Highly-Autonomous Event-Driven Spacecraft Control

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ABSTRACT

Future JPL missions will continue to be scientifically and technically more ambitious, and will demand more autonomy to accomplish complex tasks in uncertain environments and in close proximity to extraterrestrial surfaces. A prime example is small body rendezvous and sample return. In addition to mission demands, affordability is now a primary driver. The call is for smaller missions with greatly reduced cost of operation and less expensive spacecraft designs. Spacecraft with highly-autonomous, goal-directed control systems are proposed to meet these challenges.

This paper will discuss the plan to design and develop a proof-of-concept attitude and control subsystem (ACS) that has the ability to capture science events and enable a small body rendezvous and sample return mission while requiring only one person level-of-effort for ACS ground operation support.

The technology to be developed and demonstrated includes: on-board sequence generation and execution, precision closed-loop maneuver and attitude control, target acquisition and tracking, and sensing and representation of spacecraft system state.

A reference mission development scenario, complete with a representative mission, spacecraft design concept, and development process, will be used in order to incorporate all the nuances of a real mission, where experience has shown that the real problems lurk. Previously-conducted JPL studies will be used to develop the scenarios. The representative spacecraft will be small to micro and consistent with a Discovery class mission.

Possible approaches for the new paradigms in system architecture, ground commanding and test and verification that will be necessary for highly-autonomous event-driven controls will be addressed.

1 INTRODUCTION

1.1 Background

The capabilities of spacecraft guidance and control systems have undergone an evolution that has taken them from the early remote radio-controlled analog systems of the 50's and 60's to the highly successful digital reprogrammable control electronics of the 70's, first flown in a deep-space mission on Voyager. This reprogrammability permitted in-flight modification to the Voyager AACS to change and add capabilities that had not been required or envisioned prior to launch and was, thus, highly valuable as unplanned targets of opportunity surfaced during the mission. As an example, an added Image Motion Compensation capability enabled the outstanding, high-resolution smear-free images of Neptune and its moons during the August '89 flyby. Spacecraft autonomous control capabilities were further refined on later missions such as Galileo, Magellan, and Topex. The Cassini[1] AACS is currently re-defining the state-of-the-art in on-board autonomy through such new capabilities as target relative pointing, autonomous star tracking, autonomous calibration, and turn profiling independent of dynamic properties. It also maintains on-board knowledge of the angular positions and rates of up to 40 targets and planetary objects. This will support autonomous target motion compensation and a rudimentary capability in autonomous pointing constraint avoidance without sequence interruption.

Although much progress has been made, the system that has evolved is plagued with escalating costs associated with the excessive and labor-intensive ground support system and with very significant limitations in capability. Recent missions require AACS Ground Operations Teams as large as twenty to thirty people. As an example of capability limitations, pointing is still currently referenced to star attitude updates, while the capability is needed to do on-board autonomous pointing referenced to the actual object of interest, such as the actual planet, a crater, or an asteroid. Such capabilities were required by the CRAF mission (now canceled) and will be critical for future missions such as flybys and rendezvous (Pluto, and especially for small bodies/asteroids) where the short duration of the event and the uncertainties in the final encounter geometry and exact timing will demand a high degree of on-board autonomous execution in order to capture the maximum amount of science. These circumstances make a compelling argument for a systematic approach to study how, where, and to what extent autonomous pointing and control can be employed to reduce costs and enhance the scientific return. Proof-of-concept demonstrations (in space if necessary) must pave the way to convince decision makers of their viability and enormous potential.

Even though *intelligent* attitude and control subsystem (ACS) technology is in its infancy, we can automate a great deal of lower-level behavior. For example, while it is not feasible for the system to decide on its own that a volcanic eruption on 10 is interesting, it is feasible to acquire the eruption autonomously if its broad characteristics were predetermined and stored on board. Event-driven, on-board planning and execution of ACS functions is the big leap advocated here. The issue here is: what are the new paradigms for this level of autonomy? Discovering the answer is the quest of this proposal,

1.2 Vision

To develop by 1997 technology readiness of an autonomous ACS that will:

- Respond to high-level commands and capable of mission operation without intervention by ACS ground operations.
- Identify and capture science events and targets.
- Plan, verify, and execute maneuvers.

2 OBJECTIVES

The objective of this study is to develop the system architecture necessary for the design, testing, and operation of a representative on-board autonomous ACS system with high-level command interaction with the ground. Considering mission requirements and current capabilities, the highest priority automation needs to be included on board are:

- Sequence generation and execution,
- Precision closed-loop maneuvering and attitude control,
- Target acquisition and tracking, and
- Sensing and representation of spacecraft system state.

In meeting the above objective, the technology needs and readiness status will be assessed in the following areas: ACS hardware components, on-board data processing capability, and test and support systems.

The deliverable will be a proof-of-concept ACS design and code that autonomously performs AV maneuvers and acquires and tracks a representative science target. This will demonstrate the autonomous capabilities listed above and the overall system architecture, including the partition between flight and ground functions and verification requirements.

3 TECHNICAL APPROACH

3.1 Scope

The scope of the work is restricted by examining a point-design sample return mission to the asteroid Anteros that includes a hovering phase or landing. The on-board autonomous functions include; attitude and AV maneuvers, target acquisition, closed-loop tracking, and target motion compensation. Other support functions, such as engineering data calibration, health and status monitoring, resource and data management, and fault protection, are assumed to be autonomous. The representative spacecraft will be small to micro, and consistent with a Discovery-class mission costing less than $150 million.

3.2 Overall Approach

A reference mission complete with a spacecraft design concept, and development process, is chosen to guide the highly autonomous control system design. Figure 1 illustrates the approach. The strategy in understanding the level of autonomy required for target acquisition is to characterize real potential science targets and to assess the corresponding system capabilities required for pointing, image resolution, and data processing. The requirements, architecture, and design for target acquisition are then developed. The reference mission scenario development activity mentioned above is the key to this approach because it leads to a design that meets real ‘scientific needs.

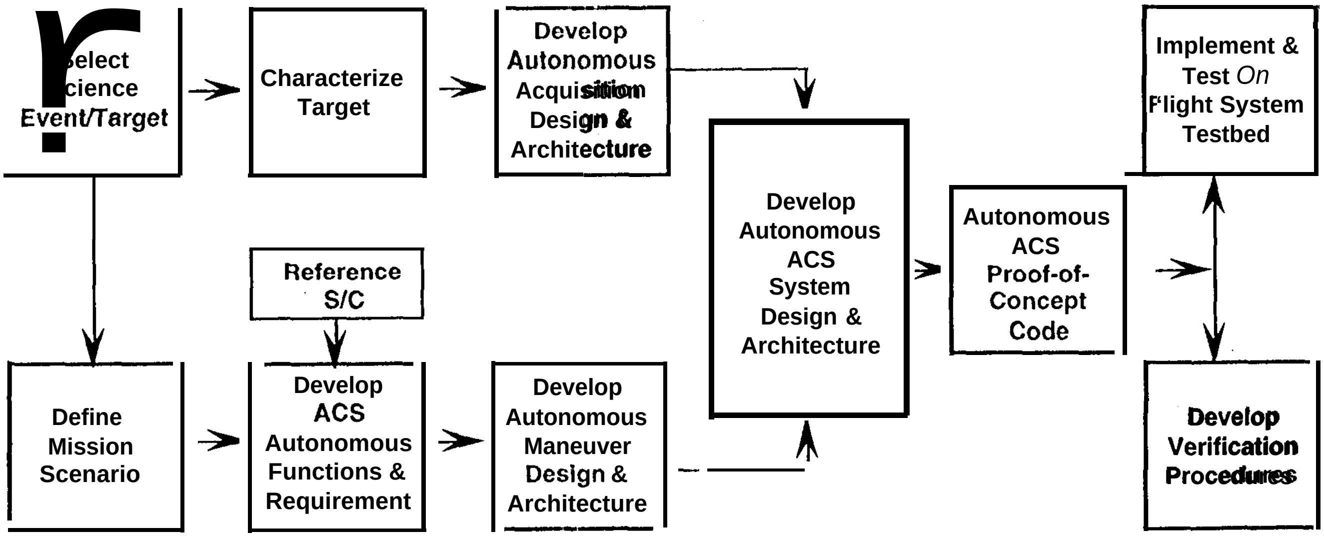

Figure 1. Autonomous ACS Architecture Development Approach.

‘**The** mission scenario is also used to identify the details of the autonomous functions needed for the mission, and to generate the requirements for developing their architecture. The strategy is to pick an autonomous function (such as AV maneuver) and use it to flush out the issues of on-board sequence generation, verification, and execution. Once again, in order to incorporate all the nuances of a real mission, where experience has shown that the real problems lurk, the maneuver is chosen not in isolation but as a segment of the mission scenario. The architectures of other autonomous functions can then be built by analogy since the functions of planning and execution are common to all of them.

For proof-of-concept, the autonomous function of the AV maneuver and target acquisition and tracking will be used to flesh out the design details and will be further developed into algorithms and code. The idea is to illustrate the utility of the architecture by demonstrating the performance of those functions. High-level commands and failure scenarios will be included.

The next stage is to implement the system on the flight system test bed (FST) and develop the verification requirements. The following are the specific tasks to realize the objectives:

- Subsystem design and architecture definition.
- Reference mission & spacecraft definition.
- Attitude & Control Subsystem design.
- Autonomous maneuvering and attitude control.
- Autonomous system proof-of-concept code.
- Implementation on flight test bed.
- Development of verification procedures.

4 TECHNICAL IMPLEMENTATION PLAN (1994)

4.1 Subsystem Architecture Definition

Current spacecraft ACS autonomous architecture is limited to support attitude estimation and control, command interpretation and maneuver execution. All other functions are decomposed into sequences of low level commands on the ground and loaded on board for execution using the combed interpreter. These deliberative functions require ground based observation, estimation and planning. In addition, current ACS architectures cannot support event-driven, real-time or near real- time reactive systems, which forms the core of any highly autonomous control system. A highly autonomous event-driven spacecraft control system implies transferring most ground commanding ‘processes to the spacecraft control subsystem, as shown in Fig. 2.

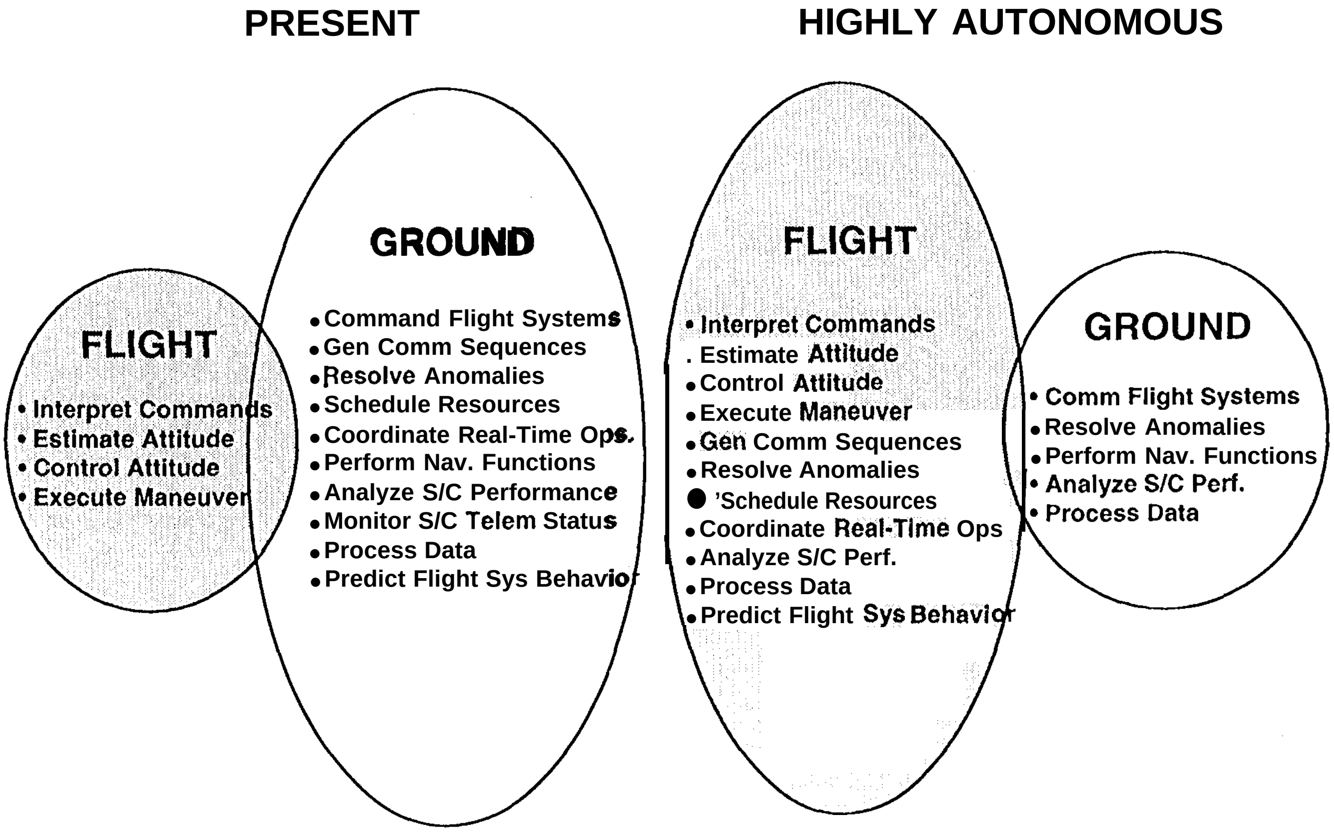

Figure 2. Spacecraft Control System Architecture.

in support of the study objective, a highly reliable and robust software architecture Will be developed. An architecture provides the design and structure of a system under construct. It should look beyond the limited scope of this study and provide flexibility and expandability. The selected architecture should allow for optimal partitioning of the activities between on-board and ground processing. An architectural specification, (Inscribing the pieces of the architecture (software, hardware, controller models, execution models, etc.) will be developed.

Functionally, the spacecraft activities may be divided into routine functions, special functions and exceptional functions. Most routine functions, such as attitude determination and science mapping functions, have already been implemented and executed as autonomous functions in previous spacecrft designs. However, current spacecraft architectures do not support autonomous special function handling, The new architecture to be developed under this study will focus on autonomy for Delta-V maneuvers and target tracking. Certain aspect of exceptional functions, fault recovery, will also be addressed.

The selected architecture for an autonomous spacecraft, as well as any other, control system, should provide both deliberative and reactive control constructs for all spacecraft behaviors under deterministic or varying conditions. The architecture should have the capability to achieve a goal, to react to the environmental changes, to recover from errors and failures, to manage resources and coordinate multiple tasks, as well as communicate with the outside world.

Goal Directed: This is perhaps the most fundamental of all of the autonomy requirements. The spacecraft must be capable of constructing and executing a plan to achieve a goal. That is the spacecraft should be capable of planning a path, Currently, high level commands (goals) are processed on the ground and decomposed into sequence of low level commands, which is then loaded onto the on-board processor for execution, Ground process must check for constraint violation, ensure proper resource allocation and predict environmental changes. It is the goal of this study to transform these activities to an on-board process.

path planning is key to a successful autonomous system, Control system should be capable of planning and executing its actions for the near term activities. It shall be capable of making decisions to carry, stop and replan in response to either a ground command or a sensed change in the environment, To accomplish this task, the system requires a complete and accurate model of the world. World model consists of information about the environment and the state of the control system. It also requires sensor and effecter information processing.

Reaction to a Changing Environment: Some of the future space missions under consideration at JPL and other centers, envision visits to unknown, or at best poorly known environments. As a minimum an autonomous spacecraft should have the capability to sense changes in the environment and update its world model to reflect the improving knowledge. Flybys at a close distance, hovering, landing and even sample retrieval from comets and asteroids are among future mission phases under consideration that could benefit from this capability.

Error Recovery : Detecting and recovering from failure to achieve a goal for any reason is a crucial autonomy requirement. Spacecraft must have the capability to detect deviation from the planned activities or divergence from the initial goal. Furthermore, it should have the decision making capability to decide the proper course of action, such as the decision to re-plan or to terminate. Ground based failure recovery may be possible under certain conditions, but error detection is a required on-board capability. Failure recovery would then enhance mission success by eliminating missed opportunities.

Visibility: To insure proper implementation of the autonomy, visibility into spacecraft actions and reactions and ground intervention will be desired. The architecture should allow for open and flexible communication. The spacecraft should be capable of broadcasting its decisions and actions. The architecture should allow intervention from ground in all levels of planning and control hierarchy.

Resource Management: Spacecraft's usually have very limited resources. As on-board consumables may not be replenished, care must be taken not to waste any of the available resources. Spacecraft must be able to keep track of its resources and plan to use them wisely.

Multi-Tasking: The architecture should support interleaved execution of two or more sequence of activities. Multi-tasking capability will allow optimal decision making on-board to insure maximum use of the spacecraft resources.

To accomplish the above requirements, as a minimum the spacecraft control constructs should include the following:

- High level command decomposition
- Constraint checking
- Resource allocation and monitoring
- Sequence generation and execution
- Execution monitoring
- Exception Handling
- Decision making
- Fault detection, protection and recovery
- Sensor and effecter processing
- World model

4. 1.7 Scope of Autonomy

The scope of this study was deliberately limited to the implementation of autonomy for trajectory correction maneuvers and target tracking. It is believed that the implementation of the autonomous trajectory correction maneuvers would reduce the operational cost, while the autonomous target body tracking enables science currently unachievable. Both of these activities encompass all aspects of an event-driven autonomous system,

4,1.8 Detailed Approach

Existing autonomous architectures, such as Task Control Architecture (TCA) and the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM), will be explored and evaluated for inclusion in a new software architecture. The new architecture will support high level commanding, on-board path planning, on-board sequence generation and execution monitoring.

4.2 Reference Mission and Spacecraft Definition

4.2.1 Reference Mission

The reference mission selected is to rendezvous and a possibly a sample return to the asteroid Anteros. Stepping through the mission phases and critical events will point out the basic requirements for the autonomous design,

Launch & Deployment: Initial spacecraft checkout. Initial testing and calibration of subsystems and state-of-health checks.

Cruise: Continued spacecraft testing and calibration.

Rendezvous: Obtain data to reduce ephemeris error for target asteroid, and to search for possible satellites. Science mosaicking of asteroid begins as soon as it is five or more pixels in diameter. Rendezvous maneuver performed at > 100 asteroid diameters, to slow relative spacecraft motion to < 100 m/s. Maneuver towards asteroid, with planned rectilinear flyby at > 20 asteroid diameters to sun ward, at < 30 m/s. Doppler tracking for mass determination. Additional slow asteroid flybys, above and below asteroid, at > 10 asteroid diameters, at <20 m/s, with multicolor mosaicking. Doppler tracking for further mass refinement and gravity harmonics.

Orbits Around Asteroid: Maneuver into circular orbit around asteroid and map lit asteroid surface with multicolor filters at multiple phase angles. Maneuver into circular gravity orbit at altitude of -3-5 asteroid radii, for gravity field measurements. Occasional high resolution imaging of selected target sites on the asteroid during this period.

Site Selection: Obtain multicolor mosaics of six candidate landing sites, selected from previous orbital mapping. Change orbit as necessary to access all six sites, Decrease orbital altitude and perform high resolution imaging of the six sites. Maneuver into delivery orbit and place spacecraft in a hover position over selected site.

4.2.2 Reference Spacecraft

The reference spacecraft will be defined to enable the requirements to be flowed to the autonomous ACS and navigation functions being developed in this study. The spacecraft will be developed to be compatible with a design that includes the following automated system-level features:

- Redefined system architecture for control of complex tasks and on-board resource management and sequence generation.
- On-board sensing and representation of spacecraft system state and operating environment.
- Improved system robustness to provide continued operation in the presence of faults and uncertainties.
- Miniaturized sensor and computing systems offering a high throughput rate and large memory space with minimal mass and power requirements.

Highly-autonomous spacecraft will require greater subsystem interactions. These interactive functions demand system-level prioritization, arbitration, and decision making. Three prominent system-level functions of control, planning and data analysis emerge. The traditional command and data subsystem will involve a greater and more frequent interface with other subsystems that it will be subsumed at the system-level. The command and data flow of an automated spacecraft is shown in the block diagram of Figure 3. The attitude and control, navigation and fault-protection subsystems embody most of the desired increase in autonomy.

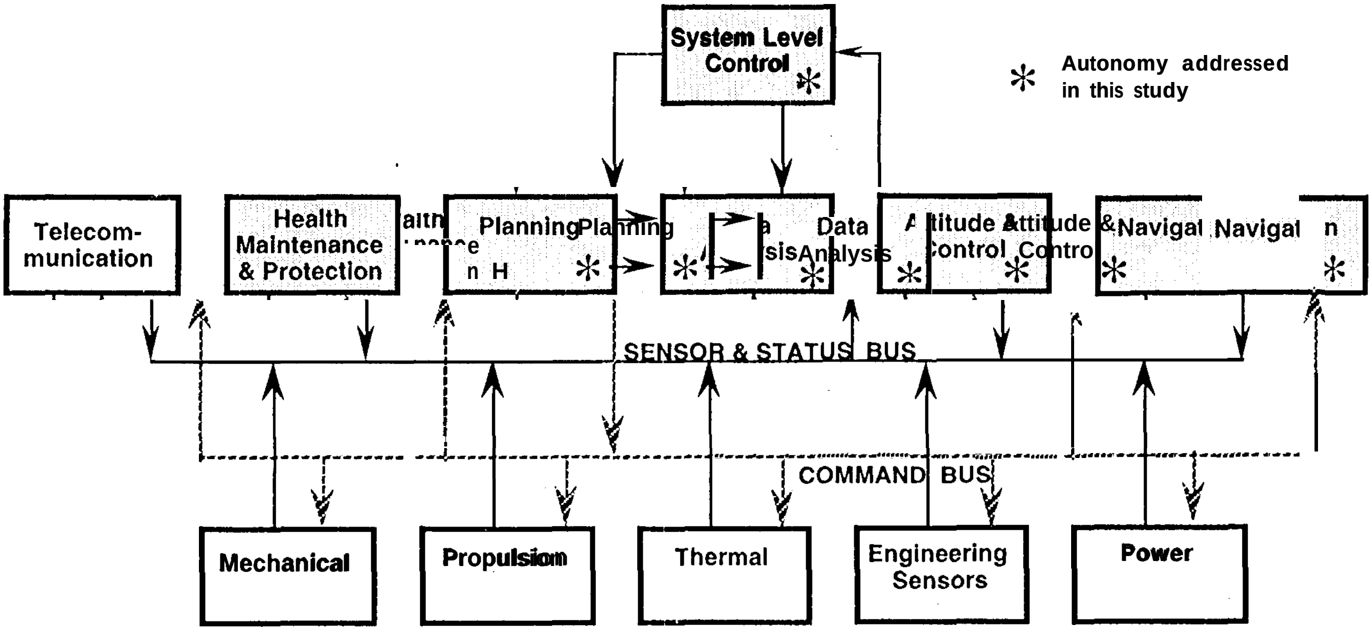

Figure 3. Automated Spacecraft System Block Diagram- Command & Data Flow.

4.3 Attitude and Control Subsystem Development

'1 'hc ACS is responsible for attitude determination, attitude control, trajectory change maneuvers, fault protection, spacecraft attitude broadcast and visibility of the ACS state-of-health. These traditional functions will be targeted for increased autonomy as described below.

- Attitude Determination is obtained autonomously using a star tracker and an all-sky catalog and attitude is propagated between star updates using a dynamic model augmented by an Inertial Reference unit (IRU), this feature is already available on Cassini, reference XX. \
- Autonomous attitude control is easily achieved once a system is in place to generate the sequences on-board. .
- Autonomous AV maneuvers is a subject of this study and is addressed in section 4.4.
- While autonomous failure detection, is currently available, autonomous location and recovery are needed and will be a, subject of subsequent study.

The ACS requirements will be derived from the mission and spacecraft definitions and a complement of hardware will be specified to meet the objectives. Detailed maneuvers and target acquisition and tracking functions will be developed to execute the defined mission phases.

4.4 Autonomous DV Maneuver

4.4.1 overview of Current Approach

Delta V maneuver is a prime candidate for autonomy due to the extensive amount of ground support currently required to perform this task, Substantial savings in mission operations cost can be realized if ground involvement can be minimized or eliminated entirely. To accomplish this objective, essential tasks that are currently performed on the ground will have to be optimized for on-board implementation.

A brief survey of the ground mission operations indicates that the following tasks are performed for maneuver design and command generat ion,

(i) Maneuver design process is initiated when Navigation team requests to perform a DV maneuver for trajectory correction. This request is usually specified in the form of a DV vector to be executed by the spacecraft at a certain epoch.

(ii) Upon receiving navigation's request, the maneuver designer will proceed to execute a series of ground operation software to perform the design as well as command generation, This design software involves two major steps, The first step is the ideal maneuver design which is accomplished by solving for an analytical solution using a simplified dynamic and spacecraft model, The second step is the detailed maneuver design which uses the ideal solution to initialize an iterative process to minimize the error between the requested and achievable DV while using a detailed dynamic and spacecraft model. Commandable parameters from the ideal solution are modified according to the error at each iteration to achieve optimality.

(iii) The optimal and achievable DV solution is then processed through a constraint checking module to ensure that flight rules or mission rules are not being violated. Upon a successful constraint checking, the comrnandable parameters of the achievable solution is converted to a block of sequence commands for spacecraft uplink. If there is any flight rule violation, the analyst will be required to repeat step (ii) and (iii) with an alternate path.

It is obvious from the above description that the current process is an open-loop feed forward commanding process. Thus, the accuracy of the resulting DV is heavily dependent on how accurate the detailed models in representing the real spacecraft behavior. The scope of this study includes the software architecture and algorithm design for on-board implementation of steps (ii) and (iii). It is assumed that the Navigation provided DV vector can be directly uplinked to the spacecraft for

execution. The traditional ground operations involving maneuver sequence generation, constraint checks, and resolution of constraint violations will be eliminated,

4.4.2 Software Architecture for Autonomous Implementation

The proposed flight software architecture for autonomous DV implementation is baselined from the current Cassini spacecraft design which employs the object-oriented analysis and design methodology. A detailed description of this approach is presented in reference 1. in essence , the software architecture consists of twenty plus objects with each providing a specific set of operations for manipulation of a data set specific to the object. Examples of these objects include flight software executive/scheduler, command processor, telemetry processor, hardware managers, mode commander, configuration manager, attitude controller, attitude estimator, constraint monitor and fault analyzer. To avoid duplication, only the additional objects for implementing the autonomous DV will be described in this paper. The software object diagram is depicted in Figure 4.

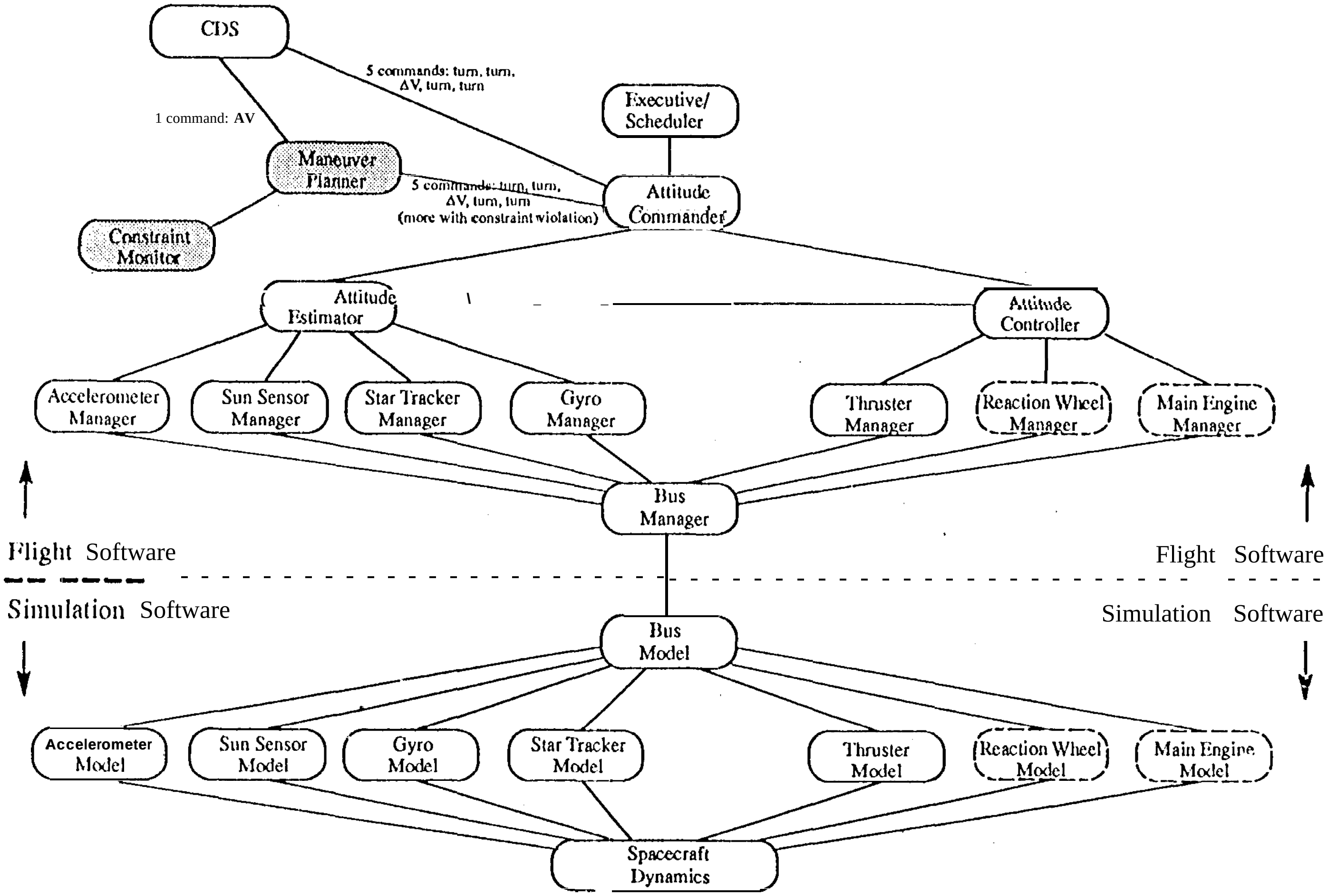

Figure 4. Autonomous DV M-aneuver Software Architecture Diagram.

4.4.3 Object Descriptions

Maneuver Sequence Planner: The purpose of this object is to plan the maneuver sequence upon reception of the DV command from the ground. To achieve the commanded DV, maneuvering of the spacecraft will be required to align the main engine thrust vector along the desired thrust attitude prior to ignition. Upon completion of main engine firing, the spacecraft will be required to turn back to the initial attitude such as Earth or Sun point. This is usually refer to the turn-burn-unwind sequence. The turn or unwind segment is achieved by pulsing a set of attitude control thrusters in a balanced or unbalanced mode, Due to pulsing of the attitude thrusters for turns, a small amount of residual DV will be imparted to the spacecraft. The direction and magnitude of the residual DV depends on the commanded turn rate

and turn angle from the current to the **desired** burn **attitude.** This contribution due to turn and unwind segment has to be accounted for so that **all** DVs', including the burn segment, when summed vectorially should be equaled to the Navigation requested value in both magnitude and direction.

The process of the sequence planner is to resolve, analytically, all relevant parameters in executing the turn-burn-unwind sequence. These include the turn start time, turn angle, turn rate, bum attitude, burn delta V, burn start/end time, unwind start time, unwind rate and unwind attitude. The definition of these parameters require the current attitude and mass properties of the spacecraft along with thruster and main engine models, Accuracy of sequence execution by the spacecraft depends on the accuracy of the models used in the planning process.

Sequence Validation: Prior to execution of the maneuver sequence, it is important to ensure that the spacecraft siew path will not incur any damage to the on-board sensitive instruments due to bright bodies within sensors' field-of-view. These constraints are checked by the validation object based on the planned sequence as discussed above. The validation process includes prediction of the slew path traversed by all relevant instruments during maneuver. The boresights of these instruments are then compared against the bright body (Sun) vector to determine the aspect angle between both directions, If the angle is less than a specific threshold at any instance during the maneuver, it will invalidate the sequence,

Implementation of the validation object requires the knowledge of bright bodies in inertial space. The baseline Cassini design has included a software object to provide ephemeris information of celestial bodies from which the inertial vectors can be derived.

Alternate Path Definition: When bright body constraints are violated, the maneuver sequence is re-defined by specifying alternate paths which bypasses the constraint regions. One approach is to break up the direct path into multiple segments with way points defined in between. The constraint regions are assumed to be circular on the surface of a celestial sphere. Way point are defined such that the slew paths connecting the initial point and to the target point are both tangential to the circular constraint region. The sequence planner is then invoked again to evaluate the residual and total DV contributed from multiple turn/burn segments and to re-define the maneuver parameters in order to ensure that the planned DV is as requested from the ground,

Delta V Estimator: This object provides the capability to estimate the achieved delta V during maneuver. A. total DV vector defined in inertial coordinate system is estimated by using the on-board attitude information and measured DV magnitude in spacecraft fixed coordinate system. Attitude estimates relative to inertial coordinate system is available at all times using measurements from celestial sensors (star tracker) and/or inertial sensor (gyros), Three axes DV magnitudes are either measured by accelerometers or computed using thruster on-off cycles, thruster models and spacecraft mass properties. The inertially referenced total DV vector is then computed by transforming the body fixed DV magnitude vector to inertial coordinate system using the spacecraft attitude matrix and summing the estimate at each software cycle throughout the entire turn-burn-unwind sequence.

Sequence Adjuster: Due to knowledge uncertainty of the thruster model and spacecraft mass properties, the planned maneuver profile will not be exactly implemented by the spacecraft. DV deviations will require adjustments of the remaining portions of the planned maneuver profile to minimize the final error. The concept of "Delta V to go" which is defined as the difference between ground requested and currently achieved DV, is computed for adjusting the planned maneuver sequence during actual implementation. A linearized process is defined to modify the available control parameters in order to minimize the "Delta V to go" upon completion of the maneuver sequence. During the turn, the turn angle, burn attitude, burn magnitude may be adjusted from the planned sequence. During the main engine burn, the burn attitude and burn magnitude may be adjusted. During the unwind process, the turn angle and turn rate may be adjusted. The objective of this module is to miminize the total DV error at the end of the maneuver sequence.

Spacecraft Characterization: To accomplish full autonomy, on-board characterizations of essential hardware are required to maintain optimal performance. These include thrusters (thrust vector, thruster magnitude), gyros (drift, scale factors, misalignments), accelerometers (bias, scale factors, misalignments), and spacecraft mass/inertial properties. These processes which are currently performed on the ground should be implemented on-board if computing resource is available. However, for the scope of this paper, these algorithms will not be further addressed.

5. SCHEDULE

As shown in Figure 5, the ultimate goal is to achieve technology readiness for new projects. This product is projected to be ready for application in mid- 1997.

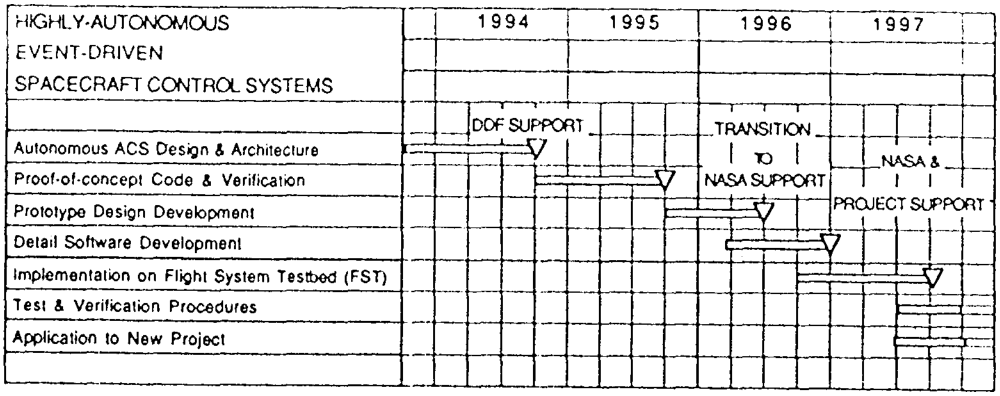

Figure 5. Schedule for Autonomous ACS Development

6 CONCLUSION

This paper discusses the plan to design and develop a proof-of-concept attitude and control subsystem that has the ability to capture science events and enable a small body rendezvous and sample return mission whith minimal intervention by ACS ground operation support. The technology to be developed and demonstrated includes: on-board sequence generation and execution, precision closed-loop maneuver and attitude control, target acquisition and tracking, and sensing and representation of spacecraft system state.

7 ACKNOWLEDGMENT

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