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Centaur D-1A Guidance/Software System

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NASA

CENTAUR D-1A GUIDANCE/SOFTWARE SYSTEM

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ABSTRACT

The main body of this paper describes the evolution of the Centaur D-1A Guidance and Software System. Specifically, the performance of the explicit guidance equations, using a linear tangent steering law. Inherent flexibility exists in the equations in that they have multimission capability. They can accommodate both earth-orbital and earth-escape missions with either one or two Centaur burns. They can also guide for multi-burn earth orbital missions. The Centaur performance is indicated in terms of optimality (propellant usage), accuracy, flexibility and computer requirements.

In the course of the Centaur Guidance development substantial changes and improvements have been made and more improvements are on the way for the Shuttle/Centaur Guidance. It is the intent of this paper to describe, provide insight into, and identify certain unique aspects of the individual Centaur flight profiles. Mission profile(s) are described narratively with some numerical data given in cases where it may be useful.

INTRODUCTION

The purpose of this paper is to describe the basic philosophy of the Centaur D-1 Guidance modules and its application to powered flight. It is a guidance scheme which can compute an optimum thrust attitude as an explicit solution to a two-point boundary-value problem. That is, the commanded thrust vector is found by a direct solution of the appropriate equations of motion subject to the initial boundary condition of the vehicles instantaneous state and final boundary condition at thrust termination. The guidance scheme is truly an explicit guidance scheme in that it will retain its optimization properties under vehicle perturbations without any loss in accuracy at cutoff. The instantaneous state of the vehicle-velocity, position, longitudinal acceleration, and gravitational acceleration are available from the on-board Centaur navigation system.

The objective of the Centaur guidance system is to provide the maximum amount of explicit guidance for a set of space mission objectives such as:

-- Deliver a payload into a specified elliptical orbit about the earth for a wide range of apogees, perigees, inclination with respect to the equatorial plane and/or longitude of the ascending node. Argument of perigee and true anomaly at injection may or may not be constrained.

-- Deliver a payload into a pre-specified transfer conic (ellipse, parabola, or hyperbola) which will intercept a "target" point in N-body inertial space at a fixed time.

-- Deliver a payload into a minimum delta V transfer conic (conic parameters determined in flight) which will intercept a "target" point in N-body inertial space. Time-of-arrival may or may not be specified.

For reasons of launch window, tracking coverage, fuel economy, and vehicle design limitations, it may be desirable to attain the final desired orbit through a series of alternate thrusting periods and free-flight coasts. The Centaur Guidance System handles these multiple-burn type missions in a series of "stages," steering to appropriate interim conics for each free-flight coast with the final burn guided to achieve the desired terminal conditions.

INERTIAL MEASUREMENT GROUP (IMG)

If a perfectly accurate and flexible hardware system(s) could be built, the rocket thrust vector could be pre-programmed as a function of time, and the mission objectives could be satisfied without closed-loop guidance. In reality, the rocket engine and other vehicle hardware will not perform ideally; the thrust vector will differ in magnitude and direction from the model. This difference can be sensed (directly or indirectly) by the guidance sensors (gyros and accelerometers). For Centaur these sensors are provided by the Honeywell Inertial Measurement Group (IMG). These sensors will in themselves have errors, but the errors are much smaller than the deviations in the engine system. The purpose of guidance is then to command the rocket thrust vector attitude and engine on and off commands based on the sensed position, velocity, and acceleration to meet the mission objectives.

Gimbal Platform - Approximately 13 years ago, a decision on a gimbal platform for the Centaur D1 Inertial Reference Unit (IRU) was made on the data base established through the 29 flights of the Centaur D. The decision was made because of the knowledge developed on the set of problems peculiar to gimbal platforms against the uncertainty of new state of the art strapdown systems and the reluctance to go with a yet-to-be-discovered set of strapdown problems. Figure 1 below is a simplified block diagram depicting the Centaur D-1A Guidance System.

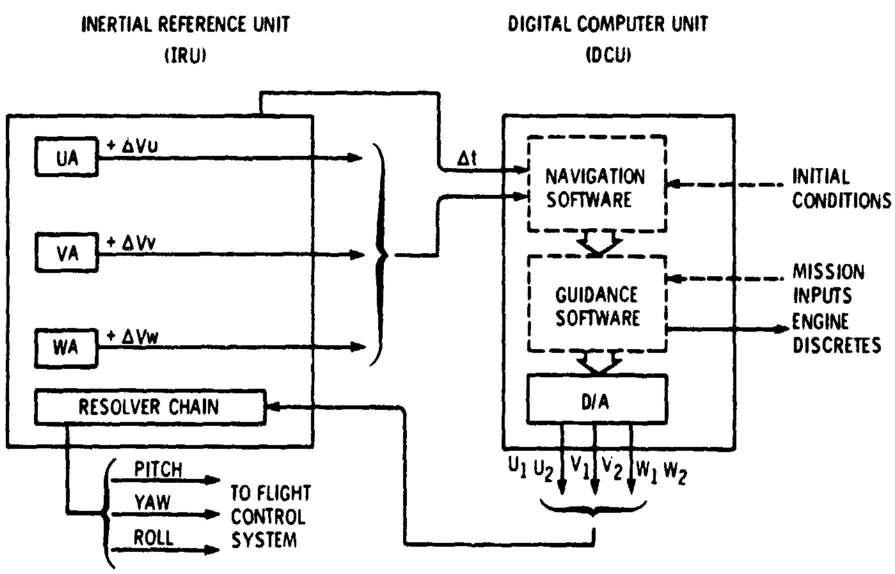

Figure 1. - Centaur D-1A guidance system.

IMPLICIT VERSUS EXPLICIT GUIDANCE EQUATIONS

A terse statement of the guidance problem as given above is the process of determining steering commands, and engine on-off commands, using data obtained from the guidance sensors, which will lead to mission success. For the Centaur inertial guidance system described in this paper, this process is oriented toward a self-sufficient set of equations that are programmed in the Centaur Digital Computer Unit (DCU).

Guidance equations are usually termed "explicit" or "implicit." Explicit guidance equations solve the problem of how to get from an instantaneous position and velocity vector to the desired cutoff conditions according to an optimal principle (i.e., minimum propellant utilization).

Implicit guidance equations basically rely heavily on data derived from preflight nominal trajectories. The guidance philosophy may be to either try to steer back to a nominal trajectory, or to steer optimally to the target. If the latter approach is chosen, a much greater number of pseudo-nominal trajectories are required to account for possible vehicle or state perturbations. Within the range of perturbations considered, the guidance equations will work satisfactorily. However, for vehicle conditions outside this range, the scheme does not adapt as accurately as explicit equations will.

Implicit Targeting - The general approach to targeting an implicit set of guidance equations is based upon determining the coefficients of a polynominal expansion about a nominal trajectory. These expansions provide an implicit guidance scheme with the ability to continuously steer to a nominal flight path. Guidance targeting is contained within the guidance polynominals obtained for the implicit scheme. The preflight guidance targeting effort involves the determination of the coefficients for these polynominals. The optimality of this approach depends on the validity of the nominal trajectories used to generate the polynominals. For the implicit type which returns to a nominal trajectory, a greater amount of propellant is usually required, since the original path may no longer be the optimum one if perturbations, in state or the vehicle, have occurred.

Explicit Targeting - As discussed in implicit guidance targeting, the number of mission targeting trajectories required are roughly the same for both implicit and explicit schemes and are usually obtained in the same manner. Other than these, nearly all of the remaining complex preflight guidance coefficient calculations required for implicit guidance are eliminated with explicit schemes.

EVOLUTION OF CENTAUR D-1A GUIDANCE; RATIONALE FOR

Prior to Atlas/Centaur-30, all Centaur D guidance was based on implicit guidance. After an exhaustive analysis and simulation of features of the guidance equations, i.e., implicit versus explicit, the advantage of explicit guidance was clearly recognized. A set of explicit guidance equations was then developed that incorporated some of the best features of each guidance equation set provided by NASA, GDC, and TRW. The criteria for selection of the equations were accuracy, performance (optimality in the sense of minimum propellant expenditure) and flexibility. Flexibility in a set of guidance equations implies the ability to guide a wide spectrum of missions with a minimum of equation changes. The Centaur D-1 equations are extremely flexible and reliable as indicated by the results shown in the subsequent discussions.

R and D flight failure. In tabular form, Centaur's flight record is summarized below:

Centaur	R and D Flights	Operational Flights
D	4 successes out of 7 (1 no-trial not included)	19 successes out of 21
D-1	1 failure (out of 1)	33 successes out of 33 (2 no-trials not included)

Of the 33 successful D1 missions, 20 involved placement of communication satellites into earth orbit and 13 involved injection of planetary spacecraft into escape orbit.

Accuracy - Payload placement accuracy is an important part of the mission success record. The combination of the highly accurate inertial guidance system together with flexible guidance software provides the Atlas/Centaur with the capability to achieve precise payload injection conditions for many different types of missions. The injection precision has been demonstrated on many interplanetary, near-earth orbital, and synchronous orbit missions.

On Pioneer missions to Jupiter, the guidance requirement included precision orientation of a solid-rocket kick stage to achieve the proper final planetary intersect conditions. The major error source on these missions was the solid rocket impulse uncertainty.

A summary of Atlas/Centaur mission accuracies for various types of missions together with flight results and mission requirements are tabulated as follows:

	Transfer Orbit Error (Centaur 2nd Burn)	
Typical Synchronous Orbit Missions - INTELSATS	Flight Data	Guidance System 3 σ
Perigee (N.Mi.)	0.03-1.2	2.5
Apogee (N.Mi.)	3.7-26.3	77
Inclination (Deg.)	Not Available	0.024

Lunar and Interplanetary Mission Accuracy	Midcourse Correction Requirement (MCR) m/sec.		
	Mission Requirement	Flight Data	Guidance Sys. 3 σ
Surveyor	<50	1-6	17
Mariner Mars	<13.5	1-2	9
Mariner Venus Mercury	<13.5	7	7
Pioneer 10	<117	14	117
Pioneer 11	<108	40	108

Examples of Titan/Centaur accuracies based upon flight results and guidance accuracy analysis studies.

Typical Heliocentric Mission Helios A	Mission Requirement	Flight Data	Guidance System 3 σ
Perihelion (A.U.)	±0.01	0.0004	0.0015
Eclipic Inclination (Deg.)	±0.60	0.02	0.32

Titan/Centaur Interplanetary Missions	Midcourse Correction Requirement (MCR) m/sec.		
	Mission Requirement	Flight Result	Guidance System 3 σ
Viking A	<15	3.9	11.1
Viking B	<15	4.7	11.1

The flight record has demonstrated that the D1 Centaur has a mission success probability of ~98 percent. Continuation of this perfect operational flight record, the mission success probability will reach > 0.99 in time for its use in the Shuttle program.

UNIQUENESS OF CENTAUR D-1 EQUATIONS

The explicit nature of the D-1 Centaur equations means that targeting is much simplified with a minimum number of mission dependant constants, in contrast to D Centaur. Also, the incorporation of the linear tangent steering law allows optimum trajectory profiles which were not available under the D Centaur program. The technique used is to integrate numerically the equations of motion to the predicted cutoff time to generate injection parameter error signals. The integration is then repeated to produce partial derivatives of the injection parameters with respect to the steering coefficients. Finally, a linear system of equations is solved for corrections to the steering coefficients. It would be prudent at this point to mention the use of Calculus of Variations (COV). The D-1 yaw steering laws are designed to minimize performance loss due to out-of-plane steering. This is accomplished by the use of COV to compute the nominal components of the commanded vector, i.e., yaw steering nodes; target vector, orbital inclination, or orbital inclination and node. The COV technique reaches the same end conditions as the corresponding guided trajectory, but in addition establishes a lower bound for fuel requirements.

CENTAUR D-1 DIGITAL COMPUTER UNIT (DCU)

A major characteristic of the D-1 Centaur is the integration of several functions through the use of a powerful airborne Digital Computer Unit (DCU). The DCU plays a role in several functions; navigation, guidance, control, sequencing, propellant utilization, propellant tank pressurization, and instrumentation and telemetry. Its speed, storage capacity, and input/output also provides additional capacity for growth. A variety of DCU I/O are shown in Figure 2 below.

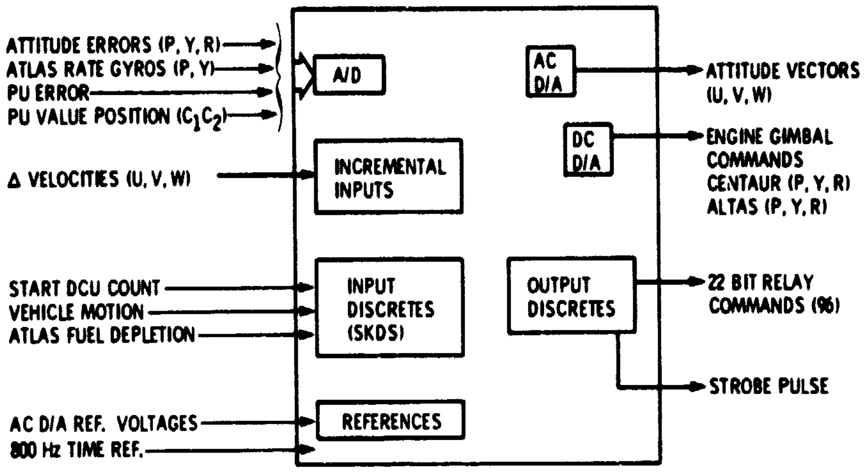

Figure 2. - DCU input/output.

The use of a powerful digital computer has permitted many functions to be done by software, which are normally done by other hardware. In particular, mission-peculiar requirements are handled by software where practical, permitting changes to be expressed in mission constants.

The DCU is a stored program, random access core machine. Memory is composed of 16,384 words of 24 bits each. Hardware interlocks prevent changing contents of 12,280 of these words, however, when special laboratory equipment is connected the contents can be changed. The flight program and telemetry formats are loaded into this area, and cannot be altered on the vehicle. Memory cycle time is nominally three microseconds.

For the purpose of this paper the remaining discussion will address the DCU as part of the guidance system. It is assumed that the reader is well versed in the details of digital computers and as such these details will not be considered in this paper.

DCU SOFTWARE - To provide insight into the functional aspects of the guidance/navigational system, a brief description of the DCU software is provided.

As discussed above, the DCU plays a significant role in the Centaur D-1A ascrionics system. The software is an integral part of the DCU. As pointed out previously, the D-1A software incorporates many functions done by hardware on Centaur D. This reduction in hardware allows the vehicle configuration to remain static while adding in the software the design flexibility for mission peculiar requirements.

The D-1A software was designed to satisfy specific objectives in the areas of cost, reliability, launch simplicity, response and resiliency. For example, to provide resiliency, the software is designed to remain intact and functioning in the unforeseen event of failures in the extended system hardware. Its task is to achieve maximum flight success in spite of system failures.

SOFTWARE DESIGN CONCEPTS - Within the D-1A software specific concepts have been developed to achieve the following objectives:

Modularity: A modular software concept fulfills the requirements for a cost effective and flexible software system. The concept classifies software into two categories: an executive software system that remains unchanged through all missions, and a set of mission-or-vehicle-peculiar task modules that can be selected from a library and adopted for the current mission. The task modules can be scheduled by the executive at different frequencies during the flight. They can be turned off or reactivated for different phases of flight, and interrupted at any time during their operation. Since the modules do not communicate with each other, but only through the Executive, they are assured of consistent sets of data. Program changes are inserted at the module level, and checked at the module and integrated program level (all task modules operating together as a system). Figure 3 below illustrate the flexible modularity.

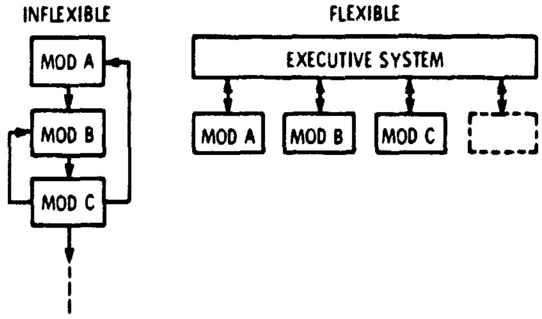

Figure 3. - A flexible kind of modularity.

Independence from Interrupts: The design of the D-1A software is such that any combination of two or more modules can be in a simultaneous state of interrupt; furthermore, the interrupt is allowed at any location in the modular program. Thus the modular task programs are completely independent of the interrupts, and each one can be coded as if it were the only module in the computer. This "independence" concept is implemented by task scheduling and real-time interrupt system service techniques, at the DCU level, and by appropriate design of all modules only at the final program level.

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SOFTWARE DEVELOPMENT

Functional tasks are designed as separate software modules, and are developed and checked out in a parallel process. The checkout of the software is subdivided into the task level and integrated level. The software system structure is designed general enough so that after the first integrated checkout has occurred, revised or new modules can be incorporated with minimum effort. Once a revised module is completely checked out, it is added to the modular library. Figure 4 depicts the flow of software development.

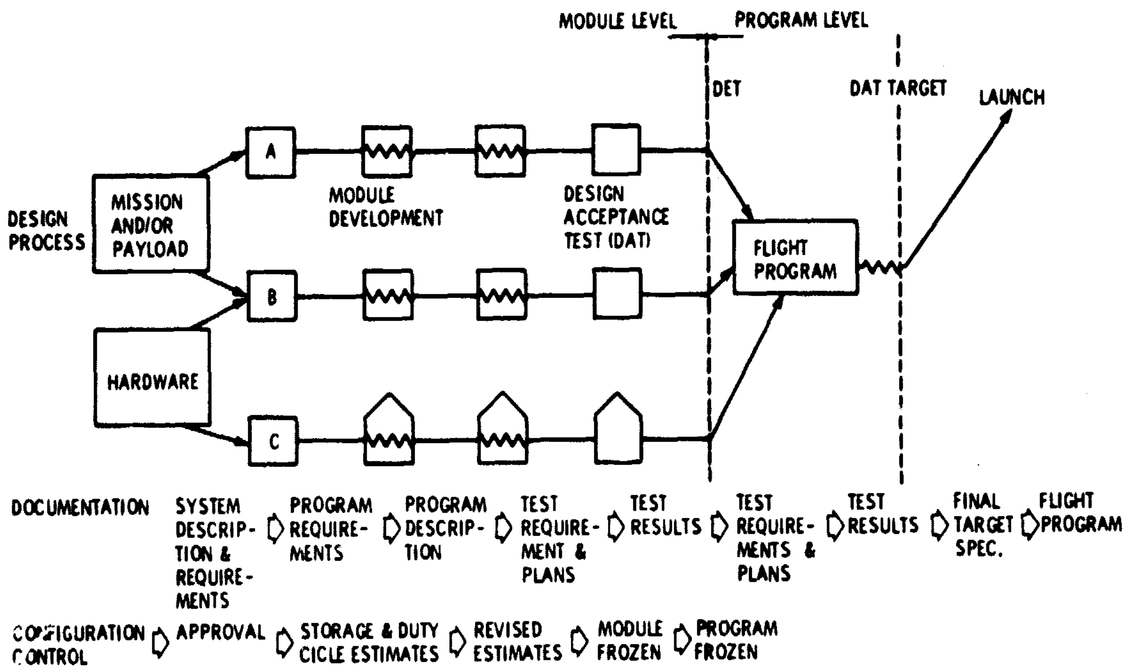

FIGURE 4. Software Development - Parallel Module Design and Checkout

Contingency Software. - A prime uniqueness of the DCU/Flight software is that it is designed failure tolerant. In the event of certain external equipment failures (such as, unscheduled thrust termination, or failure to start a stage) the software provides the capability of selecting reasonable alternative strategies.

For nonstandard environments (such as large steady-state drop in thrust level) the software senses the environment and makes appropriate adjustments to the trajectory. The recovery techniques are designed so that the mission is achieved within the performance capability of the launch vehicle. Every conceivable extreme nonstandard environment cannot be protected; however, a reasonable balance is achieved between software complexity and protection attained.

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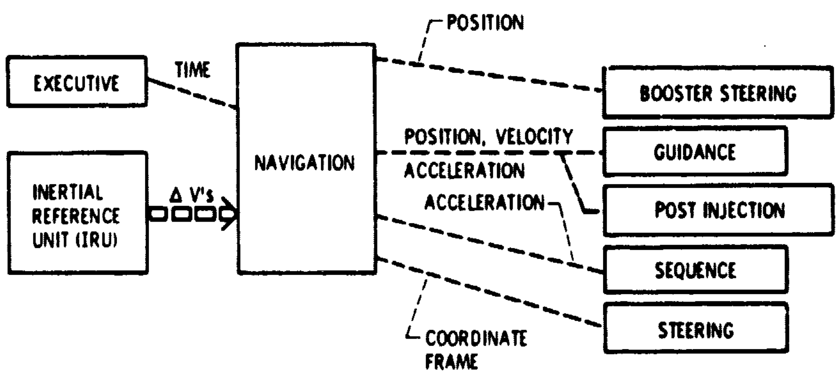
DCU/GUIDANCE FUNCTIONAL TASKS

The functional tasks performed by the DCU are coded in program modules. These modules are listed in the task table from which they are called by the executive for operations at the proper time to ensure correct module frequency. Some of the modules, e.g., navigation, operate throughout flight, while others are scheduled for only certain phases, e.g., Powered Autopilot. The modules do not interface with each other. Data flow is controlled by the data management portion of the executive. The following is a brief description and pictural representation of these modules pertinent to the Guidance function.

Navigation

Function. Furnish position, velocity, and acceleration data to guidance.

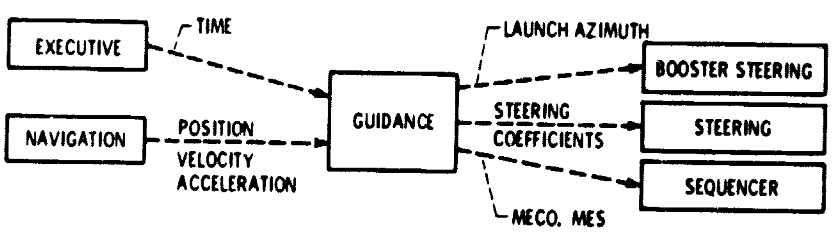
Method. Integrate in true inertial coordinate system, having previously converted for known platform drifts.



Guidance

Function. Determine steering coefficient data for optimizing the trajectory and furnish engine cutoff time to the sequencer.

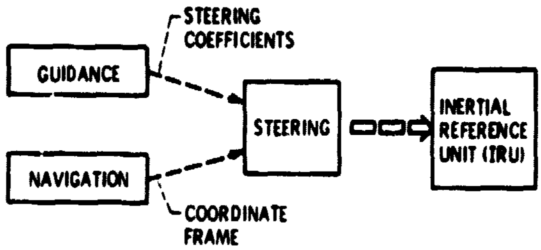
Method. Assumes a near-optimum linear tangent steering law in pitch and a calculus of variation (COV) steering law in yaw.



Steering

Function. Furnish the desired vehicle attitude to the platform resolver chain.

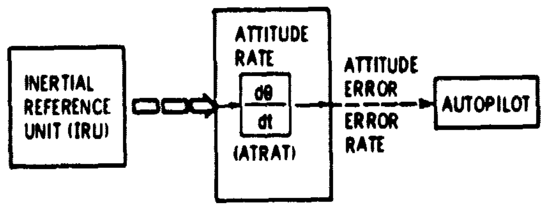
Method. Compute the desired vehicle attitude from the guidance-supplied steering coefficients.



Attitude Rate (ATRAT)

Function. Furnish rate information to powered and coast phase autopilots.

Method. Computes the time derivative of the attitude rate signal.



Powered Phase Autopilot

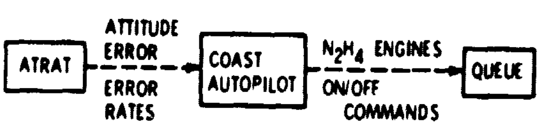
Function. Maintain control stability during main engine firings and control the vehicle axes to the desired attitude.

Method. Engine gimbal angle output commands are computed using attitude errors and error rates as inputs to control laws.

Coast Phase Autopilot

Function. Control the vehicle attitude during coast phase maneuvers.

Method. Command N_2H_4 attitude control engines in on/off mode.



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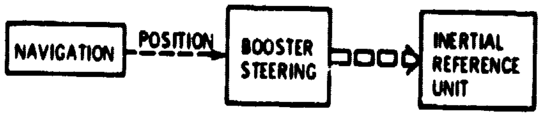
Booster Steering

Function. Steer the booster in pitch, yaw, and roll in an open-loop manner during ascent through the atmosphere.

Method. Using polynomials in altitude, generate attitude as a function of altitude.



Post Injection

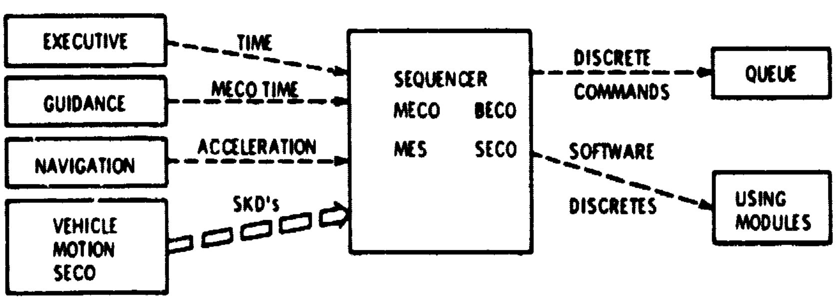
Function. Provide steering coefficients to point the vehicle for separation and retromaneuver.

Method. Output to the resolve chain roll and pitch axes pointing vectors.

Sequencer

Function. Generate discretes for sequencing of all events during flight.

Method. Perform various tests to determine time to issue event discretes or to accept from selected modules for module dependent discretes.



Propellant Utilization (PU)

Function. Maintain a proper ratio of LH_2 and LO_2 in the tanks to preclude a premature depletion of one or the other.

Method. Monitor the propellant ratio error signal and command the PU values to a position which will null the error.

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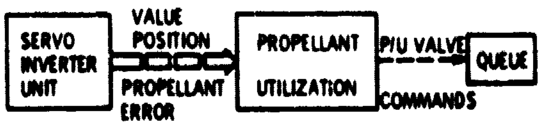
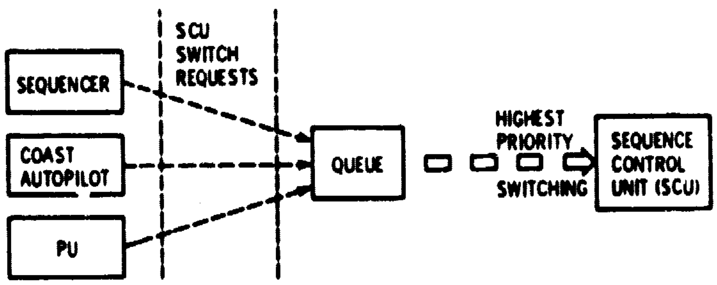


QUEUE

Function. Resolve any potential conflict of simultaneous requests for switch action.

Method. Assign priorities to switch requests and command switches to the priorities.



An example of the software modules linked together to perform a specific function, in this case Centaur powered phase steering, is depicted below in Figure 5.

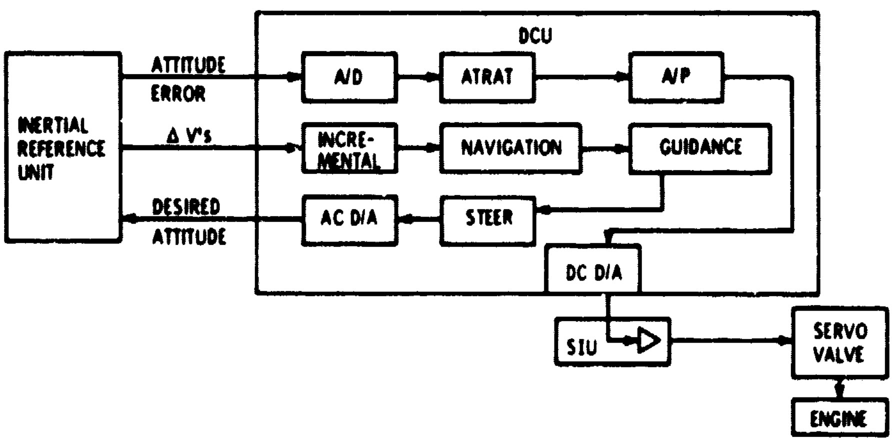


Figure 5. - Module combination example.

SHUTTLE/CENTAUR

The adaptation of Centaur as an upper stage in the Space Transportation System is a key element in NASA's space transportation plans. The primary missions for the STS/Centaur combination is Galileo and ISPM in 1986.

Software Flexibility. The versatility of Centaur software and the excess payload capability for existing missions provide mission flexibility by allowing many options for contingency planning. For example, Centaur software capability increases mission flexibility by allowing Centaur deployment and/or mission initiation on any revolution in the parking orbit. Orbit parameters can be selected from previously validated multiple-targeting sets as a function of revolution to account for mission initiation delays. The software contingency options have been flight-proven; typical examples are automated in-flight re-targeting capability for HEAO launches (Atlas/Centaur) and provision for contingency parking orbit revolution for Voyager launches (Titan/Centaur).

Guidance and Navigation. The guidance and navigation functions will be implemented using the DI Centaur inertial measurement group (IMG) for measurement of vehicle accelerations and the digital computer unit (DCU) for computation of vehicle position and velocity and generation of the required steering signals. The D1 Centaur IMG will be slightly modified for DOD missions to improve gyro torquing command accuracy to accomplish the attitude update and azimuth alignment. A gyrocompassing mode will be used for inertial azimuth alignment of the inertial element for Shuttle missions.

Although IRU accuracy is sufficient to meet the mission requirements for deployment eight hours after liftoff, by navigating from the ground up without external navigation or attitude assist, extended period in the Orbiter payload bay may necessitate navigation and attitude updates. Navigation update can be provided, if necessary, from the Orbiter via the PSP interface. Attitude update can or will be accomplished by a Ball Aerospace Systems star scanner.

Deployment Delays. A few words concerning the DCU real time. The DCU is synchronized to real time (GMT) through the GSE before liftoff. Since the system is navigating from the ground up, the Centaur is insensitive to delays in deployment on the Centaur from the Orbiter. This permits the mission to be accomplished on any deployment opportunity. For those missions that have a time-dependent target condition (such as ascending node), the appropriate target-orbit data can be selected from prestored options within the DCU once the deployment time is established. The synchronization of DCU time and GMT thus makes the Centaur system autonomous, and obviates the need for Orbiter crew-initiated functions to initialize the software or communicate the deployment time.

Adaptability. Within the framework of system maturity, changes are continually evaluated to improve Centaur capability and performance. As an example, several block changes have been incorporated into the IMG that have resulted in an order of magnitude improvement in predicted reliability from the 1250 hour MTFB initial specification requirement to an actual MTBF of 12,500 hours. Two factors drive the continual upgrading of Centaur's hardware and software:

- New technology accounts for improved electronic parts, components, and techniques.

- New mission requirements demand increased capability; from more computational capacity to increased accuracy.

As an added note, one of the most important pre-launch tests conducted just prior to launch is the recalibration of the inertial reference platform. Values of gyro drift (as well as other error source parameters) are updated from this test and are stored for use in the navigation computations to compensate for errors caused by gyro drifts, etc. The new calibration values are compared by the Computer Controlled Launch Set (CCLS) to the previous values for significant changes. This technique will detect "soft" failures in gyros from out of tolerance drift values.

CONCLUSION

The Centaur D-1A guidance equations sets and software are extremely flexible and provide accuracy and performance. A two fold advantage emerges by the use of explicit over that of the Centaur D implicit guidance sets. First, the preflight targeting requirements have been shown to be much less for the explicit scheme than for an implicit scheme. Second, the mission targeting subphase can itself be performed by the partial, or full use of an explicit guidance scheme: optimum capability demonstrated by past Centaur D-1A missions.

The flight software is kept simple to reduce checkout costs and minimize storage required. Maximum use of prime sequencing software (back-up software included) is made, and the software is mission and vehicle independent to the maximum extent possible.

The reliability of the D-1A software is enhanced through controls from module inception through flight. These controls ensure that the management of the software will be thorough and complete. A Change Requirement System is a formalized procedure for initiating, approving, and recording changes to modules or programs.

In summary, it has been the purpose of this paper to demonstrate to the reader the highlights of the Centaur D-1A guidance scheme and to provide a qualitative feeling for the different levels of effort involved. Levels included the desirability of using explicit guidance, and the uniqueness of the software.

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