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Topex/Posiedon Autonomous Maneuver Experiment (TAME)

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neuvers. Under this experiment, TOPEX Autonomous Maneuver Experiment (TAME), JPL will develop and test on-board software to autonomously plan constraint free attitude maneuvers and execute an Orbital Maintenance Maneuver (OMM). The planning software along with the required database will reside on an existing satellite sensor processor subsystem. The database includes satellite and orbit parameters as well as the mission constraints. Upon receiving an OMM request, the planner software will design an attitude maneuver plan, which is free of constraints. A sequence of commands will then be generated which include this plan and other necessary commands to correctly reconfigure the satellite. The generated command sequence will then be transferred to the T/P main processor (OBC) for implementation.

This technology demonstration will provide data to perform cost/benefits analysis to determine the proper trades between flight- and ground-based spacecraft mission operation. It will also provide approaches for the new paradigms in system architecture, ground commanding and test and verification that will be necessary for highly autonomous event-driven controls.

TOPEX MISSION

The TOPEX/Poseidon Satellite, hereafter referred to as TOPEX (Ocean Topology Experiment) was launched on August 10, 1992, from the Kourou Space Center in French Guyana. The satellite was launched into a nominal circular orbit with an altitude of 1336 Km and an inclination of 66 degrees. The TOPEX is a remote sensing mission with the primary science objective of providing sea surface altimetery from space. TOPEX/Poseidon program is jointly sponsored by 'The National Aeronautics and Space Administration (NASA) and Centre National d'Etudes Spatiales (CNES). This joint U.S./French mission combines each countries' space ocean research missions. The TOPEX mission is managed by the Jet Propulsion Laboratory (JPL) for the NASA office of Space Sciences Application. JPL, is also responsible for the day to day operation of the satellite. The Poseidon is managed by the Toulouse Space Laboratory for CNES. TOPEX was slated for a prime mission of three years, which was completed in September 1995. A three years' extension to the mission has been approved by NASA.

The primary science objective. of the TOPEX satellite is to provide highly accurate measurements of the sea surface elevation over all of the ocean basins. The primary science requirement is to provide geocentric measurement of the. global ocean sea level accurate to 14 cm with a precision of 2.4 cm along track. These requirements necessitated a frozen orbit that provides a fixed ground track every 10 sidereal days (127 orbits)[2]. To maintain the frozen orbit, the satellite occasionally performs small burns referred to as Orbit Maintenance Maneuver (OMM). It is the objective of TAME to develop the software that provides the capability for on-board planning and execution of an OMM.

TAME IMPLEMENTATION

Orbit Maintenance Maneuver (OMM) execution is a multi-discipline activity. The need to perform a correction is first determined by the mission navigation function. The navigation function includes orbit determination, orbit control and orbit propagation. The navigation function will calculate the required AV then requests an implementation plan from the mission operations team, The. implementation activity is then converted to a sequence of low-level satellite commands that will be uploaded to the satellite for execution. Currently, all of these functions are performed on the ground. Figure 1 summerizes the current TOPEX maneuver implementation activity.

In the autonomous approach all activities are performed on-board without ground intervention. This level of autonomy was deemed as inappropriate. for TAME. TOPEX on-board computers, the OBC and the 1750A, simply do not have sufficient unused capacity to support total autonomy, Additionally, safety considerations required a step-by-step implementation of the autonomy. Therefore.

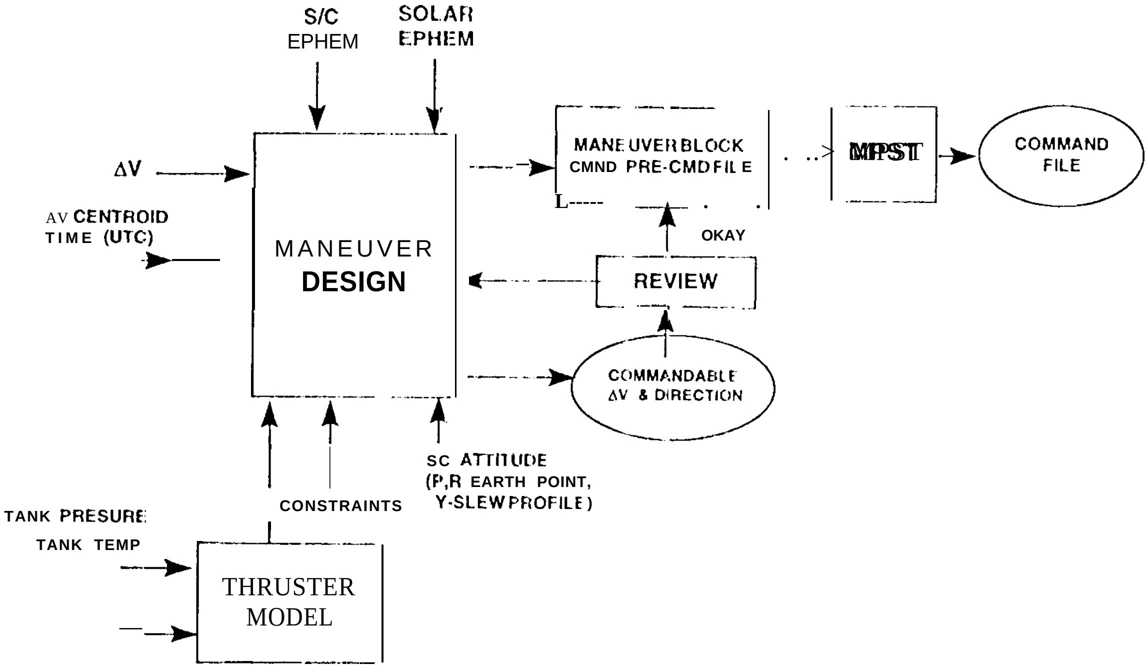


Figure 1 Current TOPEX/Poseidon Maneuver Implementation Design Activity.

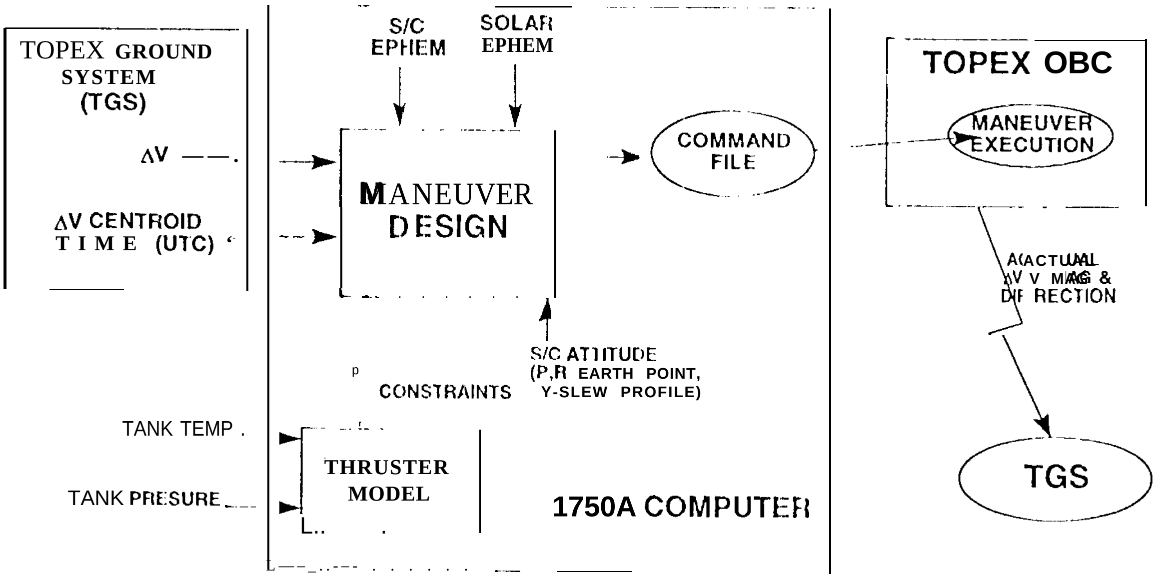
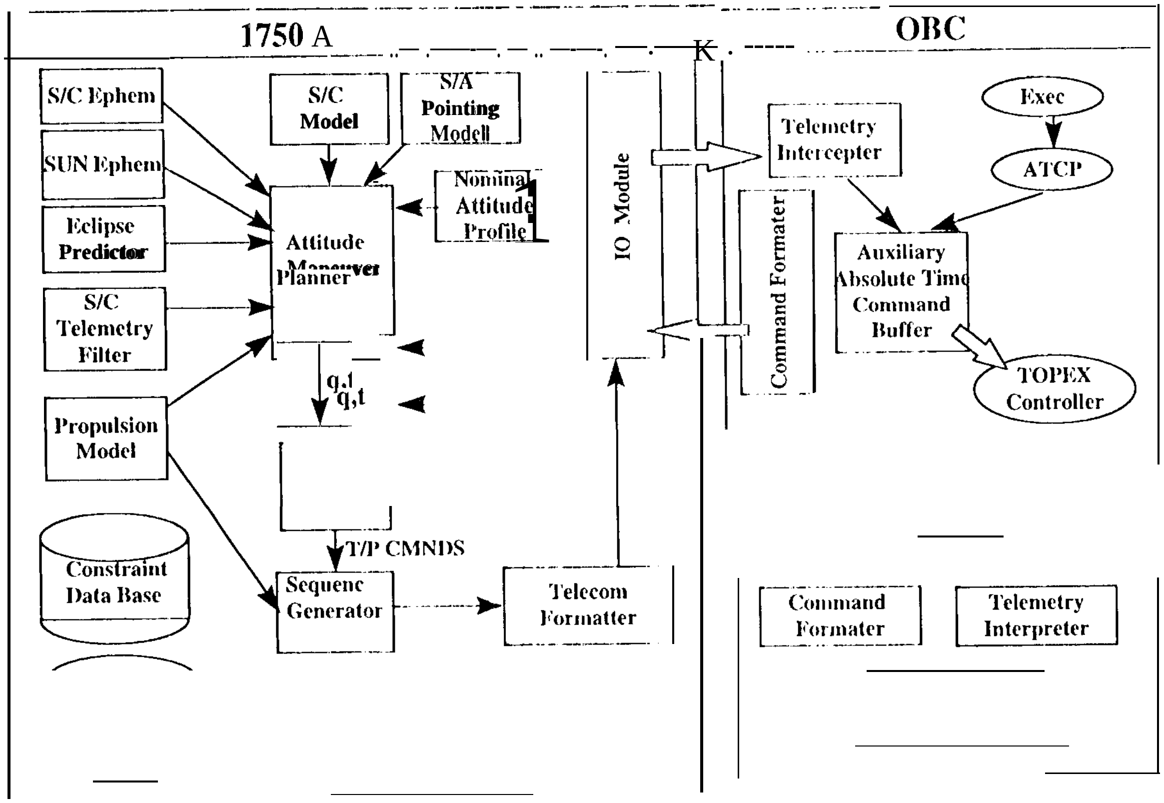


Figure 2 Proposed TOPEX/Poseidon Autonomous Maneuver Implementation.


1750 A
OBC
K
S/C Ephem
SUN Ephem
Eclipse Predictor
S/C Telemetry Filter
Propulsion Model
Constraint Data Base
S/C Model
S/A Pointing Modell
Nominal Attitude Profile
Attitude Maneuver Planner
q,t
q,t
T/P CMNDS
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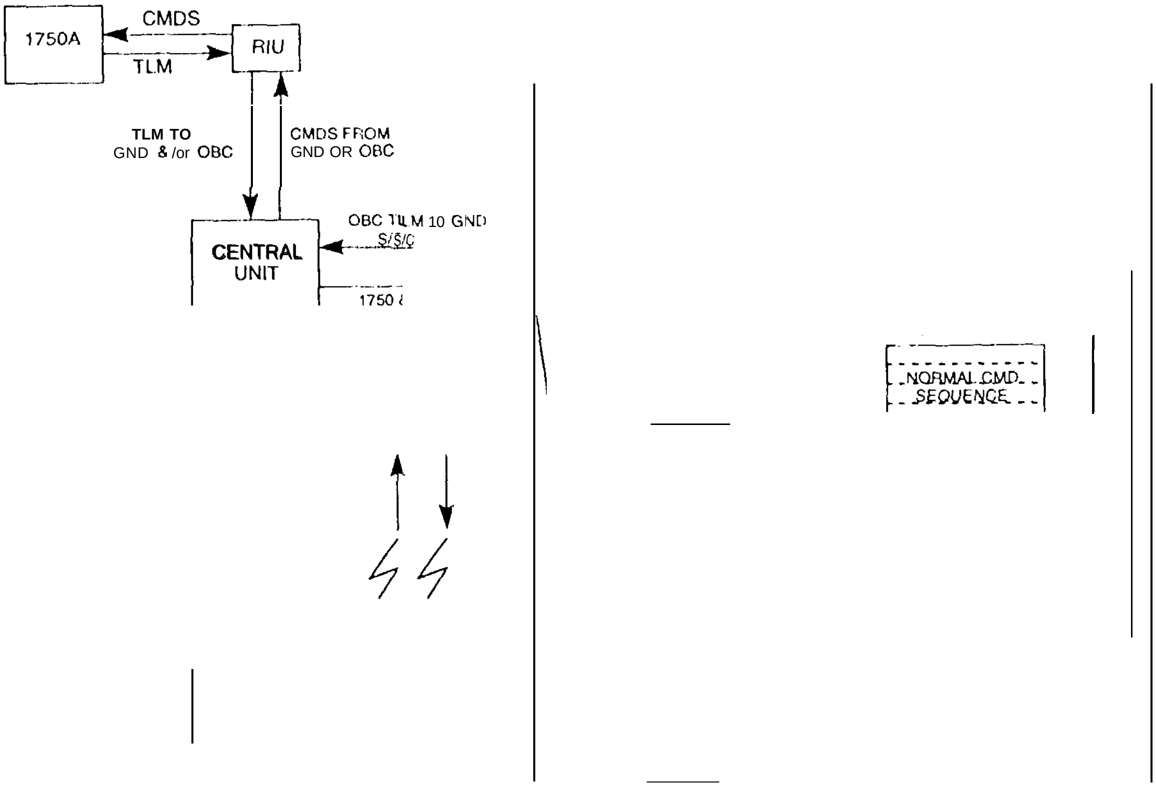
Auxiliary Absolute Time Command Buffer
TOPEX Controller
Command Formater
Telemetry Interpreter


1750A
CMDS
TLM
RIU
TLM TO
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GND OR OBC
CENTRAL
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OBC TLM 10 GND
S/S/C
1750
NORMAL CMD
SEQUENCE

On-Board Computer

The TOPEX On-Board Computer (OBC) is part of the Command & Data Handling Subsystem (C&DH). The OBC is comprised of three key elements, the Central Processing Module (CPM), Core Memory Unit (CMU) and the STandard INTerface (STINT). The CPM consists of a NASA Standard Spacecraft Computer (NSSC- 1). The NSSC- 1 is an 18-bit fixed point CPU running on a 1.8MHz clock. The CMU consists of 64K words (18-bit word), which are divided into 16 4K banks. The STINT provides the serial interface between the CPM and the Central Unit (CU). The CU performs all the spacecraft command & telemetry routing and properly formats the 1 Kbps & 16Kbps telemetry stream to be sent to the ground.

Each spacecraft subsystem is connected with the Multiplexed Data Bus (MDB) via a Remote Interface Unit (RI U). When a command is received by the CU, it routes the command to the proper subsystem based upon an RIU number and a channel number. The same process occurs whether the command is sent from the ground or by the OBC. The OBC is capable of processing commands from the ground and send commands in real time from a timed stored sequence. Also the OBC has access to both the 1 & 16Kbps telemetry stream streams.

The OBC flight software (FSW) performs all of the major attitude control and fault detection as well as other miscellaneous command and telemetry functions. The FSW is divided into separate tasks which run at specific times and for specific intervals based upon a scheduler. All the 1/() and main operating system functions are performed by the Executive which runs every 64msec. The other tasks run at a slower intervals of 256, 512 or 1024 msec.

Since the 1750A hardware does not allow spacecraft commands to be issued, the TAME architecture depends on the 1750A processor to transfer the commands to the OBC for transmission. This requires the 1750A to communicate with the OBC via the existing 16K telemetry stream. The overall process consists of the 1750A generating the maneuver commands and formatting the commands to look like telemetry data. The OBC intercepts the 1750A telemetry and stores the commands for transmission at a later time.

Since the executive performs critical low level functions it is desirable to limit the amount of changes to the executive code. This means making most of the code changes to the Absolute Time Command Processor (ATCP) task. The changes to this task have been designed to not interfere with normal operations. The ATCP processes stored commands based upon a 18-bit time tag which is compared with the FSW time. When the time tag matches the FSW time, the command is sent.

The code changes for TAME involve three major functions. Intercept the 1750A telemetry and store commands into proper memory locations. Checksums will be used to assure the data integrity during the data transfer. The second major function is to integrate the maneuver store sequence from the 1750A into the normal stored sequence of commands.

This process eliminates any interference with normal operations performed by the stored sequence. The third function involves managing communications with the 1750A. This is a accomplished via a predefined protocol for 1750A telemetry and OBC commands. To ensure data quality and avoid confusion the OBC sends commands to the 1750A to provide status and telemetry information.

1750A Computer

The Global Positioning System Demonstration Receiver (GPSDR) on the TOPEX satellite is a sensor used in the JPL GPS Navigation) Experiment. In addition to the custom hardware needed to track GPS satellites, it includes a user programmable general purpose computer. It is this computer that will be used to implement the TAME specific software. Since this computer is based on the MIL-STD- 1750A, the TAME effort calls this subsystem the 1750A. Memory and throughput issues preclude the 1750A from using any of the GPS tracking hardware.

The 1750A subsystem is composed of an interface to the satellite, a microprocessor, and read-only- and random-access memory (ROM and RAM). This provides all the components necessary to receive commands, execute a user program, and send data to the TOPEX OBC. It is this communication with the OBC, described above, that allows the 1750A to generate the maneuver information and have the satellite perform it. There is no direct 1750A communication with any satellite component other than the command and telemetry systems. The OBC is able to send data to the 1750A and sample the telemetry stream and therefore communicate with the 1750A.

The 1750A has standard TOPEX

ROM and custom hardware. This leaves 60 Kwords (120 Kbytes) for memory-mapped RAM.

ATTITUDE MANEUVER PLANNER MODULE

The maneuver planning module processes requests for orbital change maneuvers and generates spacecraft commands for maneuver execution.. An orbital change maneuver modifies the orbit characteristics for drag make-up. Orbital change maneuvers are accomplished by pointing the spacecraft thruster in the direction of the requested impulse. A maneuver consists of

(1) turns to accomplish the requested pointing
(2) an orbital change propulsive butn at constant attitude, and
(3) turns tore-acquire a nominal spacecraft attitude.

The maneuver planning module ensures that all spacecraft pointing constraints are satisfied during the maneuver turns and burns. The maneuver planning module *a priori* computes a maneuver which

(1) acquires the requested attitude at the requested epoch
(2) satisfies all active pointing constraints
(3) includes the spacecraft dynamic behavior
(4) includes settling times
(5) includes turn rate limits

Maneuver Planning Task

The maneuver planning task is to align a body-fixed vector and an inertially fixed vector, Figure 5. This consists of rotating the spacecraft to an orientation sufficient to align the two vectors, performing a thruster(s) bum, and rotating the. spacecraft to a new orientation. The basic maneuver component is a constant eigenaxis rotation with respect to an inertial frame. A turn begins from an initial stationary attitude, continues with spin-up to a constant rotation rate about a single eigenaxis, and ends with spin-down to a new stationary attitude, Figure 6. Thus all spacecraft body-fixed vectors generate a cone trajectory about the eigenaxis, while inertial vectors remain stationary. The magnitude of the spin vector, $\vec{\omega}$, or *turn rate* is a function of the spacecraft controller turn characteristic. A typical turn rate curve characteristic, shown in Figure 6, consists of a ramp during spin-up, a constant turn rate during coast, and a negative ramp during spin-down.

Maneuver Planning

The planning task of the maneuver planning module is to satisfy constraints. Most maneuvers are subject to constraints. Constraints are modeled as pointing constraints associated with a pair of vectors: a body-fixed vector and an inertially-fixed or orbitally-fixed vector (Figure 7). A constraint is violated if the body-fixed vector is within a specified angular distance, or half-cone angle, of the inertially-fixed vector. Two constraints are illustrated in Figure 8; each constraint pair is indicated by an index. There is no theoretical limit on the maximum number, n, of constraints. Each constraint associates one vector pair; i.e., a constraint violation can occur only between vectors of equal index.

The Maneuver Planner, Figure 9, consists of three main functions:

(1) initialization
(2) optimization.
(3) maneuver profile generation

The Path Initializer searches for a maneuver profile that satisfies all constraints listed in the Constraint Table. The Path initializer outputs a quaternion/timeline set (maneuver profile) representing a constraint-free maneuver. Next, the Path optimizer adjusts the maneuver profile to locally minimize the total maneuver time, Finally, the Maneuver Commander converts the optimized maneuver profile to time tagged quaternions to command TOPEX controller.

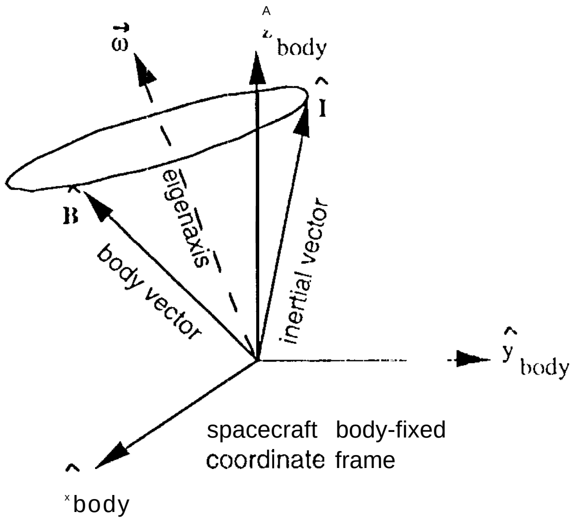

Figure 5 Eigenaxis Turn With Respect to an Inertial Frame (for simplicity the rotations of the body coordinate axes are not shown)

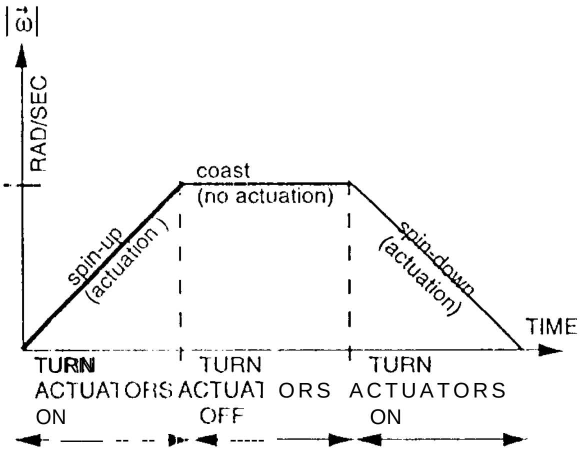

Figure 6 Typical Turn Rate Characteristic

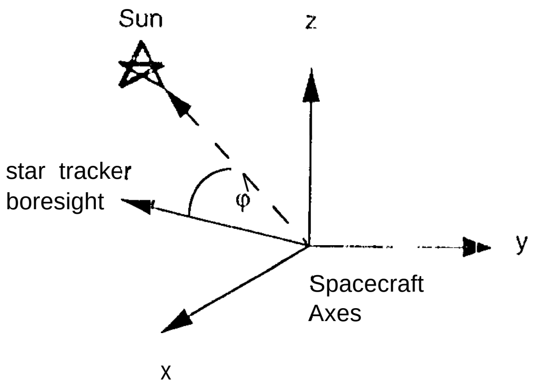

Figure 7 Typical Constraint: Sun Does Not Lie in Star Tracker Field of View(φ).

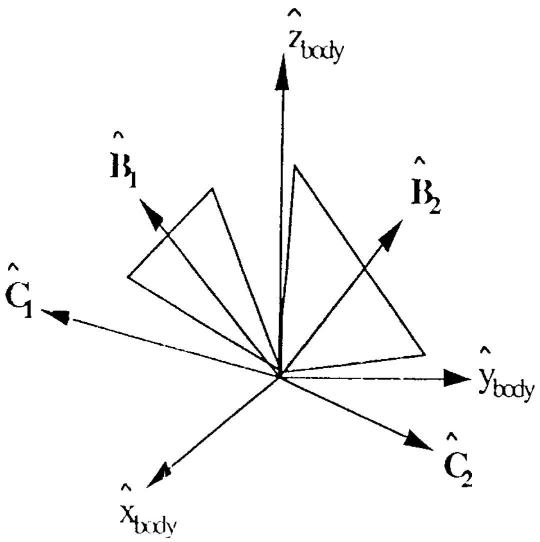

Figure 8 Two Active Constraints

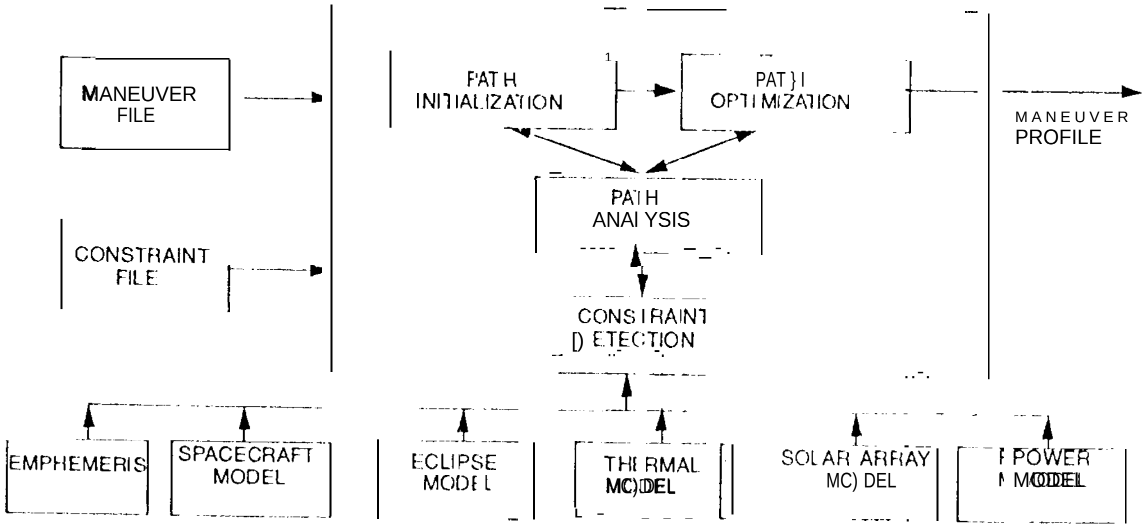

Figure 9 TAME Maneuver Planner Block Diagram

Constraints Table

All active constraints are stored on-board. An active constraint is defined as a requirement for the next requested maneuver. Constraints are stored in a specific form denoted as the Constraint Table. The Constraint Table logically has a row

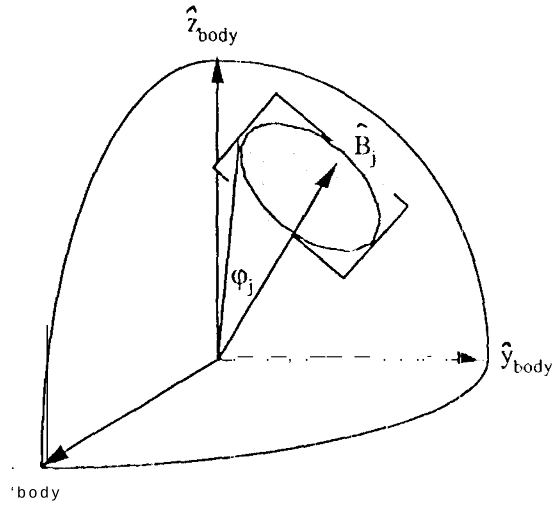

Figure 10 Constraint Modeling with Spherical Circles

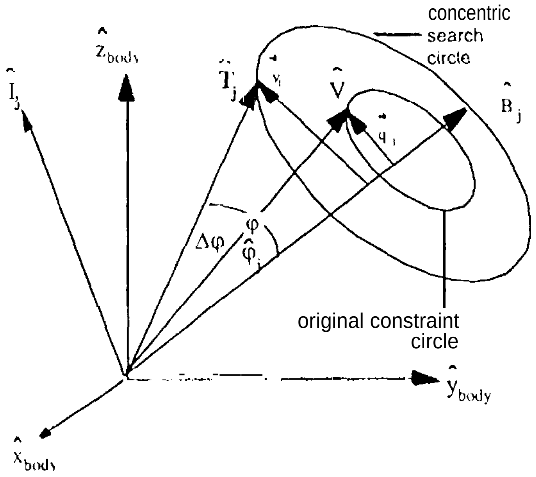

Figure 11 Constraint Avoidance with Concentric Spherical Circles

The algorithm attempts to find an intermediate attitude to avoid the constraint by aligning the inertially-fixed vector, $\hat{I}_j$, with tile test vector, $\hat{T}_j$. The following equations generate the search basis with two parameters:

$$\vec{q}_1 = \hat{V} - \cos(\varphi_j)\,\hat{B}_j;$$

$$\vec{v}_1 = \left(\frac{\sin(\varphi)}{\sin(\varphi_j)}\right)\vec{q}_1;$$

$$\vec{v}_2 = \vec{v}_1 \times \hat{B}_j;$$

$$\hat{T} = \left(\cos(\eta)\,\vec{v}_1 + \sin(\eta)\,\vec{v}_2\right) + \cos(\varphi)\,\hat{B}_j$$

Next, the path from the intermediate attitude to the maneuver attitude is computed and checked for constraint violations. If constraint-free, the maneuver profile is admissible, The

Path Optimization

The Path Optimizer converges the maneuver profile to a local minimum. This strategy allows the initialization to proceed without regard to optimality. Let q denote a quaternion and T denote spacecraft time. Then a typical maneuver profile is illustrated in Figure 12. The function of the intermediate attitudes, “A” and "B", is to avoid the constraints. These quaternions are computed in the Path Initializer.

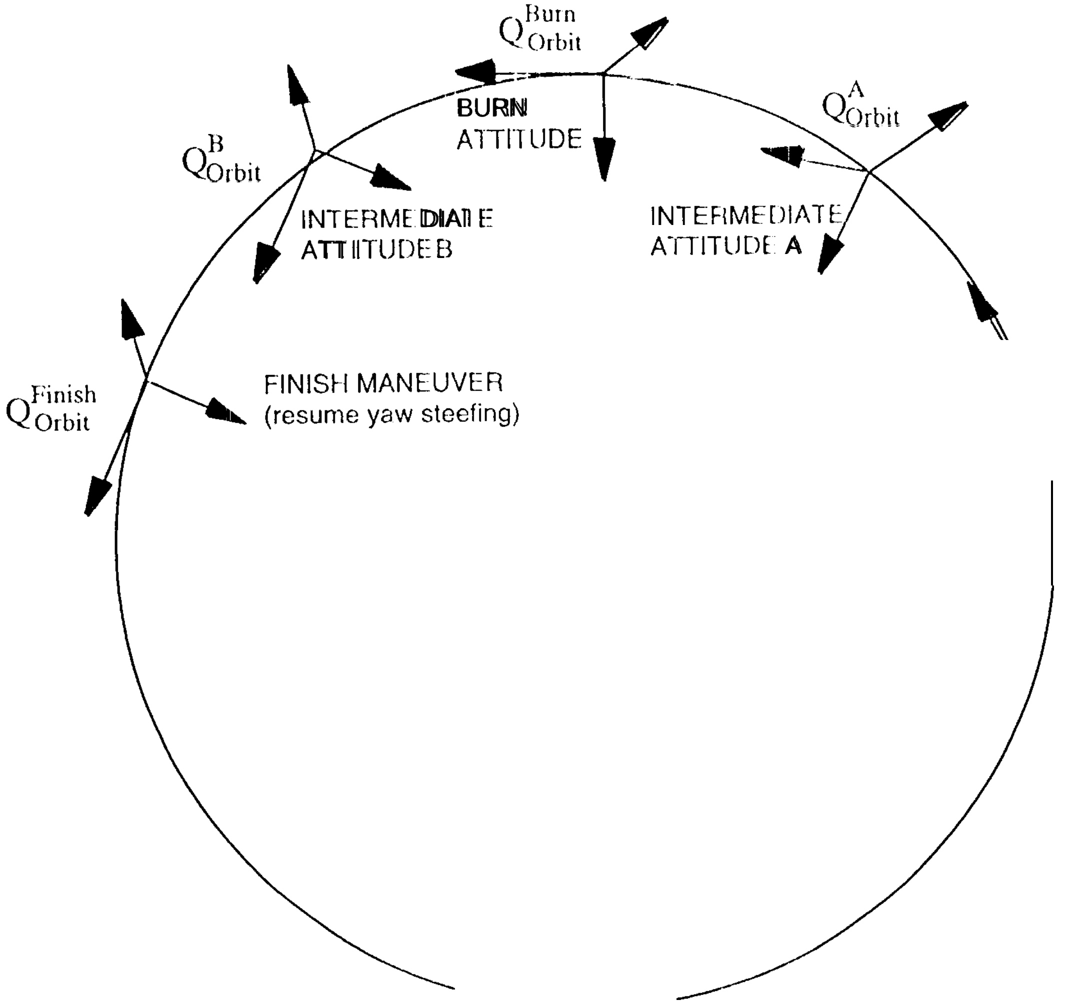

Figure 12 Maneuver Profile Defined By Attitude Quaternions

Local minima are defined with respect to a specific cost function. The TAME cost function is computed as follows:

$$j = (T_{finish} - T_{start}) + \lambda T_a$$

where

$$T_a = \sum_{j=1}^{n} (\text{time inside constraint cone for } j \text{ th constraint})$$

The term T_a **is** a penalty function that causes the cost function j to peak if the maneuver is adjusted into a constraint and λ is a sensitivity multiplier. Thus the Path Optimizer causes the trajectories to be as direct as possible until a constraint spherical circle is tangentially intersected by a body vector.

Six degrees of freedom exist to plan a maneuver: the two intermediate attitudes q_a and q_b. Let the independent coordinates of the quaternions be indicated as:

$$q_a = [x_1, x_2, x_3]^t;$$

$$q_b = [{}^{x}4, x_5, x_6]^t;$$

$$\vec{x} = x_1, x_2, x_3, x_4, x_5, x_6]^t;$$

where $\vec{\mathbf{x}}$ is the maneuver profile. Then the cost function and its gradient with respect to the maneuver profile are:

$$j = j(\vec{x});$$

$$\mathbf{V\,j} = \left[\frac{\partial j}{\partial x_1}, \frac{\partial j}{\partial x_2}, \frac{\partial j}{\partial x_3}, \frac{\partial j}{\partial x_4}, \frac{\partial j}{\partial x_5}, \frac{\partial j}{\partial x_6} \right]^t$$

The gradient vector points in the direction of steepest descent to minimize the cost function (j). The Path Optimizer converges the maneuver profile ($\vec{x}$) via the following dynamics:

$$j = j(\vec{x});$$

$$\nabla j = \left[\frac{\partial j}{\partial x_1}, \frac{\partial j}{\partial x_2}, \frac{\partial j}{\partial x_3}, \frac{\partial j}{\partial x_4}, \frac{\partial j}{\partial x_5}, \frac{\partial j}{\partial x_6} \right]^t$$

In Figure 13, the converge law integrator terminates at a. local minima of the cost function.

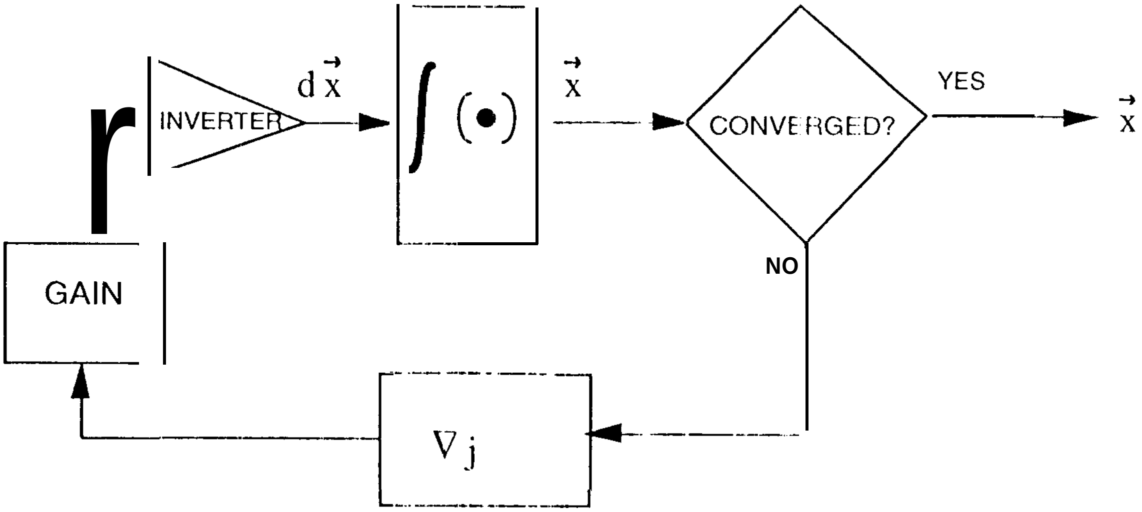

Figure 13 Path Optimizer Maneuver Profile Convergence Law

CONCLUSIONS

The feasibility for autonomous propulsive maneuver planning sequence generation was demonstrated in 19944. The 1995S effort generalized the algorithms allowing arbitrary Euler turns in place of the single axis turns and the code is being written to comply with flight software code requirements. The TOPEX Autonomous Maneuver Experiment (TAME) applies these concepts to a real operational nadir pointed orbiter,

The experiment is scheduled for early calendar 1997. Recently the TAME team completed the algorithm design review. Current schedule calls for the implementation and test to be completed by October of 1996..

The challenge of the TAME experiment will not bc limited to the maneuver planner algorithm. Real mission constraints and oversights would have to be considered for their full impact to ensure a safe experiment.

ACKNOWLEDGMENTS

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