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SPACECRAFT CONTROL SYSTEM FOR THE RELATIVITY MISSION

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Abstract. The attitude and translation control system described in this paper provides precision pointing and drag-free control to accomplish a scientific mission. The unique proportional helium thruster, which uses helium boiloff from the payload, controls thrust using pressure feedback to meet the high-accuracy requirements for force knowledge. The attitude control law torque commands are combined with the translation control law force commands through a distribution matrix to determine individual thruster commands. The Global Positioning System (GPS) is used to determine position and velocity.

Key Words. Actuators, aerospace control, attitude control, closed-loop systems, control applications, control system design, conventional control, satellite control

1. INTRODUCTION

The Stanford Relativity Mission experiment is designed to test two relativistic effects, the geodetic effect and the frame-dragging effect. The space vehicle (Fig. 1) is in a 650 km polar orbit. The scientific payload consists of four electronically suspended gyroscopes and a telescope contained in a cryogenic dewar, which is cooled by super fluid helium. The telescope provides the "distant inertial" space reference, and the gyroscopes, the "local inertial" space reference. Einstein's General Theory of Relativity predicts a shift between the "inertial" measurements of the telescope and the gyroscopes. The geodetic effect, caused by the earth, and the frame dragging effect, due to the dragging of the "inertial" frame by the massive rotating earth, are predicted to cause deviations between the spin axis of the gyroscopes and the reference provided by the telescope of 6.6 arc-seconds and 0.042 arcseconds per year, respectively.

The attitude and translation control system, shown in Figs 2 and 3, provides precision pointing control to accomplish the scientific mission. The unique proportional helium thruster design controls thrust using pressure feedback, providing accurate force output. The control system operates autonomously, requiring only minimal interaction with ground control.

Command handlers for mission timeline, payload, safemode responses, and special events are implemented, allowing special command constructs and eliminating the need for software recoding for changes to the command logic. For example, the guide star acquisition process can be modified by changing the com-

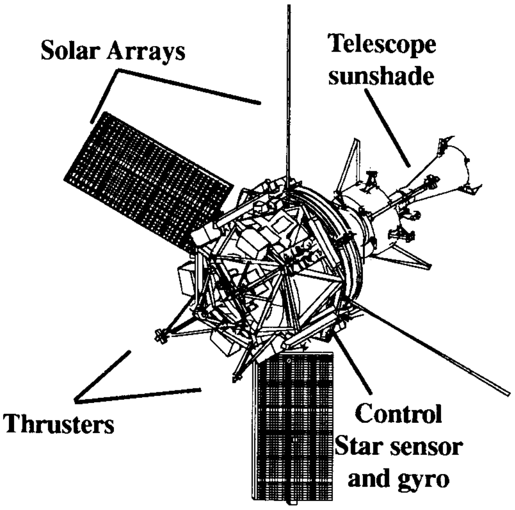


Fig. 1. Relativity Mission space vehicle

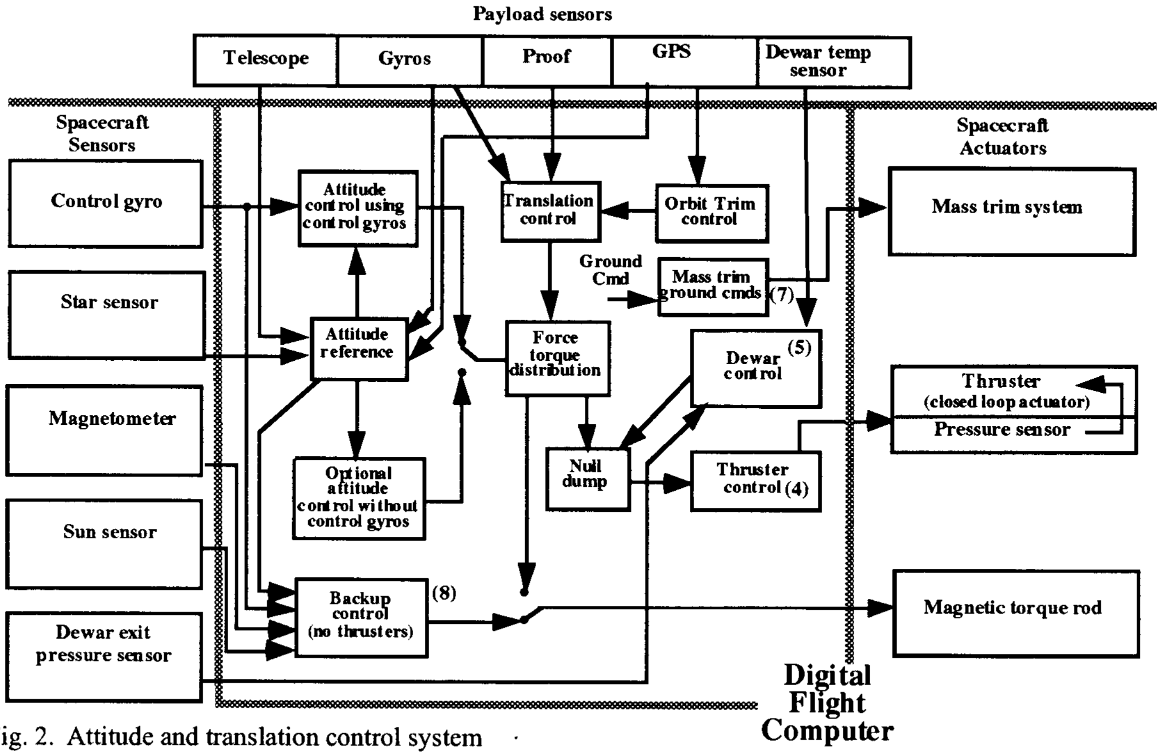


Fig. 2. Attitude and translation control system

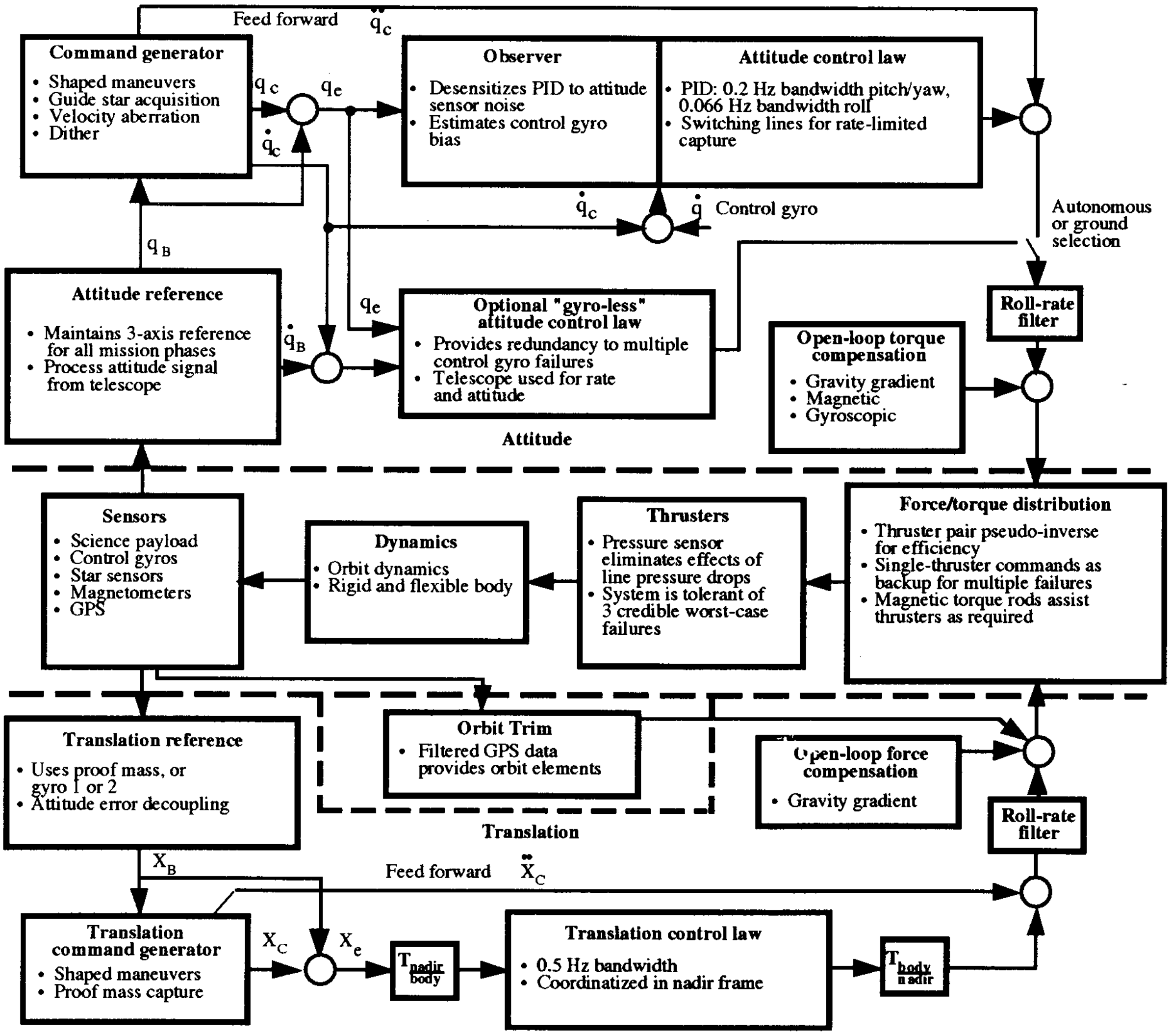


Fig. 3. Attitude and translation control system block diagram

mand sequence, rather than by updating the software code. A command generator performs maneuvers such as slews, dither, and search scans.

2. ATTITUDE CONTROL

The attitude control system (Fig. 3) uses a modified proportional, integral, and derivative (PID) control law. The attitude sensors and control gyros provide the reference. Limiters are used to provide rate-limited capture following maneuvers.

The control system structure is used for all mission modes; only sensors, gains, and limits are changed. Stability margins (Fig. 4) for pitch/yaw and roll are greater than 30 degrees and 6 dB in the presence of structural bending modes. An observer blends attitude reference and gyro data to filter the noise of the telescope and control star sensors and provide an estimate of the gyro bias. A tuned roll-rate filter reduces the effects of roll-rate disturbances on the scientific measurements.

A three-axis attitude reference is maintained during all mission phases. The control star sensors allow placement of the guide star in the field of view of the telescope. An autonomous rate-limited capture places the guide star in the linear range of the telescope, which provides the pitch-yaw reference when the guide star is in view. When the guide star is obscured, the control gyroscopes are used to provide a pitch-yaw attitude reference, with the gyroscope spin axis available as a backup reference. The telescope boresight is pointed toward the calculated location of the optical image of the guide star while the guide star is obscured, reducing reacquisition time. Roll reference is provided by a control star sensor.

A gyroless control mode is provided using the telescope for pitch-yaw and the control star sensors for roll control. The control systems are robust in the presence of structural bending modes, as shown for the pitch/yaw axis in Fig. 5.

The command generator provides smooth jerk-limited and acceleration-limited acceleration, velocity, and position command profiles to the attitude control law. This reduces transient space vehicle accelerations, avoids any excitation of structural bending modes, and prevents helium thruster saturation. Maneuver command sizing and shaping are calculated autonomously by the flight software.

The Global Positioning System is used for position and velocity determination. If data is not available due to a receiver failure, an onboard ephemeris model propagates position and velocity. Ephemeris processing determines sun, moon, and Tracking and Data Relay Satellite positions; guide star visibility; control star sensor obscuration; velocity aberration; Stanford ground station visibility for autonomous data downlink; and telescope shutter closure to block the earth's albedo.

3. TRANSLATION CONTROL

The translation control system (Fig. 3) can select either gyroscope 1, gyroscope 2, or the proof mass as the drag-free sensor. Each has a capacitive proximity sensor to give a measure of the distance between the sensor sphere and the wall. The translation reference compensates for apparent translation error due to rotation of the space vehicle about its mass center. Translation control stability margins ensure robust performance in the presence of structural bending modes.

Attitude control law torque commands are combined with the translation control law force commands through a distribution matrix to determine individual thruster commands. The fault-tolerant distribution design bypasses failed thrusters, which are isolated by shut-off valves. Alternate distribution matrices are stored onboard for autonomous use if needed. Excess helium mass flow is evenly null-dumped among all thrusters. Magnetic torque rods are available to assist the thrusters for attitude control if required.

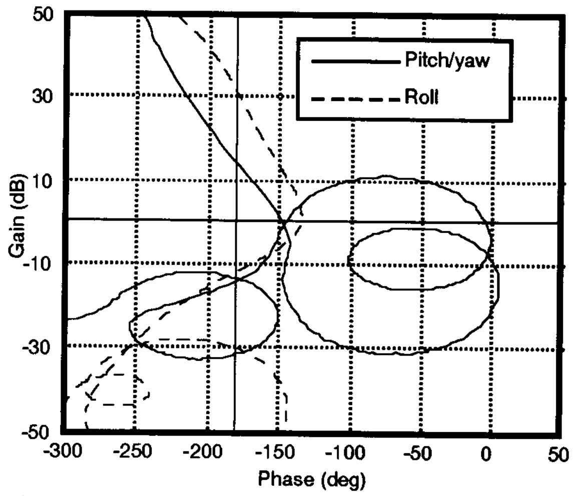


Fig. 4. Attitude Nichols plot (with control gyros)

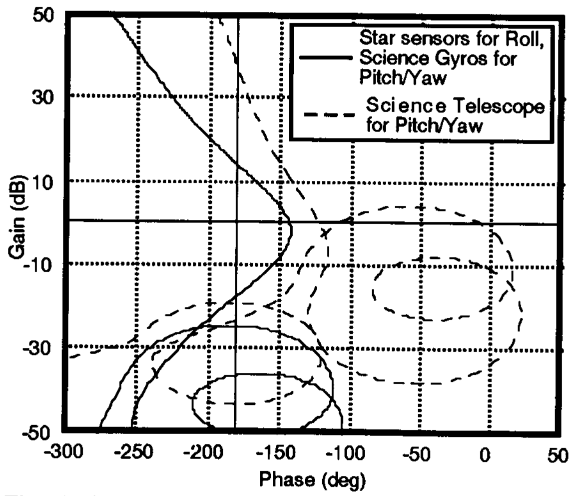


Fig. 5. Attitude Nichols plot (gyroless)

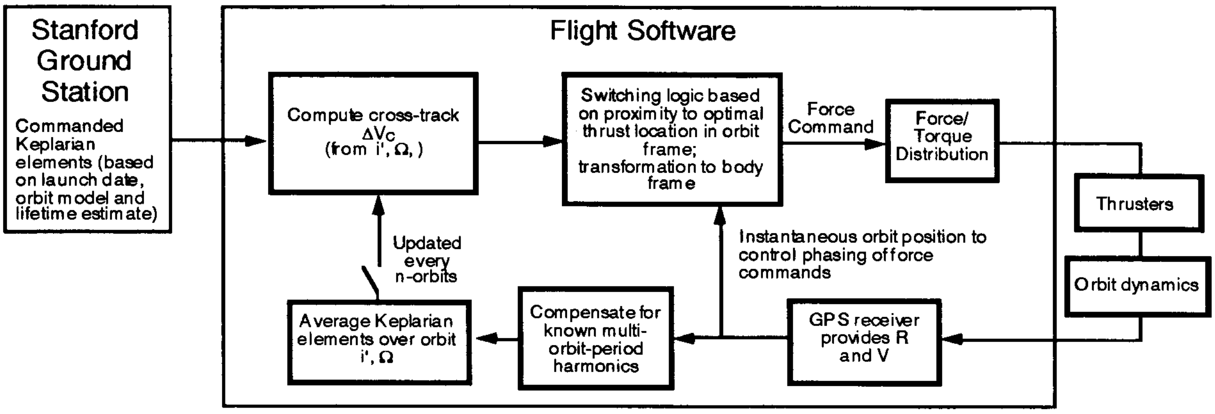


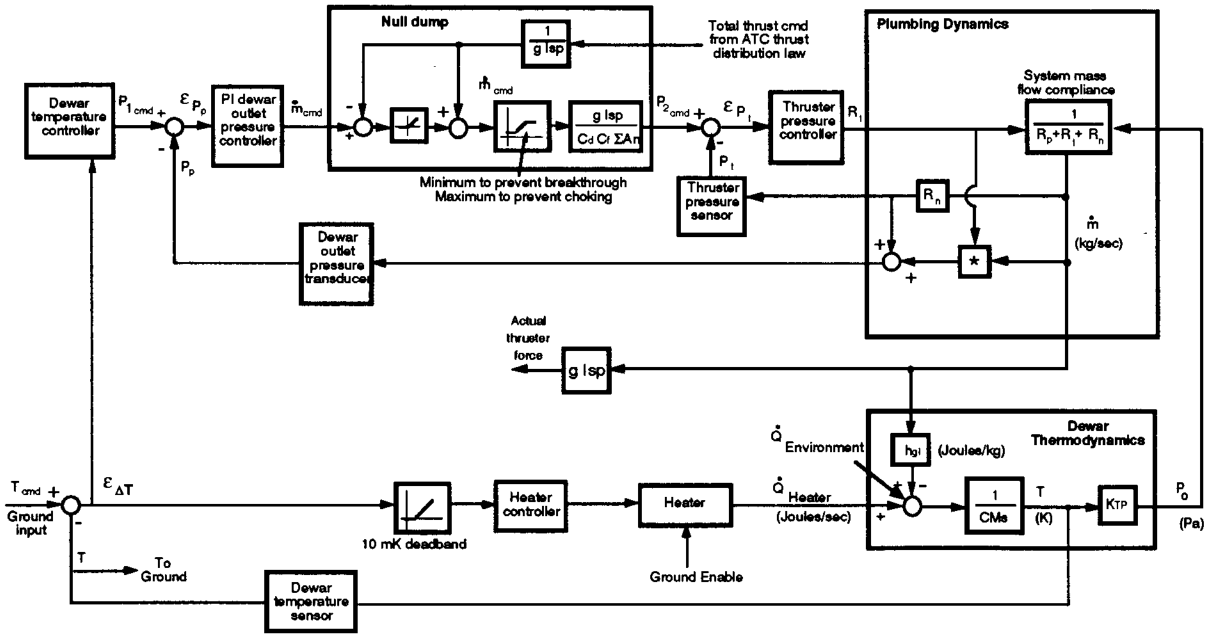
Fig. 6. Orbit trim block diagram

4. ORBIT TRIM CONTROL

Closed-loop orbit trim control (Fig. 6) is based on a time-optimal approach developed at Stanford (Axelrad, et al., 1991). The Global Positioning System receiver provides high-accuracy instantaneous position and velocity, which are converted to orbital elements. Mean orbital elements are corrected for known orbit perturbations due to the sun, moon, tesseral harmonics and oblateness, and compared to target elements to determine the required in-track and cross-track thrust. Thruster commands are based on how efficiently the thrusters are aligned with the desired thrust direction.

5. DEWAR PRESSURE CONTROL

The dewar temperature-pressure controller (Fig. 7) operates over the full range of dewar helium capacity and mass flow: 95% full (maximum capacity), 0.01% full (11 hours before depletion), and 4 to 16 mg/sec flow rate. The baseline proportional and integral (PI) pressure control loop also controls dewar temperature by controlling pressure at the dewar outlet.



LEGEND

T = Helium temperature

P_o = Helium vapor pressure

P_p = Sensed pressure in plumbing

P_t = Sensed pressure in thruster

P_s = Space ($P_s = 0$)

R_p = Payload plumbing mass flow resistance (including porous plug)

R_t = Thruster valve mass flow resistance (including spacecraft plumbing)

R_n = Thruster nozzle mass flow resistance

Fig. 7. Dewar pressure control block diagram

6. SAFEMODE

A safemode control system (Fig. 8) uses the star sensors, control gyros, magnetometers, and magnetic torque rods to provide control without the helium thrusters. The control system points the space vehicle by nulling the angle between the actual angular momentum vector and the desired angular momentum vector in the vehicle frame, while simultaneously nulling the angle between the actual angular momentum vector and the commanded vector in the inertial frame.

7. HELIUM THRUSTER

The helium thrusters are mounted on rigid mounts sized close to the edge of the DeltaII payload fairing dynamic envelope, providing maximum torque authority. They are positioned in opposing pairs for efficient mass flow distribution, and are grouped to minimize plumbing weight. The maximum thrust design point is 8mN per thruster.

The flight thruster design is based on the two prototype thrusters, built by Lockheed and extensively tested. A unique feature of the Lockheed thruster design (Fig. 9) is the pressure control concept.

Pressure is controlled in a small chamber (the restrictor) just upstream of the nozzle throat. Thrust is directly proportional to this pressure. If only the piston position is controlled, the thruster output is dependent on the inlet pressure. Controlling the restrictor pressure makes the thruster output independent of inlet pressure. This is an important benefit because the thruster inlet pressure varies due to pressure drops in the plumbing, which vary with the distribution of mass flow through the plumbing. The pressure-control approach improves thruster output accuracy, which improves pointing performance.

The commanded restrictor pressure is maintained by a controller that moves the thruster piston on the basis of measurements from the restrictor pressure transducer.

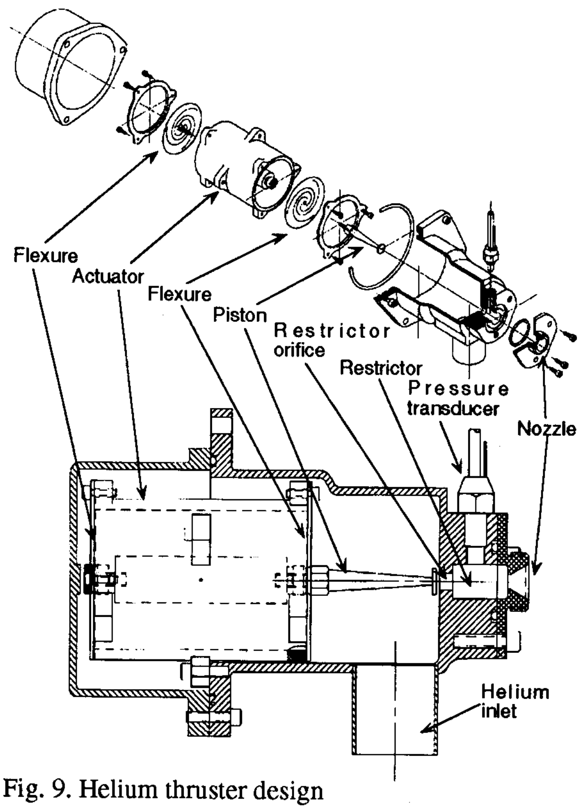


Fig. 9. Helium thruster design

The thruster piston is supported by two spiral spring flexures. The actuator is a linear motor.

8. ACKNOWLEDGMENT

Grateful acknowledgment is given to Dr. Ken Lorell, Dr. Jean Aubrun and Don Zacharie of the Lockheed Missile and Space Company, Dynamics and Control Laboratory, for their work in conceiving the pressure control concept and in the initial design of the prototype helium thruster and control system.

9. REFERENCE

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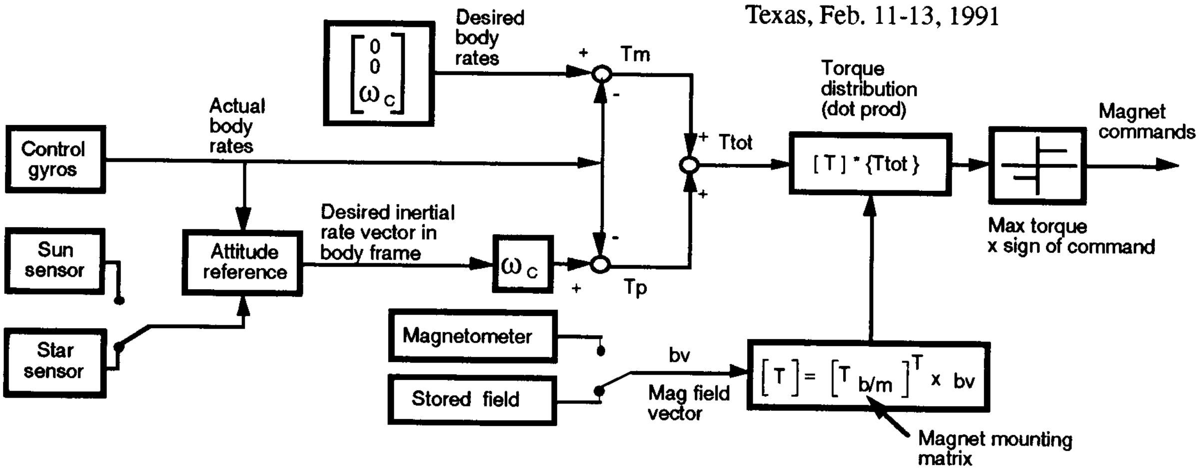

Fig. 8. Extended mission mode block diagram