Video-Guidance Design for the DART Rendezvous Mission

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Abstract

NASA's Demonstration of Autonomous Rendezvous Technology (DART) mission will validate a number of different guidance technologies, including state-differenced GPS transfers and close-approach video guidance. The video guidance for DART will employ NASA/Marshall's Advanced Video Guidance Sensor (AVGS). This paper focuses on the terminal phase of the DART mission that includes close-approach maneuvers under AVGS guidance. The closed-loop video guidance design for DART is driven by a number of competing requirements, including a need for maximizing tracking bandwidths while coping with measurement noise and the need to minimize RCS firings. A range of different strategies for attitude control and docking guidance have been considered for the DART mission, and design decisions are driven by a goal of minimizing both the design complexity and the effects of video guidance lags. The DART design employs an indirect docking approach, in which the guidance position targets are defined using relative attitude information. Flight simulation results have proven the effectiveness of the video guidance design.

Keywords: Video guidance, rendezvous, proximity operations, docking, filtering, attitude control, spacecraft, guidance and control.

1. Introduction

Rendezvous missions that require close-approach or docking have a common requirement for use of a high-accuracy short-range sensor. Typically the various sensor elements are blended together for the NAV solution, with the highest weight applied to the short-range sensor during docking approaches. For DART, navigation at distances greater than several hundred meters is provided by state-differenced GPS, with a transition to AVGS data inside that range.

This paper will address use of the advanced video guidance sensor (AVGS) for guidance and NAV in the DART mission. The paper is organized into several additional sections. The DART mission is described first, followed by a description of the vehicle physical architecture. Attitude control and the NAV design are summarized next, followed by a discussion of target pointing and docking guidance. Close-approach and docking guidance responses are illustrated using the vehicle 6-DOF simulation.

2. DART Design Reference Mission Summary

The DART mission begins with an air-launch by Orbital's Pegasus rocket, into a 500-km phasing orbit, as depicted as Point A in Figure 1. The figure provides a high-level overview of the mission elements; the rendezvous phase (starting from phasing orbit Point B, to Point C near the target) is performed using the Hydrazine Auxiliary Propulsion System (HAPS), while the subsequent proximity operations are conducted using the DART RCS system.

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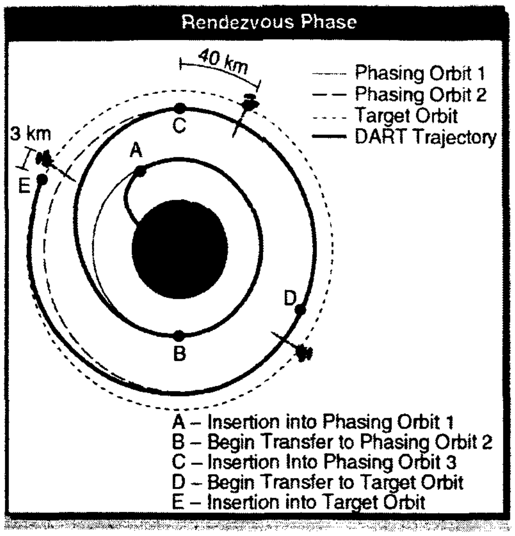


Figure 1: DART Reference Mission Schematic Through Vbar Transfer

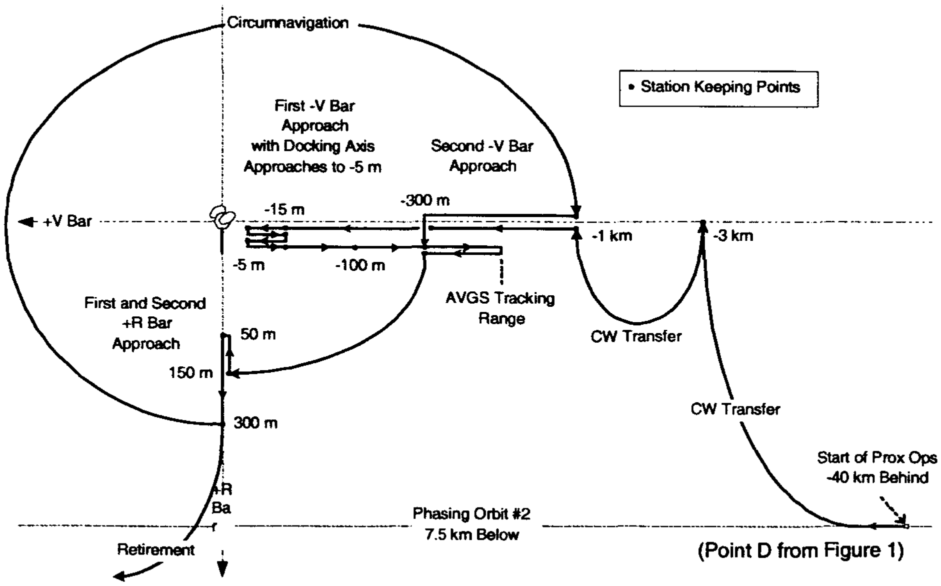


Figure 2: Proximity Operations Schematic

Figure 2 above depicts the proximity operations beginning with a point 40 km aft of the MUBLCOM target satellite. MUBLCOM is a target-of-opportunity spacecraft, launched in 1999 and equipped with AVGS retro-reflectors.

For reference, Figure 3 depicts the MUBLCOM vehicle. This vehicle includes several pairs of AVGS reflector sets (corner cubes). The long-range and short-range AVGS reflectors are designed to form an approach-and-docking pair for a rendezvous mission.

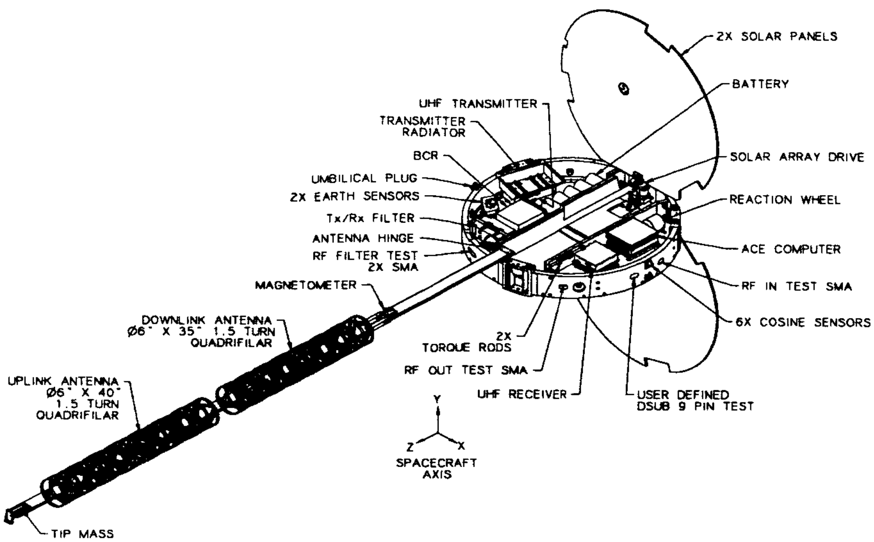


Figure 3: MUBLCOM Target Vehicle

At distances in the range of about 10-200 m, the long-range reflector set is used, followed by a transition to the short-range set at about the 10m range point. Two reflector sets are used for this mission, to provide for maximizing the AVGS range capability while ensuring that the AVGS field-of-view is not compromised at docking distance.

3. Vehicle Configuration Summary

The DART vehicle is pictured below. Note that the spacecraft consists of two major elements – the HAPS (hydrazine propulsion) system and the AVGS bus. The AVGS sensor is located at the front of the vehicle, with boresight slightly above the centerline. Other critical avionics components include a SIGI system (used primarily for attitude information) and a Surrey SGR-10 24 channel GPS receiver.

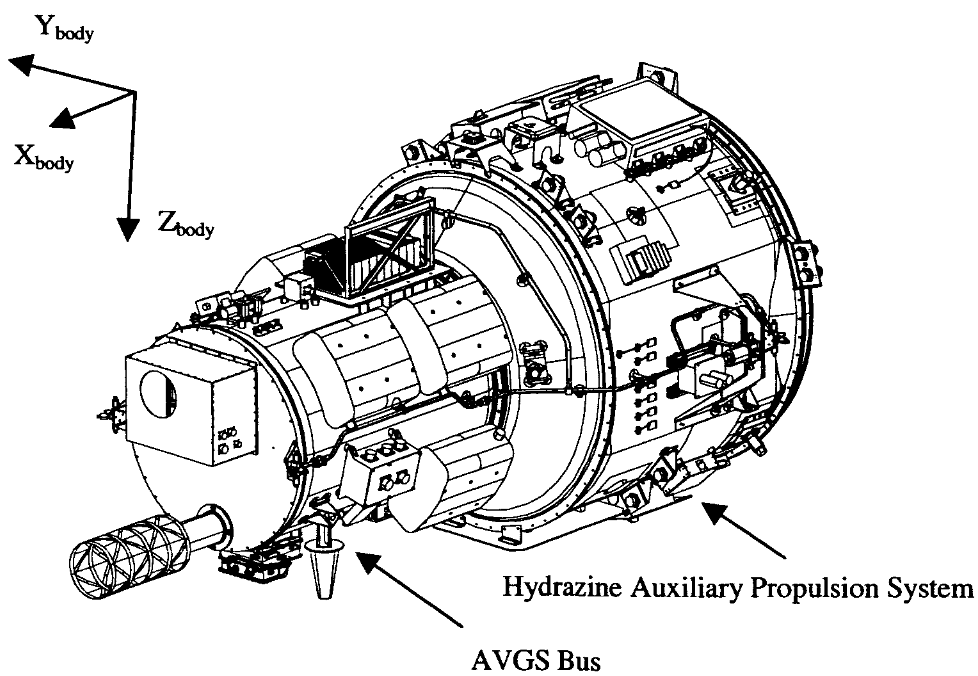


Figure 4: DART Configuration

As is typical for rendezvous vehicle, a range of thruster capabilities is available, as described in Table 1 below.

Table 1:DART Thruster Properties

System	Properties	Mission Usage
HAPS (hydrazine)	Three aft thrusters, nom. 160 N each; Approx total delta V of 400 m/sec	Used for major rendezvous burns and retirement burn; off-pulsing used for pitch/yaw control
Pegasus RCS (cold-gas)	6-thrusters, three on each side of vehicle; nominal thrust of 50 –100 N	Three-axis control during coast; roll control during HAPS burns
DART RCS (cold-gas)	16 thrusters, arranged in banks of 4, at 4N thrust; Approx total delta V of 40 m/sec	Used for DART prox-ops, for both translation and rotation

4. Attitude and Translational Control

The basic attitude and translational control system for DART has been chosen with simplicity and robustness as primary goals. A schematic of the control law appears in Figure 5, and Table 2 compares several feedback design approaches in general terms.

The DART vehicle uses a linear static-gain feedback control law for both attitude and translational control, with a PWM logic element applied at the inner loop where RCS control allocation is defined.

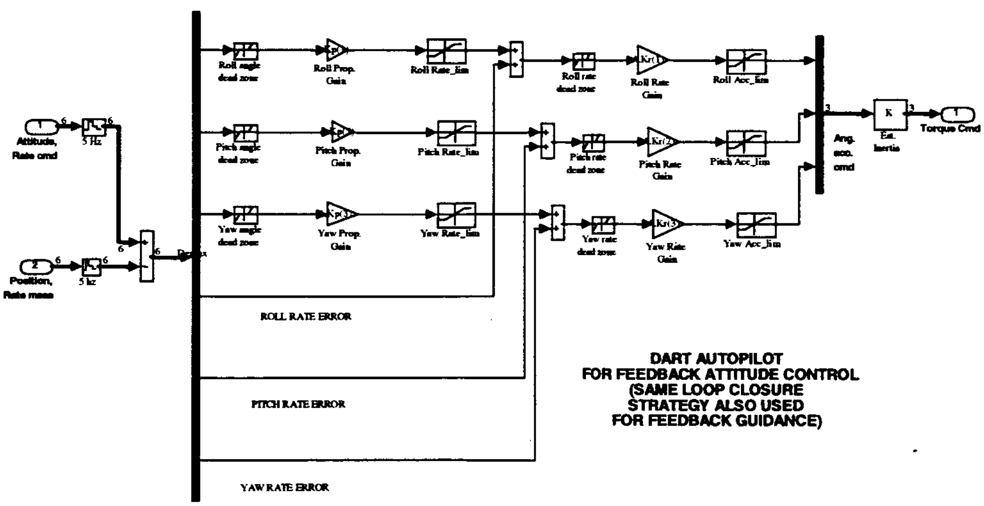


Figure 5: Attitude Control Schematic

Table 2 : Comparison of Feedback Control Approaches

Feedback Control Approach	Attributes
Phase Plane	Potentially, high performance and repeatability with respect to minimizing initial condition errors; time-optimal slew response
Linear control with pulse-width modulation logic	Very simple implementation; easily tunable; requires limiters on error signals to provide adequate large-signal response
Sliding mode (pure switching surface)	Requires "boundary zone" to avoid chatter; typically very robust; may exhibit higher fuel consumption than linear control

The control structure shown in Figure 5 is very straightforward, and is similar to science-mode control laws used in satellite designs developed by Orbital. The forward- path gains may validly be interpreted as bandwidth goals with dimensions of rad/sec. The result of each control loop (attitude or translation) is an angular or linear acceleration command. These acceleration commands are then dimensionalized into torque or force commands, via use of onboard estimates of the vehicle inertia and mass. This follows typical practice for satellite control, and allows the control bandwidths to be easily adjusted during the GNC design cycle.

The DART vehicle thrusters are arranged as shown in Figure 6. The forward thrusters have been canted at 45-deg to minimize concerns with impingement on the target satellite.

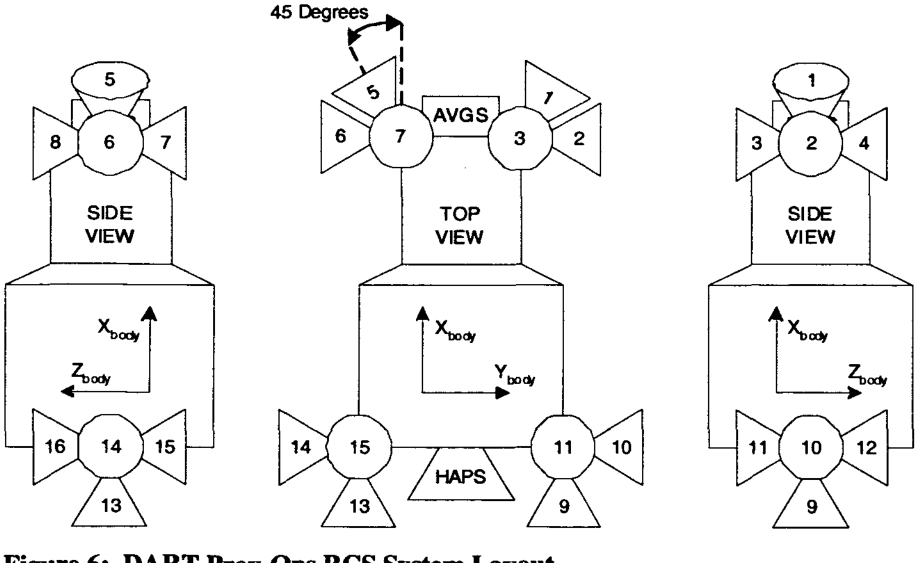


Figure 6: DART Prox-Ops RCS System Layout

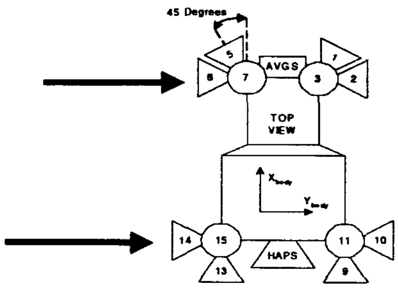
A number of options are available for allocating this control authority. Table 3 provides a qualitative comparison of several options for jet-select or control allocation logic. The approach chosen for DART is the use of pre-computed jet-select maps that combine the attitude control and translational control functions together.

Use of pre-computed maps keeps the computational load to a minimum, and mitigates any potential concerns with convergence issues that may occur for real-time optimization such as Simplex algorithms. Missions with a longer duration than the 24-hour DART sequence might benefit from a real-time optimization of fuel usage.

Table 3 : Comparison of Jet-Select Control Allocation Approaches

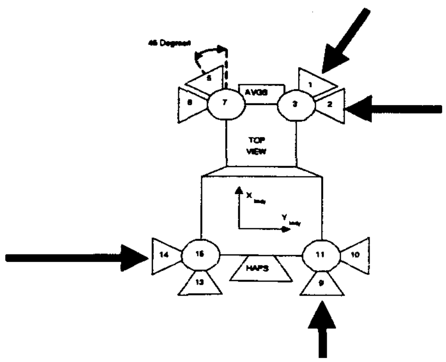
Jet-Select Approach	Attributes
Hardware design and allocation of physical thruster sets uniquely to physical control axes	Simple implementation; failure modes may not introduce strong coupling; not amenable to vehicle configuration changes during design cycle
Use of simplex algorithm for defining minimum-fuel command set	Allows for fuel-optimal jet selection; may require more testing to prove convergence of algorithms; may not provide natural robustness to failure cases
Pre-computed maps per control axis	Allows for designing to arbitrary goals (minimum fuel, control decoupling, fault-tolerance) offline; may provide natural redundancy to failure cases; does not adapt in real-time
Real-time ID and reconfig-uration	Requires adaptation model for thruster response, and excitation commands; may provide for highest true redundancy for a given configuration but stability of adaptation process must be certified through extensive simulation

Figure 7 and Figure 8 show a representative set of thruster maps, first for a side force command and secondly for a yaw moment command. Note that for this case, thruster number 14 is used with equal priority for lateral translation and yaw moment generation. The jet select maps are computed to provide a decoupled response; for example the small difference in the duration commands for lateral-force thrusting yields a side force with minimal yaw moment. Similarly, the yaw command mapping provides near-zero side-force and axial for thruster commands.



Per Cent Duty Cycle	Duration Command (msec)
0	0
0	0
0	0
0	0
0	0
63	126
0	0
0	0
0	0
0	0
0	0
0	0
0	0
66	132
0	0
0	0

Figure 7: Sample Jet-Select Mapping (+Y Force Command)



Per Cent Duty Cycle	Duration Command (msec)
12	24
13	26
0	0
0	0
0	0
0	0
0	0
0	0
8	16
0	0
0	0

Figure 8 : Jet-Select Mapping for the +Yaw Moment Command

The use of multiple thrusters for the jet select map provides some degree of natural redundancy. For example, in a nadir-directed force command all four of the top thrusters are used rather than just a diagonal pair. This still allows for effective control and pitch control in the event of a single-thruster failure. The closed-loop feedback in all axes provides additional mitigation for imperfect cancellation of out-of-plane forces and moments.

5. Navigation Processing Summary

The DART vehicle uses a range of sensors depending primarily on distance to the target vehicle. Table 4 below provides a summary of the various sensor combinations used for the DART mission.

Figure 9 provides a high-level schematic of the overall NAV processing. At ranges beyond 1km, GPS state differencing – from independent filters for the DART and target vehicles – provides the primary nav reference. At a range near 1mm, the AVGS sensor provides bearing information that is useful for centering the vehicle on the minus-VBAR. For reference the guidance-oriented frame has directions of VBAR (velocity vector or downtrack); HBAR (negative orbit normal or crosstrack; and RBAR (approximately nadir-directed, formed from the cross-product of VBAR and HBAR.)

Table 4: NAV Processing Summary

MISSION MODE	Data Sources	Processing Description
Pre-Launch	Downlinked MUBLCOM GPS Data	MUBLCOM GPS telemetry will be processed on the ground to provide an initial target vehicle state for the GOODS navigation filter prior to launch.
Launch	None	None
Rendezvous Prior to UHF Acquisition	Surrey GPS SIGI Blended GPS/INS Solution (Backup)	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI) GOODS target filter will propagate initial state
Rendezvous After UHF Acquisition	Surrey GPS SIGI Blended GPS/INS Solution (Backup) MUBLCOM UHF Updates	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI) GOODS target filter will be updated with MUBLCOM GPS measurements
Proximity Operations Range > 500 m	Surrey GPS SIGI Blended GPS/INS Solution (Backup) MUBLCOM UHF Updates	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI) GOODS target filter will be updated with MUBLCOM GPS measurements

MISSION MODE	Data Sources	Processing Description
Prox. Operations Rng 500 m to 200 m	Surrey GPS SIGI Blended GPS/INS Solution (Backup) MUBLCOM UHF Updates AVGS Bearing	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI) GOODS target filter will be updated with MUBLCOM GPS measurements Correction filter will process AVGS bearing measurements to partially estimate GPS state differencing offset
Proximity Operations Range < 200 m	Surrey GPS SIGI Blended GPS/INS Solution (Backup) MUBLCOM UHF Updates AVGS Bearing and Range	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI) GOODS target filter will be updated with MUBLCOM GPS measurements Correction filter will process AVGS measurements to estimate GPS state differencing offset
Retirement	Surrey GPS SIGI Blended GPS/INS Solution (Backup)	Surrey GPS measurements will be processed by the DART GPS filter (supplemented with accelerometer data from the SIGI)

In the DART mission, the bearing-only capability of AVGS is not used until the vehicle-to-target range is within several hundred meters. At this point the GPS-only state estimate is modified by the bearing information, to yield a position estimate which has high-accuracy crosstrack/radial information. Using this bearing information allows the chase vehicle to center itself on the –VBAR and allows for successful acquisition of the AVGS in track / relative attitude mode.

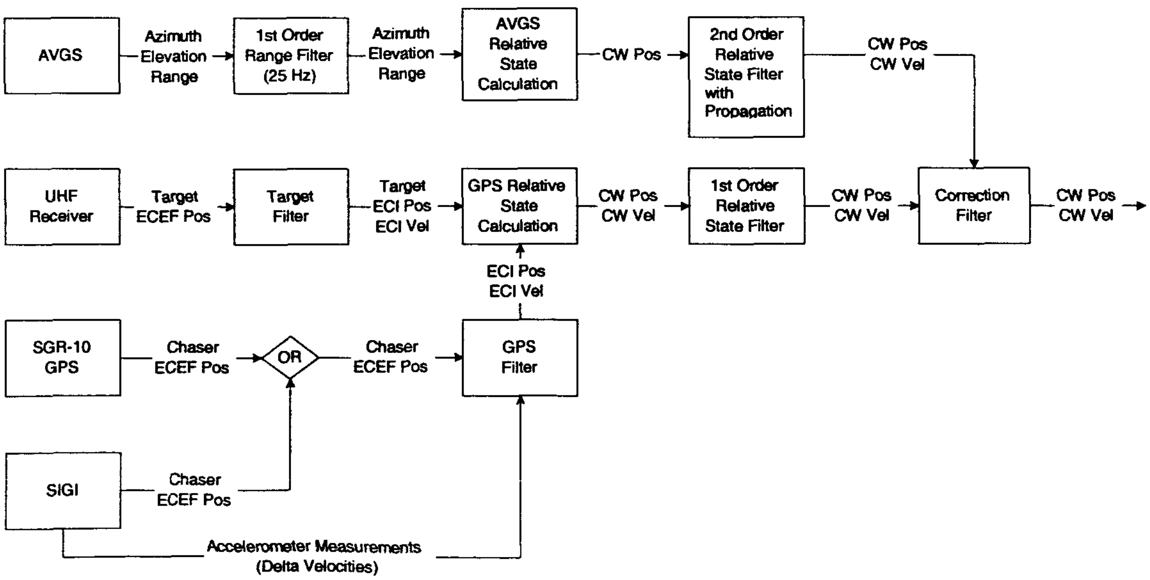


Figure 9 : Navigation Processing Schematic

6. AVGS Acquisition and Forced Motion Guidance

The AVGS system provides for several basic modes, including bearing-only ("spot") and tracking mode. The spot mode provides information on bearing (yielding azimuth and elevation signals), while the track mode provides range and relative attitude information. Additional details on these modes are available in Ref. 3, 4 and 5.

The basic acquisition sequence for AVGS consists of several steps:

- At a range below 1 KM, transition to spot mode by issuing the appropriate mode command. If bearing information is not then available, execute an attitude acquisition scan in a spiral pattern, out to a range of 30-40 deg in pitch and yaw. If the attitude scan is unsuccessful, the most likely cause is a large state-differencing GPS error equivalent to several tens of deg in bearing; in this case, a translational command is executed, with a length scale of 50-100 meters in the plane perpendicular to the target line-of-sight. At designated stop points on the translational scan, attitude scans are repeated until the AVGS reflectors are in view.

- After successful acquisition in spot mode, the bearing information is used to improve the cross-track and radial guidance solution. The DART vehicle is commanded to zero offset in crosstrack/radial (or HBAR/RBAR), and is commanded to point its centerline toward the estimated target position ("target-pointing" attitude guidance"). The command set will drive the chase vehicle onto the true –VBAR axis, with its centerline also aligned to that axis.

- Command the DART vehicle to move forward in forced-motion guidance, and mode the AVGS sensor to (range) acquisition. At a nominal range of 200+ meters the sensor will acquire the full AVGS reflector set information, providing the information for an inverse kinematics solution for range and attitude. At this point the accuracy of the range solution will be much better than GPS state-differencing, allowing for close-approach maneuvers.

- At a nominal range of 15 meters, transition to use of the relative attitude information for docking guidance, and execute approach/retreat maneuvers to 5 m.

Figure 10 depicts the formation of the target pointing command, as well as the coordinate axes of the target-centered guidance frame. Often this frame is referred to as the Clohessy-Wiltshire (or CW) frame, after its originators. Note that as the vehicle moves toward the –VBAR coordinate axis, the chase vehicle axis will naturally line up parallel to the –VBAR axis. This property of target pointing is useful for applications such as satellite inspection. The DART mission includes a circumnavigation maneuver in which the chase vehicle executes a local orbit around the target. Use of target pointing throughout such a maneuver allows for the vehicle sensor and camera axis to naturally point toward the vehicle without the need for injecting an open-loop attitude rate command.

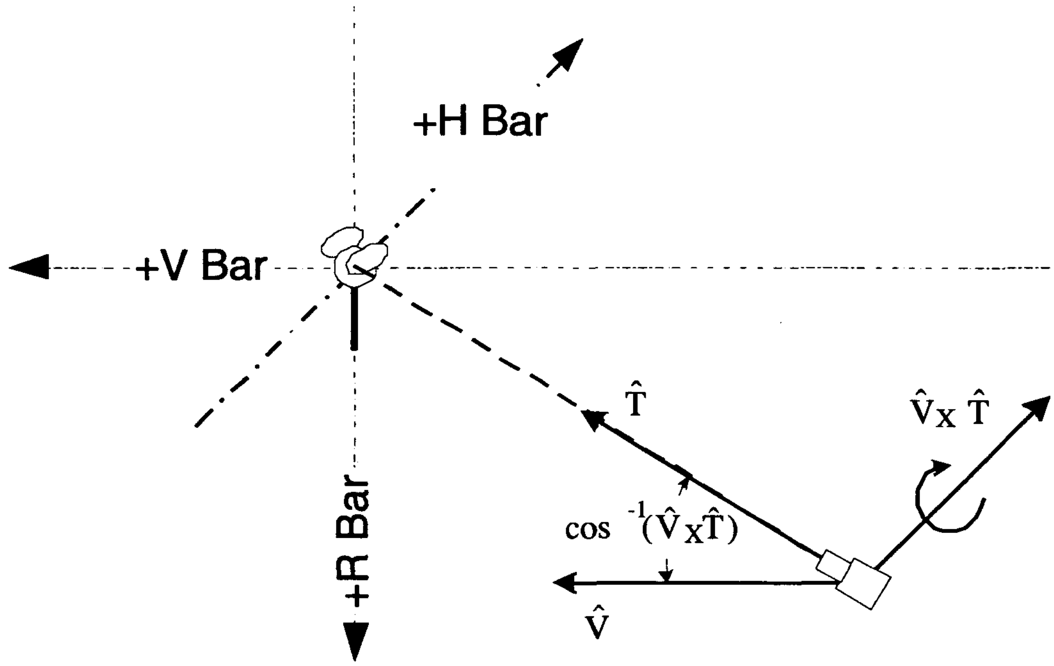


Figure 10: Target Pointing Command Formation

During docking guidance, a modified target formulation is used. In docking guidance there are two basic goals:

1) Track the translational position of a point corresponding to an extension of the AVGS target reflector set (the "mathematical docking port"); and
2) Minimize the relative attitude excursions between the target reflector plane and the chase vehicle AVGS sensor plane.

The first requirement above is required to properly center the chase vehicle, for a rotating or maneuvering target. For example, a passive or non-cooperative target may exhibit transient attitude motions on the order of several tenths deg/sec. As a rendezvous vehicle drives in toward a true docking pointing, the docking target will exhibit a cross-track and radial motion that must then be tracked. The second requirement ensures attitude compatibility of the docking mechanism for the final docking or capture sequence. Note that the DART mission will execute an approach to 5m since the target vehicle does not have a docking mechanism; the guidance used, however, would support an approach through final capture.

These two high-level functional requirements may be met in more than one way. For example, the relative attitude quaternion output from the video guidance sensor may be used to directly close the attitude feedback look, or it may be used instead to define a crosstrack/radial position command for the docking port. Table 5 illustrates the attributes of different docking guidance approaches.

Table 5: Typical Tradeoffs in Definition of Docking Guidance Signals

Relative Attitude Guidance Type	Attitude Error	Attitude Rate Error	Translation Error	Translation Rate Error	Comments
"Direct docking" (goal is to null the relative attitude quaternion components and AZ/EL components)	AVGS relative attitude quaternion	Derivative of relative attitude quaternion	AVGS AZ/EL signals	Filtered derivative of AVGS AZ/EL signals	Most physically direct means for control. Potentially provides for the smallest relative attitude errors; Injects latency of the AVGS signals into the outer and inner loops of the attitude and translational control loops AVGS data latency limits tracking bandwidths
"Direct docking with rate damping" (same as direct approach but with inner-loop damping from inertial solution)	AVGS relative attitude quaternion	Rate gyro output	AVGS AZ/EL signals	Inertial sensor data or propagated solution	Direct control of outer-loop signals Indirect inner-loop control Minimizes latency at frequencies where stability concerns are typically most pronounced (ie, rate loops)
"Indirect docking" with rate damping (define the position target from rel. attitude; target point for angle guidance)	Target pointing error (use AVGS-aided line-of-sight bearing error, indep.of target pitch/yaw)	Rate gyro output	Derived from relative attitude signals; projection of target attitude frame onto CW frame	Inertial sensor data or propagated solution aided by AVGS	Relative attitude data is used to define the docking port translational target Minimizes latency effects in outer-loop attitude control, allowing for high attitude bandwidth Reduces likelihood of loss-of-lock for transient attitude motions. Control is indirect and dependent on intermediate coordinate transformations to CW frame

For the DART project, indirect guidance with rate damping (the third option in Table 5) was selected. DART GNC design has been intentionally biased towards minimizing complexity and risk, and ensuring stability of the various control loops. The indirect guidance option offers the lowest latency for outer-loop closure, and provides for a very simple mechanization in that the docking guidance is realized via definition of position targets for the existing stationkeeping loops.

Figure 11 provides a typical comparison showing the effects of increased latency on feedback stability margins; in these plots the attitude guidance bandwidth is a factor-of-several greater than the position loop bandwidth, per standard aerospace design practice. The higher bandwidths used for the attitude loop induce a greater sensitivity to transport lag. The right subplot of this figure shows that a transport lag of 40 msec still provides for reasonable stability margins. It is possible that latencies from video guidance processing may exceed this number, and the DART program has parametrically explored the effect of latencies through a range up to 200 msec. Using the same docking bandwidths, the left subplot shows the decrease in stability margins which occurs as the true relative attitude information is introduced into the angle and angle rate loops. This stability margin trend may be mitigated via bandwidth reduction, trading off performance vs linear margin goals.

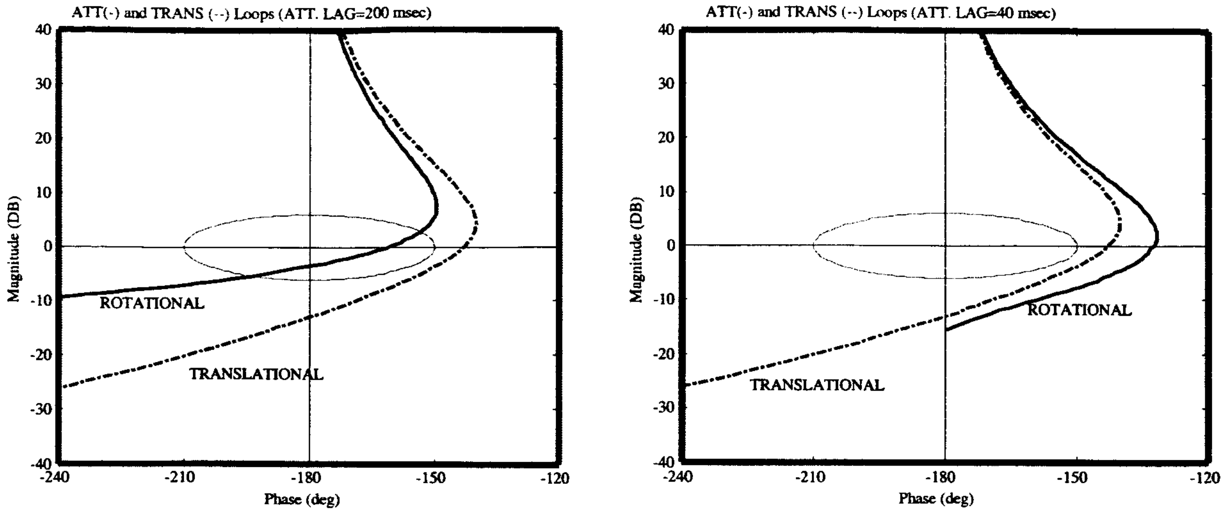


Figure 11 : Nichols Stability Response for 200 msec and 40 msec Relative Attitude Transport Lag

Note that the DART docking guidance approach is termed indirect, because the relative-attitude-hold goal is actually realized by a target pointing (or line-of-sight) pointing command. The true relative attitude information is used to define a position error. For example, a target yaw motion will yield a relative attitude error for the AVGS output quaternion yaw component, and this relative angle error is equivalent to a crosstrack shift in the location of the docking port target. The relative yaw error is then mapped directly into the docking port position command, and this loop is closed using the position loop for stationkeeping guidance. As the chase vehicle then translates in crosstrack to follow the docking command, it is commanded to align its centerline along the line of sight based on its bearing to the target (independent of target attitude). The long-term effect of enabling both these guidance loops – docking-port tracking, and target pointing – is to yield a response which keeps the target and chase vehicle relative attitude errors near zero. Simulation work has shown successful tracking of target yaw excursions in excess of 60 deg, while relative attitude errors are maintained to within 2-3 deg.

7. Guidance Simulation Outputs

The DART guidance design and flight software has been incorporated into the nonrealtime (NRTSIM) and realtime (RTSIM) environment. Representative simulation outputs are provided below.

Figure 12 and Figure 13 show response during close-in operations, with the second figure depicting the 45 minutes of docking guidance command response. Note that the docking guidance mode is entered near time-zero of Figure 12, and the initiation of that mode is apparent in the radial command-and-response that shifts several meters below the VBAR. This shift occurs because the MUBLCOM target reflector plane is depressed to 7-deg below the horizontal; thus the docking port at 15-meter range may be visualized as a 15-m line segment originating at the target satellite, at an elevation of –7 deg. The DART vehicle is able to acquire the docking port – that is, to drive position errors to near-zero – within several tens of seconds. The remaining vertical excursions in the radial response are driven by target vehicle pitch motions, which cause the docking port location to translate vertically. These commands are tracked very well by the vehicle's guidance system, as shown by the close correspondence of commands and response.

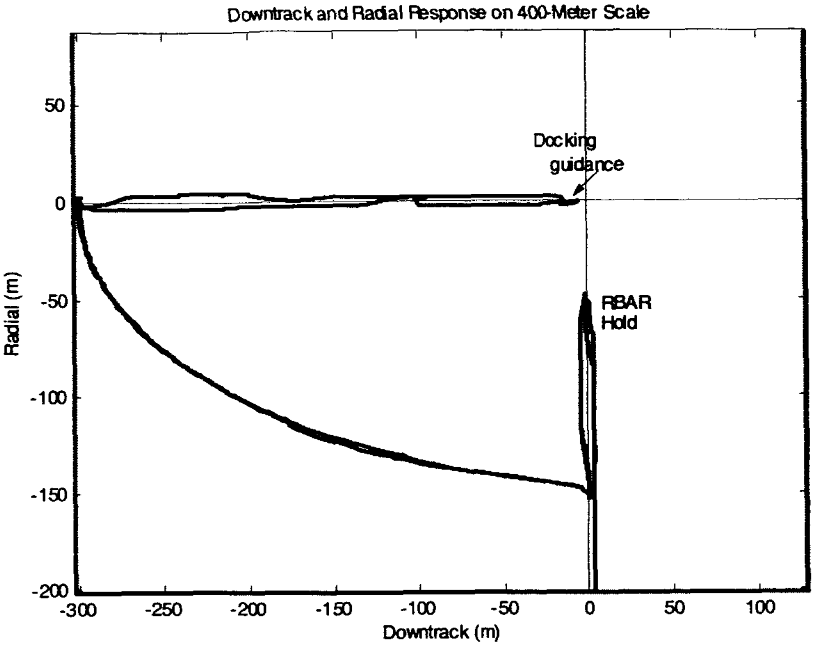


Figure 12: Downtrack and Radial Simulation Response, 400-m

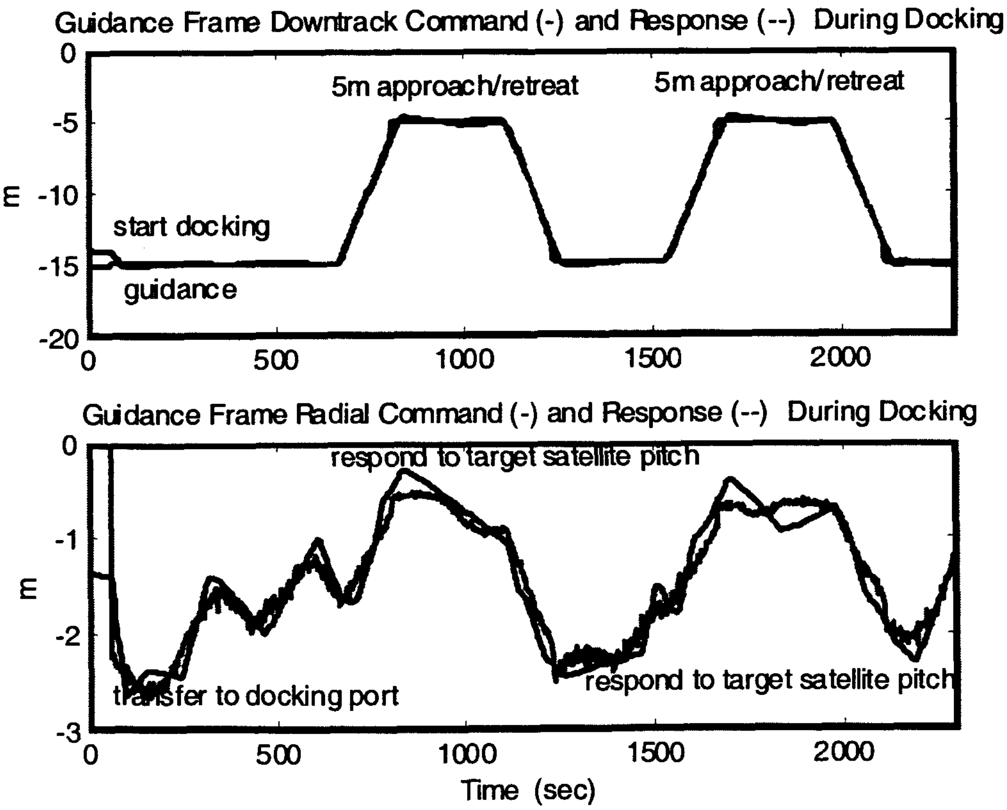


Figure 13: Docking Command Responses

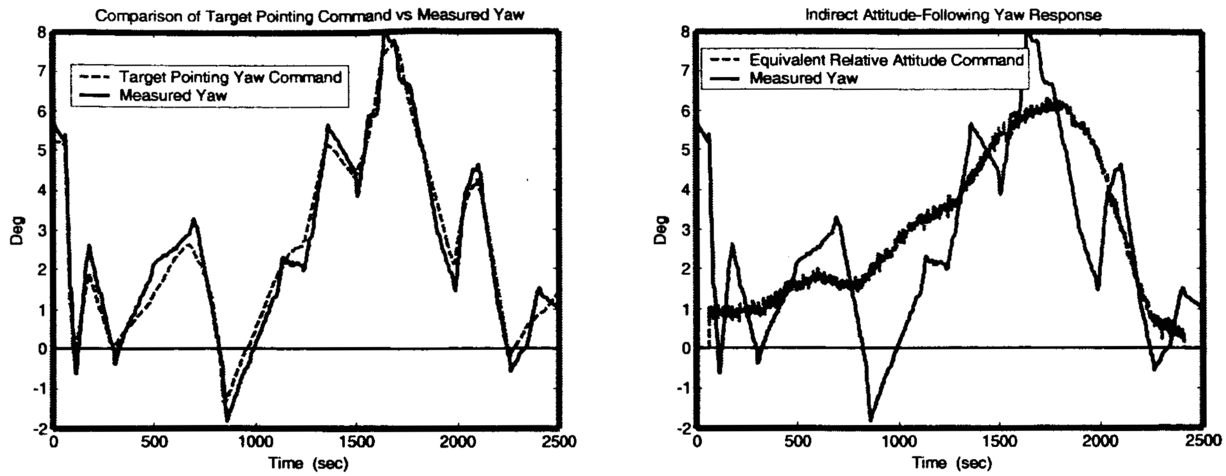


Figure 14: Comparison of Different Yaw Tracking Signals

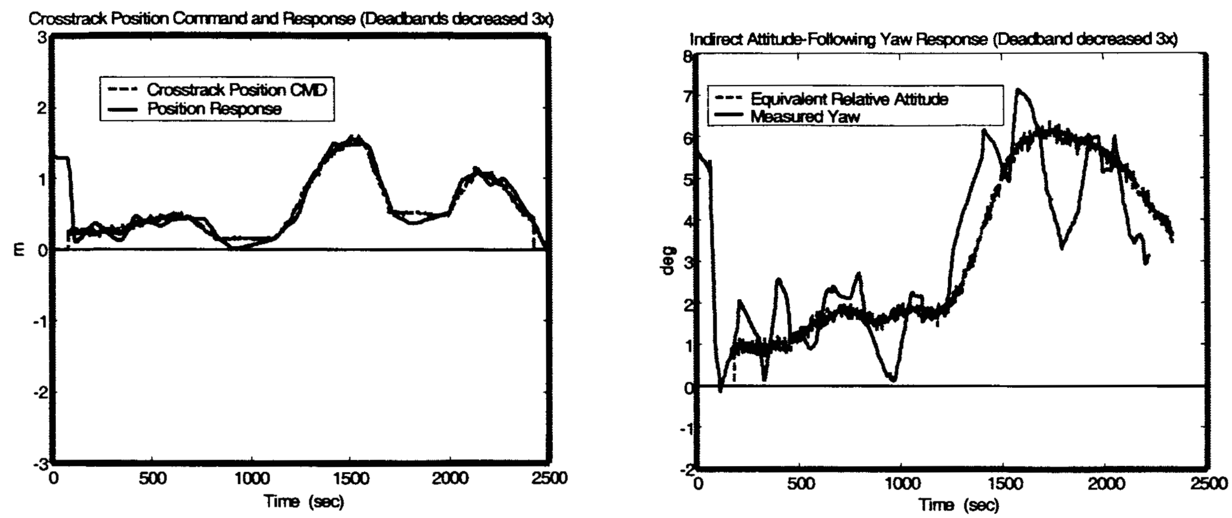


Figure 15: Effect of Position Deadband on Reducing Relative Attitude Errors

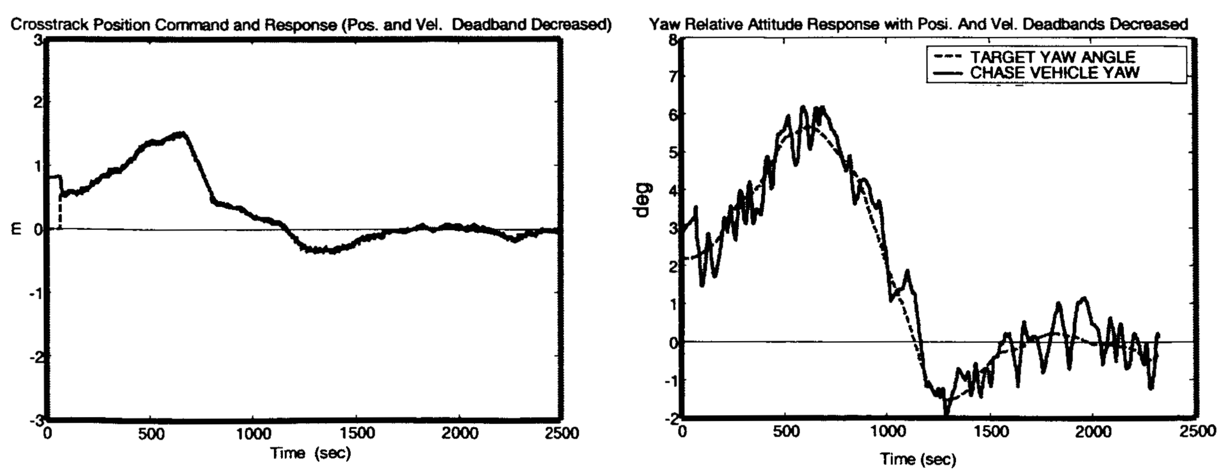


Figure 16: Effect of Combined Position and Velocity Deadband Decrease, on Relative Yaw Tracking

Figure 14 and Figure 15 illustrate some additional response signals, now in the crosstrack or yaw plane. The left subplot of Figure 15 shows the target pointing guidance performance. For the DART design, the target pointing error yaw signal represents the azimuth component of the angle between the estimated line of sight (from the NAV solution aided by AVGS), and the vehicle centerline. This signal is independent of target yaw angle, and is tracked very well in the guidance design. The relative attitude error is the angle between the target vehicle yaw, and the chase vehicle yaw. On average the vehicle yaw response will respond in a direction to yield a mean value of zero for the relative attitude error, as shown by the right-hand subplot of Figure 15.

The response of Figure 14 shows errors on the order of 2-4 deg in relative yaw. This performance may be improved via reductions in the position deadband thresholds for docking guidance, as shown in Figure 15. A further improvement in yaw and crosstrack position response appears in Figure 16, where both the position and velocity deadbands have been decreased to reduced tracking errors. The DART docking guidance may readily be tuned as shown in these figures, to trade off tracking performance against control activity and RCS fuel usage.

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