Flight Control Overview of STS-88, the First Space Station Assembly Flight

Robert Hall[†], Kim Kirchwey[†], Michael Martin[†], Gene Rosch[†], Douglas Zimpfer[†]
The Charles Stark Draper Laboratory, Cambridge, Massachusetts

When the Space Shuttle Endeavour undocked from the Zarya/Unity configuration on STS-88 it marked the completion of the most challenging shuttle mission to date and the beginning of an enormous task of assembling the International Space Station. The flight offered an array of complex dynamics and control related challenges to mate the American module 'Unity' to the Russian module 'Zarya'. Capability demonstrated on the flight included closed-loop thruster control in the presence of low frequency structural dynamics and mated-vehicle translational maneuvers in the presence of structural loads and thruster hardware constraints. The flight was a complete success from all aspects.

This paper will give an overview of the flight control challenges encountered and the actual control performance observed for the on-orbit operations. Included will be the shuttle analysis and filtering strategies to ensure control system stability in the presence of low frequency flex-body dynamics. The paper will key on the following operations:

Shuttle Rendezvous to Zarya: To ensure mission success it was required to extend the load-sensitive Unity out of the Shuttle cargo bay prior to performing the rendezvous burns necessary to dock to Zarya. An illustration of this configuration is shown in Figure 1.

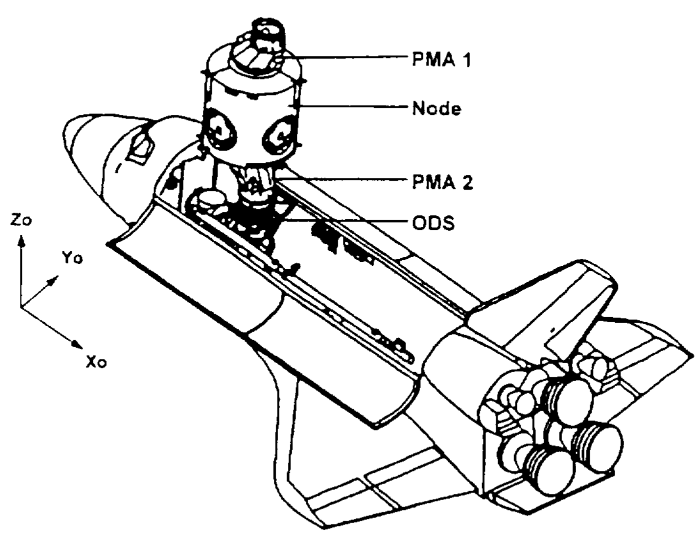


Figure 1: Extended Payload Configuration During Shuttle Rendezvous

[†] Senior Member, Technical Staff

The shuttle had never performed a rendezvous in a large payload extended configuration and two key challenges existed:

1. The extension of Unity resulted in a mass center location outside of nominal gimbal capability of the shuttle Thrust Vector Control (TVC) system. Failure to trim through the mass center would result in failure of the TVC to control the rotational dynamics. In this event the non-linear Primary Reaction Control System (PRCS) "wraparound" control would be activated, which would quickly lead to violation of Unity load capability. In addition, the TVC had not been certified for low structural frequencies on the order of those expected with the Unity extended. A unique modification was made to the Shuttle software to increase the gimbal capability and minimize wraparound effects, and the TVC stability in the presence of low-frequency dynamics was certified with linear analysis techniques and singular value analysis. Acceptable structural loading of the Unity during the TVC burn was assured by simulating an analytical "wraparound" firing pattern which was defined assuming 3-sigma system uncertainties and worst-case frequency content. On-orbit, the burns were successful and without issue.

2. Smaller translational commands during the rendezvous are performed by the shuttle non-linear PRCS and it was found that high frequency PRCS pulsing during closed-loop control or manual (crew) control would again result in loads exceeding Unity capability. The resulting solution involved significant operational constraints placed on crew and the flight control system, the latter including an increase in the allowable attitude error value in the Shuttle phase plane from two degrees to 40.

Shuttle control with Zarya deployed on the Shuttle Arm: The Zarya, weighing over 42000 pounds, represented the largest payload ever deployed on the Shuttle arm and the corresponding arm structural frequencies were well within the bandwidth of the Shuttle flight control system. The installation of the Zarya is illustrated in Figure 2.

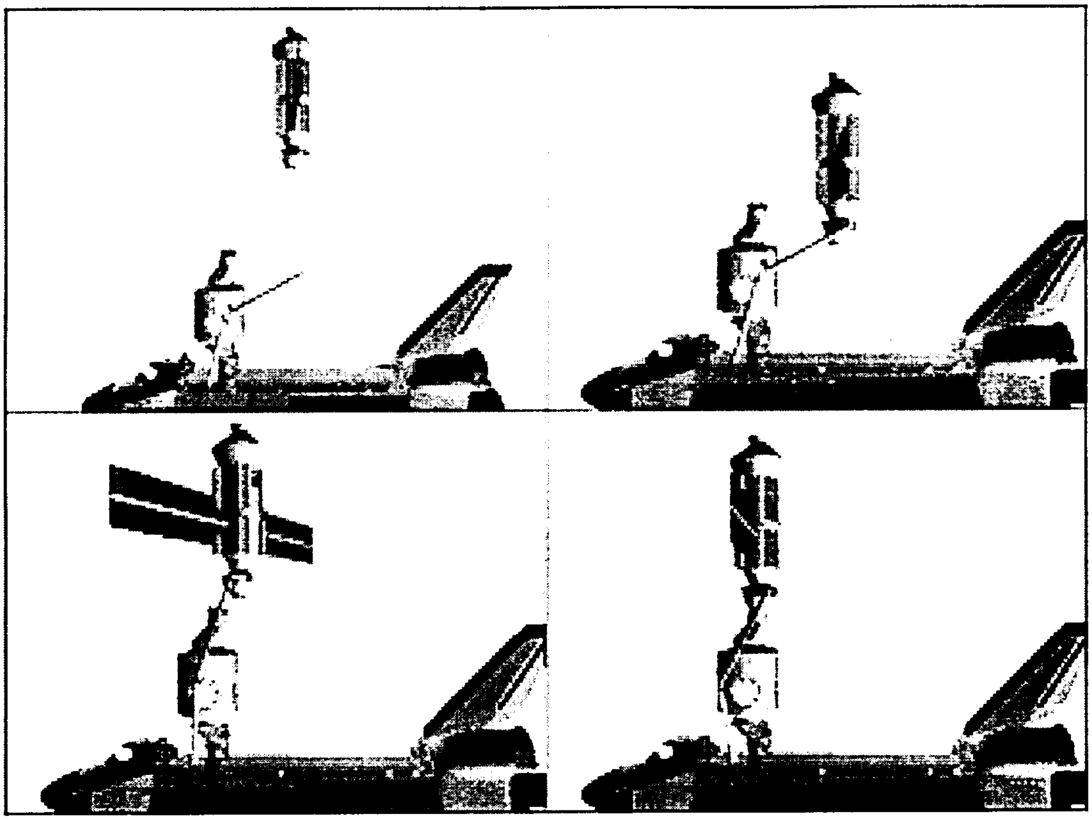


Figure 2: Berthing of the Russian Zayra onto the American Unity.

Bandstop filtering was employed to minimize control structure dynamic interaction and software-controlled pulsing constraints were utilized to minimize arm motion during active Shuttle control. A Bode plot of the Shuttle state estimator with the bandstop filtering included is shown in Figure 3.

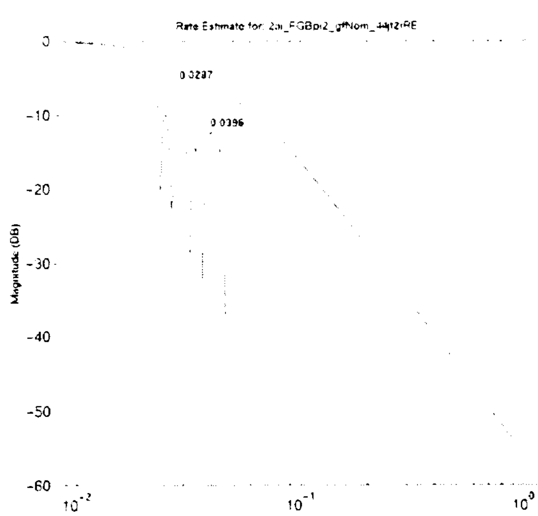
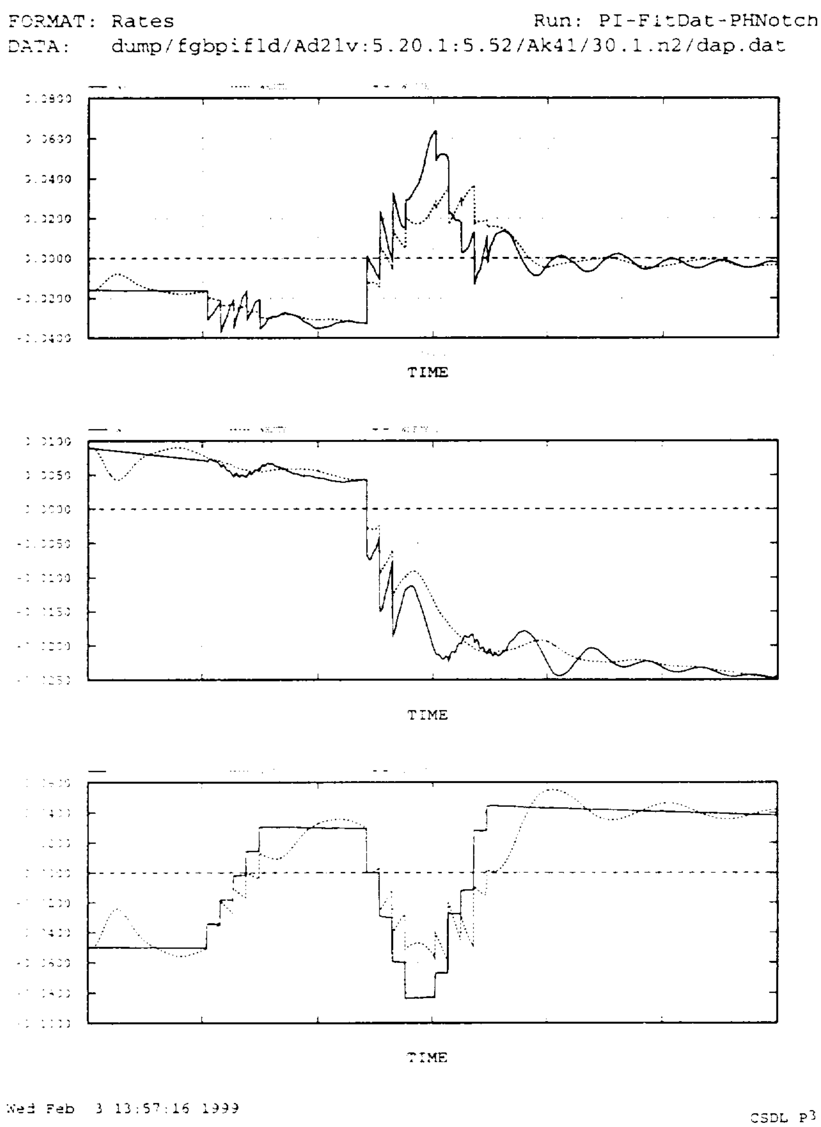


Figure 3: Shuttle State Estimator Frequency Response with Bandstop Filtering for Zarya deployed on the Shuttle Arm.

Bandstop filter width and attenuation were dictated by modeling uncertainties. The low frequency dynamics and corresponding filtering introduced significant lag between the actual rotational rate and Shuttle estimated rate. Correspondingly, control performance was compromised but still adequate. Reconstructed on-orbit performance is shown in Figure 4 illustrating the error and transients introduced by the filtering during attitude control thruster firings. Pulsing constraints designed to minimize the arm motion proved extremely successful even in the presence of the 870 pound shuttle thrusters used for rotational control.



——— Actual Rate

.... Estimated Rate

- - - - - Desired Rate

Figure 4: Shuttle On-Orbit Rotational Rates During Attitude Hold with Zarya Extended on the Shuttle Arm.

Shuttle Reboost of the Mated Configuration: The altitude of the mated Shuttle/Station configuration was increased by three nautical miles prior to Station release by utilizing the Shuttle thrusters. With consideration of flight control stability, controllability, and structural loads, a technique was designed which utilized the large Shuttle primary shuttle thrusters (870 lbf) for translational acceleration followed by the smaller vernier thrusters (25 lbf) for attitude and rate control. An overview of the reboost technique is provided in Figure 5, where the Shuttle thruster command is given along with expected pitch axis attitude and rate error dynamics. The pulse pattern is repeated until the desired altitude increase is achieved. The paper will discuss flight control stability, performance, and thruster hardware certification for the reboost procedure and illustrate actual on-orbit performance.

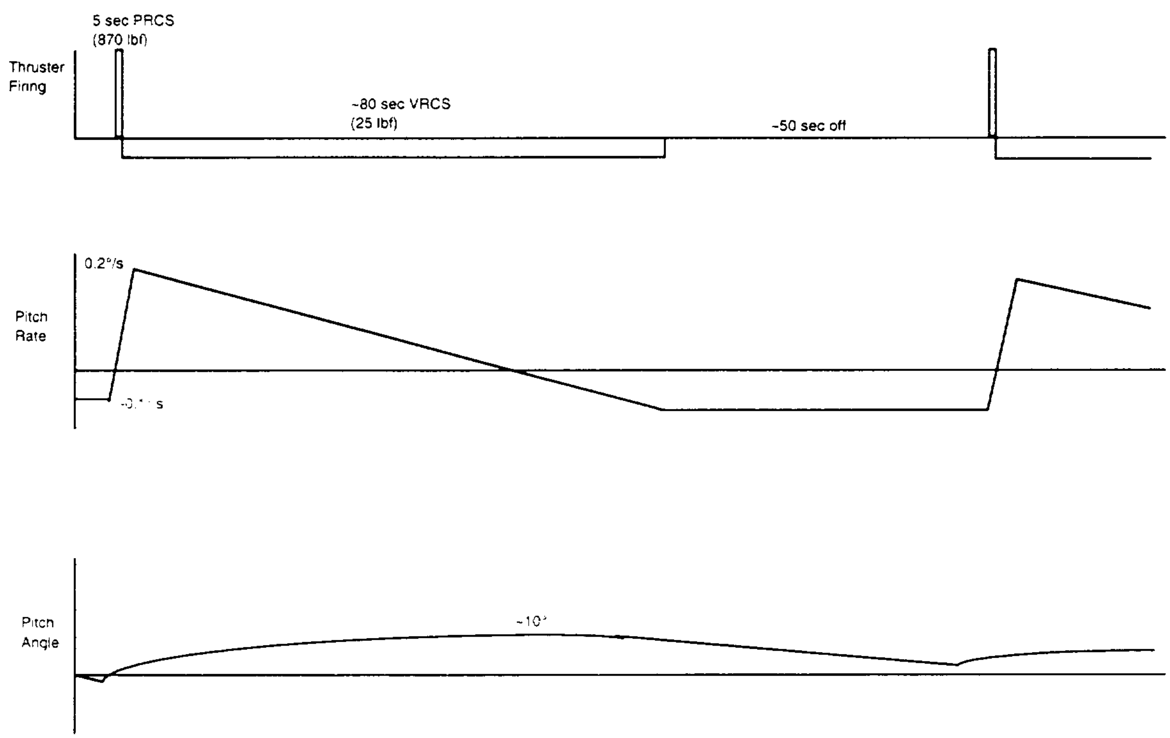


Figure 5: Illustration of Thruster and Pitch Axis Dynamics During Shuttle Mated Vehicle Reboost.