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APPLICATION STUDY: 3.4.1h

SIMULATION OF SPACE VEHICLE WITH REACTION JET CONTROL SYSTEM

ABSTRACT: This report describes a program for the simulation of a digital controller for a space vehicle, used for the purpose of evaluating a system for controlling the attitude of the vehicle. A reaction jet control system, inherently digital in nature, is represented by the digital components of the HYDAC* system. The equations describing the characteristics of the vehicle are solved with analog components.

An increasing number of problems are encountered whose solution require the representation of digital control systems in combination with the simulation of the physical system being controlled. Although this type of problem can often be solved with the analog computer alone with suitable approximations by continuous control functions, or on the digital computer at relatively high costs and with long solution times, a more effective approach is through the use of hybrid techniques. A combination of both analog and digital operations allow the non-linearities of the digital controller to be evaluated as well as the efficiency of various digital control schemes.

This program effectively illustrates the use of digital and analog components in one integrated system. Added complexity may be included, however, with the availability of additional digital operations. The re-entry phase, for example, including the deployment of parachutes, etc., can be simulated effectively with digital control on analog hardware. The HYDAC System can also be programmed to investigate the parameters in the control system so that the best combination of smooth response and minimum control energy can be determined.

The specific problem is to simulate, at real time frequencies, an attitude control system for a space vehicle, assuming no aerodynamic forces. Major functions of the system are shown in the block diagram of Figure 1. Certain configurations of reaction jets and control functions (see Figures 4, 5, and 6) are assumed which are typical of those employed. All unnecessary complexities in the physical system are omitted which are not pertinent to the control system.

The capsule equations and the necessary error relationships will be solved on the analog computer. The commanded angles ϕ_c, θ_c, and ψ_c may be supplied automatically, such as for re-entry, or from a source of manual control. The error terms $\epsilon_\phi, \epsilon_\theta$, e_ψ will be transmitted to the digital controller where they will be analyzed and converted into the appropriate jet pulses 1 through 8. These jet signals will then pass through an interface of switching to produce M_x, M_y, and M_z so that the errors are driven toward zero.

The appropriate velocity damping terms must be included in the error calculations since the vehicle has no natural damping.

VEHICLE EQUATIONS are written using the coordinate system for vehicle attitude of Figure 2 and the following terms:

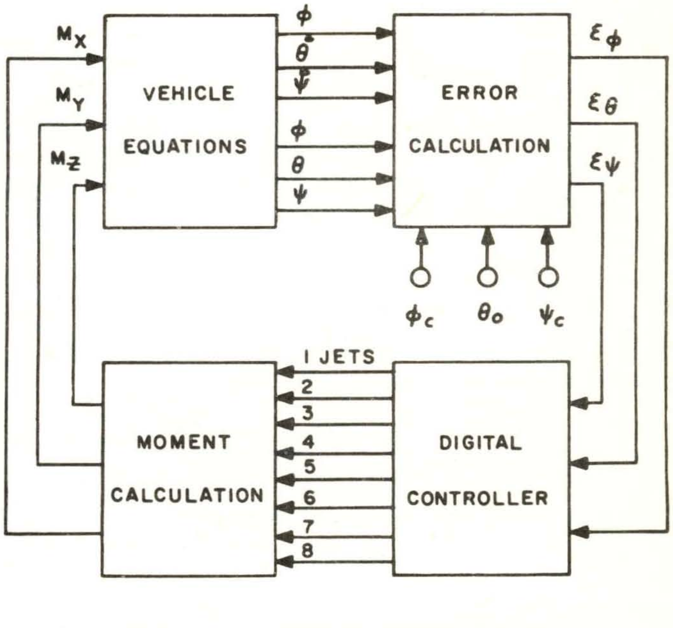

Figure 1. General Block Diagram of Space Vehicle Control System

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X_I, Y_I, Z_I — Inertial Frame
X, Y, Z — Body Axes
p — Roll Rate
q — Pitch Rate
r — Yaw Rate
ϕ — Roll Angle
θ — Pitch Angle
ψ — Yaw Angle
M_x, M_y, M_z — Control Moments
ϕ_c, θ_c, ψ_c — Commanded Angles

Appropriate equations are:

Roll Moment (1)

$$I_x \frac{dp}{dt} = I \text{[illegible]} - \left[I_z - I_y\right] qr + I_{xz} pq + M_x$$

Pitch Moment

$$I_y \frac{dq}{dt} = \left[I_z - I_x\right] rp + I_{xz} \left[r^2 + p^2\right] + M_y \quad (2)$$

Yaw Moment (3)

$$I_z \frac{dr}{dt} = I_{xz} \frac{dp}{dt} - \left[I_y - I_x\right] pq - I_{xz} qr + M_z$$

Roll Attitude Angle

$$\dot{\phi} = p + \dot{\psi} \text{ SIN } \theta \quad (4)$$

Pitch Attitude Angle

$$\dot{\theta} = Q \text{ COS} \phi - r \text{ SIN } \phi \quad (5)$$

Yaw Attitude Angle

$$\dot{\psi} = \frac{Q \text{ SIN} \phi + r \text{ COS } \phi}{\text{COS } \theta} \quad (6)$$

Roll Error

$$\epsilon_\phi = \phi_c - \phi - K_{\dot{\phi}} \dot{\phi} \quad (7)$$

Pitch Error

$$\epsilon_\theta = \theta_c - \theta - K_{\dot{\theta}} \dot{\theta} \quad (8)$$

Yaw Error

$$\epsilon_\psi = \psi_c - \psi - K_{\dot{\psi}} \dot{\psi} \quad (9)$$

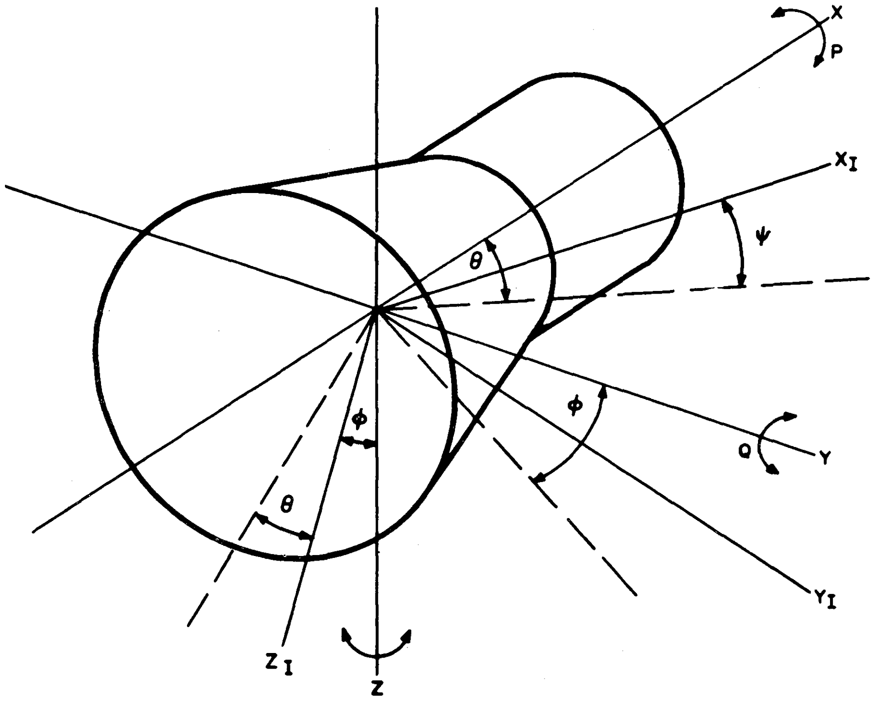

Figure 2. Space Vehicle Attitude Coordinate System

Solution of the vehicle equations using analog techniques are relatively simple and straightforward. A representative analog circuit for calculating the roll and pitch rates and errors (the attitude angle equations have been simplified for brevity) is shown in Figure 7. Note that digital signals representing the control commands developed in the controller simulation are used to drive interface switches to provide the moment terms M_x and M_y.

ATTITUDE CONTROL is implemented by the use of stored energy to produce moments on the capsule since space vehicles cannot employ aerodynamic forces on surfaces for control. This stored energy is typically in the form of hydrogen peroxide steam which is released through fine ports. To precisely control the level of the forces supplied would require complicated, bulky control equipment. Therefore, a scheme of pulsing these jets is employed which supplies a net impulse which follows some functional relationship between the error signals and the desired torque.

THE DIGITAL CONTROLLER chosen to illustrate the solution technique is described schematically in Figure 3. This control scheme is representative of the types one must study in the design of a space capsule.

SIMULATION of the operations of the digital controller are as follows:

Error Testing

The error magnitude and sign for the roll axis are tested in a typical analog fashion as shown in Figure 8. The circuits for the pitch and yaw axis are identical. The "Latch" input L is used to hold the analog comparison in the comparator flip-flop output for a specific time. This digital signal is generated in the pulse-width command modulation circuit.

Pulse Width Command Modulation

The operation of Block 2 of Figure 3 can be performed by various combinations of analog and digital operations. An approach with analog sampling and timing under digital control is satisfactory for the real time simulation, but for higher calculation speeds one must employ high speed Analog-to-Digital converters and digital timing. The program shown in Figure 9 employs electronic sample-hold units and electronic switching under control of the digital components and logic. This program must be repeated for the pitch and yaw axis.

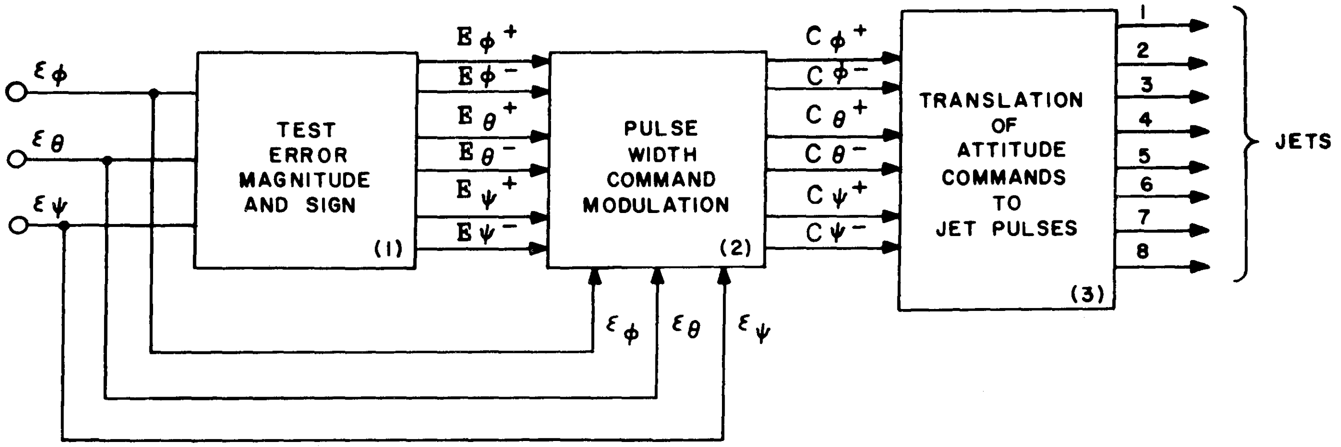

Figure 3. Block Diagram of Digital Controller

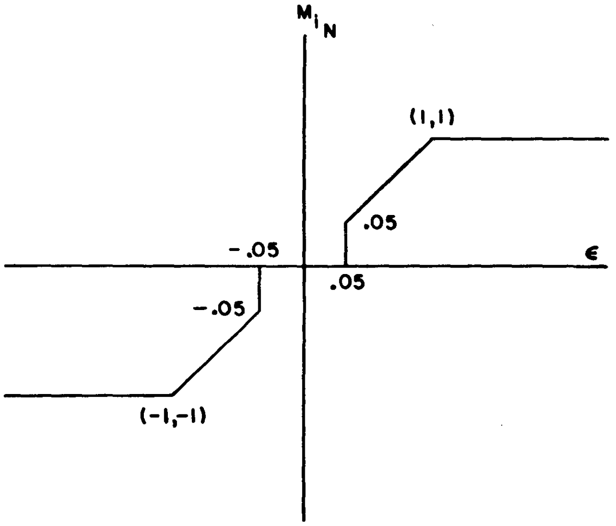

Figure 4. Reaction Jet Control Characteristics (Normalized)

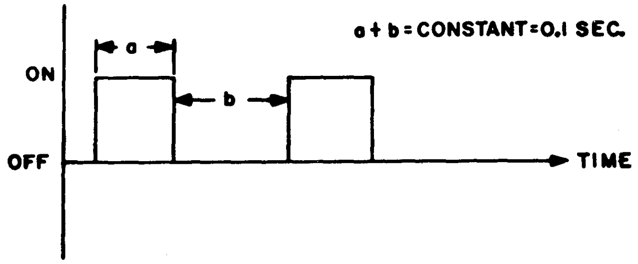

Figure 5. Pulse Jet Characteristics

The following operations are performed by the circuit of Figure 9.

1. When $(E_\phi+)$ or $(E_\phi-) = 1$
   - a. Latch $(E_\phi+)$ and $(E_\phi-)$ comparators
   - b. Sample ϵ_ϕ (called $\epsilon_{\phi s}$)
   - c. Reset t_p (period time) integration
2. After sample and reset period
   - a. Turn on E^*_ϕ
   - b. Begin integration of t_p
3. When $(t_p)\left(\frac{\epsilon_\phi \max}{t_p \max}\right) = \epsilon_{\phi s}$
   - a. Turn off E^*_ϕ
4. When $t_p = t_p \max$
   - a. Unlatch $(E_\phi+)$ and $(E_\phi-)$
5. Repeat 1 through 4
6. E^*_ϕ is used to gate $(E_\phi+)$ and $(E_\phi-)$ to generate the command signals $(C_\phi+)$ and $(C_\phi-)$.

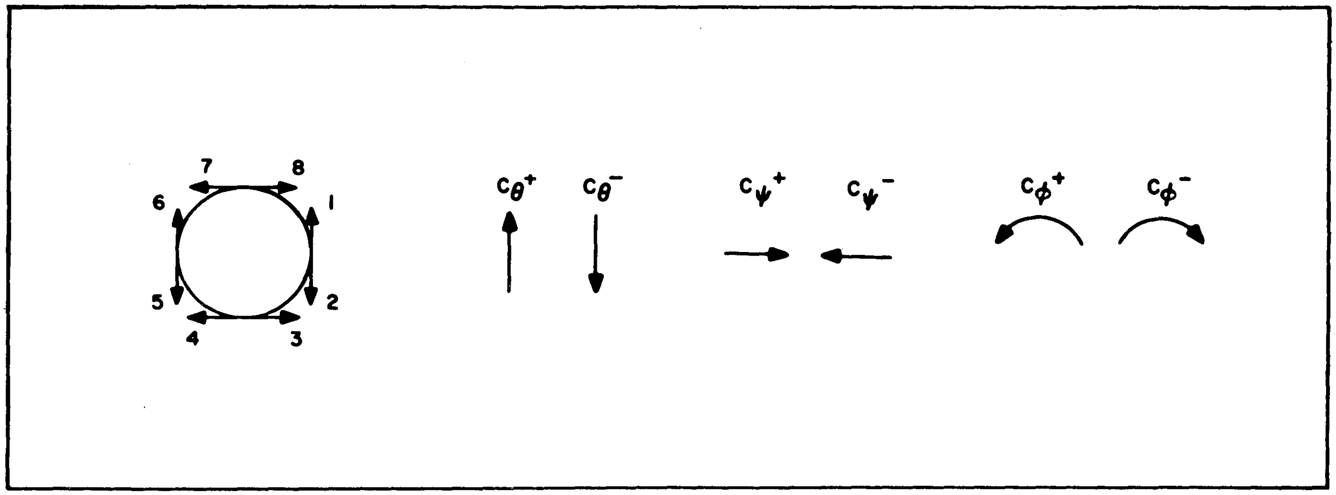

Figure 6. Assumed Configuration of Jets and Relationships Between Jets and Desired Commands

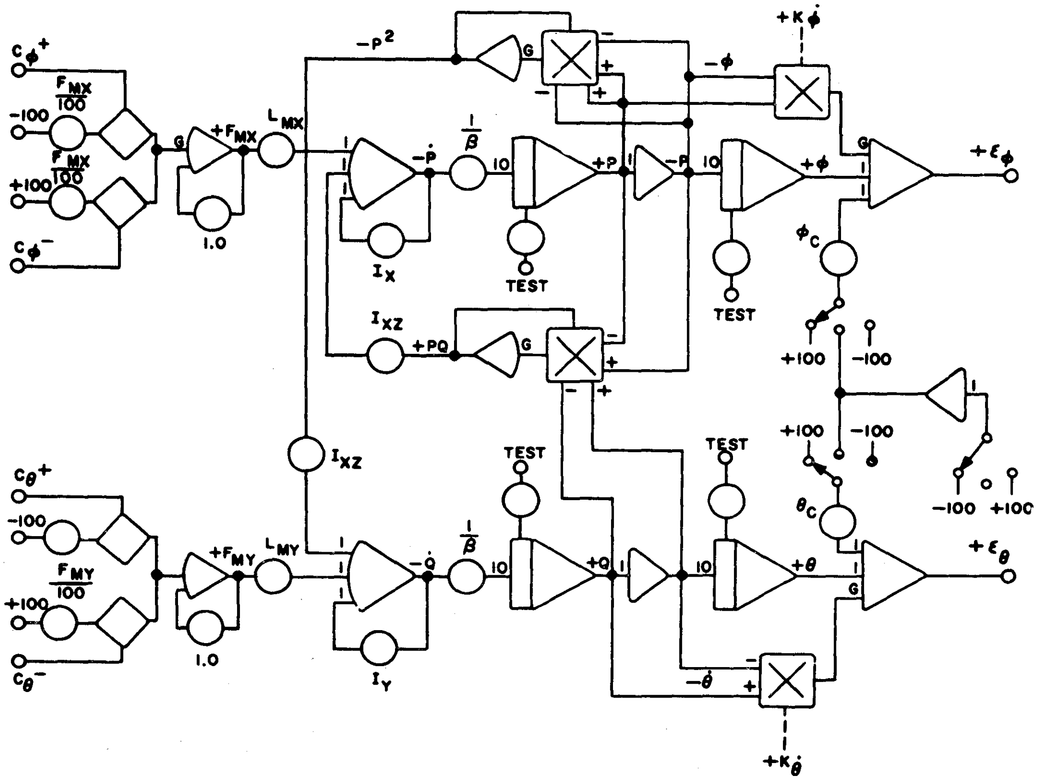

Figure 7. Analog Program for Representing Simplified Two Dimensional Model of Space Vehicle

Translation of Commands to Jets

The six command signals from the Pulse Width Command Modulation circuits must be converted into the appropriate jet control signals before the final moment terms can be generated. The relationships between the commands and the jets are described in TABLE I. This translation is an application of pure logic and is a difficult set of relationships to simulate with purely analog operations. The operations can be performed in a variety of ways with digital techniques but the simplest and fastest scheme is simply a logic matrix. This is illustrated in Figure 10.

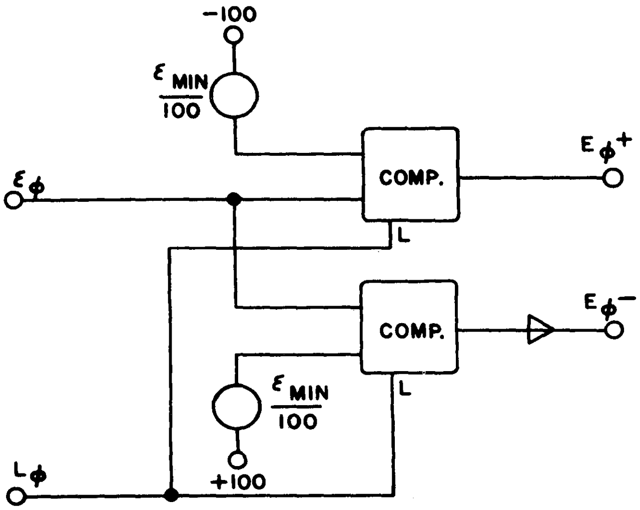

Figure 8. Circuit for Testing Roll Error Magnitude and Sign

The commands and the jets could be connected to indicators or could be buffered by flip-flops so that the operator can see the particular jets which are activated for a particular configuration of commands.

COMMAND	JET	COMMAND	JET
$C_\theta+$	1-6	$(C_\theta+)(C_\phi+)$	1-6-3-7
$C_\theta-$	2-5	$(C_\theta+)(C_\phi-)$	1-6-4-8
$C_\psi+$	3-8	$(C_\theta+)(C_\psi+)(C_\phi+)$	1-3
$C_\psi-$	4-7		
$C_\phi+$	1-5	$(C_\theta+)(C_\psi+)(C_\phi-)$	6-8
$C_\phi-$	2-6	$(C_\theta+)(C_\psi-)(C_\phi+)$	1-7
$(C_\theta+)\ (C_\psi+)$	1-6-3-8	$(C_\theta+)(C_\psi-)(C_\phi-)$	4-6
$(C_\theta+)\ (C_\psi-)$	1-6-4-7		
$(C_\theta-)\ (C_\psi+)$	2-5-3-8	$(C_\theta-)(C_\phi+)$	2-5-3-7
$(C_\theta-)\ (C_\psi-)$	2-5-4-7	$(C_\theta-)(C_\phi-)$	2-5-4-8
$(C_\psi+)\ (C_\phi+)$	3-8-1-5	$(C_\theta-)(C_\psi+)(C_\phi+)$	3-5
$(C_\psi+)\ (C_\phi-)$	3-8-6-2	$(C_\theta-)(C_\psi+)(C_\phi-)$	2-8
$(C_\psi-)\ (C_\phi+)$	4-7-1-5	$(C_\theta-)(C_\psi-)(C_\phi+)$	5-7
$(C_\psi-)\ (C_\phi-)$	4-7-6-2	$(C_\theta-)(C_\psi-)(C_\phi-)$	2-4

TABLE I. Relationships Between Commands and Jets

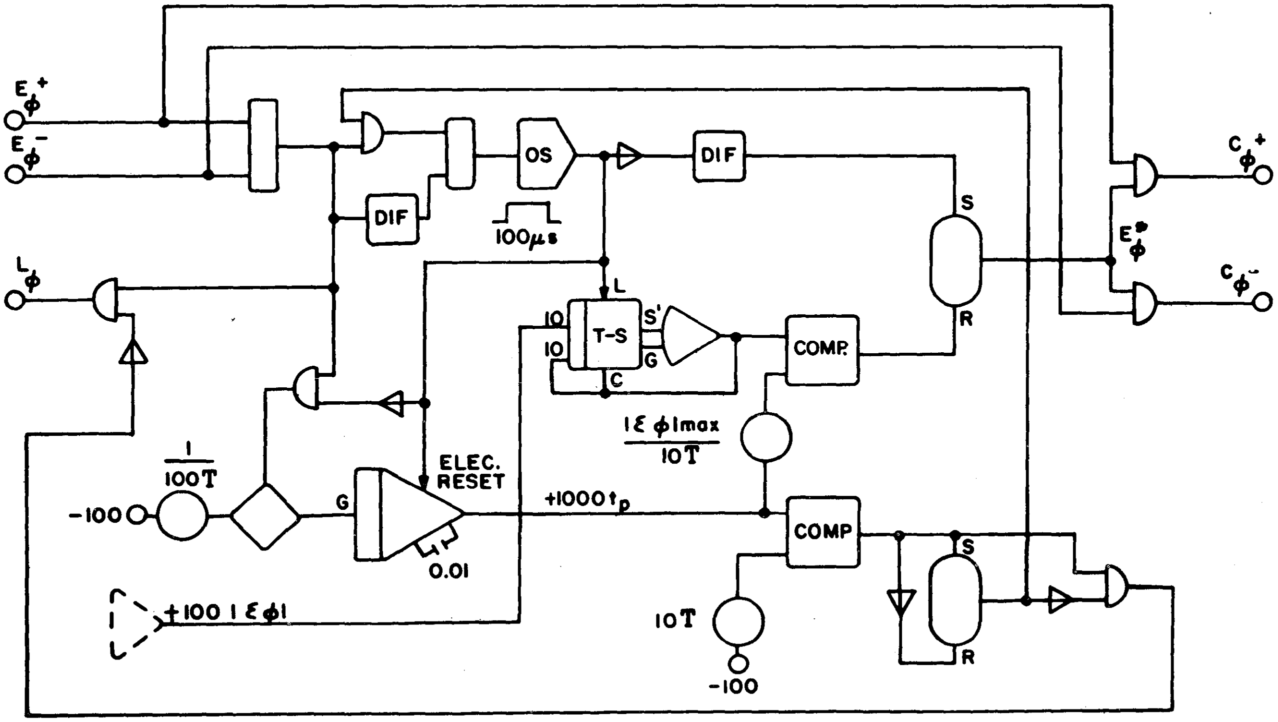

Figure 9. Pulse Width Command Modulation Circuit for Roll Angle

	ϕ		θ		ψ	
JETS	M_x+	M_x-	M_y+	M_y-	M_z+	M_z-
1	X		X			
2		X		X		
3	X				X	
4		X				X
5	X			X		
6		X	X			
7	X					X
8		X			X	

TABLE II. Relationship Between Jets and Moments

THE CONTROL LOOP is completed by a program for computation of the moments (M_x, M_y, M_z) from the jet control signals. TABLE II shows the relations between the jet configuration and the various moments. Figure 11 shows a circuit for implementation of these relationships. The forces and lever arms are constants which are switched by high-speed, solid-state switches into the analog moment computation as a function of the jet control signals. A high (binary 1) signal from the OR gate of the logic matrix used to represent the jet control switches a constant analog voltage representing the jet force to the grid of an operational amplifier. A low (binary 0) signal from the OR gate represents the OFF condition of the jet by blocking the voltage from the grid of the amplifier.

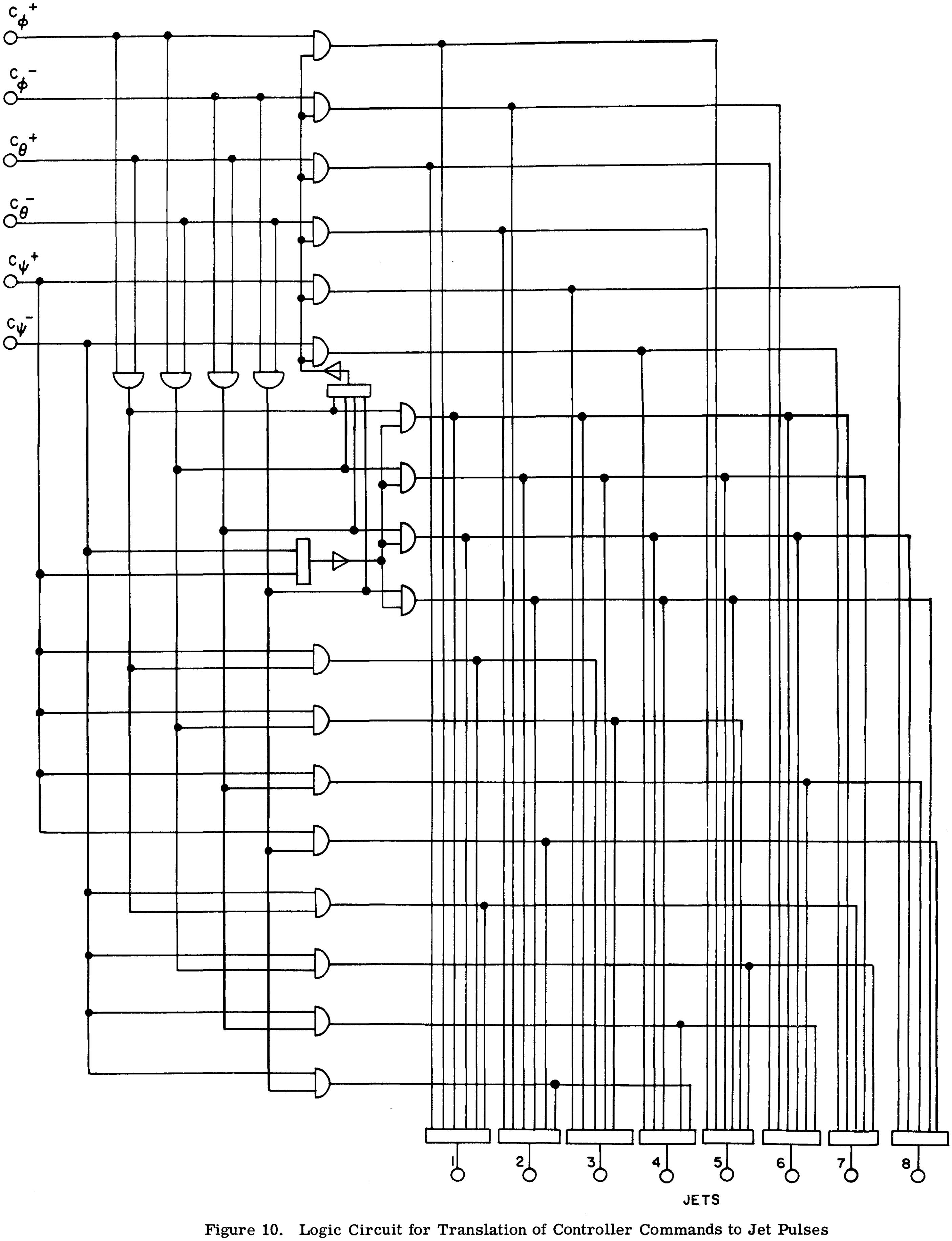

Figure 10. Logic Circuit for Translation of Controller Commands to Jet Pulses

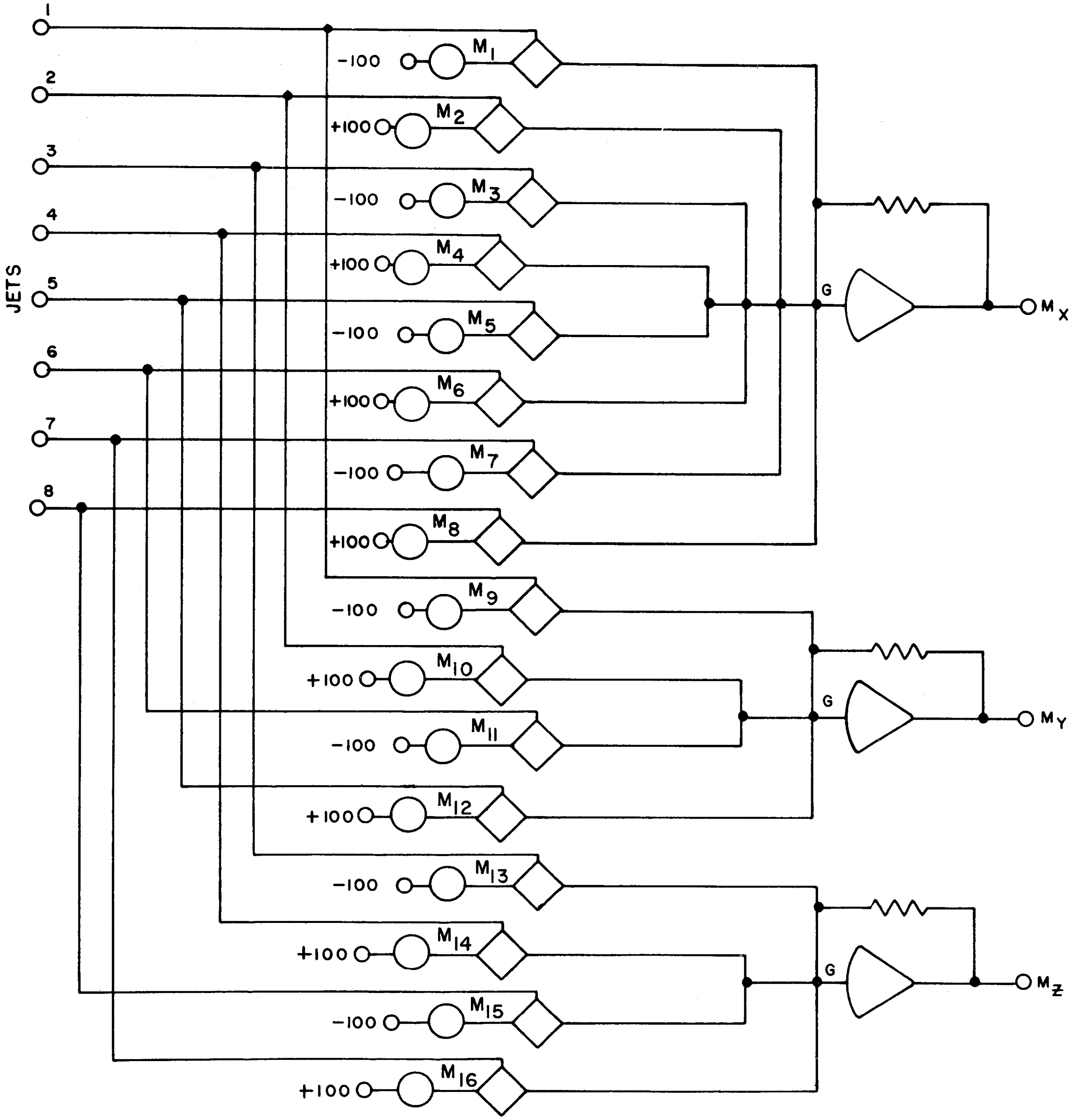

Figure 11. Circuit for Translation of Jet Pulses to Moments

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