AUTONOMOUS GUIDANCE AND CONTROL OF A SOLAR ELECTRIC PROPULSION SPACECRAFT'

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1.0 Abstract

The New Millennium Deep Space Mission 1 (DS 1), a NASA designed advanced technology demonstration mission to flyby an asteroid and a comet, is the first deep space solar electric propulsion spacecraft (S/C). Several new challenges are presented in autonomous guidance and control of this spacecraft. The New Millennium DS1 onboard guidance and control (G&C) system has accommodated these challenges in a simple yet robust architecture. The DS 1 G&C system will implement trajectory correction maneuvers autonomously to support onboard optical navigation. This capability will be implemented for the traditional chemical propulsion system and the new ion propulsion system, both available onboard DS 1. A thrust vector controller has been designed to control the ion engine using 2-axis engine gimbal actuators. A solar panel controller has been designed to keep the large solar panels to within 2 degrees of total pointing control with respect to the Sun. An onboard autonomous pointing capability ensures that the solar panels remain sun pointed during basebody turns. Solar panel flexibility has been studied and modeled for the DS 1 spacecraft, and all controllers have been designed to be robust to the flexible modes. Additionally, all S/C attitude adjustments are implemented autonomously with onboard constraint checking. The G&C autonomous architecture incorporates the low level control components, the "traditional G&C", with high level interfaces to autonomous attitude planning. An earlier description of the DS 1 Autonomous Guidance and Control System is available in Reference [1].

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2.0 Introduction

2.1 Program and Project Description

Planetary spacecraft have been progressing toward autonomous operations with regards to many guidance and control functions. Building upon experience gained from Galileo, Mars Pathfinder, and Cassini WC, the JPL Guidance and Control experts have embarked upon a new level of autonomous operations for an interplanetary spacecraft design which has not been tried before. The first of the New Millennium Program (NMP) spacecraft series, the Deep Space Mission 1 spacecraft is designed to help enable science missions by developing and validating some of the key technologies they require [2]. One of the key technologies selected for the DS 1 mission is the autonomous onboard optical navigation. The integration of this technology with an onboard autonomous attitude control leads to significant accomplishments in the autonomous spacecraft development.

2.2 Mission and Spacecraft Description

The DS1 spacecraft, slated for launch on July 1, 1998, is jointly developed by NASA and the industry partner, Spectrum Astro, Inc. The DS 1 spacecraft will weigh approximately 400 kg at launch and will use the Delta 7326-9.5 (Med-Lite) launch vehicle from Goddard Space Flight Center Orbital Launch Services. The current targets of the mission are asteroid McAuliffe flyby on 1/20/1 999 and comet West-Kohouteck-Ikemura ftyby on 6/2/2000. A flyby of Mars is also planned between the asteroid and the comet encounters, on 4/18/2000. The configuration of the S/C is depicted in Figure 1.

This spacecraft will be the first deep space mission to use Solar Electric Propulsion (SEP) as the main propulsion stage. The SEP stage has been selected as one of the technologies to be validated and is provided by the NSTAR (NASA SEP Technology Applications

Readiness) program. The Ion Propulsion System (IPS) utilizes highly accelerated xenon propellant emitted from a 30-cm diameter thruster through a molybdenum grid. The thruster will require gimbaled Thrust Vector Control (TVC) by the autonomous attitude control system.

Due to high power requirements of the IPS (2.5 kW), a solar concentrator array technology will also be required and validated. The Ballistic Missile Defense Organization, working with NASA Lewis Research Center and AEC-Able Inc., will provide Solar Concentrator Arrays with Linear Element Technology (SCARLET). SCARLET uses Fresnel lenses to concentrate sunlight onto cells with an expected average efficiency of 24%. The pair of arrays with a total area of approximately 10 m^2, will produce 2.6 kW at 1 AU, using much smaller area and mass than conventional arrays. However they do require much tighter pointing control by the autonomous attitude control. The one axis which is gimbaled (the Alpha axis) requires a total of 2 degrees pointing control accuracy and the non-gimbaled axis (the Beta axis) requires 2.5 degrees of pointing control accuracy.

The high-gain antenna will require a pointing control of 1 degree for peak data rate and 4 degree for -3 dB data rate.

The Miniature Integrated Camera and Spectrometer (MICAS) will be used both for optical navigation and science observations. The tightest pointing control required for some science observations is 0.03 degrees.

The single flight computer for the DS1 mission is based on the RAD6000-5L chipset from Federal Systems Co. of Manassas, Virginia. It is the same computer as the one used by the Mars Pathfinder mission. All devices on the S/C communicate via the 1553B standard bus. The flight computer is the single bus master; all other devices are remote terminals.

The S/C will utilize an autonomous all-sky acquisition charged coupled device star tracker (AST), procured from Lockheed Martin Corporation in Sunnyvale, California, and a 3-axis rate sensor (LN-200) procured from Litton Guidance and Control Systems, Woodlandhills, California, for attitude determination. One digital two-axis 64x64 degree sun sensor, procured from Adcole Corporation, Marlborough, Massachusetts, is used for fault protection and as a back up for attitude determination, in case of permanent star tracker failure.

The S/C attitude during ballistic cruise is maintained by eight Reaction Control System (RCS) hydrazine thrusters (MR-103C), procured form Primex Aerospace, Redmond, Washington. During ion propulsion thrusting phases, the control of the S/C X and Y axis is handled by the thrust vector controller, using two-axis linear engine gimbal actuators, procured from Moog Corporation, East Aurora, New York. The RCS thrusters continue to control the S/C Z-axis. The control of the solar panel alpha axis is maintained at all times, using solar array drive actuators with type 2 stepper motors, procured from Schaeffer Magnetics, Chatsworth, California. All controllers have taken the solar panel structural flexibility into account by being gain stabilized and having control bandwidths which are much lower than the first flexible mode of the panel (0.25 Hz).

Major Flight Software Subsystems

The architecture of the DS 1 flight software is depicted in Figure 2. Major components will now be described.

3.0 Autonomous Navigation

An important technology to be validated is the autonomous onboard Optical Navigation (OPNAV) [3, 4]. Although optical navigation has been used by previous JPL spacecraft, such as Voyager and Galileo, the DS 1 mission will be the first mission to utilize a completely onboard OPNAV system.

OPNAV requires that multiple images are taken of asteroids and background stars at frequent intervals. Observational windows are defined and scheduled onboard. The obtained images are returned to the onboard navigation software and processed to identify the beacon asteroids and calculate their line of sight vector against the known star background. Spacecraft state (position, velocity, and associated force models) is updated onboard periodically using a batch algorithm.

4.0 Flight System Control

The Flight System Control (FSC) fills the role of traditional "Command and Data System" module on the DS 1 spacecraft. It is responsible for low-level interfaces to the hardware, including bus input/output. It provides the system services including the operating system (OS), timing and file system management and InterProcess communications. It is also responsible for collection and downlink of telemetry as well as the distribution of the uplinked data.

5.0 The Executive/Loop Closer/Sequencer

Since the Autonomous Remote Agent (RA) technology, which was slated to fly on the DS 1 spacecraft, was demanifested in March of 1997, a new flight software element has been introduced to replace the functions of the RA. This flight software module, still at the definition stage at this time, will serve as the coordinator and the intermediary between other flight software modules. Specifically, all messages and commands required to cause specific actions by other modules, such as mode changes, are passed through this module. In the cases where closure of onboard loops are required, for example between onboard navigation and onboard guidance and control to accomplish the flybys, the loop closer, coordinates and manages the interactions. The sequencer will coordinate the execution of sequences, both those issued from the ground and those generated onboard.

6.0 Autonomous Guidance and Control (Attitude Control)

The Autonomous Guidance and Control is responsible for the traditional tasks of the "Attitude Control System (ACS)", enhanced with additional autonomy.

Several of the autonomous G&C developed capabilities for DS 1 will now be discussed in detail.

6.1 Autonomous Attitude Planning

Without autonomous attitude planning capabilities, the frequent OPNAV observations (currently envisioned to be 10 consecutive image sets once a week) may become a labor intensive activity for the ground operations team. The onboard navigation, along with the G&C's Attitude Planning Expert (APE), will simplify this task tremendously.

Once the optical navigation module has selected a set of target asteroids for the next observation window, the request is forwarded to the APE to check for the validity of the targets. APE is a stand alone process which has no real-time requirements. APE performs the necessary computations, including potential geometric constraint violations and dynamic turn violations, such as maximum turn profile rate/acceleration limits, and reports back on the acceptability of the planned observation. APE also handles the expansion of the turn requests to low level commands. Once the turn sequence is constructed, the onboard navigation software will construct and forward a mini-sequence to the Executive/sequencer which in turn will forward that to the onboard Attitude Commanding (ACM) function for execution of the observation sequence.

6.2 Autonomous Execution: Overview

The DS 1 G&C system also supports the autonomous execution of several S/C functions. Upon the generation of the mini-sequences by onboard navigation, autonomous execution of OPNAV observational sequences and trajectory correction maneuvers is implemented within the G&C area. The interfaces are similar to the traditional ground sequence interfaces. The commanding interfaces and the resultant attitude control modes are depicted in the state transition diagram (Figure 3). Additional logic also exists in the Executive whose effects show up as commanded state changes (for example sequence necessary to initiate G&C transition into the TVC mode is handled by the Executive).

6.2.1 Autonomous Execution: Attitude coremanding

The attitude control system will autonomously implement requested attitude changes. Upon the arrival of turn specifications form the sequence, the ACM establishes the proper turn parameters. It profiles the turns such that no S/C turn rate/acceleration limits are violated. It also ensures that the tight solar panel pointing constraints, mentioned earlier, are observed such that the Alpha axis is maintained within the 2 degree pointing requirement during the entire turn duration and the Beta axis is quickly returned to within the pointing requirement after the end of the turn.

Other geometric constraints are also kept under observation during the attitude changes. A constraint monitor function is active at all times and if an imminent constraint violation is detected, a new path is generated autonomously to get around the constraint region. The ACM performs the function of commanding a self-consistent set of attitude, rate, and acceleration profiles which the attitude controller must nominally follow. The attitude and rate commands are continuous but the acceleration command is allowed to be discontinuous. The commander makes no checks on the legality of the attitude, rate and acceleration commands. This function is left to the Constraint

Monitor (CMT) which performs the requisite checks before allowing the ACM data to pass on to the Attitude Controllers. When one or more checks fail, CMT modifies the ACM commands such that the modified result is not in violation of any constraints. Two types of constraints are enforced by CMT: the dynamic and the geometric constraints. Dynamic constraints, which are hardware capability driven, ensure that the commanded rate and it's time-derivative do not exceed the specified rate and acceleration limits. This prevents the attitude controller from being commanded prohibitively large rates and accelerations. These constraints are specified as rate and acceleration ellipsoids in the spacecraft fixed coordinates. The geometric constraints are essentially conical constraints and which may be specified as: do not let spacecraft fixed vector B come within D degrees of the inertial vector L The inertial and body objects are referred to by name, the actual directions (unit vectors) are maintained in an updatable table on board. The inertial object directions are derived from the position vectors supplied by navigation. Several such constraint cones maybe in force at the same time. The definitions of the set in force resides in a constraint table onboard (Table 1). The set in force depends on the S/C activity.

CMT is essentially a predictor-corrector which propagates ACM commanded motion into a reasonable future and takes appropriate avoidance action when a geometric constraint is found to be in an imminent violation. The corrective action taken is designed to be such that the constraint in question is not violated eventually. The corrective action consists of three steps, which may be repeated several times until the CMT commanded motion merges with the ACM commanded motion. The end goal is to always try to move towards a goal attitude, a point in space which is not violating any geometric constraints and is close to the ACM commanded path. When the ACM is not in violation, the goal is of course the ACM command itself. The first action taken when a violation is declared imminent is the so-called Escape where an acceleration is commanded such that it pushes the offending body vector radially away from the inertial vector. This action is maintained until the constraint in question is no longer in imminent violation. If at this point it is possible to move along a great circle towards the goal attitude and not violate any constraint in the immediate future, a Clear mode is declared (CMT, when it is not in avoidance, is always in the Clear mode) where the motion is a great circle arc heading towards the goal. When this is not possible, the constraint (or a collection of constraints) has to be circum-navigated until it is possible to transition to the Clear mode. This intermediate mode is called the Circulate mode. Several cycles of Escape - Circulate - Clear (not necessarily in this order) may be required until the goal attitude is reached. When the CMT attitude is far from the goal it is trying to attain, largest possible rate is commanded until the S/C is in the vicinity of the goal, where a rate proportional to the distance from the goal attitude is commanded.

It should be noted that, at the planning stage (APE), constraint avoidance actions have to be taken into account in the turn completion time predictions. The approach taken is to allow sufficient margin such that the avoidance actions can be completed should the nominal ACM-commanded path be found to be in violation.

The attitude commanding is performed via a specification of "primary and secondary vectors". This specification method has also been used for the Cassini and Mars Pathfinder spacecraft, Each new attitude will be completely defined using four vectors : a primary inertial vector, a primary body vector, a secondary inertial vector and a secondary body vector. Examples of inertial vectors include : Earth, Sun, or target asteroids. Examples of body vectors include : MICAS boresight, high-gain antenna boresight, or panel yoke. ACM will attempt to completely align the specified primary inertial and body vectors. ACM, depending on the mode specified, will attempt to also either make the secondary inertial and body vectors parallel or make them orthogonal (used for pointing solar panel normal to Sun).

6.2.2 Autonomous Execution: Maneuvers

Another feature of the onboard autonomous navigation is that it will compute the required trajectory correction maneuvers. Going hand-in-hand, the attitude control system will autonomously execute the requested maneuvers. There will be two types of maneuvers on the DS 1 WC. The Ion Propulsion System will produce a low thrust level of 0.05 to 0.09 Newtons and requires long durations of continuous thrust to accomplish the mission objectives. For example the current mission design requires that the IPS be continuously operated from Launch + 15 days to Launch + 26 days. The thrust is resumed after the asteroid flyby on Launch + 207 days and terminated before the comet flyby on Launch + 563 days. As mentioned earlier, the OPNAV will update the state of the S/C at specific intervals and may request either a new IPS thrusting profile or slight adjustments to the profile currently in process. The navigation request will appear in the form of a thrust vector and epoch. Due to relatively large misalignment and center-of-mass migration errors, the IPS execution is achieved via TVC. This will require that ion thruster be gimbaled such that the thrust vector passes through the center-of-mass of the S/C. This will create an additional body vector to be maintained and updated.

Navigation area requires that TVC be executed to 30 milliradians (3 sigma) knowledge in inertial space and to 60 milliradians (3 sigma) stability over 10 hours. The required travel range for the gimbals was initially a large unknown, since the particular configuration of DS 1 for the ion propulsion system was never tried before. An extensive error budgeting effort was spent to clearly define and understand all of the contributions to the TVC execution error budget and gimbal travel error budget. The TVC knowledge and stability error budget is documented in Table 2.

Entry into TVC mode requires special care. The onboard navigation starts the activities by computing direction and thrust level for the ion engine for the upcoming window, which may be up to 24 hours. Navigation then launches a mini-sequence (through the Executive/Sequencer) asking ACS to turn the spacecraft to an attitude defined by pointing the solar panel at Sun and aligning the IPS pre-aim vector with the inertial thrust vector requested by OPNAV. ACS achieves this entry attitude using RCS. Navigation will wait for the turn completion message to arrive from ACS (again through Executive/Sequencer). The Executive then commands the IPS to the required thrust level and ACS into the TVC mode.

Another type of maneuver possible on the DS1 S/C is the RCS delta-V. This type of maneuver will be utilized for final targeting maneuvers prior to the flybys. It simultaneously utilizes the four RCS thrusters along the S/C Z-axis to impart a short duration, small delta-V. These thrusters are fixed to the S/C structure and will not require a pre-aim vector. Special interactions are also required for the autonomous execution of the RCS delta-V's, since the maneuvers are scheduled too close (12 hours and 6 hours to each closest approach) to allow interactions with the ground system. Again, the process is started by onboard navigation software calculating required maneuver size and attitude based on recent orbit determination computations. The request is forwarded to the APE. The APE will check for legality of the requested maneuver attitude. Since these maneuvers are probabilistic in nature, it is highly likely that they will fall into a constraint zone. In that case, the APE will vectorize the requested delta-V into two other vectors which will fall on the outside edges of the constraint zone. The APE will calculate the resultant new attitudes and maneuver sizes and return them to navigation, along with requited turn parameters to set up the new attitudes. Navigation software will again recompute the maneuver parameters, and construct a mini-sequence asking ACS (through the Executive/Sequencer) to turn the spacecraft to first attitude, and enter the RCS delta-V mode to impart the first component of the delta-V. ACS will autonomously exit the delta-V mode, once the requested delta-V has been accumulated. Then another turn command is issued via the mini-sequence and the whole process is repeated for the second leg of the maneuver.

7.0 G&C Software Organization

The flight computer runs the VxWorks real-time operating system (version 5.1), developed and ported to the RAD6000 by Wind River Systems of Alameda, CA and procured by JPL. In both flight software and testbed development, DS 1 heavily exploits VxWorks' cross-platform compatibility and close relationship to Unix.

All G&C flight software for the DS 1 mission are written in ANSI C. As Figure 4 shows, the G&C components are contained in two VxWorks processes.

The bulk of the G&C code runs in a single real-time priority process, while the APE runs at below real-time priority. The main sampling rate for the G&C control and estimation loops is 1 Hz. Despite the real-time nature of attitude control, G&C code occupies a sufficiently high level in the DS 1 software hierarchy to permit avoidance of all operating-system dependent services, a key factor in the development and testing approach. Only two services are required by the G&C code timer-services and InterProcess Communications (IPC). Unix and VxWorks versions of both services are developed with identical Application Programming Interfaces.

The IPC permits a fully data driven architecture for the G&C code. Effectively, the required sensor data act as semaphores for the real-time loop. Sensor data is made available as IPC messages from the 1553 Bus Controller, and triggers the real-time loop to produce actuator command messages. Synchronization to the design sampling rate of 1 Hz is therefore implicit in this architecture. State, parameter, and other data required by G&C also arrive via IPC messages, and are handled at the appropriate time with the assurance that the IPC provides a reliable transport layer with sufficient queuing. The need for semaphores, shared memory, sockets, and other low-level OS services are eliminated, enhancing both modularity and portability.

8.0 Development & Testing Approach

The greatly shortened schedule of DS 1 has forced the adoption of a lean development and testing approach to the G&C flight software. In addition, the autonomous architecture described here requires greater integration with other software subsystems earlier in the development cycle. Factors in our favor, which are fully exploited, include the use of C and a modern real-time operating system, the intimate relationship between VxWorks and Unix (with its rich set of development tools, both commercial and public domain), the availability of VxWorks on commercial real-time computers which approximate the final flight target, and the careful isolation of OS-dependent services in the software architecture as described above. These factors permit the development of flight software concurrently with analysis and design, to a greater extent than previous deep space flight projects. All G&C simulations are performed with steadily maturing versions of flight code.

While this may seem as obvious approach on the surface, its details are challenging to implement, as conflicting requirements must be satisfied while minimizing the pitfalls of independent, "dead-end" work. Early in development, isolation of interfering effects (for example, estimation from control and profile generation, TVC from SAC and RCS) and a fast compile-simulate-analyze cycle must be supported. Detailed performance analysis of the entire G&C system using high fidelity models comes later, along with the greater overhead of a larger testbed. Verification on a real-time testbed is an adjunct activity which may not require the same level of fidelity, but occupies an increasing fraction of the testing effort as development proceeds. Throughout the development process, the concurrent development of other software subsystems require partially functional G&C code. These requirements indicate two orthogonal processes to concentrate on: incremental capability of the testing environment, and incremental release of interim versions.

The testing environment divides into roughly three stages: unit test, integrated non-realtime test, and integrated realtime test. The first is not a coherent "environment" at all. The Attitude Estimator (ATE) is developed with only sensor and kinematics models, the Solar Array Controller (SAC) is developed using an independent SADA/SCARLET model, and the TVC and Basebody Controller (BC) are developed using simple dynamics models generated using the commercial tool SD-FAST. It is our experience that the effort invested in developing these small, independent unit testbeds is small and pays off in the balance, although attention must constantly be paid to properly define the scope and avoid over-development.

The second environment used is an integrated non-realtime Unix simulation environment. The complete ACS task is run, taking sensor inputs and sending actuator outputs to an SD-FAST based dynamics simulation via the same IPC channels as on the spacecraft. This permits us to enter the real-time test environment with much greater confidence for success than we otherwise would have.

The development of the flight software-wide real-time testbed providing high fidelity simulation and hardware models, including fault modeling, is a separate and well supported task under DS 1. It leverages the Unix/VxWorks commonality to produce one testbed which runs under both. This, in conjunction with the porting of underlying software services, minimizes the overhead transitioning through the second and third stages of testing. The real-time testbed itself divides into versions which hosts the flight software on both commercial single board computers and the flight computer itself, the former being used to avoid availability bottlenecks,

The process by which incremental releases are defined and integrated in DS 1 is experimental, and pushes the experience base of previous missions. Three staged releases (R), coined R 1 through R3, were attempted between the start of the flight software development and up to the point which the RA architecture was demanifested from DS 1. Four other releases, coined MO through M3, are planned for the remainder of the project, with the Ml product being ready for delivery to the Assembly, Test, Launch and Operations (ATLO) environment and M2 and M3 product providing final algorithmic enhancements in specific areas. This was necessary, since the flight soft ware architecture had to undergo significant restructuring once the RA was demanifested. An architecture similar the Mars

Pathfinder S/C was adopted, requiring many of the existing modules to be modified or re-written.

For each release, all flight software subsystem undergo a process: definition of an interim scenario which defines the capability level, resolution of all inter-subsystem interfaces, delivery, and integrated testing. The product of each release is intended to be a partially functional but complete software system for the entire spacecraft, useable as a basis for further development especially where inter-subsystem interactions are important. The potential payoffs are high: instead of resolving conflicts through extensive pre-planning and post-integration debugging of the full system, this "incremental" development model promises to utilize feedback to a greater extent to shave off integration time. However, if improperly executed, the incremental model can lead to greater net overhead brought about by each interim release. Moreover, the factors which make the product of each release useful for subsequent cross-subsystem development are subtle and easy to miss. One lesson we have learned so far is that too many incremental deliveries, early in the development phase, do not work with the attitude control algorithm and flight software development flow. In fact they hurt us by introducing artificial break points in the development flow, which force the developers to resort to unnecessary workarounds and to generate too much throwaway work. Incremental deliveries work well late in the ACS development stage, after a core design and infrastructure has been established and tested. Enhancements and modifications as a result of better H/W and S/W information and test results are well suited for later stage incremental deliveries.

9.0 List of Acronyms

ACM: Attitude Commander
ACS : Attitude Control Subsystem
APE : Attitude Planning Expert
ATE: Attitude Estimator
ATLO: Assembly, Test, and Launch Operations
BBC: Basebody Controller
CMT : Constraint Monitor
DS1 : Deep Space One
G&C : Guidance and Control
GDE: Gimbal Drive Electronics
H/W: Hardware
IMU : Inertial Measurement Unit
IPC : InterProcess Communications
IPS : Ion Propulsion System
JPL : Jet Propulsion Laboratory
MDC: Mode Commander
OPNAV : Optical Navigation
OS : Operating System
PDE : Propulsion Drive Electronics
RA : Remote Agent
RCS : Reaction Control System
RCSDV : RCS Delta-V Controller
SAC: Solar Array Controller
SADA : Solar Array Drive Actuator
SRU: Stellar Reference Unit
SSA : Sun Sensor Assembly
SIC: Spacecraft
S/W: Software
TVC : Thrust Vector Controller

10.0 Acknowledgments

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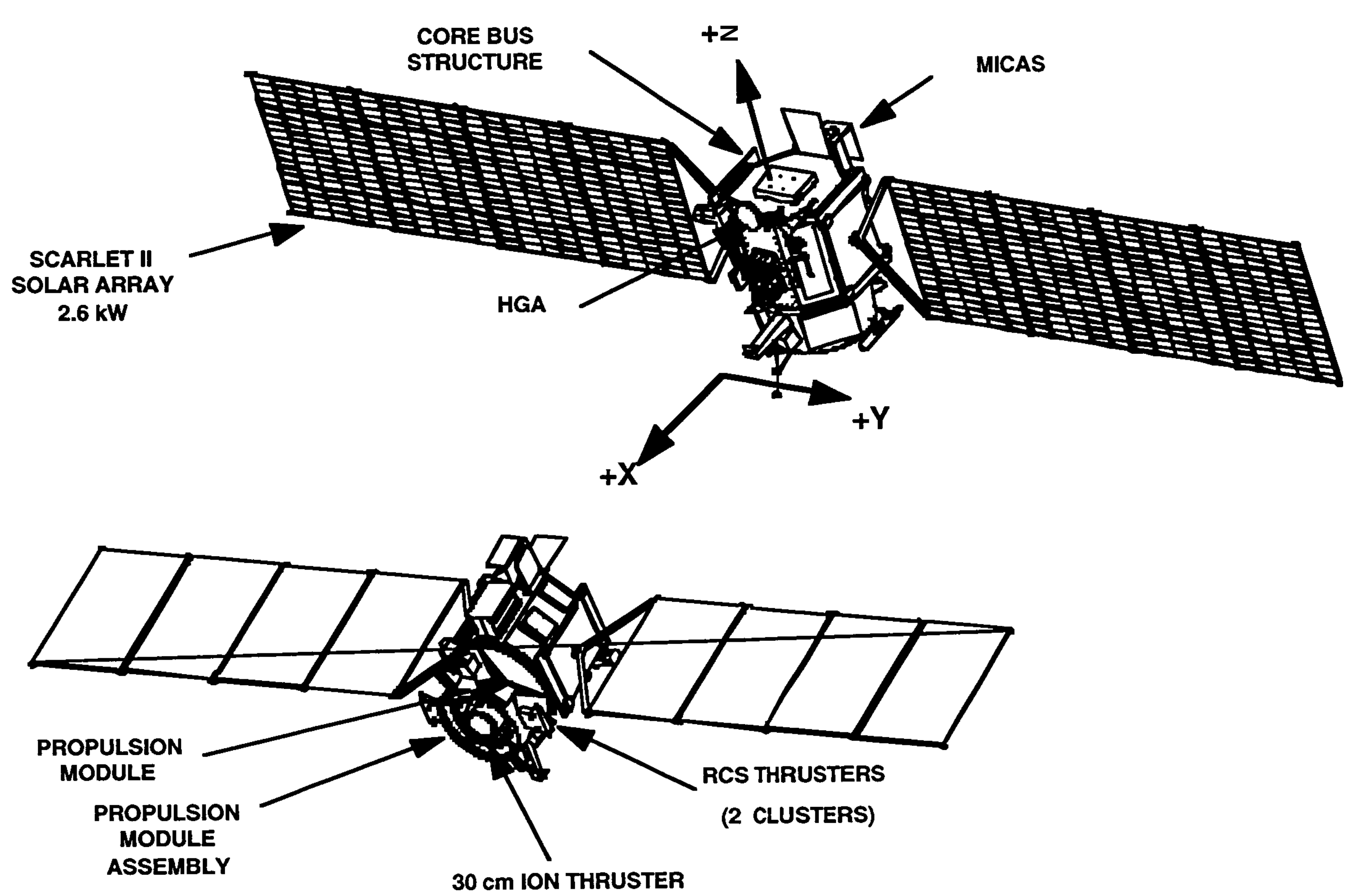
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STRUCTURE
+Z
MICAS
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HGA
+Y
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PROPULSION
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PROPULSION
MODULE
ASSEMBLY
30 cm ION THRUSTER
RCS THRUSTERS
(2 CLUSTERS)

1. DS1 nfi

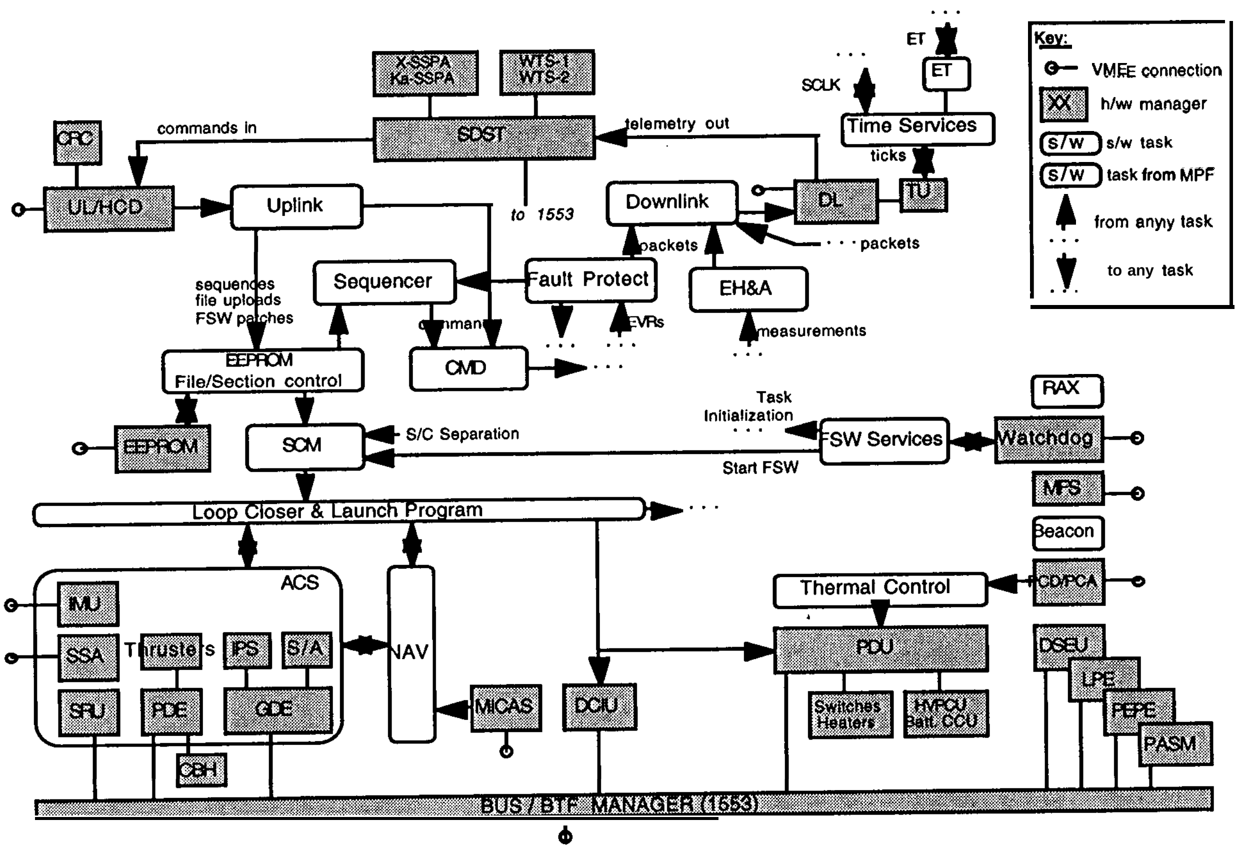

Figure 2. DS 1 Flight Software Architecture

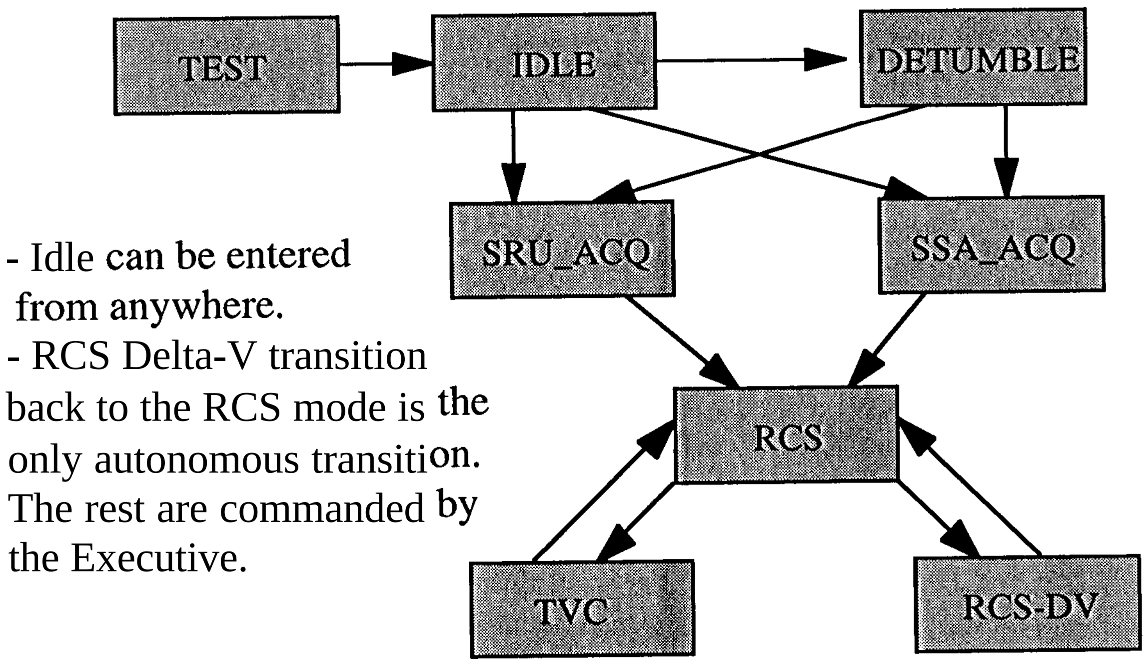

Figure 3. DS1 ACS State Transition Diagram

	Sensitive Item	Constraint Cone (Axis)	When Applicable	Time Allowed Within Cone	Time needed to Cool Down/ Recover
I	MICAS Primary Aperture	+/- 0.9 deg (+Z)	At all times	200 msec rate = 9 °/s	N/A fatal
z	MICAS Primary Aperture	+/- 10 deg (+Z)	At all times	TBD	N/Λ
3	MICAS Optical Bench Assembly Radiator	+/- 90 deg (+Z)	When MICAS operational	N/Λ	3 days for IR 1 hour for OPNAV VIS 1 day for Science VIS or UV
4	MICAS IR Radiator	+/- 70 deg (-X)	At all times	5 minutes rate = 0.47 °/s	3 days for IR
s	MICAS IR Radiator	+/, 90 deg (-X)	When MICAS IR operational	N/Λ	3 days for IR
6	MICAS Occultation Port	+/- 1.6 deg (38 deg from +Z towards +X)	At all times	20 Seconds rate = 0.16 °/s	N/A
7	PPU Radiator	+/- 30 deg (+Z)	When SEP operational	N/Λ	TBD
8	Star Tracker Boresight	+/- 35 deg (8 deg offset from +Z, 15 deg out of plane of the panel)	When SRU operational	N/A	TBD
9	Kinematics Amplification Factor	+/- 30 deg (+Z and -Z)	When SEP operational	N/Λ	N/A

Table 1. DS1 Geometric Constraints Table

Item	Description	Responsibility	Value	Unit	Remarks
	IPS Knowledge and Stability Error Budget (All values in mrads, 3 sigma)				
1	IPS thrust vector (measured at grid face) to engine centerline	NSTAR	17.5	mrad	
2	IPS thrust vector alignment instability -wear	NSTAR	19.3	mrad	Long term stability. Based on extrapolation of data assuming monotonic wear, with no additional correction Factor
3	IPS thrust vector alignment instability -thermal	NSTAR	17.5	mrad	Short term instability (over 1-2 hours)
4	Gimbal axis tilt (such that thruster mask II to gimbal bulkhead)	Spectrum	8	mrad	alpha2
5	Gimbal bulkhead till to S/C Centerline	Spectrum	4	mrad	alpha1, includes internal gimbal misalignments
6	S/C Centerline to S/C reference ham. Z axis	Spectrum	0	mrad	By definition
7	S/C reference frame to Partial Bus reference frame	Spectrum/JPL	1	mrad	
8	Partial Bus reference frame to star tracker mounting	Spectrum	7	mrad	
9	Star tracker mounting to tracker alignment cube	Spectrum	1	mrad	
10	Star tracker alignment cube to tracker boresight	Tracker vendor	0.1,	mrad	
11	Bus Thermomechanical distortions	Spectrum	2	mrad	
12	**subtotal of Angular Misalignments**		**33.4**	**mrad**	**Knowledge of thrust vector in ACS coordinates**
13	ACS Altitude Knowledge in Inertial Coordinates (X& Y)	ACS	0.1	mrad	
14	**Knowledge of IPS Thrust Vector in Inertial Coordinates (RSS 12 &13)**		**33.4**	**mrad**	**Requirement is 30 mrad**
15	Angular error due to center c4 force offset with respect to IPS engine centerline	NSTAR	23,3	mrad	Representative value. To be confirmed by NSTAR
16	Angular error due to IPS engine centerline offset w.r.t gimbal centerline	Spectrum	3.5	mrad	Using shortest moment arm
17	Angular error due to gimbal artic. axis cross hairs offset w.r.t bulkhead centerline	Spectrum	2.3	mrad	Using shortest moment arm
18	Bulkhead centerline offset w.r.t. S/C centerline	Spectrum	3.5	mrad	Using shortest moment arm
19	Angular error due to S/C centerline offset with respect to SIC center d mass	JPL	18.7	mrad	Based on initial stowed c.g X/Y position 01 <.3 mm, travel of 5 mm during the mission and uncertainty of 10 n
20	Partial Bus frame centerline offset w ft. S/C centerline	JPL/Spectrum	2.5	mrad	
21	**Stability of Thrust Direction in Inertial Space (RSS 14-20)**		4s.4	**mrad**	**Requirement is 40 mrad for [10] hours**
	Used 0.234 m for minimum Z c.g. distance to S/C reference datum (including worst case uncertainties) and 0.622 for thurst application point to S/C reference datum distance, making the shortest moment arm 0.856 m.				

Table 2. IPS Execution Knowledge and Stability Error Budget

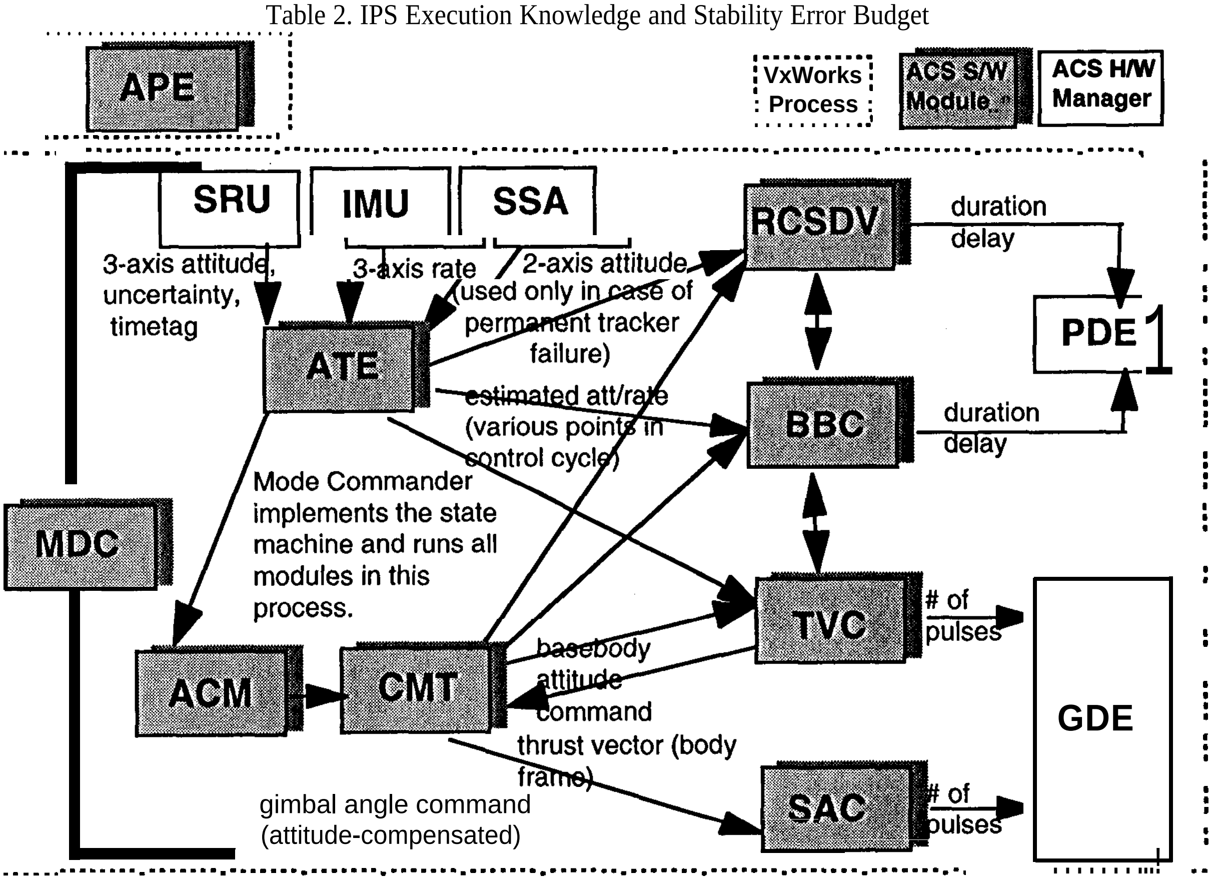

Figure 4. DS 1 ACS Software Block Diagram