealed system so that the high-speed gears may be lubricated with oil and an atmosphere inserted to transfer heat. The system developed for the LRV weighs 0.7 kg compared to 1.13 kg for the planetary-spur gear. The planetary-spur gear is more rugged, more efficient, can operate in vacuum, and has an established performance record.

A third type transmission which was developed through a program sponsored by MSFC is the roller-gear drive [3]. This transmission has a reduction ratio of 15:1 and was developed as a low-speed backup system for the two high-speed units. The program included the development of a larger brushless-type motor similar to the one described above but with torque and speed scaled to match the lower ratio. The roller-gear approach evolved from the roller-friction drive and basically consists of a roller-friction drive with gears mounted on all rolling contacts. The roller gear retains many of the advantages of the roller-friction drive while eliminating its high-preload requirements. In effect, the gears now transmit the high-torque loads while the rollers act as integral bearings supporting the gears, transmitting low-torque loads, and providing overall stable gear alignment and resultant high efficiency. The efficiency of the roller-gear developed for the LRV is better than 97 percent and, because of this high value, is very difficult to measure accurately. The curves of Figure 15 compare the maximum efficiency versus torque of the series-motor harmonic drive, the 1.56-N-m, brushless-motor, spur-gear drive, and the 8.0-N-m, brushless-motor, roller-gear drive. The larger brushless motor had a higher torque-to-weight ratio and, hence, was 2 to 3 percent less efficient than the 1.56-N-m brushless motor.

Other Motor Systems

The discussion thus far has been limited mainly to a comparison of the series motor and the brushless motor developed for the LRV. Two other types of motors which have been proposed for lunar vehicle application are the homopolar inductor motor and the variable-frequency ac induction motor. The following comments are based on experience gained in working with experimental models of these motors.

The homopolar inductor motor is a brushless dc motor with a variable-field rotor instead of a PM. The obvious advantage here is the broad torque-speed-range capability. Also, in large high-speed motors, the use of PM's may be prohibited because of limitation in the size of the magnetic materials and in centrifugal stresses which they can withstand. Two views of an experimental homopolar inductor rotor are shown in Figure 16. The field winding (lower view) is not rigidly mounted on the shaft and, therefore, does not rotate. The two excitation wires are brought out through one of the stator slots. This winding is normally wound under the stator winding in a void in the yoke of the stator to facilitate heat removal.

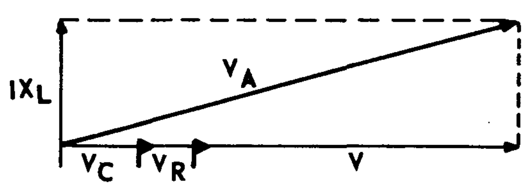
An excitation current in the field winding produces a magnetic flux with a path that leaves the salient poles at one end of the shaft, crosses the air gap, travels through the stator, and returns across the air gap back into the poles at the opposite end of the shaft. All the poles at one end of the shaft have a like polarity and are opposite in polarity to those at the other end. One disadvantage of this concept is that only a portion of the rotor spans the length of the stator winding and, therefore, less than half of the stator iron and wire are producing torque at any instant. Hence, this motor would be several times heavier than a PM brushless motor with equivalent torque and efficiency.

Another disadvantage of the homopolar motor is the effect of armature reaction caused by the soft iron rotor. Part of the flux leaving the armature (the stator) is attracted by the rotor and returns to the armature through the soft iron pole pieces of the rotor. This distorts the flux generated in the rotor and effectively shifts the center of the salient pole. In a brush-type motor this is compensated by mechanically shifting the brushes. Since brushless motors are commutated by shaft position sensors, these sensors either have to be shifted mechanically or their output signal shifted electronically. The amount of shift is proportional to the difference in the armature and field flux and is polarity sensitive. Providing this function adds significant complexity to the system. The PM brushless motor, however, is not sensitive to this problem. Since the permeability of a permanent magnet is essentially the same as that of air, the effect of armature reaction in a PM brushless motor is negligible.

Experience gained with the variable-frequency ac-induction motor indicates performance characteristics very similar to the series motor. The rotor field of the ac motor is produced by current which is induced from the stator winding. A high-stator current induces a strong rotor field and results in high-torque at low speed. As the stator current is decreased, the rotor field correspondingly decreases. The reduced counter emf now allows the motor to develop a higher speed, but at a lower output torque. As in the series motor, the torque of a variable-frequency ac induction motor varies as square of the stator current.

The broad torque-speed range of the variable-frequency ac induction motor is well suited to a vehicle propulsion system. The motor requires no position sensors and hence is one of the most rugged types of motors. The disadvantages of the LRV application are essentially the same as those of the series motor. The copper loss and controller losses required to generate the rotor flux is significant and detracts from the system efficiency. Also the motor must be made larger to minimize the heat generated in the rotor and to increase the radiating surface area to dissipate this heat.

In applications where output power and efficiency at the higher motor speeds are important factors, the PM brushless motor has an additional advantage over brushless motors with soft iron rotors. The frequency applied to the stator windings of a brushless motor is equal to the speed multiplied by the pairs of poles. (This discussion is also applicable to the variable frequency induction motor but here the frequency is found by multiplying the rotor speed times the number of pole pairs plus the slip frequency.) For example, a six-pole motor running at 9000 rpm has an applied frequency of 450 Hz. The inductive reactance of a motor designed for high stall torque would be large when running at a speed corresponding to this frequency because of the large number of turns. The voltage dropped across the reactance is in quadrature with the system losses and with the counter emf. Although this does not in itself represent a direct loss, it can severely limit the output power of a motor in a low voltage system such as the LRV. This is illustrated by the vector diagram.



The applied battery voltage V_A is the vector sum of the reactive drop IX_L and the in-phase components consisting of the controller voltage drop V_C, the winding resistance drop V_R, and the counter emf V. Since the output power of a motor is equal to the counter emf times the armature current,[3] the efficiency is given by the equation

$$N = \frac{VI}{VI + V_C I + V_R I} = \frac{V}{V + V_C + V_R} ,$$

where $V_C I$ and $V_R I$ represent the controller losses and the copper losses, respectively. If the quadrature component is small, the voltage available for counter emf is large compared to the losses, and the efficiency will be high. If, however, the quadrature component becomes large, the losses remain essentially the same while the voltage available for counter emf decreases and limits the efficiency and the output power of the motor.

The soft iron in the rotor of the induction motor and the homopolar motor significantly increases the inductance of the stator winding. The permanent magnet in the PM motor, as previously indicated, is equivalent to an air core and has negligible effect on the inductance of the stator winding. Hence, all other factors being equal, the PM motor has more voltage available for developing counter emf and can produce higher power and higher efficiency than an equivalent motor with a soft iron rotor.

3. The output power of the induction motor is usually expressed in terms of the equivalent rotor resistance rather than the counter emf.

TABLE 1. APOLLO 15 LVR PERFORMANCE SUMMARY PRELIMINARY

	EVA I	EVA II	EVA III	TOTAL
DRIVE TIME (hr + min)	1+05	1+22	0+35	3+02
MAP DISTANCE (km)	9.3	11.7	4.3	25.3
ODOMETER DISTANCE (km)	10.3	12.5	5.1	27.9
MOBILITY RATE (km/hr)	8.6	8.56	7.37	8.35
AVERAGE SPEED (km/hr)	9.5	9.15	8.75	9.20
ENERGY RATE (A-hr/km)	1.75	1.60	2.8	1.87
A-HOURS CONSUMED	18	20	14	52
NAV. CLOSURE (km)	0.10	0.20	0.0	0.1
GYRO DRIFT RATE (deg/hr)	1	1	1	1
WANDER FACTOR+SLIP (%)	10.8	6.84	18.6	10.3

$$\text{MOBILITY RATE} = \frac{\text{MAP DISTANCE}}{\text{DRIVE TIME}}$$

$$\text{WANDER FACTOR} = \frac{\text{ODOMETER} - \text{MAP DISTANCE}}{\text{MAP DISTANCE}}$$

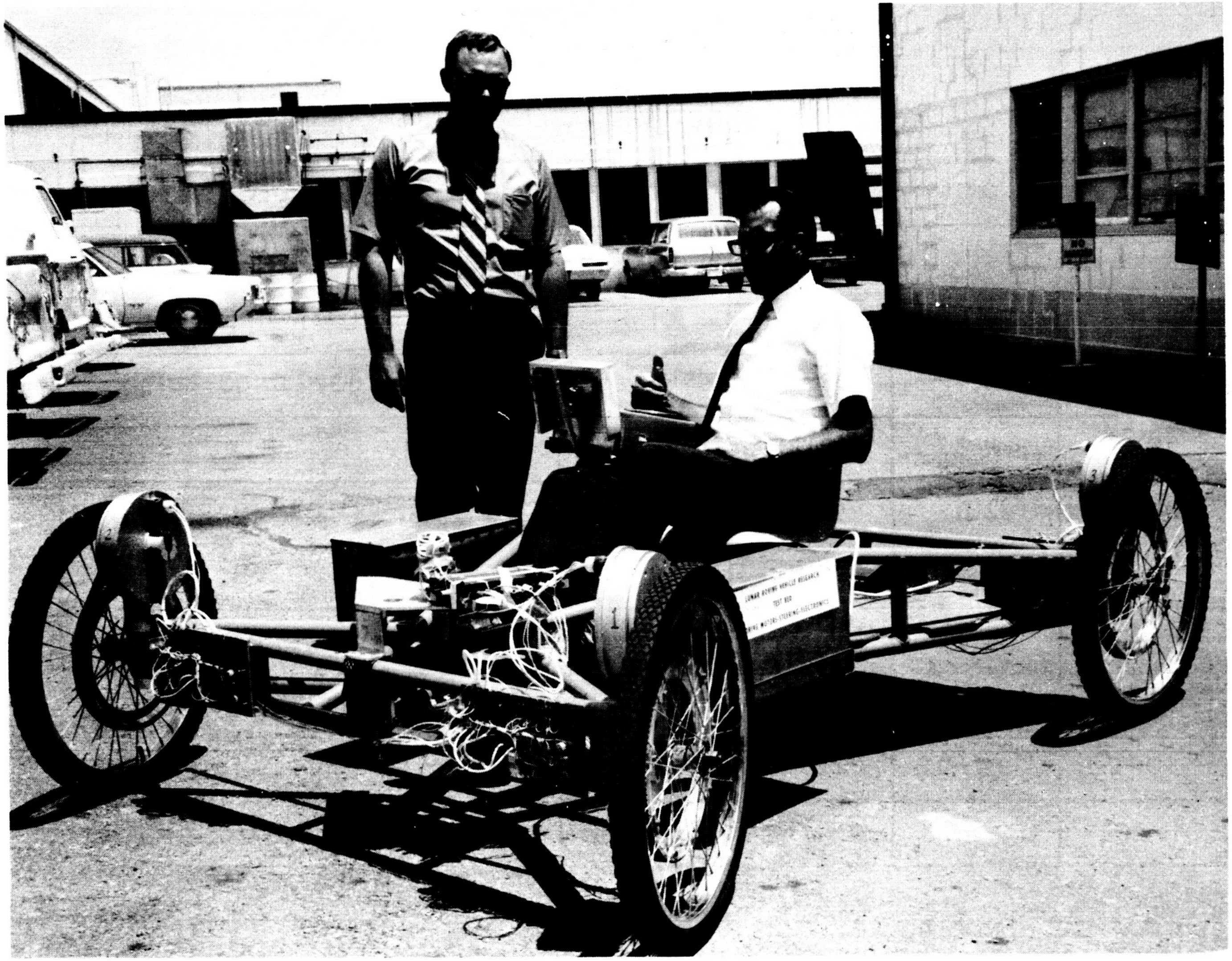


Figure 1. Breadboard vehicle.

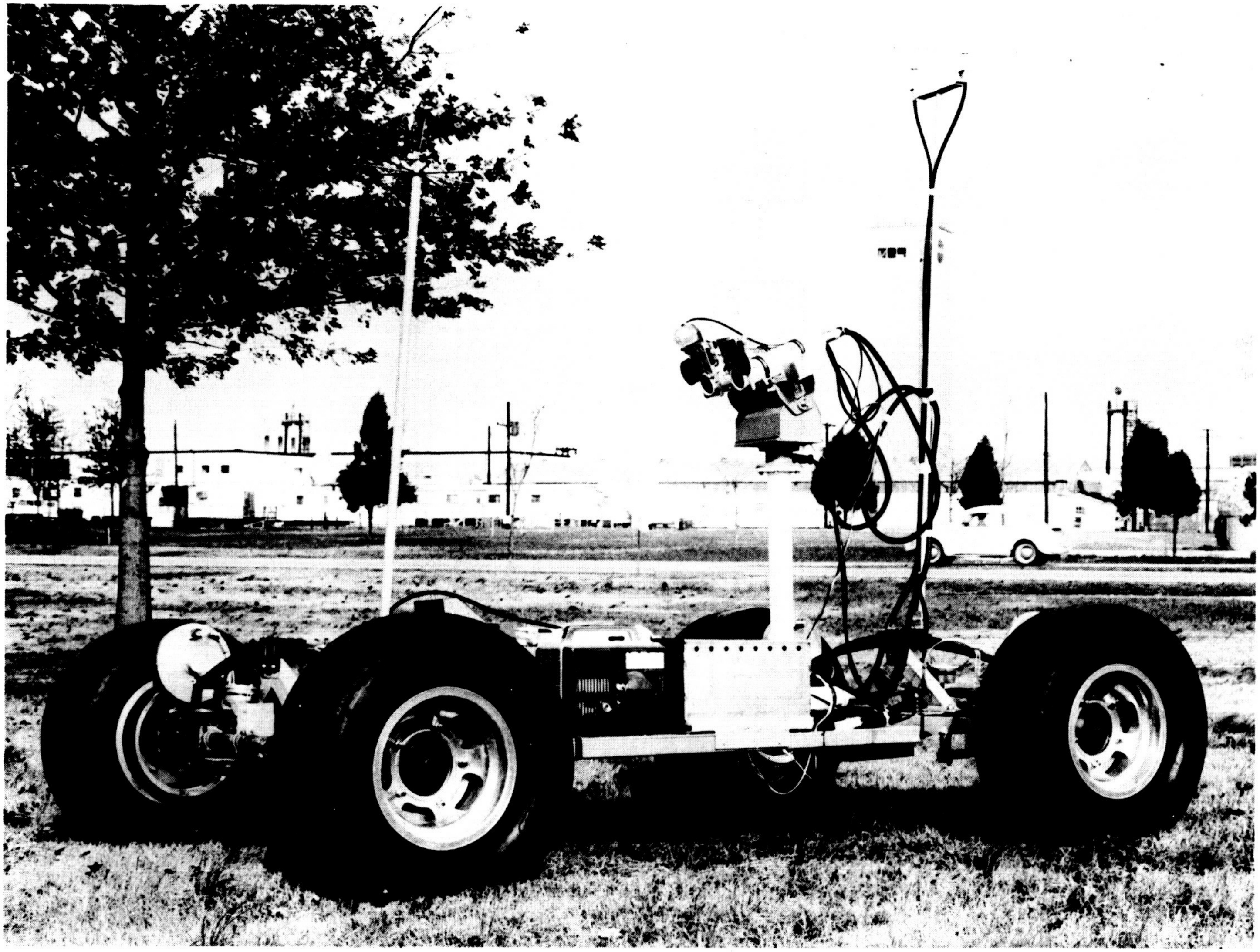


Figure 2. Breadboard vehicle with remote control operations.

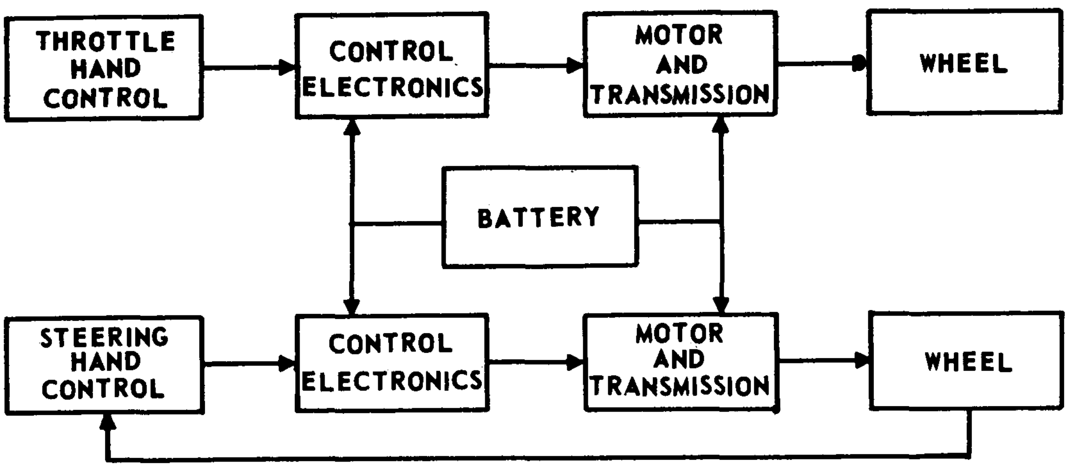


Figure 3. Mobility system components.

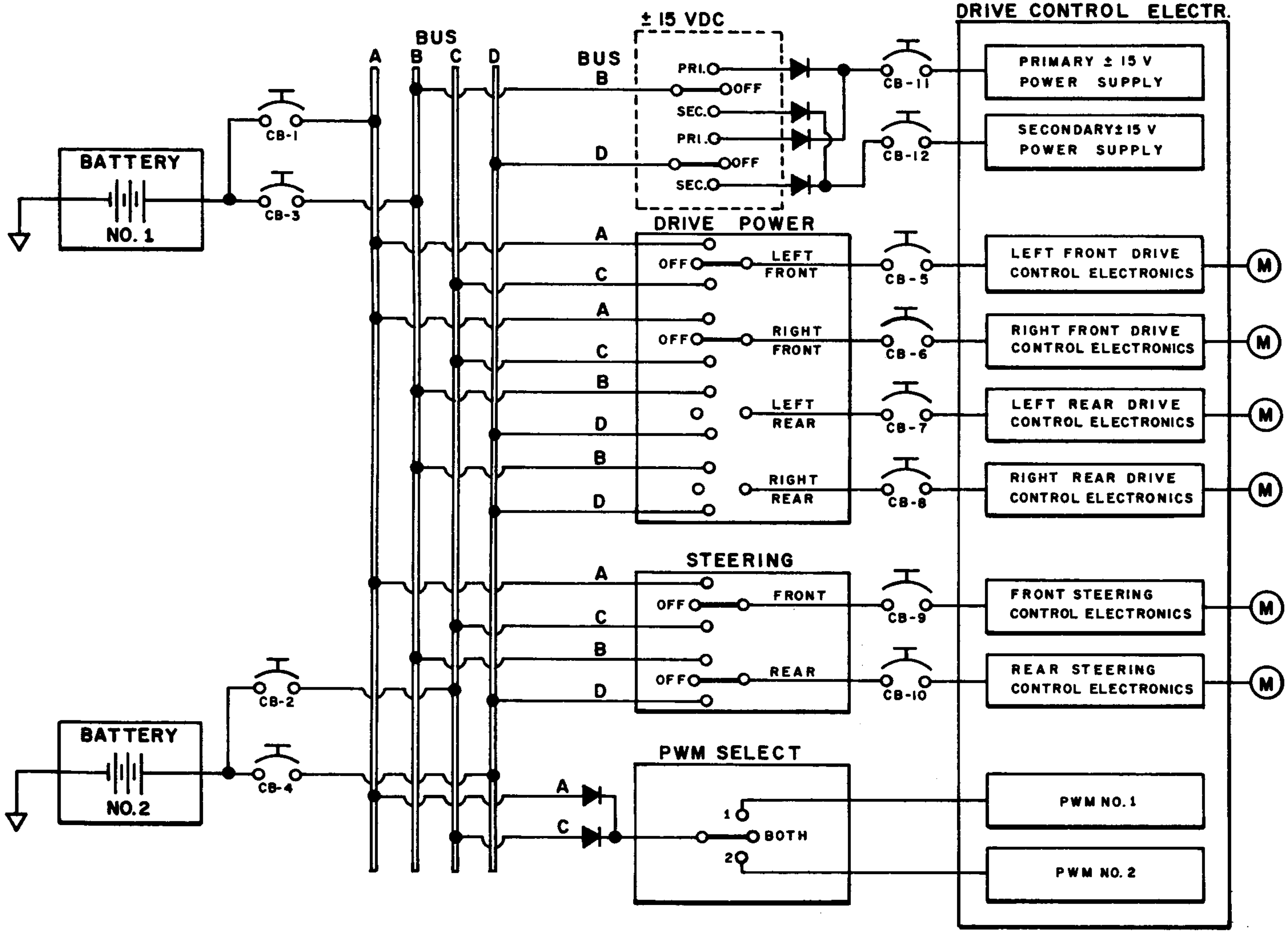


Figure 4. Power distribution.

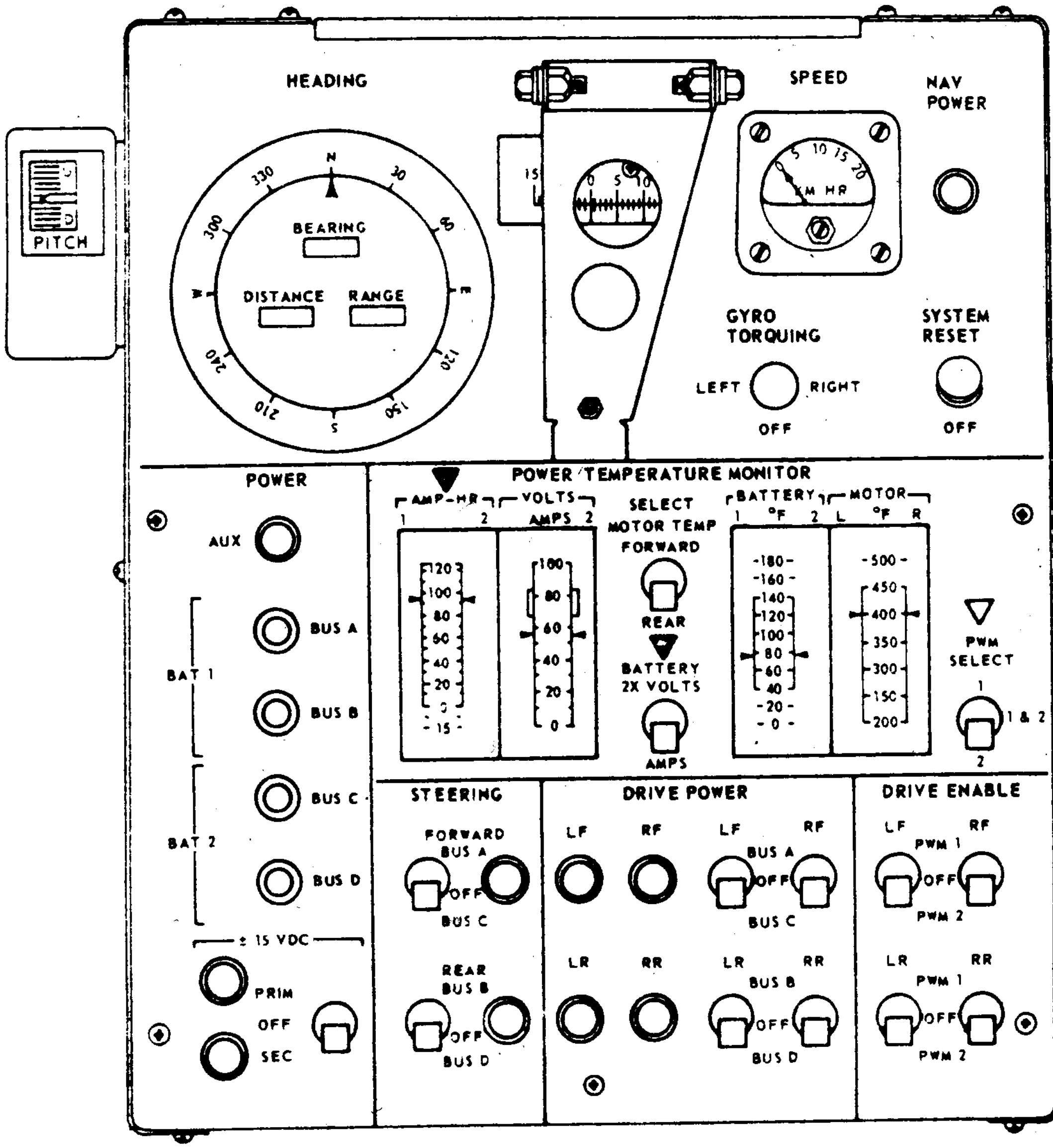


Figure 5. Control and display console.

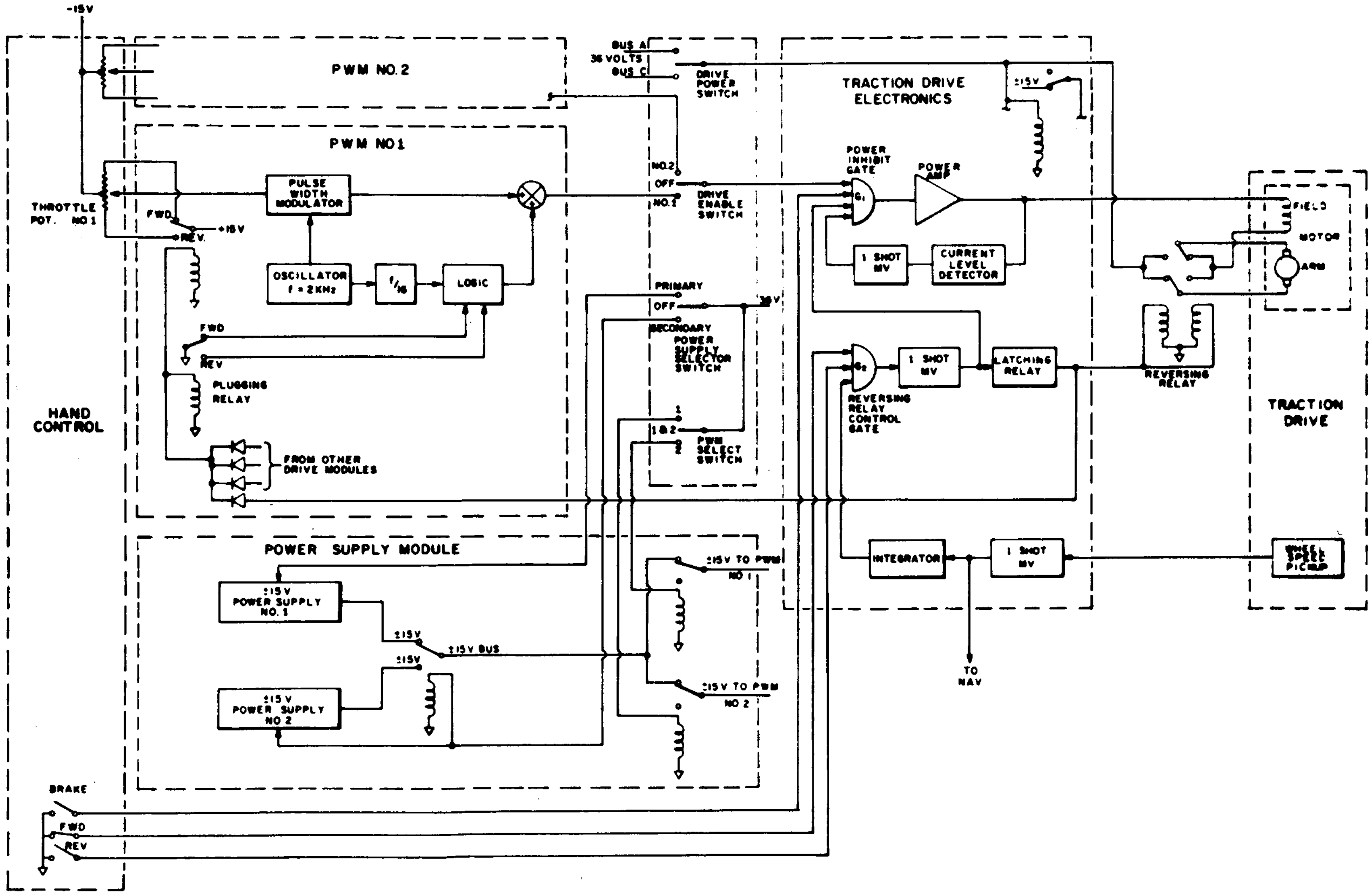


Figure 6. Block diagram of traction drive.

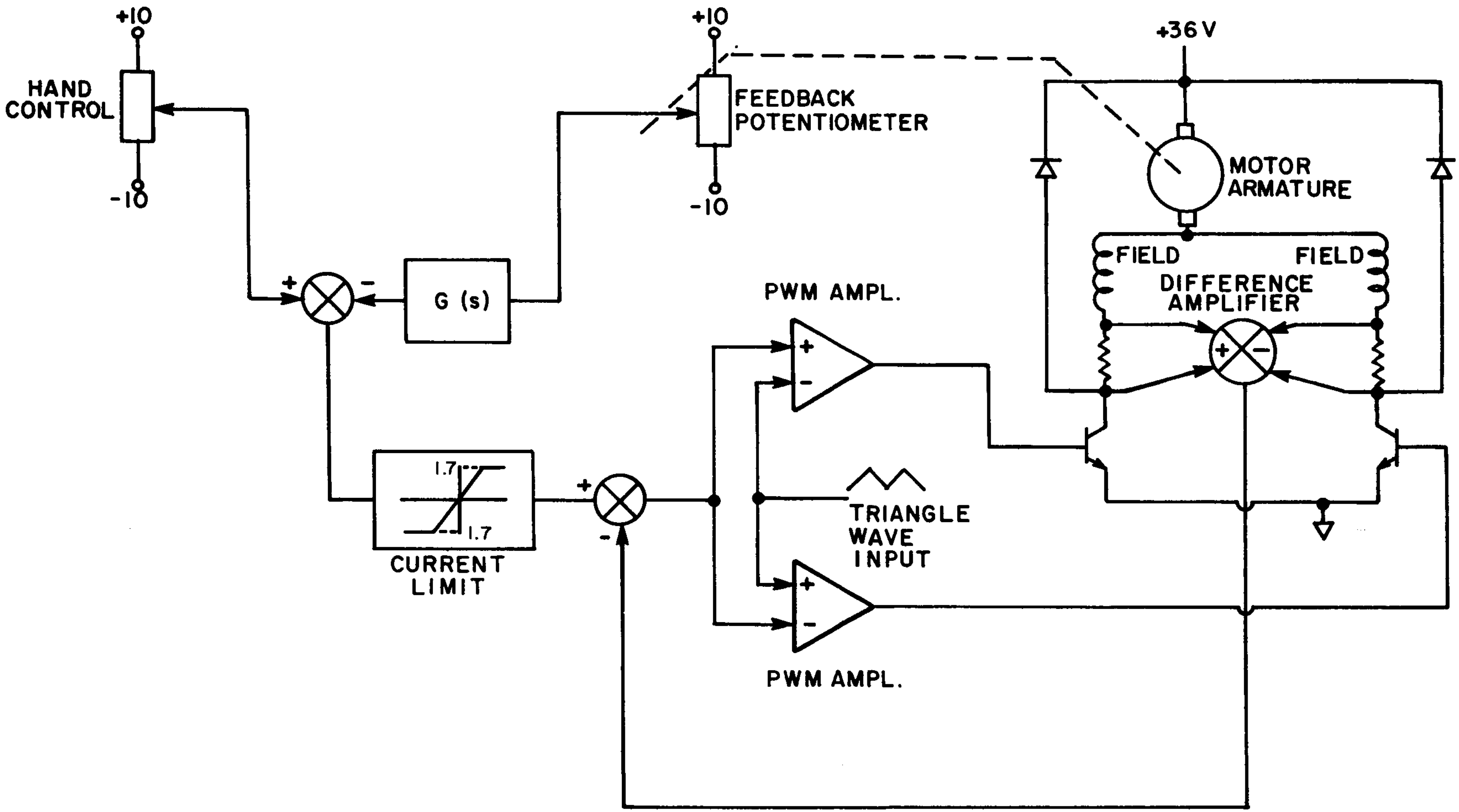


Figure 7. Block diagram of steering control.

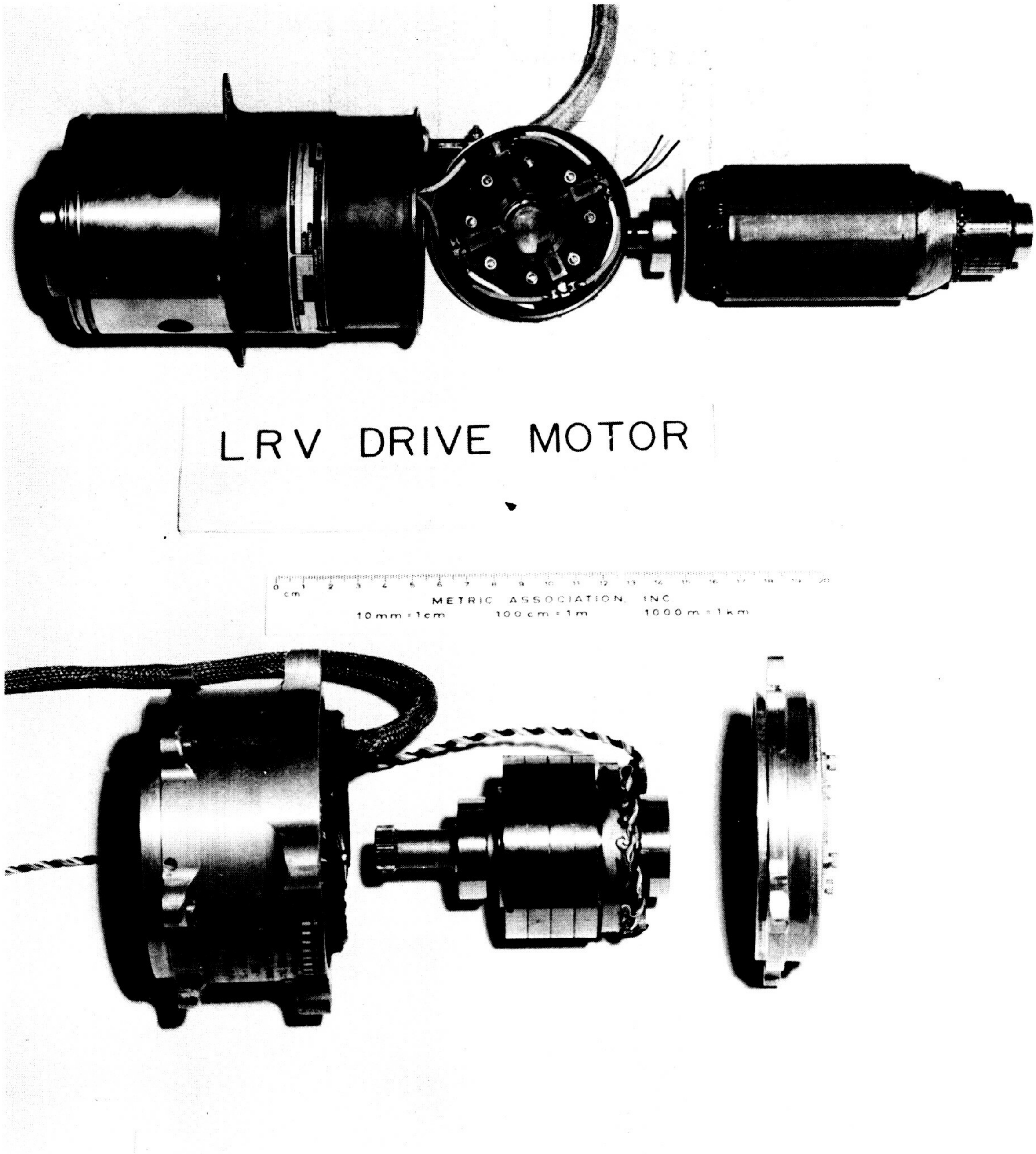


Figure 8. LRV motors.

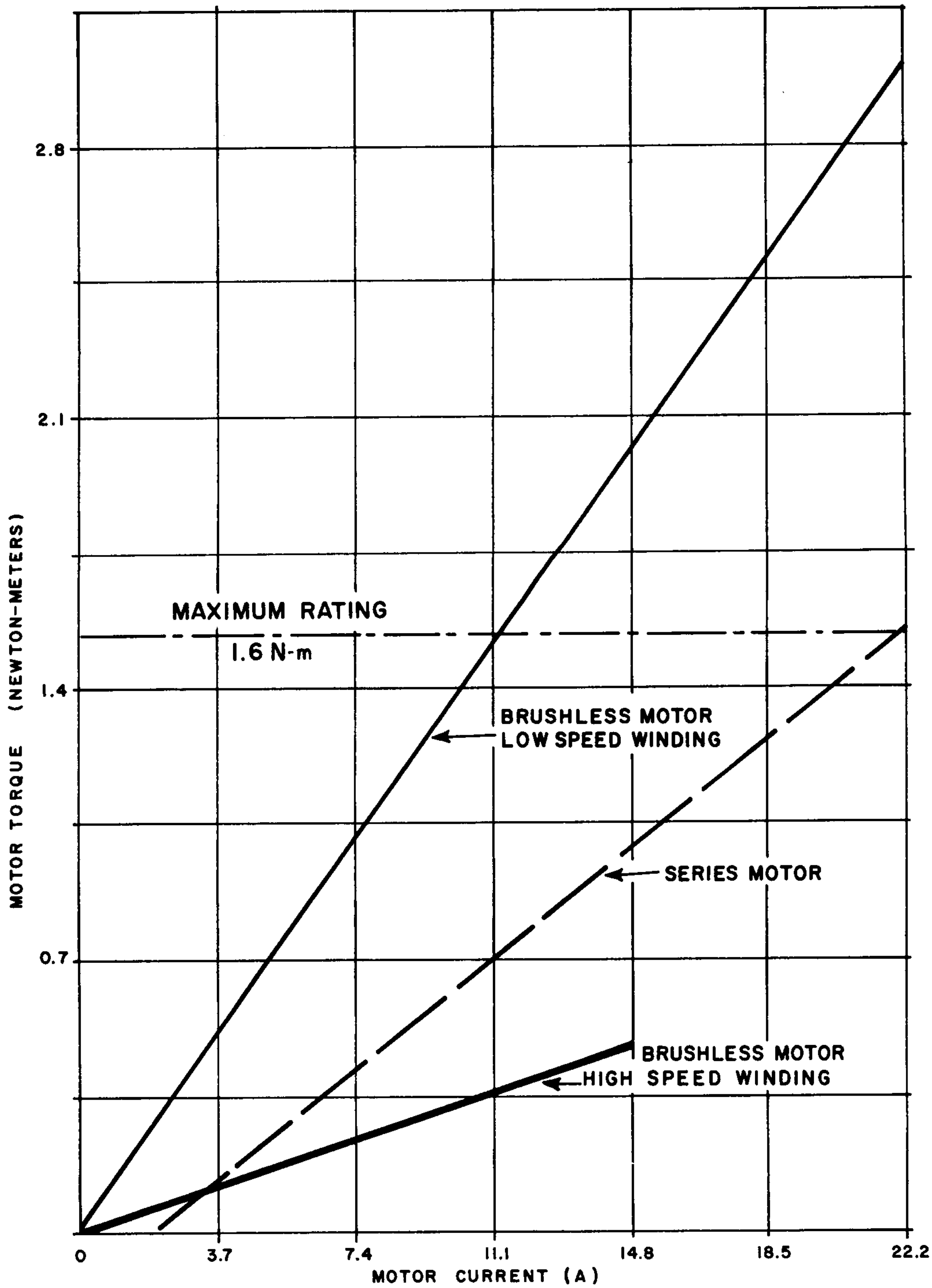


Figure 9. Stall torque vs current for brushless and series-wound brush motor.

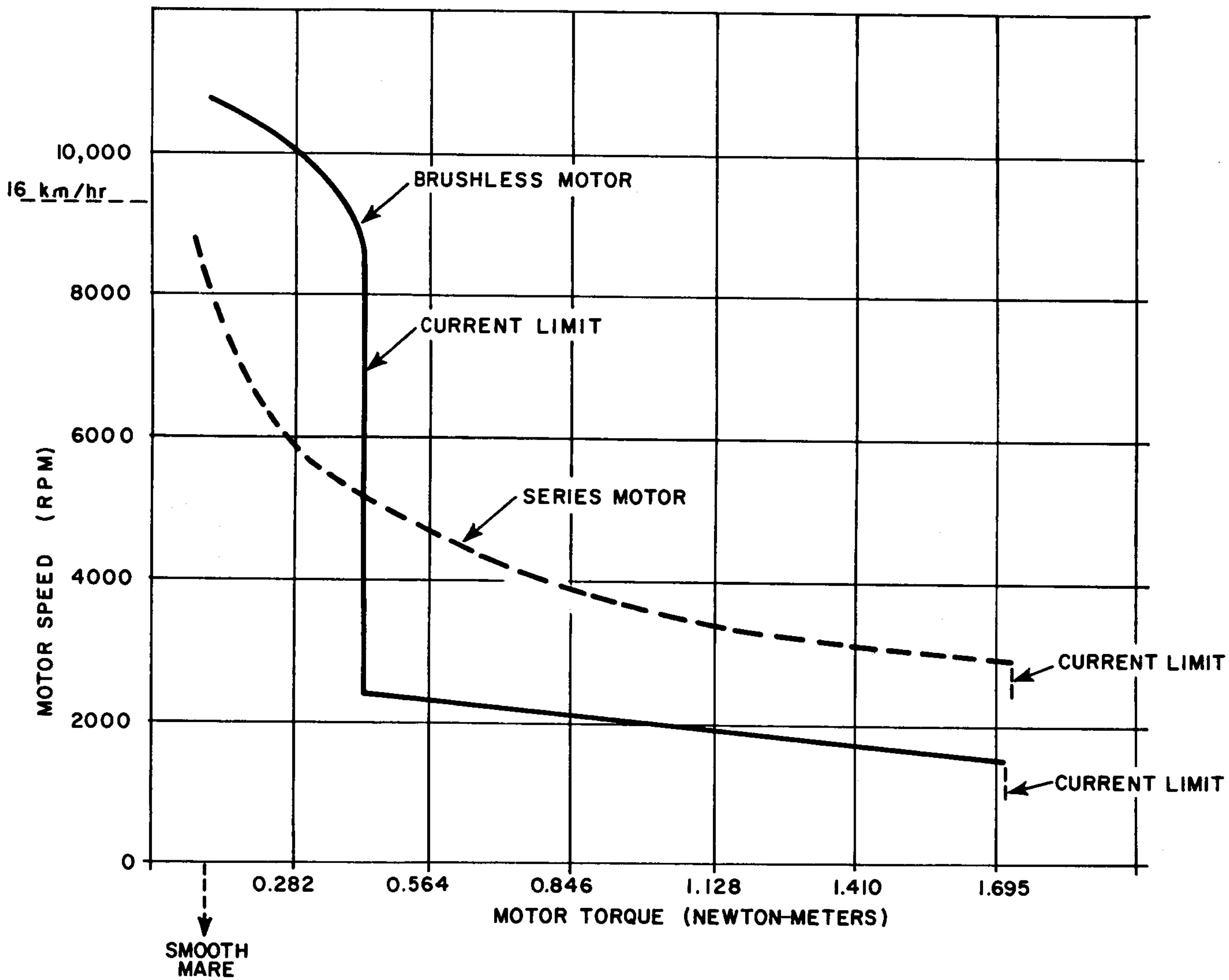


Figure 10. Torque vs speed maximum performance curves.

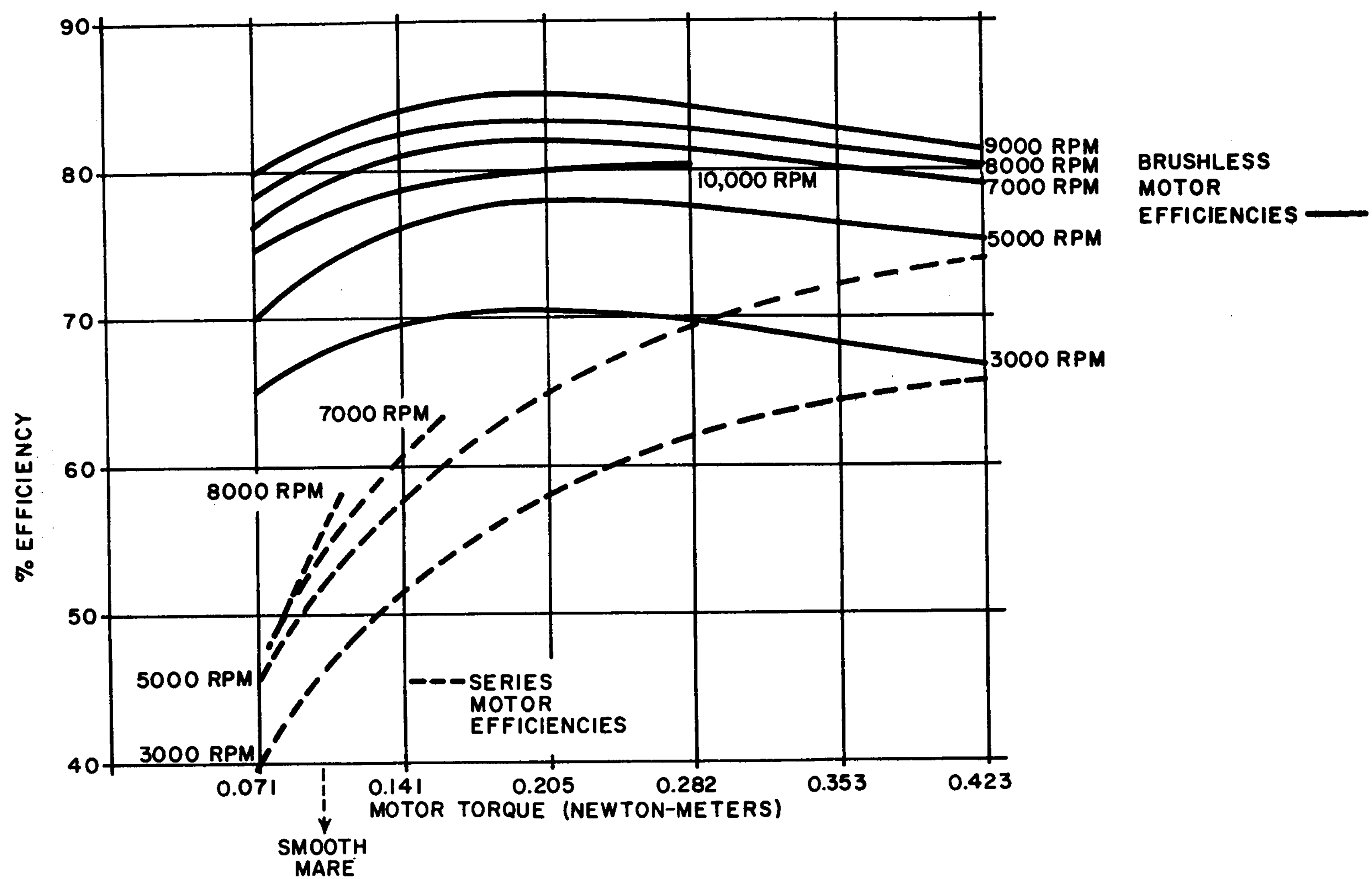


Figure 11. Efficiency vs torque.

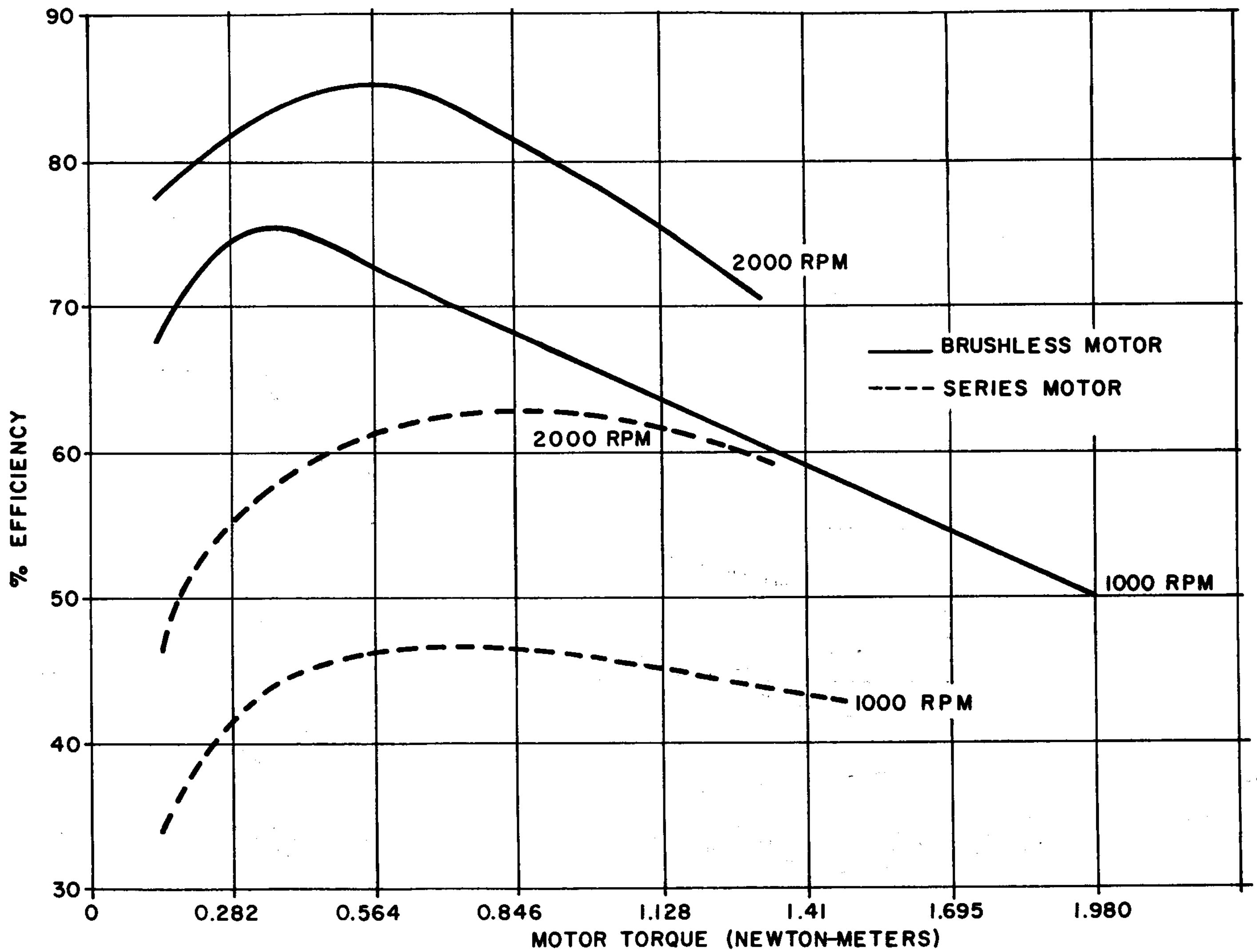


Figure 12. Efficiency vs torque

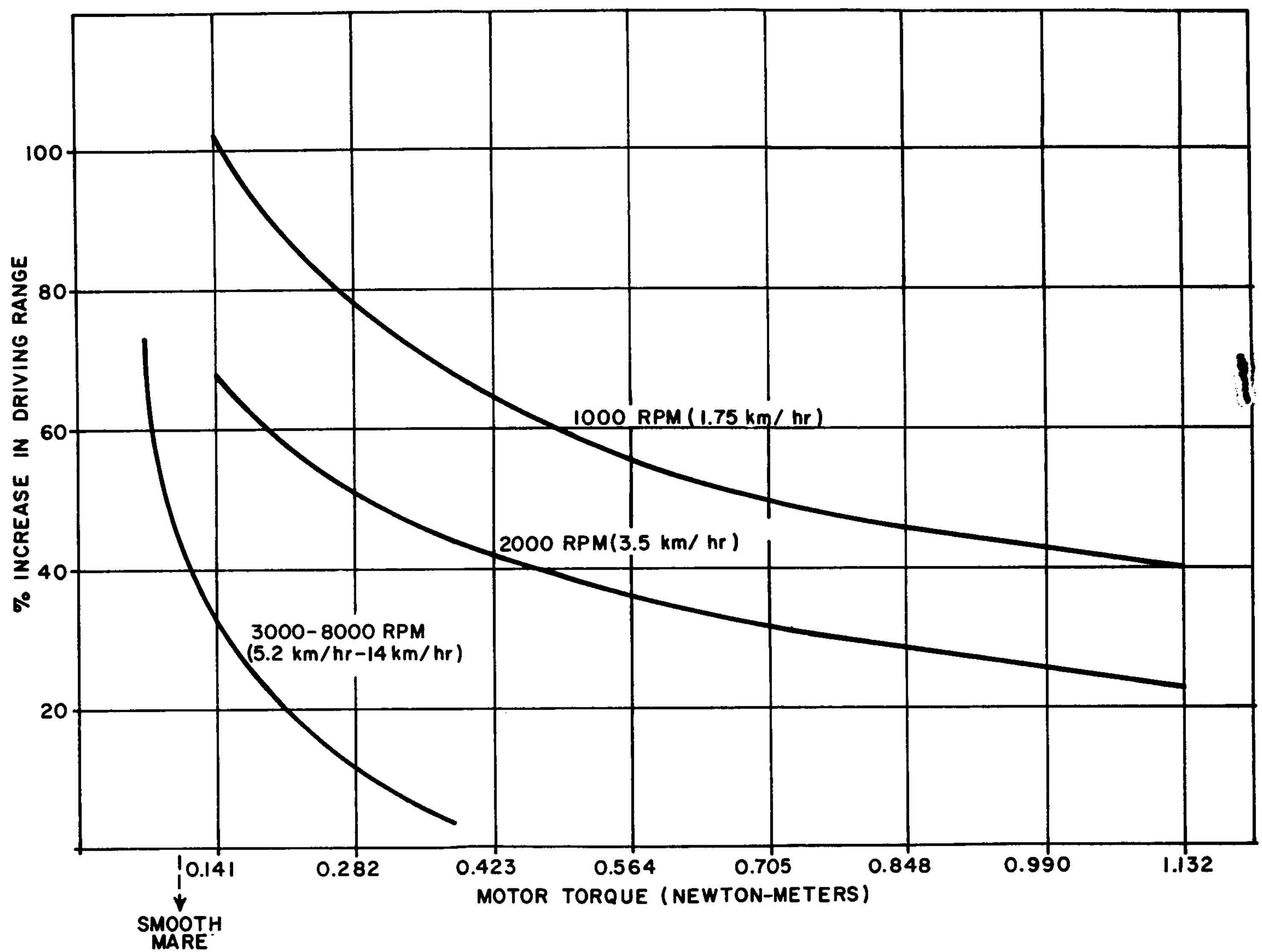


Figure 13. Percent increase in driving range of brushless motor over series motor as a function of torque.

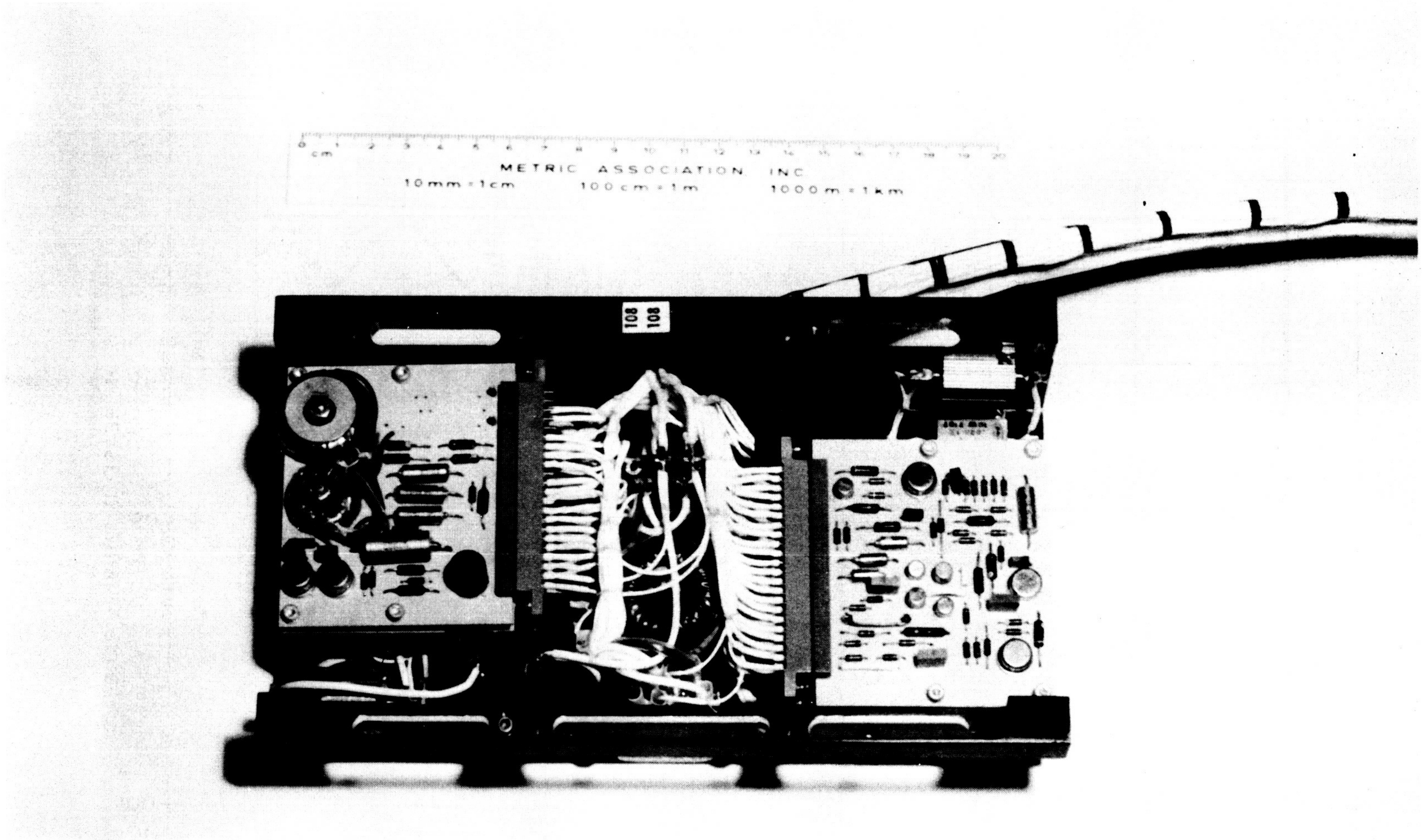


Figure 14. Brushless motor electronics.

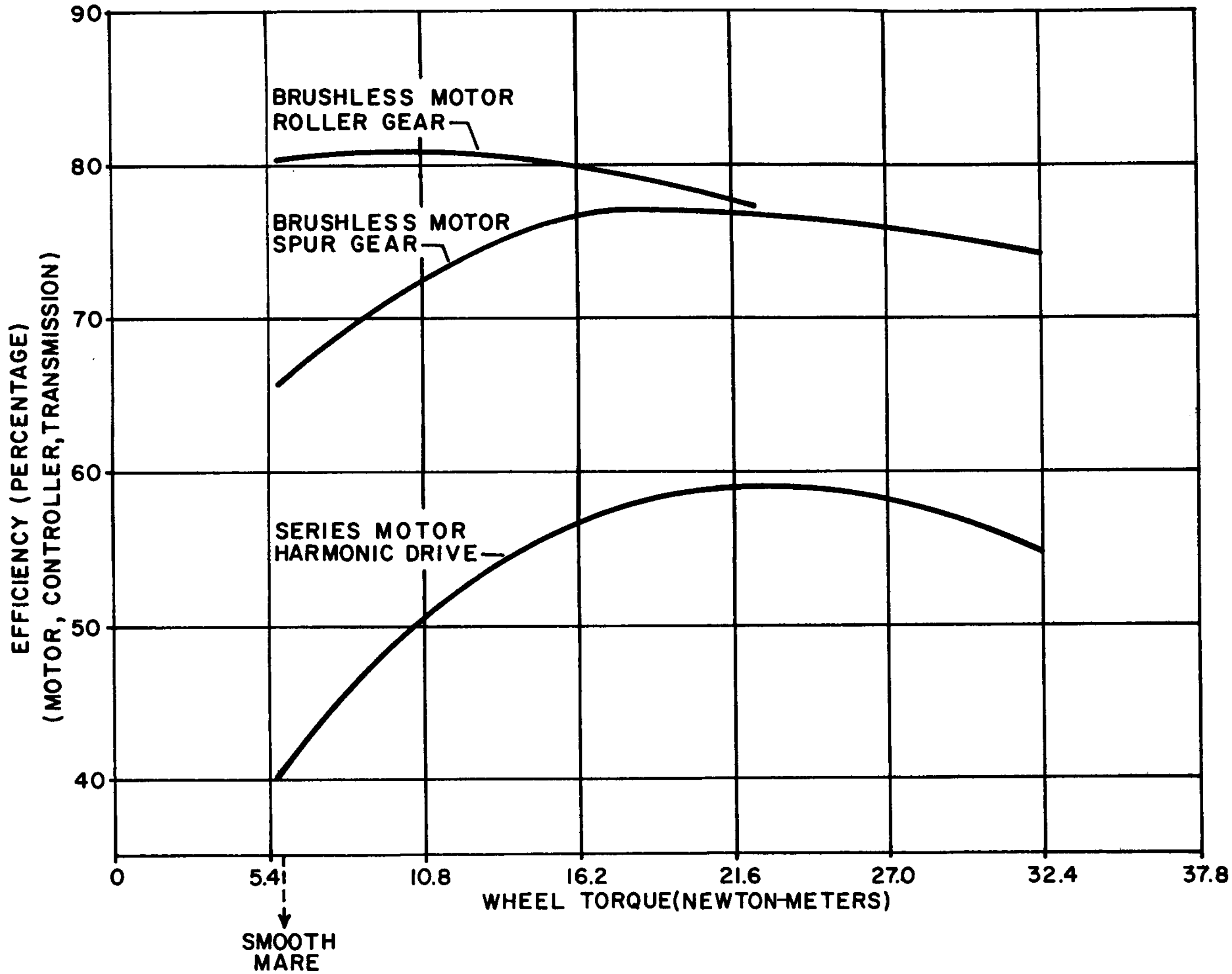


Figure 15. Efficiency vs torque for maximum torque speed.

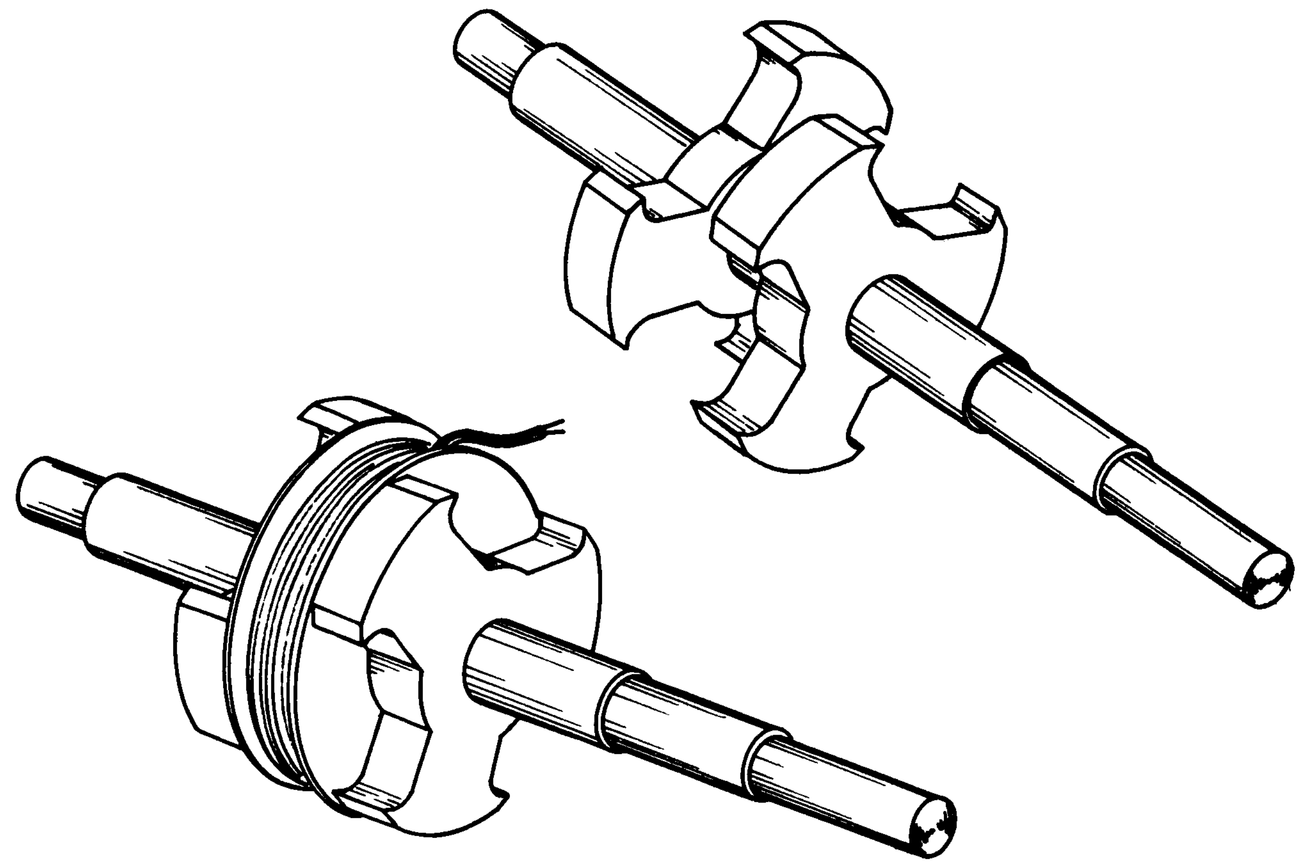


Figure 16. Homopolar inductor rotor.

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APPROVAL

MOBILITY SYSTEMS ACTIVITY FOR LUNAR ROVERS AT MSFC

By Clyde S. Jones, Jr. and Frank J. Nola

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Office. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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