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SMART MOTOR TECHNOLOGY

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ABSTRACT

Current spacecraft design relies upon microprocessor control; however, motors usually require extensive additional electronic circuitry to interface with these microprocessor controls. This paper describes an improved control technique that allows a "smart" brushless motor to connect directly to a microprocessor control system. An actuator with "smart motors" receives a spacecraft command directly and responds in a "closed loop" control mode. In fact, two or more smart motors can be controlled for synchronous operation.

SMART MOTOR TECHNOLOGY

Today's electric motors require substantial additional equipment to achieve "controlled" performance. These additional items may include a power electronics box, a servo electronics box, encoders, tachometers, or potentiometers. The use of these "extras" causes system complexity and cost to increase.

Stepper motors and controls have been introduced as a means of reducing complexity. The simpler stepper systems, however, introduce other undesirable characteristics such as slower speed, higher power dissipation, and output load sensitivity when compared to dc motors and controls.

Recent developments within the motor industry now make it possible to combine advanced brushless-motor technology, microprocessor control, and microprocessor programmability to create a "smart motor." **The smart motor possesses internal electronic controls that allow direct interface between the motor and the spacecraft command system. This eliminates the need for expensive, heavy electronic control boxes and external electromechanical devices.**

One set of smart motor performance characteristics will now be described. The control techniques to be presented are an outgrowth of the "dual drive actuator" development effort that was presented at the 16th Aerospace Mechanisms Symposium in 1982. The dual drive actuator uses an advanced brushless-motor configuration that will be discussed in detail and then used in describing smart motor characteristics.

The dual drive motor (Figure 1) is produced for the Jet Propulsion Laboratory by Aeroflex Labs of Plainview, New York. The unit contains internal electronic circuitry that provides a rudimentary degree of operating intelligence. This circuitry performs all commutation functions, thereby

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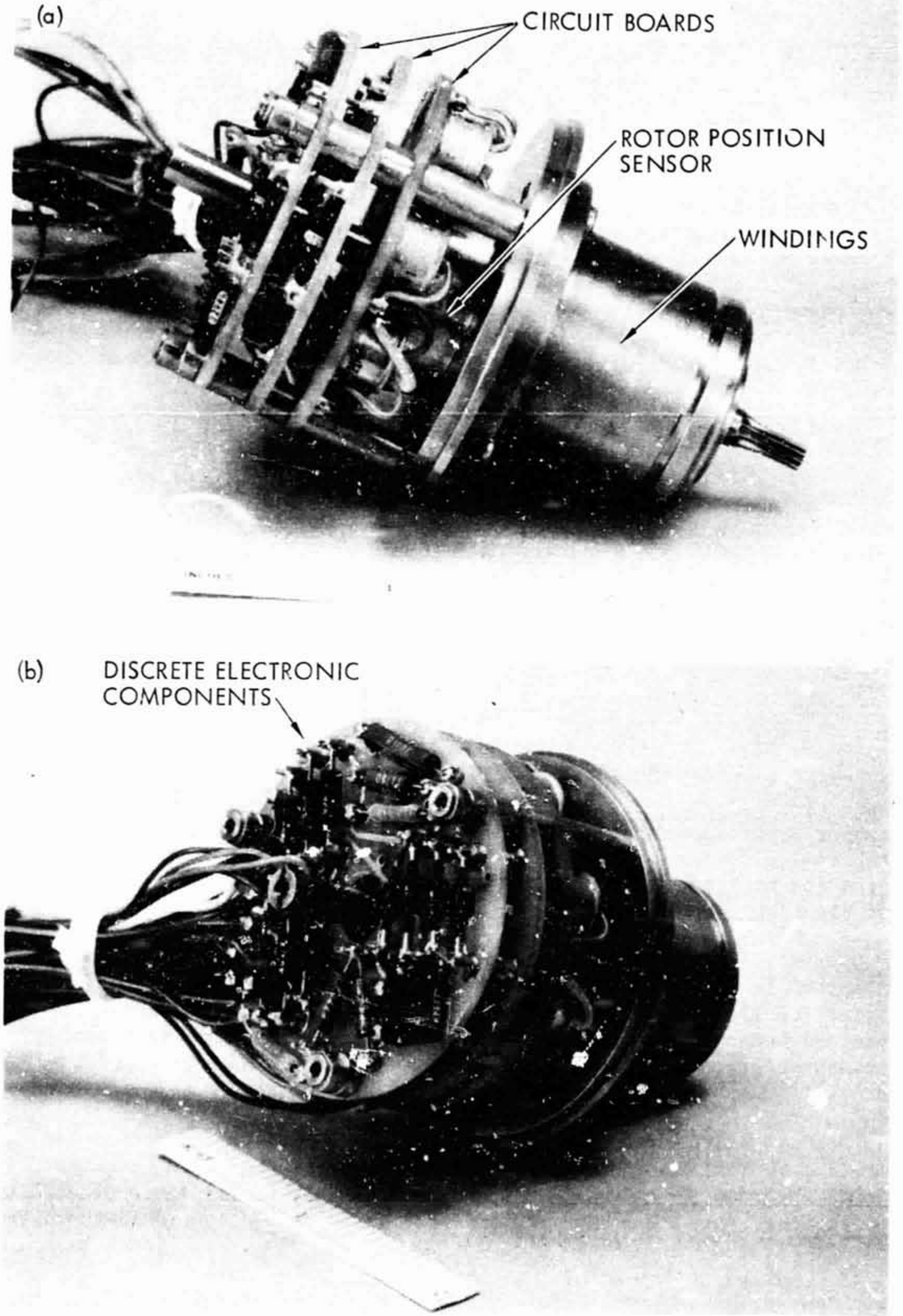

Figure 1. Dual drive motor: (a) side view, (b) rear view (rear cover removed)

providing a "two-wire" electrical interface requiring only reversible dc power for operation.

Figures 2 and 3 show mechanical and electrical design details. The rotor position sensor (Figure 2b) is a noncontacting mechanical assembly that performs the same function as the brush set and commutator in a typical dc motor

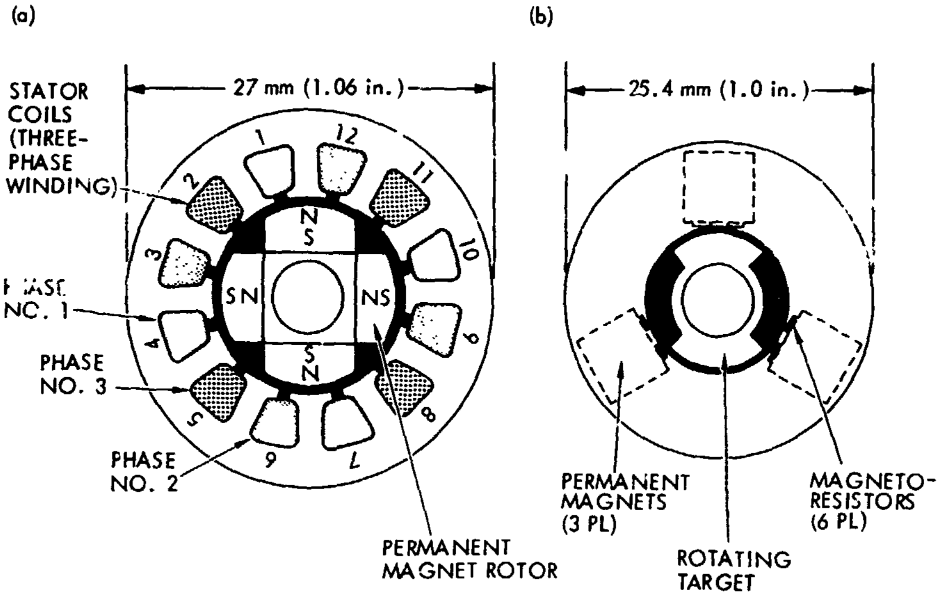

Figure 2. Motor mechanical construction: (a) rotor/stator design, (b) rotor position sensor

Magnetoresistors are the active sensor elements. These are semiconductor resistors that provide an increase in resistance when they are exposed to increased magnetic flux. Thus the proximity of the rotor target to each magnetoresistor governs its relative resistance. The magnetoresistors are connected to form the legs of a bridge network, as the target rotates, a signal is generated from the rotor position sensor for subsequent signal processing. The three magnets create a three-phase signal generated from three independent bridge circuits, thereby producing three-phase control.

A portion of the position sensor circuitry is contained within the mechanical assembly, and the remainder of the circuit is located with the drive control electronics on three printed circuit boards attached to the rear of the motor. The drive control circuit consists of four major electronic subsystems:

(1) A diode bridge controls the polarity of the reference voltage being applied to the sensor circuit. This voltage polarity reverses when the input power polarity is reversed. The reversal causes a phase change of the switching signals to the amplifiers; however, the diode bridge simultaneously applies a fixed polarity voltage to the amplifiers regardless of the input power polarity (current always flows through the motor in one direction).

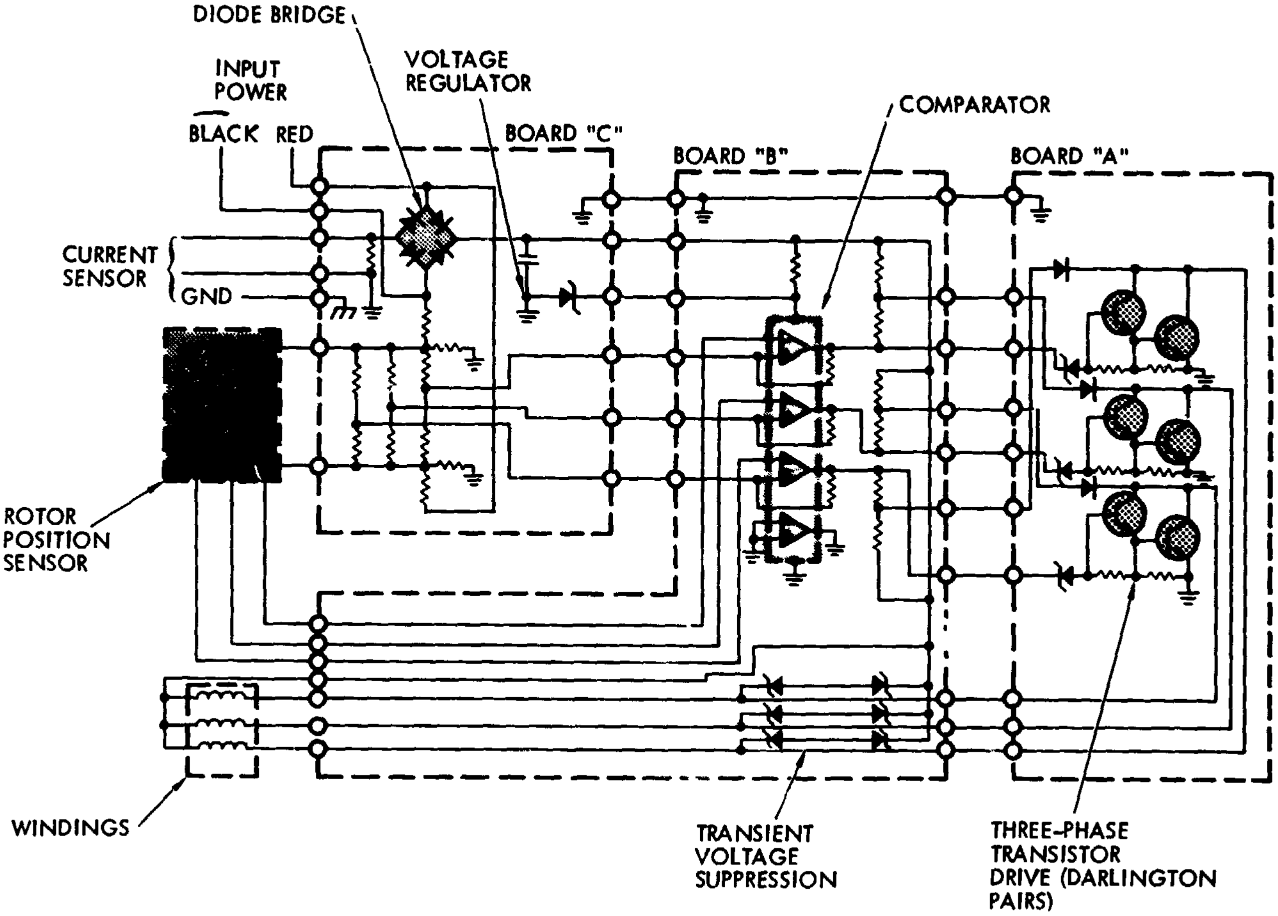

Figure 3. Dual drive motor circuit diagram

(2) A diode voltage regulation circuit provides a regulated, 15-V power supply to the comparator.

(3) The comparator receives low-level (50 mV) switching signals from the rotor position sensor and amplifies these signals into higher level switching signals capable of controlling the three-phase transistor drive circuit.

(4) The transistor drive circuits provide the three-phase (30-V) drive pulses to the windings located in the main motor stator. These drive circuits also contain diode cross-strapping, which precludes simultaneous operation of more than one winding.

The motor that has been described is a direct, highly reliable replacement for aerospace-quality, dc brush-type, permanent magnet motors. The dual drive motor has only rudimentary intelligence, making internal commutation possible. But even with this limited capability, the dual drive motor avoids the shortcomings of brush-type motors (vacuum brush wear and poor heat transfer) while providing their advantages such as a simplified electrical interface, high starting torque, and low-power/high-speed operation.

The key element in the more advanced versions of smart motor technology is based on the fact that commutation means both knowing how to switch and when to switch. Smart motors achieve this electronically through the use of a rotor position signal that is processed within the motor, starting as a low-level, 50-mV signal and ending as a 30-V, high-current drive pulse. The rotor position sensor is a coarse, but accurate incremental encoder and it is possible to "tap into" the motor circuitry through appropriate additional electrical interfaces so that the commutation signal can be processed for use just as the signal from any auxiliary servo component can be processed for closed loop control. The internal motor circuitry can also be tapped at a point that allows direct control by low-level logic signals, typical of the output from a spacecraft command system. This direct control means the total elimination of the drive electronics box usually required on today's systems.

SMART MOTOR FEATURES

Incremental Positioning (Stepping)

The two primary motor types used for spacecraft applications are high-speed dc motors and low-speed stepper motors. Each motor type has certain optimum applications. For example, the stepper motor drive usually provides superior performance when slow-speed operation is desired over a long period of time (e.g., solar array sun-pointing drives). Likewise, the high-speed dc motor (with appropriate gear reduction) provides superior performance when high torque and high speed are required (e.g., acceleration of very large inertias during deployment). Therefore, it would be very useful to have a motor that can be operated as an incremental (stepper) motor or as an analog (high-speed) motor.

The dual drive motor circuit can be used to demonstrate how easily this can be accomplished. "AND" gate circuits may be inserted into the motor circuit between the comparator and the drive transistor pairs (Figure 4). Each "GATE" has multiple inputs and all of these inputs must be simultaneously positive for the comparator drive signal to reach the transistors. This makes commutation control possible from a low-level, external logic command applied to the second input of each gate. The pulse repetition rate of this external command can be adjusted to produce stepping motion at any desired speed within the limits of the motor electrical time constant (L/R).

Motor shaft rotation will begin when both gate inputs become positive and will continue until the comparator switches to the next coil or until the external logic signal is terminated. The advantage of this scheme is twofold: (1) failure to complete a step will not cause a torque dropout because as the sequential external pulses continue, full motor torque will again be developed, and (2) a long external pulse can be used without the danger of excessive power dissipation within the motor because the comparator input to the gate will drop to zero as soon as 60° of shaft rotation occurs, thereby terminating the drive signal to that transistor pair, regardless of the status of the external command.

This technique allows a smart motor to be driven at a selectable pulse rate either by a series of manual commands from a mission specialist or by a

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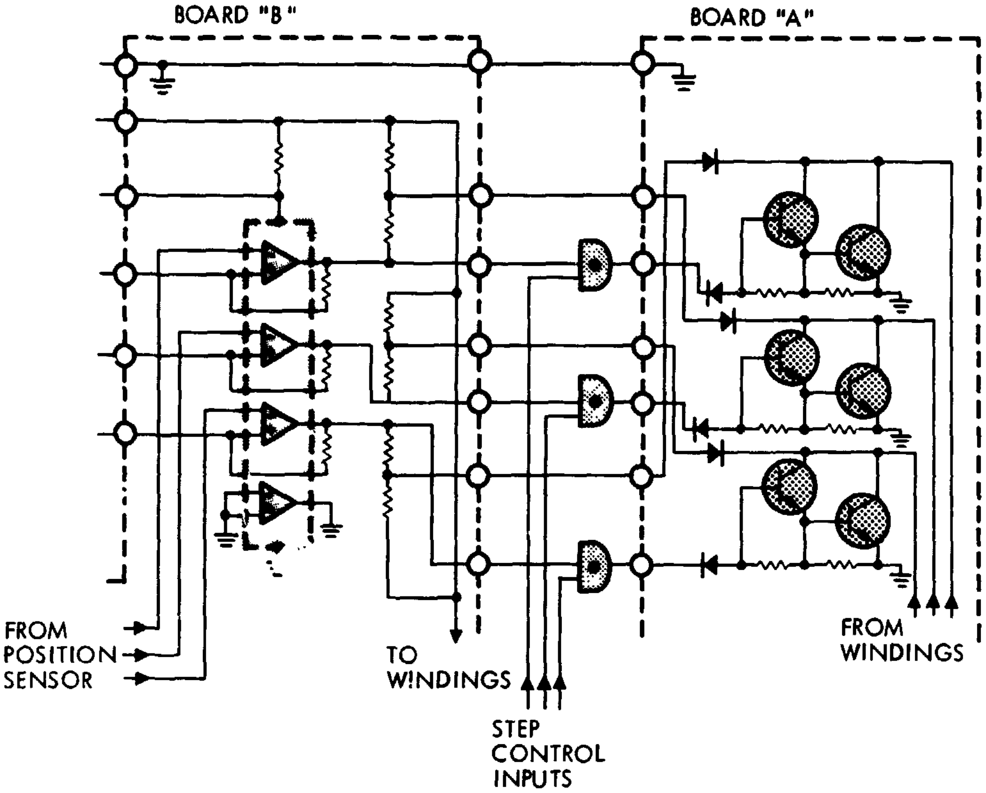

Figure 4. Incremental position control diagram

sequenced command directly from a spacecraft command system. Also, there is never a danger of torque dropout when high-speed rotation is desired because the incremental command can also be supplied as a simultaneous enable signal to all three gates. This action will cause the steppable motor to operate as a normal dc motor. The smart motor can step or run as directed by the spacecraft command system or mission specialist.

Torque Profile Control

Proper operation of stepper motors requires careful attention to the magnitude of friction and inertia in their driven loads. Because energy is added to the driven load to cause motion and must then be removed to stop the motion, stepper motor controllers usually apply a fixed-duration, ramped drive pulse that is preselected to provide the desired performance for a specific load. The pulse duration introduces motion and is applied continuously until motion ceases.

Smart motor designs can accommodate an additional capability to vary the magnitude of each drive torque pulse. This pulse width modulation technique is achieved by using a three-input, three-gate "AND" circuit as shown in Figure 5. Two of the inputs are operated as previously described for incremental motion, and the third input to each gate receives a continuous string of pulses at a frequency to provide a pulse duration greater than the motor electrical time constant, but also significantly higher than the

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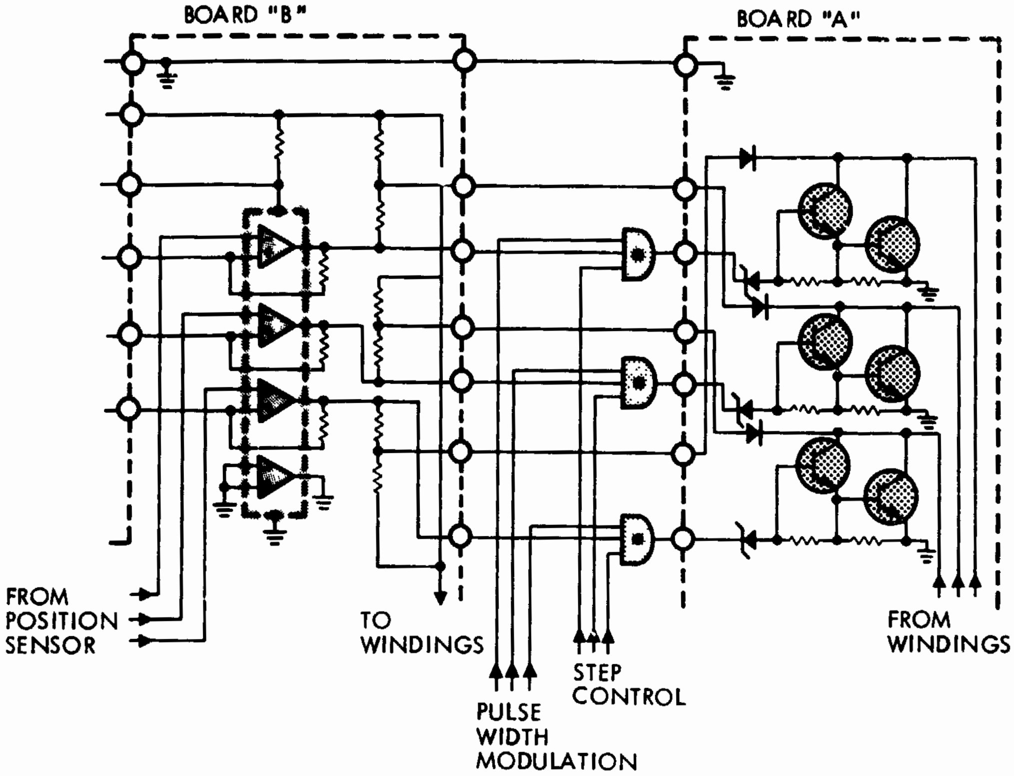

Figure 5. Torque profile control diagram

frequency of the incremental motion command being applied at the second input to each gate. The pulse width duty cycle of the third input determines the total "ON" time for each transistor pair and thereby controls the total amount of energy applied to the load during each step. The torque developed by a motor is directly proportional to current. Therefore, it is possible to use a series resistor within the motor circuit, similar to the dual drive current-sensing resistor, to provide a current feedback signal to the control system. This will provide a direct measure of the torque being generated by the motor. The independently controllable pulse width modulation with current feedback will allow the motor torque profile to be tailored to any desired function within the limits of the motor.

Multiunit Synchronization

Synchronization of the motion of two or more smart motors is also possible and is achieved by simultaneously applying the same step command to each respective smart motor gate (Figure 6). The commutation signals from all motors are then monitored with an external "OR" gate circuit. The output of the "OR" circuit controls the initiation of the next sequential step command, which cannot occur until the monitored commutation signals indicate completion of the previous step for all independent units.

Power will continue to be applied to any motor that has not completed the commanded step. As each individual unit completes the step; however, its

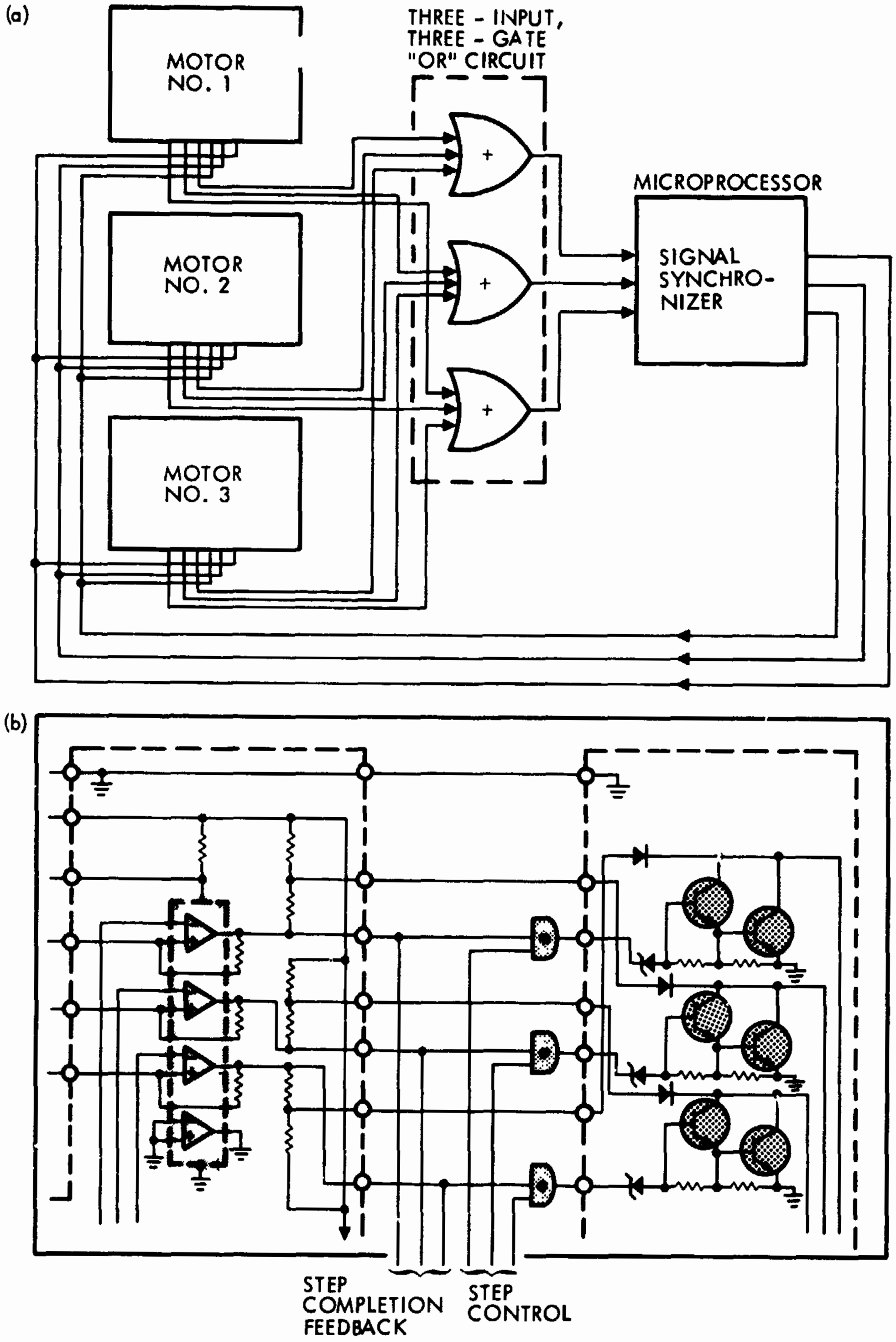

Figure 6. Multiunit synchronization: (a) three-motor diagram, (b) motor internal circuit diagram

position sensor will automatically shut power off and it will wait for the other units to catch up. This permits the use of independent motors with different output loadings yet provides synchronous motion with never more than a single step difference.

Analog Rate Control

Incremental motion control (stepping) of the smart motor, as described above, represents one of the methods of rate control. There are other control techniques that will allow the smart motor to operate as an analog (high-speed) motor with velocity control. Figure 7 shows a control method that

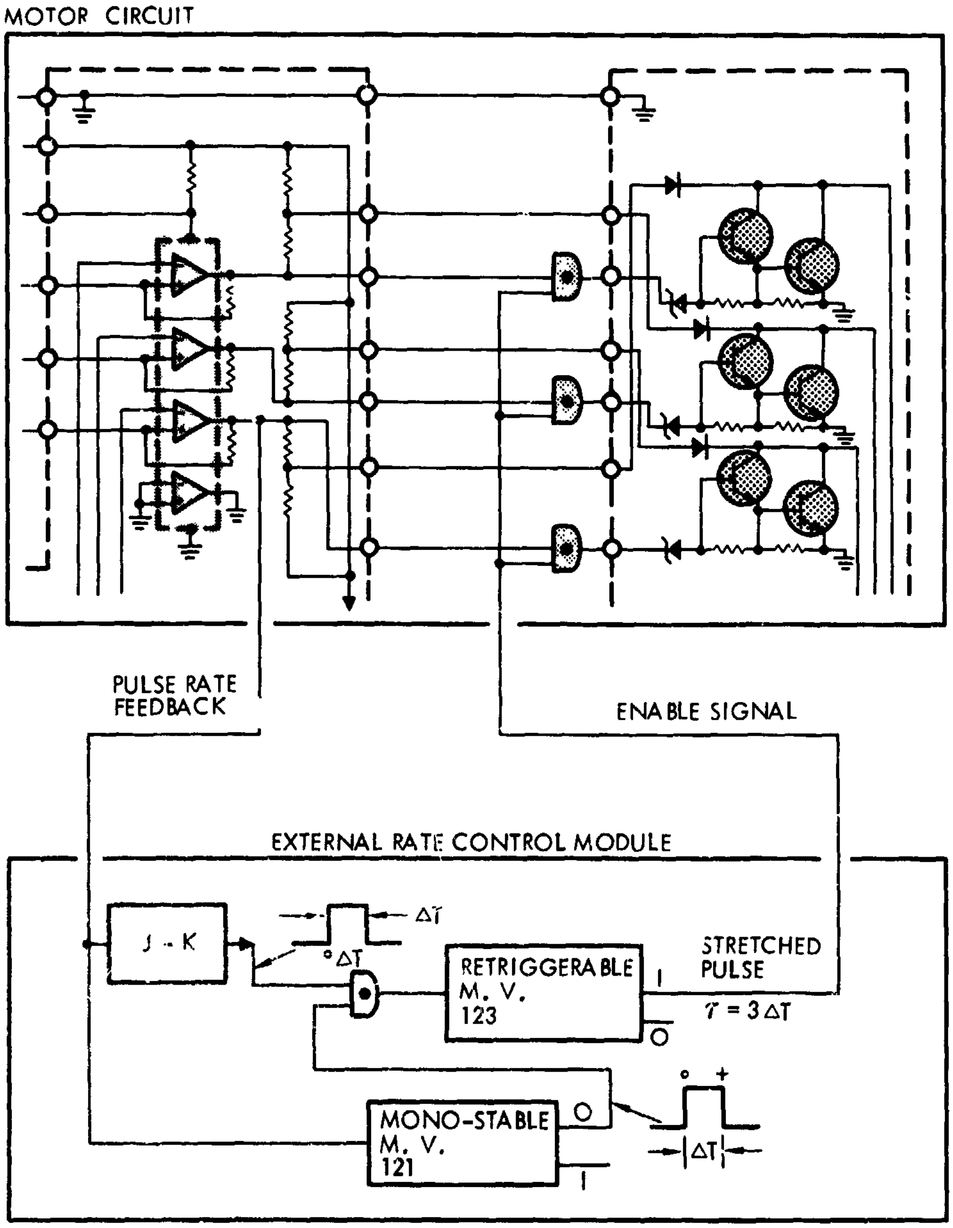

Figure 7. Analog rate control diagram

will control rate with a broad tolerance of approximately 10 percent. This control technique uses the "AND" gate discussed previously and the output signal from one phase of the motor circuit. The motor control provided by this technique will result in a sawtoothed velocity profile. The motor will turn "ON" when a minimum speed threshold is reached and turn "OFF" when a maximum speed threshold is exceeded.

A more precise rate control can be achieved through the use of pulse-width modulation of the driver signal similar to the torque control technique previously discussed. This technique will provide only the power necessary to maintain the desired velocity. With a variable load, the pulse-width modulation will be directly proportional to the load, thereby providing more power with longer driver pulses as the motor speed tends to decrease because of the added load. This high-efficiency method for rate control would be very desirable for large power units.

With pulse-width modulation, the power transistors are still used in the switching mode and are highly efficient. The power applied is directly proportional to the pulse duration. With heavy loads, the pulse width will increase to provide the necessary torque to generate power. Conversely, with light loads, the pulse width will decrease to provide only the power necessary to maintain the velocity.

The use of a pulse-width modulation for power control is suitable for high-accuracy control systems that integrate the error signal with time. Thus, a small error signal integrated over a long period of time will provide a large error signal for rate control.

This technique is easily adapted to high-power systems that need high-efficiency electronics to drive large motors. This design approach can be applied to the motor for large output power levels, yet keep the electronics small in size because of the high efficiency.

Position Control

A simple method (Figure 8) for smart motor position control is to count the output signal from the comparator. This signal, consisting of six pulses from the position sensor for each motor revolution, can be used to determine exactly how many revolutions the motor rotates to a given position.

The granularity of this position control technique is very good. Use of this smart motor in a dual drive having a gear ratio of 880:1 will provide 880 x 6 = 5280 position increments per dual drive output revolution. This amounts to more than 2^{12} bits of information per output revolution. Reasonably precise position control can be achieved when output gearing backlash/index errors are minimized and output stiffness is maximized.

For position control, a binary address can be provided corresponding to the desired position to be achieved. If the binary code address is different from the binary code generated from the serial data, the drive pulses will be provided. When the generated binary code equals the binary code address, the drive pulses to the motor will stop and the motor will be at the desired position.

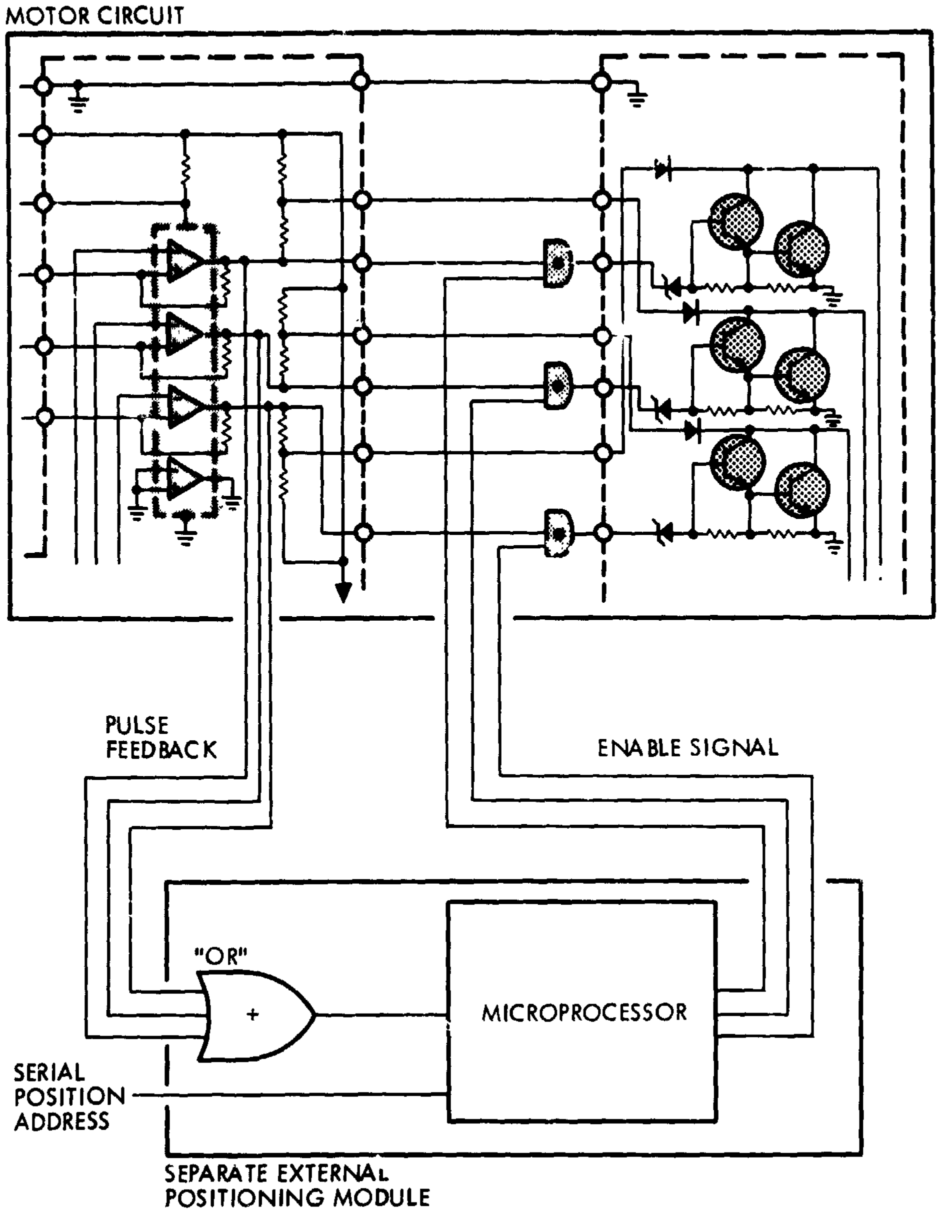

Figure 8. Position control diagram

If the generated binary code is lower than the address code, a drive signal with a given sequence will be provided to the motor and will increase the generated binary code. Conversely, if the desired address is less than the generated binary code, the motor will be driven to decrease the generated binary code to the desired address. The error signal caused by the two binary codes will provide the sequence drive pulse to the motor from the microprocessor, which will consist of three pulses in proper phase sequence. This control technique is an incremental method of establishing position, and the interruption of power will result in loss of data reference. The motor detent torque and gearing static friction, however, will hold the last commanded position until power is restored. (The dual drive gearing can be selected to provide no backdriving up to the structural load limit of the gears.) Thus, the last position command can be reentered as the new data reference. If an interruption cannot be tolerated, a small, independent battery power supply can be used to power the position storage register.

Size and Weight

The new smart motor capabilities are achieved by adding components and electrical interfaces to the motor. It is important that these additions do not cause excessive growth of the overall motor size. Figure 9 shows a photograph of the comparative sizes of an actual three-input, three-gate "AND" circuit and a pulse width-modulating circuit. These devices are very small and can be easily accommodated within the motor envelope. Both of these items are commercially available, space-qualified components.

It is also possible to greatly reduce the size of the entire motor circuit by using hybrid circuit technology. Figure 10 shows the potential reduction of motor size provided by hybridization. This hybrid configuration uses "platform" package technology and reduces the electronic packaging volume by a factor of 2.5.

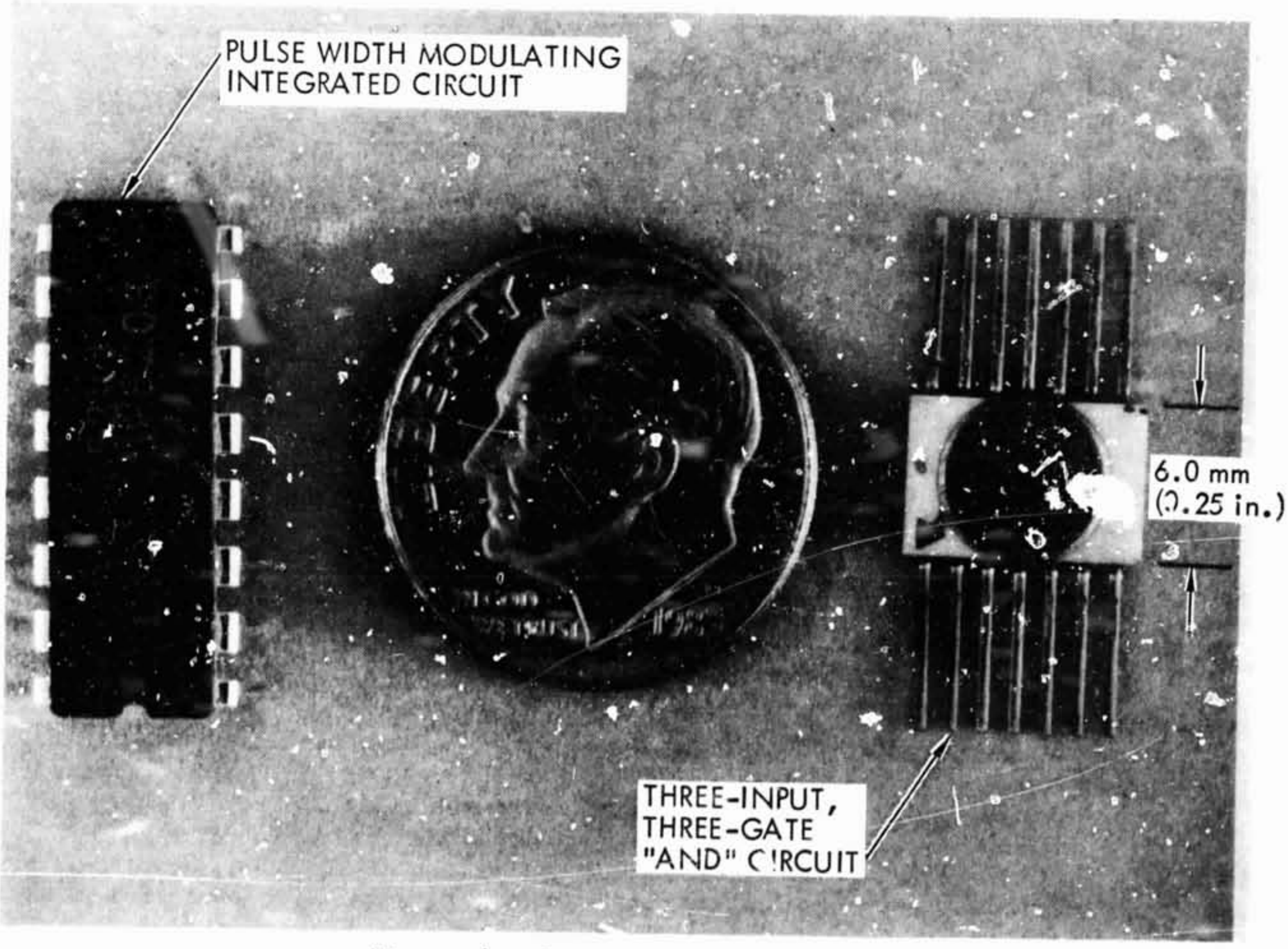

Figure 9. Component configurations

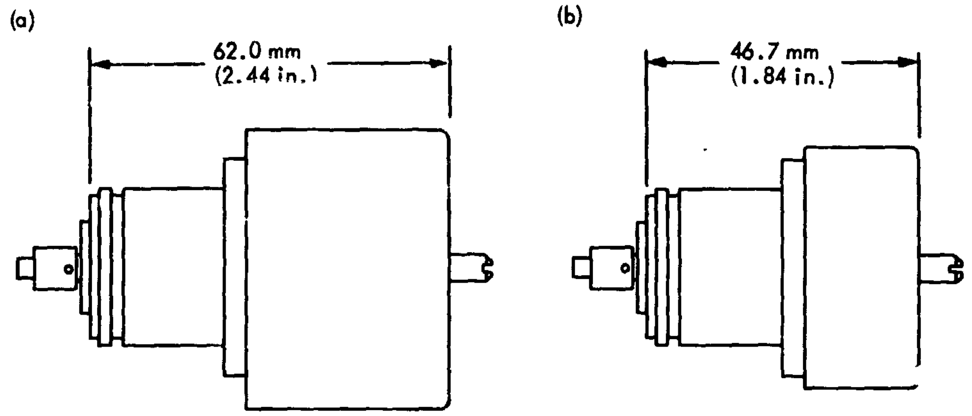

Figure 10. Size comparison: (a) dual drive motor with discrete electronic components, (b) smart motor with hybrid electronics

Expansion of the smart motor technology into higher-power/long-life applications will require consideration of a number of potential improvements. The principal limitations include direction reversing, power dissipation in the circuit components, and stability of the circuitry under "worst-case" environmental conditions.

Direction Reversals

Some applications may require that the motor rotational direction be reversed thousands of times during the normal lifetime of a spacecraft system. The use of mechanical relays is usually considered to be impractical when this amount of switching is needed. An alternate and more reliable switching scheme is possible by modifying the motor current control circuit. The motor's direction of rotation can be reversed using an electronic circuit to reverse the voltage on the position sensor circuit (Figure 11). This will provide direction control and proper phase sequence of the sensor signals. This control technique also has the advantage that the transistors are all operated as switches, either full "ON" or full "OFF," thus making them efficient. It is also important that the "ON-OFF" relationship of the transistor pairs be maintained. This will be ensured if a single component (binary flip-flop) is used to provide both the positive and negative signals simultaneously.

Power Dissipation

The present dual drive motor has a very low operating power level (3 W at no load speed, 13 W at stall) and it was not necessary to optimize the power dissipation of that unit. For larger motors, however, the power dissipation characteristics of the circuit can be significantly improved.

The present motor design uses a switching power transistor configuration called a Darlington Pair (Figure 12). Under worst-case conditions, a voltage drop of 1.7 Vdc can occur across that portion of the motor circuit. This

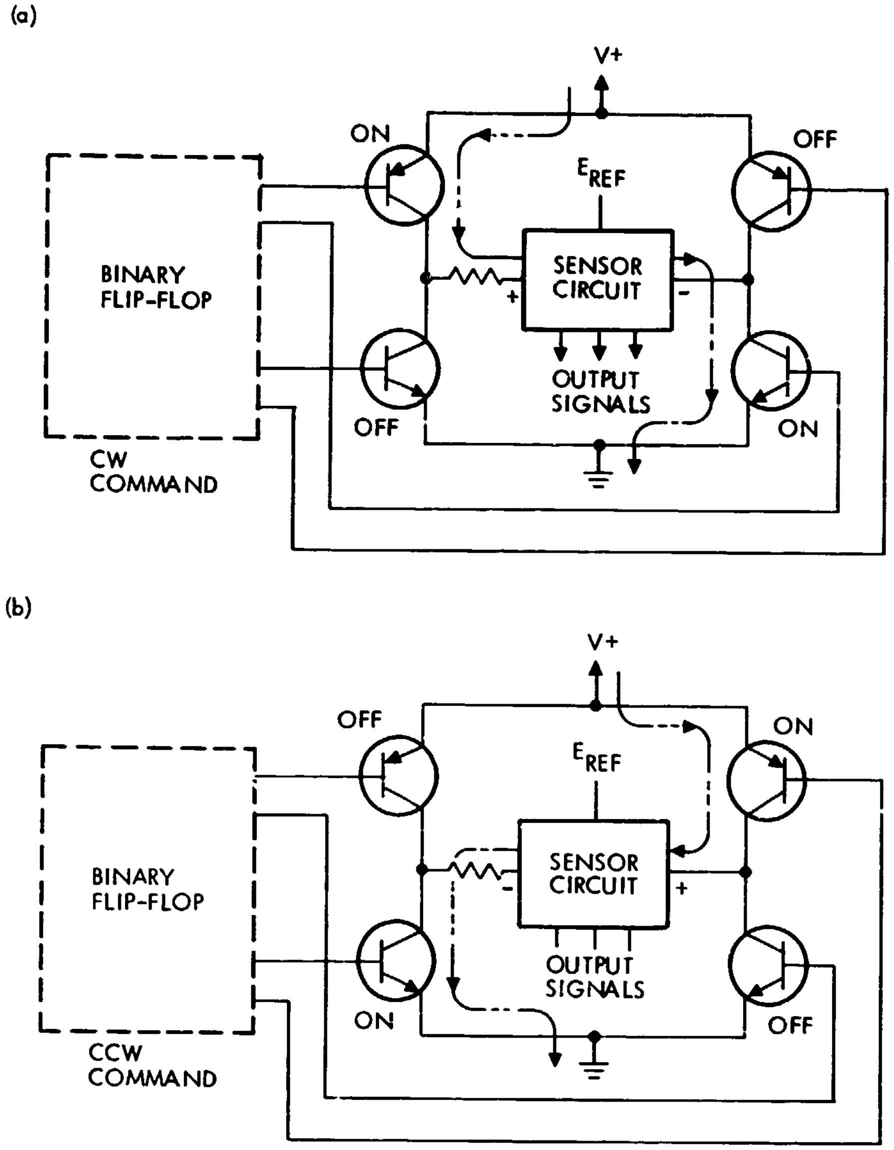

Figure 11. Direction control without mechanical relays: (a) CW command diagram, (b) CCW command diagram

results in increased power dissipation within the transistors and a reduction in output efficiency.

Figure 12 shows an alternate method for power switching. This configuration called a complementary driving circuit, will allow the power transistors to saturate fully. Use of this circuit will result in a greatly improved switching efficiency with a worst-case voltage drop of only 0.2 Vdc, and in a complementary circuit power stress level of approximately 1/8 (12 percent) of the level expected in the Darlington configuration. This significant improvement becomes very important when the higher-power configurations are considered. With the complementary configuration, the transistor environmental temperature can increase significantly without high temperature over-stress.

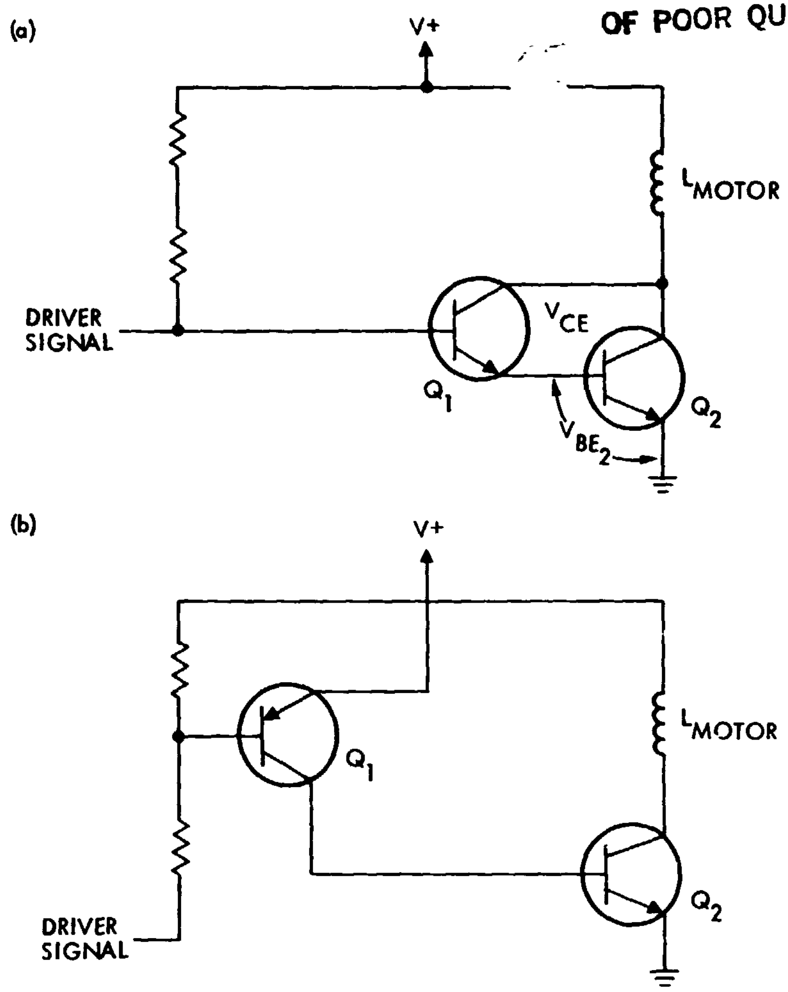

Figure 12. Comparative motor driver circuits: (a) Darlington circuit diagram, (b) complementary circuit diagram

Alternately, the amount of current can be increased by a factor of eight with the same transistor and heat sink configuration. This would permit the use of the same size of transistor to drive a motor about eight times larger than the present configuration. It reduces the requirement for special heat sinks for the power transistor to prevent over-stress conditions. The lower voltage loss in the power transistor also results in a power gain in the motor. This becomes very important when operation is at the minimum voltage condition. There will be as much as 6 percent more power available to the motor simply from the circuit configuration when the voltage is 24 Vdc. This added gain, coupled with the higher power-handling capability, makes the complementary circuit very attractive for higher-power applications.

Circuit Stability

At present, the maximum and minimum operating temperature limits (-51° to +71° C) of the dual drive motor are constrained by the voltage stability of the position sensor circuit. A major improvement of the stability can be provided through the use of a constant current control (Figure 13). This technique provides a constant reference voltage to the sensor circuit regardless of input power variations and achieves control of the sensor circuit current.

The constant reference voltage can be tailored to have a zero temperature coefficient, which will give a more uniform signal output control. In fact, the circuit can be designed to compensate for the negative temperature coefficient of the sensor elements, thereby eliminating the temperature effects on the output signals, and significantly increasing the operating temperature limits of the motor.

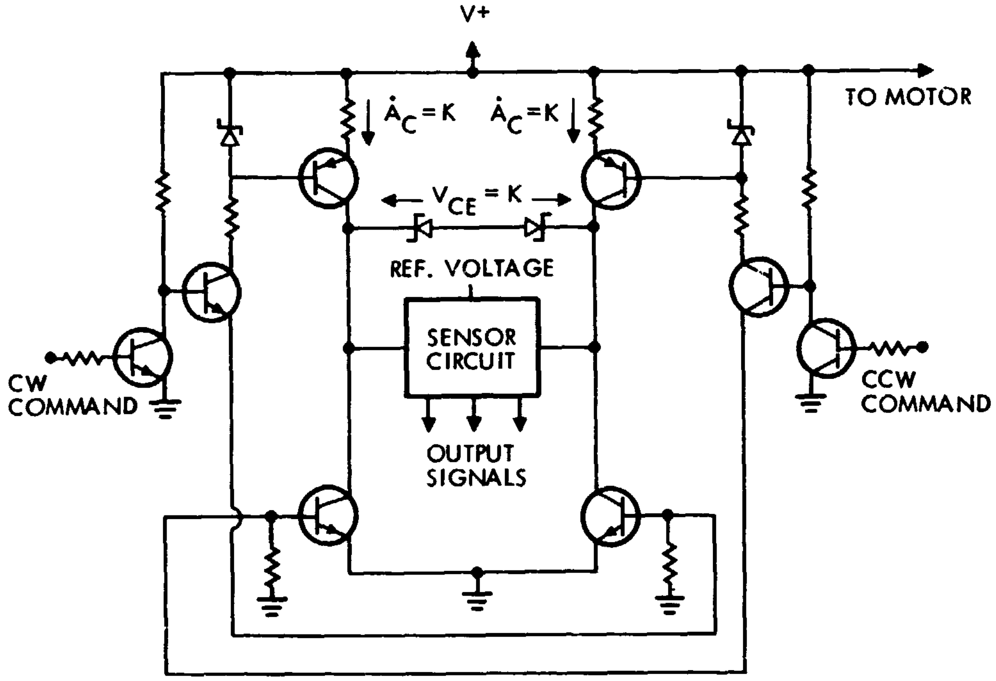

Figure 13. Constant current diagram. Constant current applied to bridge permits uniform E_{REF} independent of source voltage. E_{SIGNAL} is more uniform and independent of source voltage or temperature. V_{CE}(SAT) of switch transistors is very small and almost constant. CW and CCW command change phase of sensor circuit same as in Figure 11.

SMART MOTOR BENEFITS

The benefits of this new technology can be graphically demonstrated by comparing the future "smart drive system" with earlier systems. The NASA/JPL Seasat spacecraft, launched in 1978, contained a drive system that had been developed in the mid-1970s. The Seasat solar array drive system consisted of two rotary drives weighing a total of 10 kg (22 lb) and an electronic control box weighing 5 kg (11 lb). Figure 14 shows a schematic diagram of one of the two electronic circuits contained within the control box. The shaded

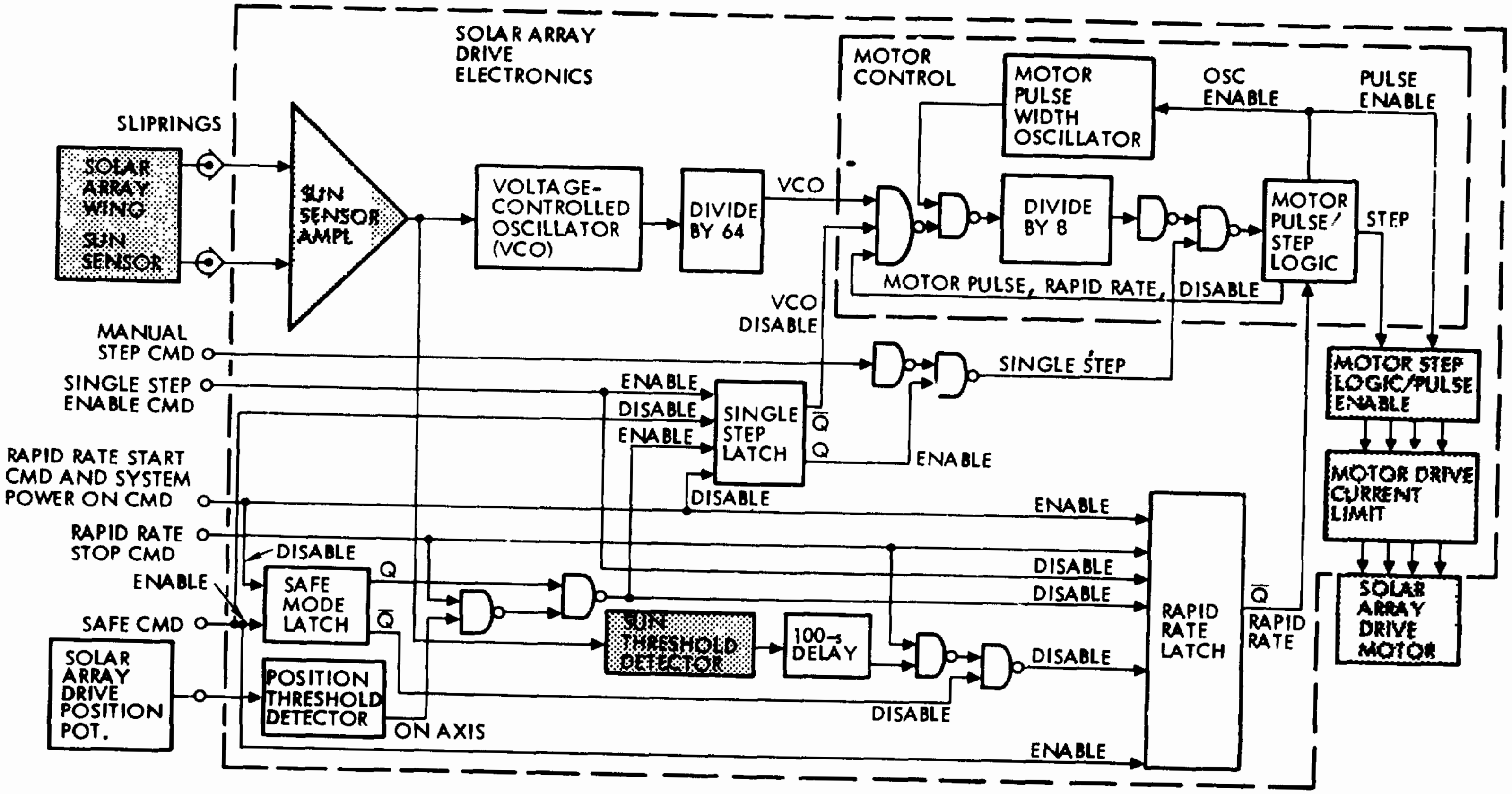

Figure 14. Solar array drive electronics block diagram

portion of the circuit is equivalent to the entire smart motor circuit required to perform the same job. Studies are being conducted of dual drive/smart motor combinations for similar drive systems. It is estimated that the "smart system" will weigh only 2.7 kg (6 lb) total, that the electronic control box can be totally eliminated, and that the total system cost will decrease by a factor of approximately 50 percent.

The versatility of a smart motor has now been presented. The incorporation of a few additional electronic interfaces into the motor greatly increases the capabilities of that unit. These approaches use simple, conventional electronic designs. The innovation is in the synergistic combination of separate technologies.

The current development work at JPL is aimed at facilitating the development of smart motors that will be the maximum number of usable interfaces and capabilities consistent with performance and packaging constraints. JPL is working with the aerospace motor industry to develop and qualify unit configurations that will be usable for widely differing applications. This development is a lengthy task with a number of sequential steps required to perfect the motor design and to ensure that stringent aerospace electronic design standards are met. JPS's motor development program, however, allows sufficient lead time to maximize the usefulness of smart motors. We expect that within 3 to 4 years the motor industry will be a complete line of fully analyzed, fully qualified smart motors available for the complex mechanisms of the future.

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