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ABSTRACT:

In this paper, the writer will review the need for, and the importance of a powered and intelligently-controlled aircraft pitch trim system. Two types of trim motors and their respective advantages and disadvantages will be presented along with motor to microprocessor interface techniques. Input command monitoring features for protecting the integrity of wiring and switches will be discussed. A variety of pitch-trim operating modes will be described, along with a discussion of the sensors needed to feed flight dynamics data to the pitch-trim controller. A fail-passive design philosophy will be presented with the goal of achieving more useful operation along with less rigorous certification requirements; and, finally, electronic hardware and redundant software will be described which will take advantage of microprocessor technology to provide an impressive cost/performance ratio in complex system design.

IT IS DESIRABLE in straight and level flight to bring all of the forces acting on the airplane into equilibrium. In this condition, the pilot (or autopilot) needs to make only minor corrections to hold heading and altitude. Various trim systems have been devised to permit adjustment for the combination of drag, lift, thrust aerodynamic moments, weight, and CG location that permits nearly hands off level flight. An aircraft in flight has six degrees of freedom which are motions parallel to longitudinal (roll), vertical (yaw), and lateral (pitch) axes as well as an ability to rotate about any combination of these axes illustrated in Figure 1. On many aircraft, trim adjustments for the ailerons (roll axis) and the rudder (yaw axis) cannot be set from the cockpit. This may be achieved if a particular airplane experiences little or no trim change on these axes during most flight conditions. All aircraft are equipped with an elevator or stabilizer (pitch axis) trim control that is operated by the pilot. A brief explanation for this in order, if the full significance of concepts to be presented are to realized. Figure 2 illustrates the fact that the center of gravity of an airplane is located forward of the center of lift so that a counterbalancing downward force is required of the stabilizer to maintain level flight. Any reduction or increase in this force will result in a corresponding dive or climb. This combination results in a very desirable flight characteristic, i.e., if an airplane pitches down, its speed increase which tends to raise the nose as the downward force on the stabilizer increases. Likewise, any pitch-up change causes airspeed to be reduced, and the reduction of downward force will tend to lower the nose--a stabilizing feedback that prevents any small departures from the trimmed condition causing precipitous and dangerous behavior in the airplane. The reason all aircraft have pitch trim systems is that the forces acting on the airplane about the pitch axis are largely affected by airspeed, power, weight, and CG location. These factors can vary widely in magnitude in the course of a flight or from one flight to the next, hence a requirement to make the pitch trim conveniently accessible to the pilot. While pitch can have an effect of climbing or diving the airplane, the most pronounced effect is on the control of airspeed. The previously described negative-feedback phenomenon affects the airplane such that if trim is not changed and power from the engine is, then the airplane can be made to dive, fly level, or climb by adjusting power, and the indicated airspeed will remain relatively constant. The tight relationahip between pitch trim and airspeed is the basis for development of some of the concepts to be presented in this paper.

The manner in which a pitch trim system is implemented can vary greatly from one airplane to the next. The methods for transmitting pilot command to the trim mechanism on the tail are dictated mostly by the loads carried by the trim actuator. If the loads are light and/or if the rate that the trim is to be moved is slow, then

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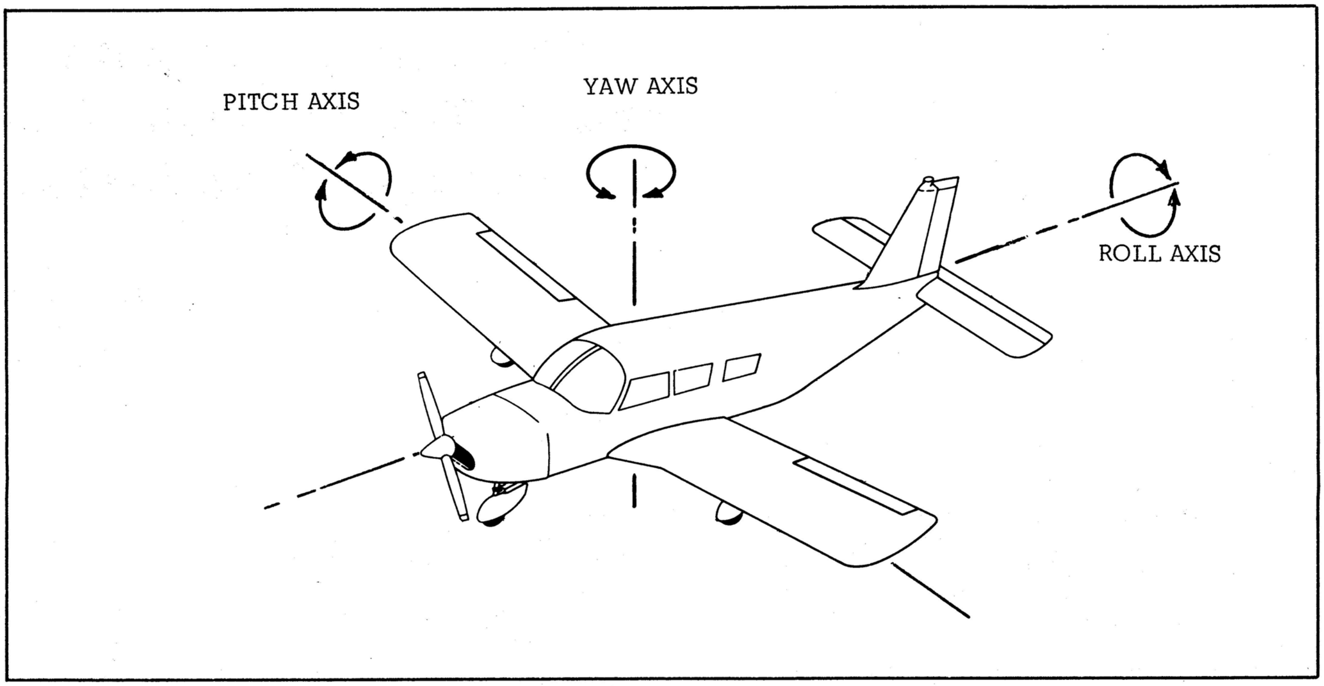

Figure 1. Aircraft Axes of Motion

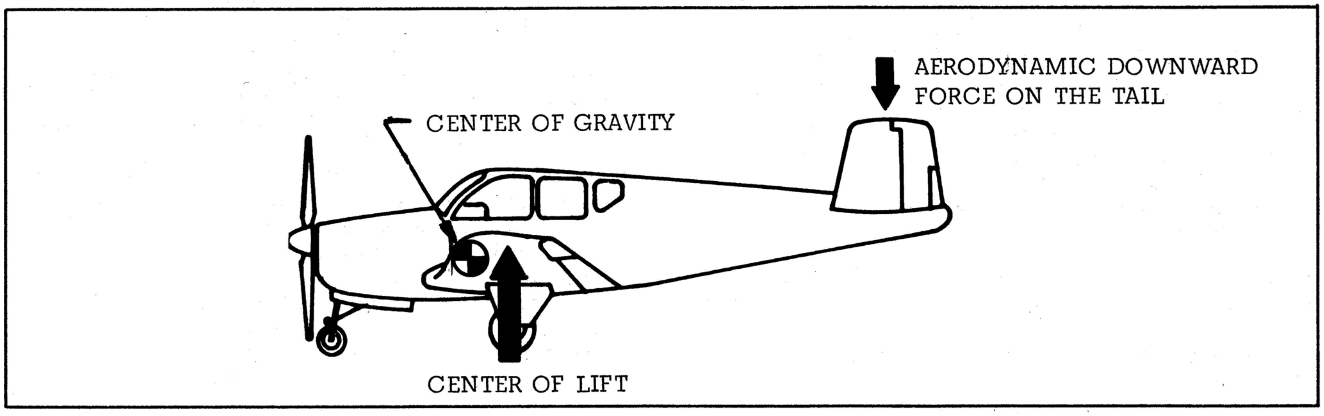

Figure 2. Primary Pitch Axis Moments

a hand-operated control of some type will suffice. If the loads are large, then some type of motor-assisted trim is used; and the pilot usually has control of the system by means of a switch on the control wheel. The size of the aircraft may not have much bearing on the type of system used. The World War II heavy aircraft up through the B-29 used manual controls. Currently there are single-engine designs being considered where loads on the pitch trim jackscrew can approach 1,000 kg and the use of an electric motor is required.

All of the trim features to be discussed are implemented electronically, and, therefore, assume some form of electric motor is available to position the trim mechanism. It is the addition of a motor that presents the first flight safety considerations. Currently, at least two criteria must be met for certification of electric trim systems: 1) The probability of an unexpected trim operation must be reduced to acceptable levels by requiring at least two and, hopefully, three failures to produce the event; 2) should such an event occur, the rate at which the trim system drives must be limited to permit a safe reaction time for the pilot to overcome the failure. Throughout this paper, a "fail-passive" design philosophy will be pursued along with an operating concept that permits no kind of trim operation to occur unless the pilot has a hand on the wheel.

The microprocessor is a very complex device capable of complex tasks, but like systems of all types, complexity is inversely related to reliability. So prudent application of the processor to the movement of flight control surfaces dictates that failure modes which would permit any kind of unexpected trim operation be eliminated.

If the trim system is totally electrically driven, then a third criterion must be met--a secondary trim motor and redundant power sources must be provided to back up the primary system. A common method of providing a secondary motor is to have two motors drive the same jackscrew system via a differential geartrain, so that either motor can be used regardless of the condition of the other motor. Some trim systems may use a mechanical hand wheel accessible to the pilot to back up electric trim. The early B-52's used a power trim system that could be operated manually by a crew member who had to crawl back to the tail section of the aircraft, and operate a handcrank while receiving instructions from the pilot over the intercom!

Selection of a suitable motor is similary dependent on load and horsepower required. Two types of motors are available for use in DC systems; 1) A commutated armature type with a fixed field flux, and 2) a synchronous/stepper wherein a permanent magnet armature is caused to rotate to stay aligned with an electircally-rotated field. The tradeoffs in selecting between the two are as follows:

Generally speaking, commutated DC motors will have the best power-to-weight ratio, but it must be noted that the commutated motor will turn at a much faster speed to achieve this efficiency, which will require a larger gearbox ratio to achieve the desired output speed. The stepper motor accelerates to full speed in the first few degrees of its output rotation and stops in a similar interval. The stepper will hold its final position as long as it is energized, whereas, the commutated DC motor may need a brake to decelerate and hold position adequately. The DC motor is many times more efficient than the stepper. This fact automatically limits the stepper to low power applications. The stepper is a synchronous device that is dependent on the frequency of the applied voltage to control speed, the commutated DC motor speed is very load and voltage dependent. Either motor may be driven by the microprocessor, but the methods are very different. Two possible solutions are as follows:

Figure 3 illustrates one solution to a commutated DC motor driver design problem. This circuit has some features which are crucial to the reliable and safe implementation of the commutated DC motor system. First, all outputs from the processor drive a grounded source or emitter control transistor which has the load impedance in its drain or collector. This makes the interface from the digital logic world to the motive-power world simple and the protection of the transistors is easily handled with transient protection devices. A unique aspect of this circuit is that the output drive from the processor is capacitively coupled to the control transistors. This technique offers some unusual fail-passive features. For the motor or other device to be powered up, the control transistor associated with that device must be on most of the time. If any one output from the processor is "written" HI by the software, the capacitor in series with that output will initially couple the full output from the processor to the transistor. If the output remains HI, then the capacitor will begin to charge through the transistor base bias resistor and if allowed to continue indefinitely, the capacitor will become charged to the same voltage level as the output from the processor. Drive to the control transistor is then removed and the motor is unpowered. To maintain a steady flow of current, the processor's port must be written LO periodically to keep the coupling capacitor nearly discharged.

This requirement presents no special problems in programming since speed control of the motor is accomplished by duty-cycle switching of the applied power. The program must limit maximum applied power to a duty cycle of 95% to keep the capacitor discharged.

When using a commutated DC motor, fail-passive design requires two control loops for the power applied to the motor along with annunciation of the failure of any one of those loops. This is accomplished by including a relay in the positive supply to the motor in addition to the direction control transistors in the negative supply. The network of transistors and resistors (Q_1, Q_1, and R_1 through R_5) form a fault or leakage detector. If the relay should stick shut or either of the control transistor become shorted, one of the two fault detector transistors will be biased on and present a fault signal to the processor. Software would be written to shut the system down and annunciate the fault condition. Applying the stepper motor to a processor-driven application is much simpler. Referring to Figure 4, it may be seen that the driver transsistors are DC coupled to the processor, and no power relay is used. Also, fault detection and tach feedback is not required. This is because a static failure in the processor will not cause runaway, and because the speed of the motor is firmly under the control of software.

Input commands to contemporary trim systems are usually +28 volt or ground signals from switches at the pilots position. However, for the processor to fully monitor the integrity of the input commands, a slightly different scheme is used. Figure 5 shows how a coded-command monitor signal is applied to both the arm and direction control sides of the trim switch. For the processor to consider any input as a valid command, both the direction command and arming signals must be present simultaneously and removed simultaneously, and the signals returned must match the signal sent. In this manner, a failed switch or a wiring fault may be detected by the processor and annunciated shutdown will occur. Trim rates may be selected by a variety of means from which the system designer may choose to achieve the desired level of conven-

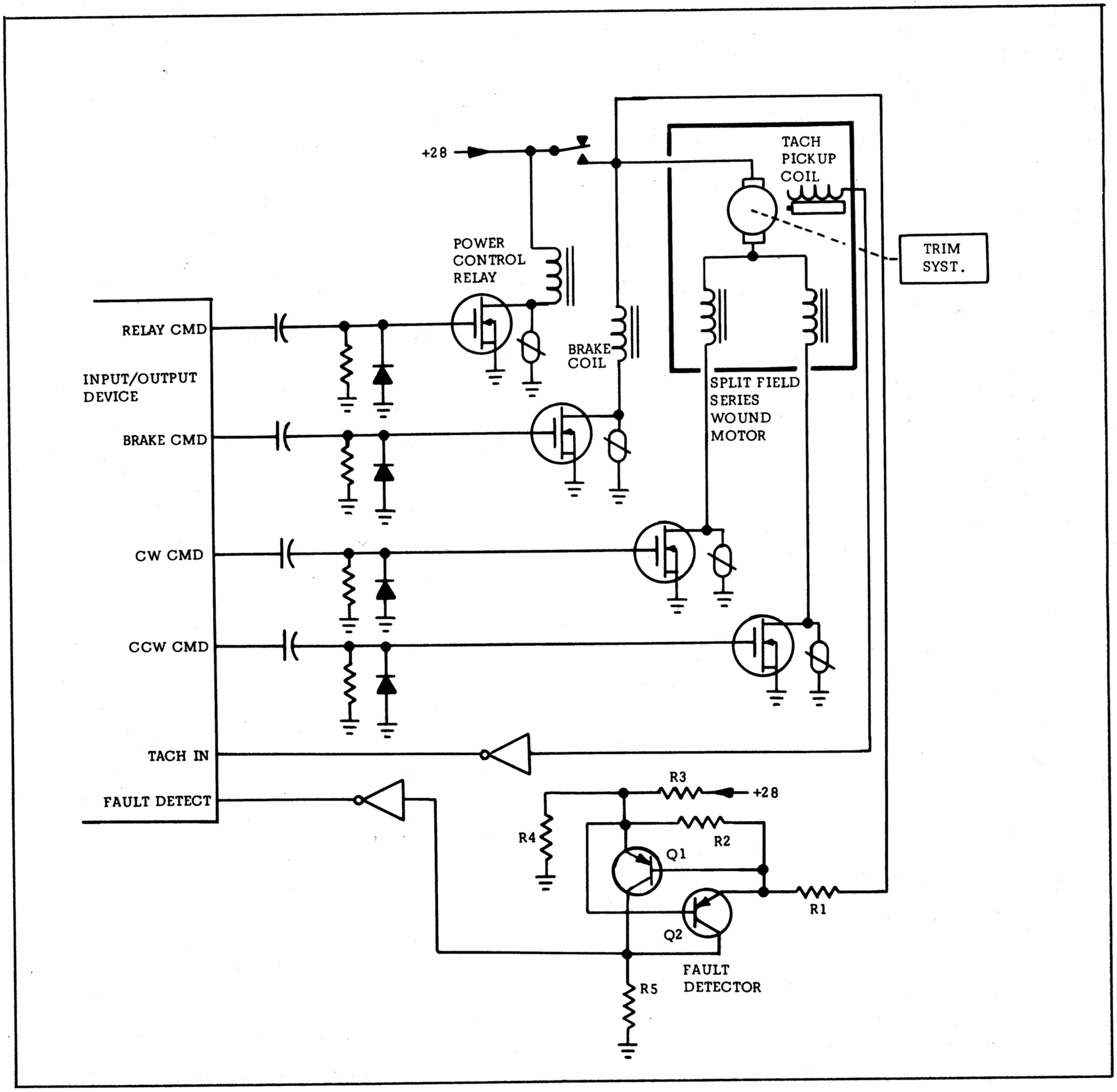

Figure 3. Commutated DC Motor Driver Circuit

ience and function. The simples for a two-speed system is to attach switches to the flap extension system to cause high-speed operation to occur in the approach or take off phase of flight when flaps are extended. Note that two switches are used to provide dual commands to the processor to call for high-speed operation. A disparity of commands from the switches can be made to keep the system in the low-speed mode and annunciate a failure of the system. Experience has shown that trim speed should be adjusted over a ratio that approximates the indicated airspeed (IAS) range of the aircraft. If an airplane capable of 300 Kts, then a 4:1 range of trim speeds is in order and a simple two-speed system may be less desirable. There is no reason why the trim controller cannot have a pitot-static transducer included to constantly monitor IAS and adjust trim rates accordingly.

The technique of choice for accomplishment of this feature is to couple an aneroid capsule to a linear variable differential transformer (LVDT). This frictionless sensing device can detect and accurately quantify movements in micro-meters. The demodulated LVDT signal is a DC level that may be of a magnitude suitable for application to an analog-to-digital converter. Special calibration and linearization

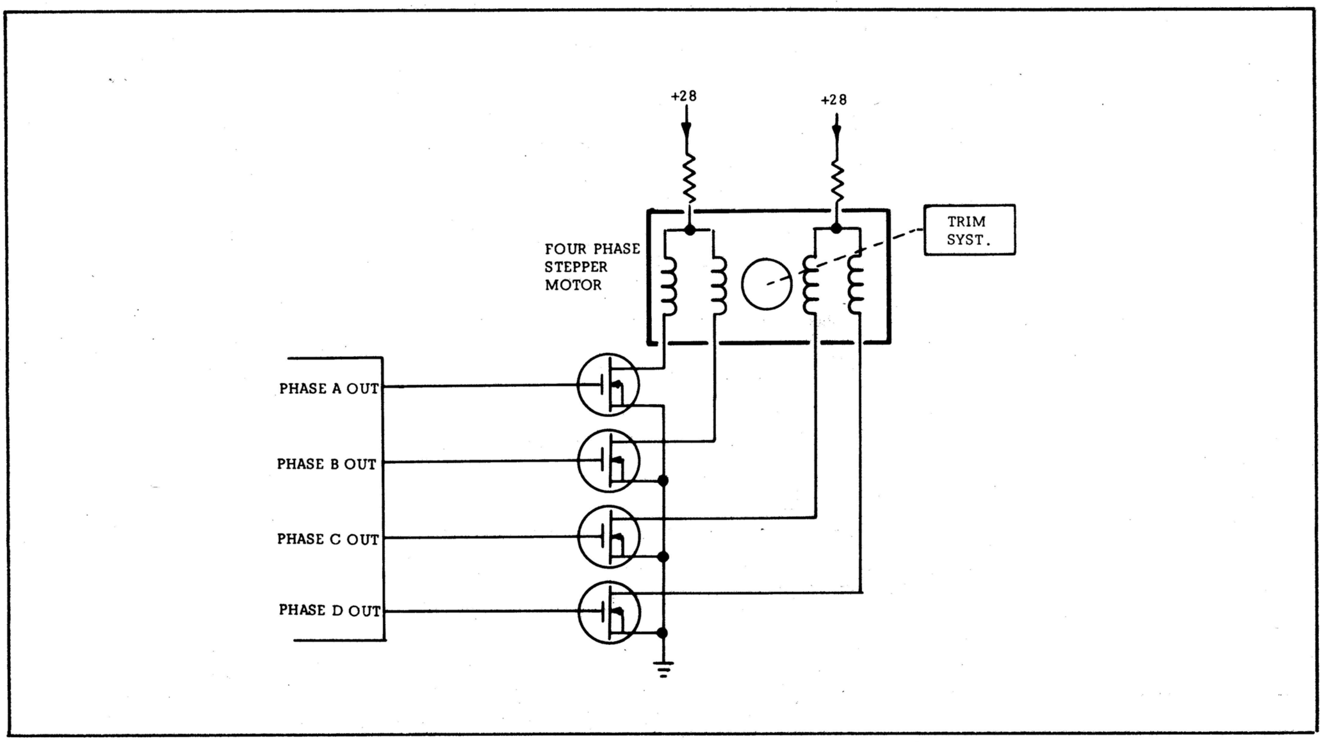

Figure 4. Stepper Motor Driver Circuit

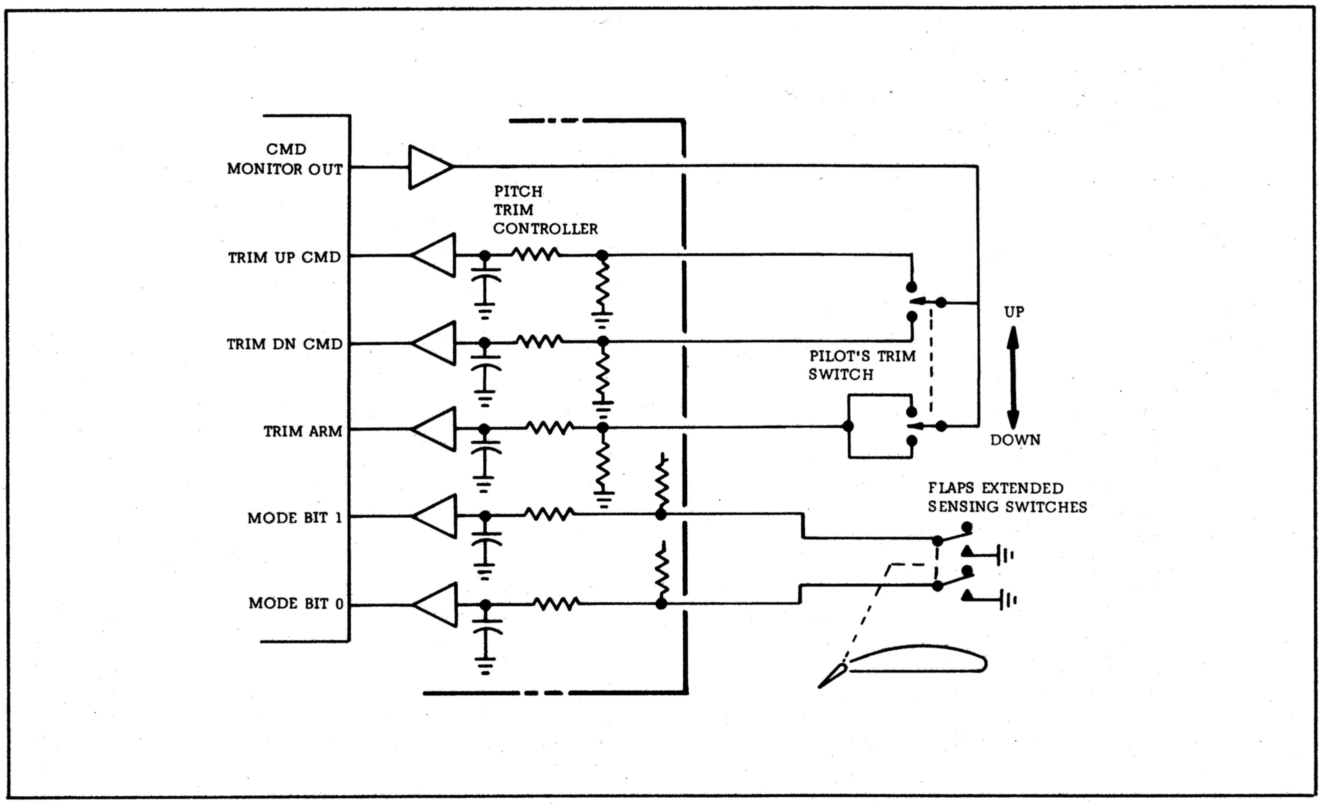

Figure 5. Pilot Trim Command and Two-Speed Select Circuit

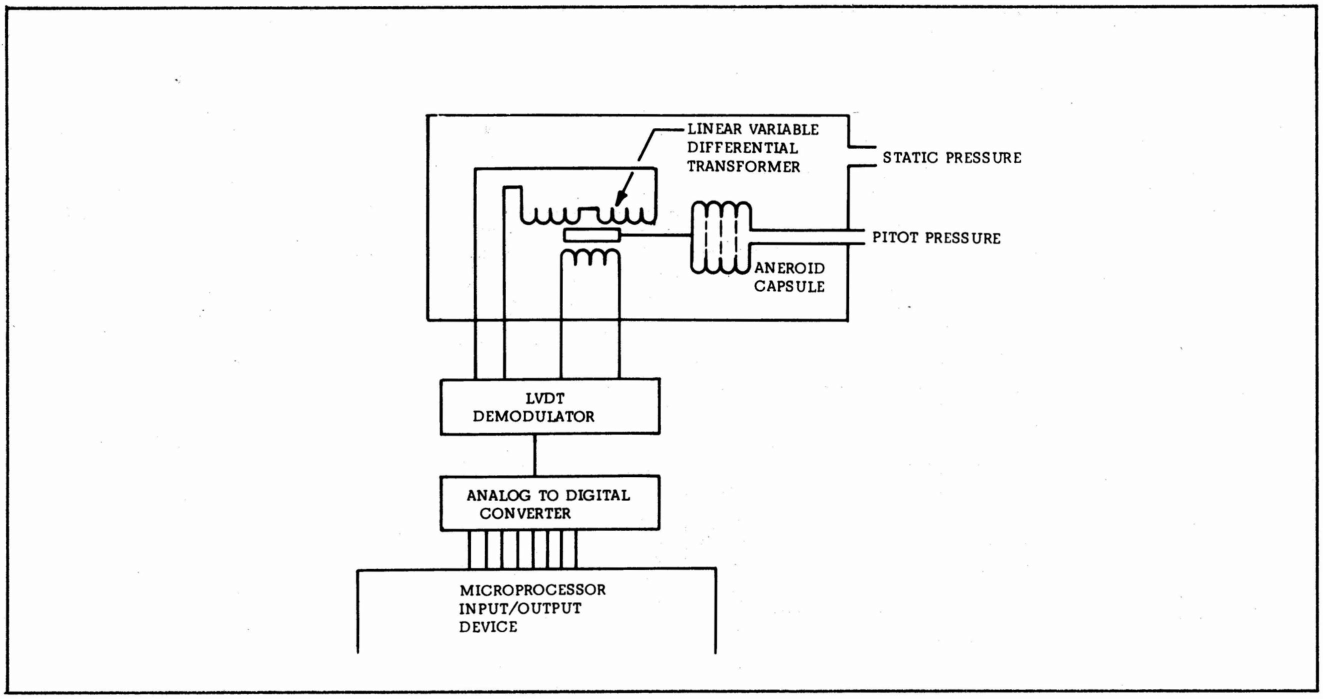

Figure 6. Interface for Indicated Airspeed Sensing

problems may be dealt with in software.

Depending on the class of aircraft and the features to be offered, control of trim rates may be further refined to enhance trim operation. It might be desirable to sense g-loading to compensate for steep turning, and to prevent g-load spiking which tends to occur if a long trim-up command is initiated. Additionally, rates for trim up and trim down might be different for the same airspeed. Additional inputs to be controlling processor from an accelerometer or rate gyro would be needed.

The trim system might also feature a power-pitch control mode somewhat analogous to power steering in a car. A force sensor measuring pitch control forces in the wheel would be used to command speed and direction of the trim to relieve the efforts put into the elevators by the pilot's pitch commands. This mode offers some intriguing possibilities. The pilot would select the powered-pitch mode and then hold the system on by depressing the trim switch to either direction; then while putting pitch commands to the wheel, the trim system would servo the stabilizer or tab to hold stick forces at zero.

An aid to execution of a missed approach might be provided in the form of a go-around mode where the trim system would drive as required to achieve and hold best rate or best angle of climb speeds. A further refinement of the speed control feature might include an approach mode where a constant approach speed is maintained and glideslope tracking can be achieved with power adjustment.

Selecting a processor for this application is relatively easy. Data processing rates of the slowest popular processors are fast enough to work in this task. The 1MHz version of the writer's favorite processor, the 6500 Series devices by Rockwell and others, will execute a series of instructions on an average of four microseconds per step or less. In a commutated DC motor controller where the armature is running at 21,000 rpm maximum and the tachometer is a four-pulse per revolution signal, the tach pulses arrive at 700 microsecond intervals. This is sufficient time for four corrections of motor speed for each revolution of the motor at 21,000 rpm.

The microprocessor in its simplest form might be described as a device having inputs and outputs constrained to ones and zeros, voltage or no voltage, open or closed circuits. The processor may be programmed to act on inputs presented to it with appropriate outputs. Being a clocked device which operates in finite steps, the processor's programming can have a sense of time; and while no single instruction for a processor is very complex, there are many different instructions which may be operated on very quickly and in powerful combinations. The basic architecture of a microprocessor is built up from four kinds of electrical hardware: 1) random access memory (RAM) which is the processor's working or scratch-pad memory, 2) read-only memory (ROM) which is non-volatile and contains the program, 3) input-output devices (I/O) to interface the processor to the outside, and 4) the central processing unit (CPU) where the decoding and response to programmed instruction takes place. The relationship and interconnection of these devices is illustrated in Figure 7 along with some of the hardware necessary to implement functions previously discussed.

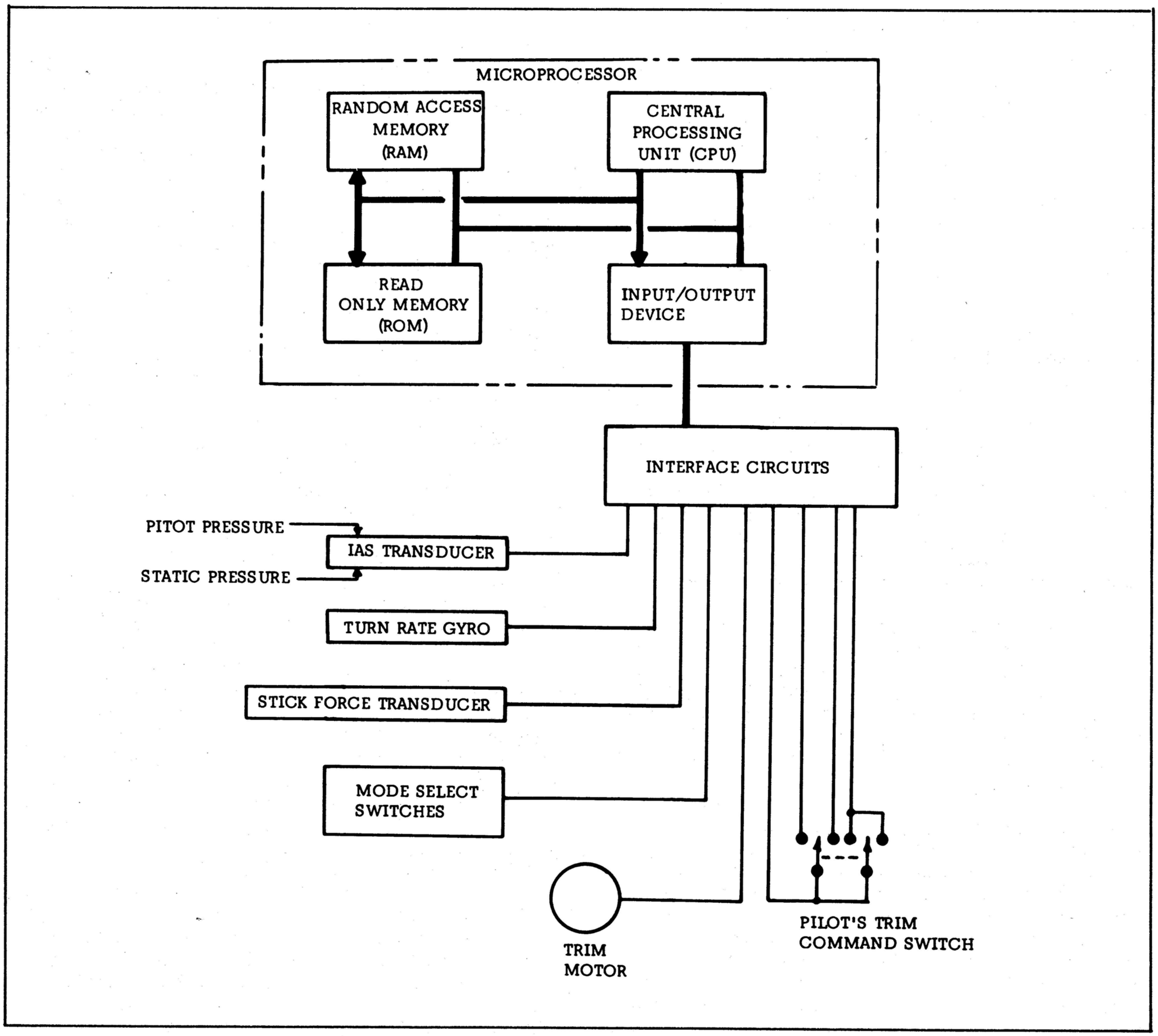

Figure 7. Architecture of a Pitch Trim System

At this point it may seem that what is being described is simply a part of an auto-pilot system. It is important to note that the trim system is a primary flight control system used to assist the pilot in controlling pitch attitude. Reduction in pilot workload and enhancement of aircraft handling qualities are the goals--not stand-alone automatic operation. In the opinion of the writer, this non-automatic, fail-passive design philosophy might well justify special consideration in certification.

Without microprocessor technology, the electronic implementation of these kinds of trim systems would be difficult and costly. Changes in operating parameters to accommodate different types of aircraft would involve extensive modification of analog circuitry, while the processor-based system parameters are contained totally in software. The replacement of a single reprogrammable device is all that would be required to make one processor-based trim controller suitable to any type aircraft.

The use of the processor permits signal conditioning in software in the form of direct computation, algorithm, or lookup table. If some non-linear but repeatable input device requires linearization, or if an otherwise linear signal is to be made into a non-linear function, the processor implements this very nicely. But, the most important aspect of applying processors to the systems described, is the safety in redundant software than can be achieved with careful programming. The processor can be programmed to take multiple looks at input commands, input flight parameters, and the computation of trim direction and speed with results compared and found equal before the trim motor is caused to run.

The use of interrupt vectoring of the processor permits redundant software to be placed in totally separated areas of program memory. Each program segment can be given the responsibility for cross-checking its counterpart elsewhere in the program. Each program segment can be provided with only partial ability to drive a trim motor. This programming technique preserves the fail-passive design philosophy of the trim system.

To illustrate the interrupt-driven programming technique, an abbreviated software flow chart is shown in Figure 8. Only one interrupt routine is shown, but two identical routines could be used for double redundancy. Note that if no interrupt requests are made of the processor, the program will stay in the normal running loop; but that loop is limited in its output drive capabilities and cannot move the motor without aid from the interrupt routine(s).

An interrupt request may be generated by a variety of hardware and software techniques suited to the task. The important consideration is that interrupts occur at a rate fast enough to make them transparent in how they affect the handling qualities of the airplane. If interrupts are generated by some hardware feature, then they will probably arrive at some regular rate--say one to two-hundred per second. The action is accurately implied by the name, i.e. the main operating program is interrupted and the processor finishes its current program instruction. The memory location for the next instruction, the processor's status and operating register, and other data are temporarily stored in a special area of the processor's memory called the "stack." The interrupt routine is then operated on; and when completed, the data necessary to continue on with the original set of instructions is restored from the stack, and the processor is allowed to continue on from where the interrupt occurred.

One of the steps in the flow chart is labeled "IN LIMITS?" This step represents an area in the program where a critical analysis of the flight dynamics data is made to see if it is believable. For example, has any input parameter varied at a rate that is not consistent with the physics involved? Or is the data moving in a direction and at a rate consistent with the command input and trim motion output? An unsatisfactory answer to these questions might spot a malfunctioning input transducer and effect a shutdown in milliseconds--much faster than the reaction time of the pilot. Another interesting feature in the software flow chart is a step labeled "CHECKSUM AND RAM TEST". In this step, the processor has determined that no pilot input command is present, and time is available to operate on test routines that add up all the values of the numbers in program ROM, test all bits of scratch-pad RAM for ability to store data, and a quick test of all input and output ports can be effected. An unsatisfactory result of this test can also effect a shutdown of the system. The last feature not yet discussed is the block labeled "FAILURE ANNUNCIATION AND SHUTDOWN." Once a failure is detected, a warning is presented to the pilot, probably in the form of a light. At the same time, a failure code can be placed somewhere in non-volatile memory to be available to service personnel when presented with the problem of trouble-shooting the system. The failure code might be displayed on the outside of the trim controller, or communicated to the service technician via a serial data line to a hand-held service monitor which would also serve to input test commands to the controller for ground testing and problem diagnosis.

The costs of producing a system of this complexity are becoming more favorable as developments in the electronic arts progress. Ninety per cent or more of the electronics required to implement the system described may be contained on a single device which costs less than seven dollars at the time of this writing. The capabilities which may be programmed into that device make it possible to use less sophisticated and, therefore, less expensive transducers. It is perhaps appropriate that a trim controller fabricated from this handful of complex but inexpensive devices might have spare devices sitting in dummy sockets beside the active devices. Quick repairs could then be made in the field. A new spare part would be installed in the dummy socket at some more convenient time.

At the current state of the art, a trim controller for commutated DC or stepper motors up to 100 watts would occupy approximately 1,000-cubic centimeters of volume and weigh about 500 gms. This class of controller would be suited to most airplanes having cockpit hand wheels for pitch trim. A larger system using motors up to 500 watts would require a controller volume of approximately 1,600-cubic centimeters and would weigh about one kg. This size of system would be appropriate to stabilizer trim actuators having up to 1,000 kg. loads.

The writer would like to acknowledge the assistance of the following persons who contributed valuable insight in the preparation of this paper: Clif Larison of Intercontinental Dynamics Corporation, Wichita. Also, Joe Hine and Paul Cork of Gates Learjet Corporation, Wichita.

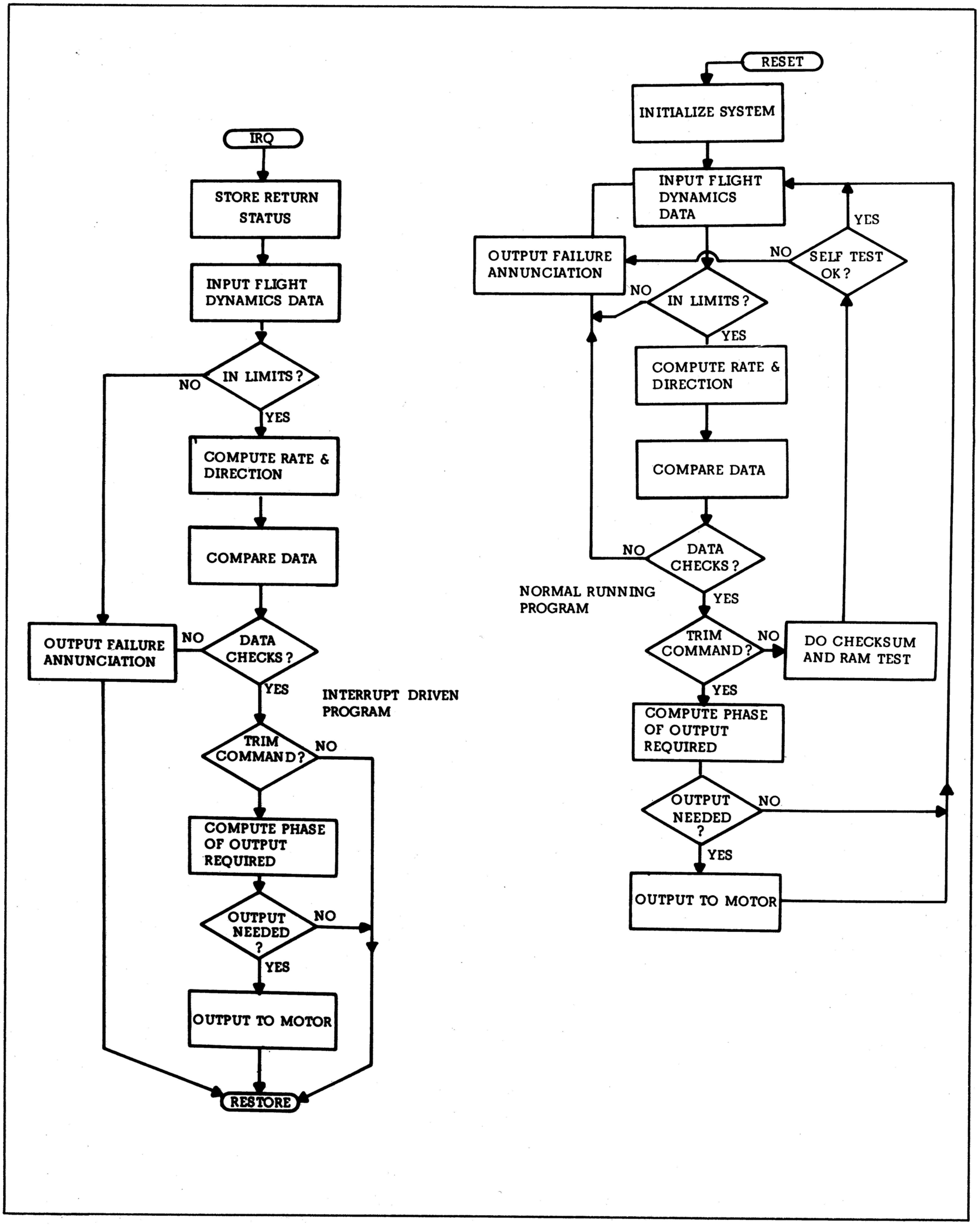

Figure 8. Microprocessor Program Flow Chart

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