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Hubble Space Telescope Pointing Control System Design Improvement Study Results

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Unexpected thermally induced disturbances originating in the solar arrays imposed deleterious effects on the pointing performance of the Hubble Space Telescope (HST). A NASA redesign of the onboard pointing control system (PCS) brought the performance back into specification during a majority of the orbit time. As a result of this controller redesign effort, a wealth of flight data was collected and control design simulation models enhanced. Under sponsorship of the NASA Controls/Structures Interaction Program at the Marshall Space Flight Center, a study was conducted to determine if performance improvements could be obtained when advanced modern control techniques under study in the program were applied to the HST PCS. Five modern control techniques were applied to the problem. Flight data and simulation models were provided to the research teams. The methods considered were reduced-order model-based control, linear-quadratic-Gaussian-based control, analytically and numerically derived H_∞ control, covariance control, and dual-mode disturbance-accommodating control design. The performance of these designs was tested in a government-furnished nonlinear simulation of the HST. In general, some performance improvements over the NASA redesigned controller were seen in the simulation studies.

Introduction

SOON after the Hubble Space Telescope (HST) was launched on April 25, 1990, and deployed the following day, the fact that a number of problems existed with the observatory became apparent. Not only was there a flaw in the main mirror, but examination of the flight data immediately revealed that there were unexpectedly large perturbations in the pointing control system (PCS).[1] An investigation was launched to determine the cause(s) of the perturbations and to explore what could be done to correct the problem. The disturbances were traced to thermally induced deformations of the solar arrays that were driven by day-night changes in the thermal environment. As soon as the problem was identified, efforts to redesign the PCS to eliminate the effects of the disturbances began. A successful reconfiguration of the flight computer and redesign of the control system, along with a slight modification of the original performance requirements, resulted in a controller that met the new specifications most of the time.

As a result of the PCS redesign efforts, a wealth of flight data was collected that was specific to the control system performance. Simulation models were enhanced as more was learned about the on-orbit dynamic behavior of the spacecraft. Techniques were developed to explore the behavior and performance of new controller designs using actual flight data to simulate the disturbances imparted on the craft by the solar arrays. To take maximum advantage of the data and simulations available, a design study was initiated under sponsorship of the Marshall Space Flight Center (MSFC) Controls/Structures Integration (CSI) research program.

MSFC began CSI research activities in the early 1980s with the initiation of the development of the Large Space Structures Laboratory under the sponsorship of the Department of Defense (DoD). Subsequent to the DoD-funded developments, NASA headquarters sponsorship supported the program through fiscal year 1993. The emphasis of the CSI program at MSFC was placed on developing ground test facilities, advanced system identification and controller design techniques, innovative sensors and actuators for flexiblespace structures, and promoting CSI technology transfer to flight programs. Two structural testbeds were eventually developed under the CSI research program. These are the Single Structure Control Facility, also know as the Advanced Control and Evaluation for Systems (ACES) Laboratory, and the CSI Ground Test Facility, also known as the Controls and Structures Experiment in Space (CASES) Laboratory.[2,3]

Transfer and application of the technologies developed during the course of the CSI research activities at MSFC have been a trademark of the program. Examples of this include the use of advanced multibody modeling and analysis codes developed under MSFC sponsorship to the Inertial Pointing System, both ASTRO missions, the Long Duration Exposure Facility retrieval mission, the Advanced X-ray Astrophysics Facility missions, Inertial Upper Stage separation dynamics analysis, Earth Observing Systems platform dynamics, and dynamic analyses of the many configurations thus far assumed by the proposed space station. One of the most striking examples of application of the testbeds and control design techniques developed in the MSFC CSI program is to the redesign of the HST PCS.[4]

Another facet of the CSI program was research in advanced control theory development. Four universities and one private corporation were performing research in this area at the time of the NASA HST PCS redesign effort. With the data and simulations available, a perfect opportunity to apply these techniques to an actual flight program arose. The HST PCS Design Improvement Study was initiated in 1992 with the goal of applying advanced control theory to the HST PCS problem and testing the results in NASA-developed simulations. In the following sections, the study is described.

Study Overview

During the course of the MSFC CSI program, a number of universities and aerospace companies worked with MSFC researchers on fundamental research in advanced control theory, including the five groups represented in the HST PCS design improvement study. Those involved in the study include Ohio University, the University of Alabama in Huntsville, the University of Colorado in Boulder, Purdue University, and Harris Corporation. To determine the potential performance gains achievable by the control design theories under study in the MSFC CSI program, the investigators employed H_∞, disturbance-accommodating control, reduced-order model-based control design and residual mode filtering, covariance control, and linear quadratic Gaussian (LQG) methods, respectively, to the PCS design problem using HST flight data and NASA-developed models and simulations. Having access to actual

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flight data and a set of proven models provided an excellent opportunity to test the advanced control design theories.

Prior to describing the design improvement study, a brief description of the HST PCS is in order. The PCS is composed of four reaction wheel assemblies, three fine guidance sensors, three or four of the six reference gyros, and the DG-224 onboard central computer. A magnetic momentum management system continuously unloads the wheels, sun sensors are used in coarse attitude determination and safemode, and three NASA standard star trackers are used for attitude updates. The reaction wheel actuators are mounted in a pyramid arrangement symmetric to the long axis (V1 in all references cited) of the telescope. The maximum torque capability of the reaction wheels is 0.82 N-m. The nominal control algorithm is a standard proportional-integral-derivative (PID) operating at 40 Hz using the rate gyro assembly measurements. References 5 and 6 provide detail on the baseline HST PCS.

The short design study was initiated in early summer 1992. The design teams were provided with identical task statements and data packages, and all had roughly the same amount of time to perform the controller design and evaluation. Each team was tasked to demonstrate their method of control design by developing a modified control law for the HST PCS to reduce the line-of-sight jitter to less than 0.005 arc-s in the presence of unknown solar array disturbances. Only the 40-Hz "gyro-hold" mode of the HST control system operation was considered, allowing the design modifications to neglect the multirate/multiloop effects of the HST observer, fine guidance electronics, high-gain antenna control, gravity gradient compensation, and momentum management systems. The modified controllers must satisfy the constraint that a state proportional to the integral of the HST attitude is included to retain the interface to the original attitude observer loop. The modified controller must update the commanded reaction wheel assembly torques within 0.008 s of each 40-Hz rate gyro assembly measurement and complete all remaining computations within 0.015 s. The 24-bit fixed-point limitations of the flight computer and the saturation limits of the reaction wheel assemblies are additional constraints.

Because the focus of the effort was intended to be on control law design and not modeling issues, MSFC provided the required data and simulations to the research teams. Gyro-hold flight data taken at 40 Hz during orbital day and night terminator crossings at four distinct solar array orientations plus one complete orbit of gyro-hold data obtained under the influence of the original HST control law at one solar array orientation were provided. A high-order (118-state) multi-input, multi-output (MIMO) linear state space "truth" model and composite single-input, single-output (SISO) control design models for the three dominant transfer functions were provided for the study. Finally, a FORTRAN simulation of the HST that employed the linear state space model to implement the NASA solar array gain augmentation (SAGA)[1,6,7] control law modification with the nonlinear effects of fixed-point scaling and reaction wheel actuator saturation was provided. This simulation, in effect, replays measured HST flight data and predicts the performance improvements for a redesigned controller. With the data and simulations in hand, the research teams began their study of applying advanced modern control techniques to the problem of improving the performance of the HST PCS in the face of unpredicted dynamic disturbances.

Design and Performance of SAGA Controllers

As soon as the problem of the thermally induced structural disturbances to the PCS was recognized, work began on its redesign. A team of engineers from MSFC, the Goddard Space Flight Center, and Lockheed Missiles & Space Company worked nearly around the clock to develop a method to correct the problem. The result was an incremental design that began with the SAGA controller followed by the SAGA-GA and finally the SAGA-II controller, which met the new performance specifications. The development of these controllers is detailed in Refs. 1 and 7. A brief description of the SAGA series is presented below.

The original pointing requirement for the HST was to maintain an image on the focal plane stable to 0.007 [arc-s] root-mean-square (rms) for observations lasting from 10 s to 24 h. A derived requirement was that the fine guidance sensors not lose lock on the guide stars. The solar array disturbances prevented the PCS from meeting this requirement with errors exceeding 0.1 arc-s seen at the terminators, and loss of lock occurring frequently. In consideration of the disturbance environment and the practical needs of the science instruments, the pointing requirements were redefined as follows. For 95% of all 1-min intervals during an orbit, the pointing errors will be less than 0.007 arc-s (rms) and loss of lock shall not occur more than once every 16 orbits.

The two solar array modes causing the most problems are a 0.11-Hz out-of-plane mode and a 0.65-Hz in-plane mode. The original PCS was not designed to compensate for structural disturbances; therefore, the entire architecture of the controller was redesigned. In essence, a "frontal lobotomy" was performed on the flight computer. Two sixth-order filters were added to the PID controller structure in each axis. The G_A filter was inserted into the forward path and the G_F filter was added to provide inner loop control.[7] To achieve the redesign, better models of the disturbances were required. Limited on-orbit modal tests were performed and the data used to update the models employed for the SAGA controller redesigns.[8]

The goal of the first SAGA controller was to attenuate the 0.11-Hz mode using the two additional filters while maintaining the good response characteristics and stability margins of the original PID controller. A number of limiters are used in the controller, the settings of which turned out to be crucial to the success of the SAGA controller. The settings were determined essentially by trial and error using the simulations. The SAGA controller was implemented in mid-October of 1990 and was successful in attenuating the 0.11-Hz mode. However, a sustained low-amplitude limit cycle was present leading to the subsequent design of the SAGA-GA and SAGA-II controllers.

The SAGA-GA controller was derived based on "lessons learned" from the SAGA design. This controller used only the G_A filters, and a reduced direct current (dc) gain. The SAGA-GA was tested on orbit in March 1991. It provided performance superior to that of the SAGA controller with no nonlinear behavior noted. The 0.11-Hz mode was attenuated by a factor of 30 and the 0.65-Hz mode was attenuated by a factor of 2. The resulting jitter level was below 0.007 arc-s for approximately 85% of each orbit, compared to 42% with the baseline PID. Loss-of-lock performance was also improved. Prior to SAGA-GA implementation, loss of lock occurred at approximately 75% of terminator crossings.

The SAGA-II, the ultimate PCS design, was based on the previous two SAGA designs. Both the G_A filters and the G_F filters are incorporated into the design with the goal of maintaining the attenuation of the 0.11-Hz mode achieved by SAGA-GA, increasing the attenuation of the 0.65-Hz mode to a factor of 5, maintaining adequate stability margins, and preventing any degradation in the loss-of-lock performance. The SAGA-II design achieves all four of these goals and was permanently installed in the HST on April 16, 1992. The performance of the SAGA-II has been excellent, maintaining jitter to less than 0.007 arc-s over 95% of the time. Loss of lock has been linked to the 0.65-Hz disturbances, which produce large torques at midday hits. Because the SAGA-II controller attenuates these disturbances by a factor of 7.5 (goal was 5), improved loss-of-lock performance has been realized. Loss-of-lock percentage at terminators has been reduced by approximately 50%. The SAGA-II performance is that against which the modern controllers are compared in subsequent sections.

Modern Control Design Approaches

The five modern control design approaches for the HST PCS are now discussed. It bears restating that each design team was provided the same data, models, and simulations. Using the models and simulations was not a simple task for the designers. The models and simulations were developed by individuals not directly associated with the design improvement study. In spite of many promises to deliver, no documentation was ever provided. Many questions submitted by the design teams still remain unanswered. A number of errors were uncovered in the simulations as the study progressed and the design teams shared this information as it was discovered. The cause of the errors has yet to be addressed. Even more confusion resulted when it was discovered that the SISO design models contained modes that the MIMO linear and nonlinear simulations did not. Four of the five design teams developed usable versions, some reduced in order, of the NASA-provided codes. The University of Alabama in Huntsville team went so far as to develop their own simulation from the fundamental equations of motion of a simplified planar model of the HST to use with their controller design. Each team has detailed in their study papers referenced in the subsections below the various problems that were encountered and how they were dealt with. This problem is addressed in the Lessons Learned section.

In the following subsections, each controller design approach is summarized with a verbal description only. The technical details and particulars of each design method are thoroughly covered in the references cited and the interested reader is encouraged to review those articles. The resulting performance of the five controller designs is then summarized.

Reduced-Order Model-Based Control Design

Mark Balas led the design team from the University of Colorado in Boulder. Their design approach is based on disturbance-accommodating control (DAC) for large flexible structures.[9] A low-order version of DAC using a reduced-order model (ROM) controller, a disturbance estimator, and a residual mode filter (RMF) is developed for the HST PCS.[10] The theoretical development of the RMF and the application of ROM/RMF control to large finite element models of structures are given in Refs. 11 and 12.

The RMF concept was developed for situations where 1) the control algorithm order is necessarily less than that of the best available system dynamics model and 2) oscillatory modes in unmodeled dynamics that were thought to be ignorable are driven into instability by a high-gain control system. Finite element models of complex space structures have far too many degrees of freedom to be used directly for control system design and implementation. However, the modal decomposition of the dynamics provided by finite element analysis provides a convenient means to formulate control models of lower order in decoupled modal coordinates. The ROM design does not consider the effect of the control system on any ignored (residual) dynamics. Often, a number of these modes are driven unstable by the controller action. The ROM controller might be redesigned to include the interacting dynamics with the effect of increasing its order, but there is always the risk of creating new interactions. The RMF is an alternative to a redesign cycle that provides independently designed, "add-on" compensation to stabilize the original ROM controller. This is the motivation for applying the technique to the HST PCS.

To accomplish the design, the original NASA-provided model of the HST is converted from a component modal model to a system modal model for reduction purposes. A balanced realization is used to reduce model order from 118th to 18th order for the DAC design. A composite state estimator is designed independently of the ROM controller. The estimator provides estimates of both the controller and the persistent disturbance states. Finally, the RMF is designed and added in parallel to the controlled system to process the commanded control actuation and define expected responses at the sensor locations. The RMF can be viewed as a feedforward around the controlled structure or as a feedback around the ROM controller. The RMF output is subtracted from the sensor measurements, having the effect of opening the feedback path for the destabilized modes. This action returns the destabilized modes to their uncontrolled, stable response character. Its effect is to restore the dynamics used for the ROM controller design and reinstate its desired properties. The RMF signal is properly phased to actual motions and does not suffer from the phase error introduced by a series notch filter. This design is implemented in the NASA-provided simulation for evaluation.

LQG-Based Controller Design

The Harris Corporation team, led by Emmanuel Collins, used the LQG approach to design an HST PCS.[13] The Harris team used the SISO composite models to develop the LQG controllers based on the observation that the transformed plant is approximately decoupled. This implies that the performance achievable by the SISO designs should be close to the performance achievable by the MIMO design. SISO designs are fault tolerant and are thus safer to implement on-orbit. Furthermore, the SISO models provided include the higher frequency scissors modes that are not included in the MIMO model. These modes exist and should be accounted for in the controller design.

The design for the HST PCS LQG tracking/integral controller is posed as a disturbance rejection problem. The critical element of this design is to select the disturbance rejection filter such that the controller has the proper number of integrators (two) while achieving the desired tracking performance. Selecting the disturbance rejection filter such that it has the same number of integrators as the compensator is a natural inclination; however, this leads to an ill-posed problem since the design model would have uncontrollable, neutrally stable poles.[13] To avoid ill-conditioning in the LQG Riccati equation solvers, a precompensation technique is employed. This methodology can be used to imbed the desired number of controller integrators in a modified plant model so that the corresponding LQG compensator actually contains no integrators. This precompensation strategy has been successfully employed on NASA structural control testbeds.[14,15] After the LQG controller is designed, the order of the controller is reduced to two by using pole-zero deletions based on approximate pole-zero cancellations.

A separate LQG design is performed to accomplish the higher frequency disturbance rejection once the tracking/integral control described above is completed. In this fashion, the solar panel disturbances are compensated by the PCS. The disturbance rejection compensator acts on the closed-loop plant that includes the tracking/integral controller. This closed-loop plant does not contain the very low frequency dynamics that cause numerical conditioning problems. The disturbance rejection compensator for the HST PCS is designed using a 33rd-order design model that includes the reduced-order tracking/integral controller. The disturbance rejection filter is designed with emphasis on rejecting disturbances at 0.11 Hz. The controller order is then reduced to 13 using pole-zero deletions. Once designed, the tracking controller and the disturbance rejection controller are combined into a single compensator in the forward path. The performance of the LQG controller was evaluated in the NASA-provided simulations.

Analytically and Numerically Derived H_∞ Controller Designs

Led by Dennis Irwin, the Ohio University design team applied H_∞ design constraints and numerical methods to the HST PCS design improvement study.[16] The idea is to apply MIMO analysis and design techniques using the notion of the singular value frequency response, the H_∞ specifications, to formulate performance specifications and perform stability analyses for the HST, a coupled MIMO system. This approach attempts to reduce the effects of low-frequency disturbances by providing high, broadband controller gain in the frequency ranges where the disturbances are known to exist. The resulting increased loop gain provides broadband attenuation of low-frequency disturbances. Simultaneously, the MIMO stability margins are enhanced.

In their efforts to apply the MIMO techniques to the design of the HST PCS, the Ohio team encountered difficulties with the models provided. A coupled MIMO model is essential for the design process. The SISO models are not sufficient as no information on how to correctly couple the models is available. Model reduction techniques were applied to the high-order MIMO simulation model, which was reduced to 66th order using Schur and balanced model reduction techniques. However, the reduced models are not both stabilizable and detectable, making them unsuitable for use with H_∞ techniques. A continuous-time 90 deg solar array orientation model was constructed using the modal gain product matrices of the MIMO modal model that correspond to the frequencies of the 23 flexible modes included in the composite SISO modal model. These modal gain product matrices are in Ref. 17. Inclusion of the rigid-body modes yields a 52nd-order noncomposite MIMO model that is fully state observable and fully state controllable. The model is discretized, incorporates a computational delay, and is expressed in the w plane, resulting in a model that is minimal and suitable for use with H_∞ design techniques.

The H_∞ controller design is a MIMO loop-shaping approach that yields a controller that satisfies desired performance and robustness specifications. The philosophy applied to the PCS redesign is to obtain high controller gain in the frequency range of the dominant disturbances, thereby accomplishing some degree of disturbance rejection. The loop-shaping approach of H_∞ controller design theory is ideally suited to achieving this type of specification. In using H_∞ design algorithms, frequency-dependent weighting functions are applied to certain outputs of the control system; these weighting functions specify the desired system performance and robustness. Once the weighting functions are determined, the H_∞ algorithms determine whether an internally stabilizing controller exists that satisfies the desired constraints. An 82nd-order H_∞ controller design was obtained using the 90 deg MIMO modal plant model. However, testing of this design reveals that, although providing superior performance to SAGA-II in the 90 deg MIMO modal plant model (which turns out to be the "worst case" scenario), it does not stabilize any other HST model, linear or nonlinear, other than the one for which it is designed.

To achieve H_∞-type closed-loop specifications and to obtain a controller of acceptable order, an iterative numerical method is employed. This method, which is similar to multiple objective optimization, has been used to aid in the design of controllers for the ACES facility.[18] Advantages of this approach include the ability to use frequency response estimates of the plant derived from either experimental data or an analytical model, the ability to control the structure of the compensator, and the capability to simultaneously satisfy several closed-loop design constraints. Disadvantages include the fact that the designer must supply an initial, stabilizing controller and the fact that the conditions for constraint feasibility are often very difficult to obtain. The software that implements this method is called the Model and Data-Oriented Computer-Aided Design System (MADCADS). Using the SAGA-II as the baseline controller along with the NASA-provided MIMO model to generate the HST plant frequency response, MADCADS is employed with the appropriate H_∞ design constraints to develop the improved HST PCS.

Covariance Control Design

The Purdue University team, led by Robert E. Skelton, applied two variations of covariance control to the redesign of the HST PCS.[19] In the first, control energy is minimized subject to inequality constraints on the output covariance matrix. This is the output covariance constraint (OCC) controller. In the second, using alternating projections, the same covariance constraints are imposed on the output, with an additional equality constraint on the controller covariance (the covariance (COV) controller, obtained from covariance control theory[20]). An advantage of the controller covariance constraint is that it allows for proper scaling of the controller for digital implementation in a control computer using fixed-point arithmetic, which the case for the HST PCS.

Covariance control is a natural methodology with which to integrate modeling, control, and signal processing issues, since both the effects of coefficient and state roundoff errors can easily be modeled in the covariance equations. The state space realization is invisible in a transfer function. Hence, transfer function models are powerless to treat the roundoff error, a function of the state realization. Covariance control theory provides a characterization of all assignable covariance matrices and, in addition, a parameterization of all controllers that assign a particular assignable covariance. The covariance control design problem is accomplished in three basic steps:

1) Formulate the assignability conditions and the desired performance objectives as constraints in the space of covariance matrices.

2) Use numerical techniques to obtain an assignable covariance that satisfies the constraints of step 1.

3) From the parameterization of all controllers that assign the desired covariance computed in step 2, obtain a satisfactory one according to some given criteria.

Hence, covariance control theory allows the formulation of the design problem in the space of covariance matrices, rather than in the space of controllers, exploiting desirable properties like convexity.

In the Purdue design approach, modal cost analysis is used to reduce the NASA-provided 118th-order model to a new "truth" model of order 83 and to develop a 32nd-order "design" model. Then, the OCC design algorithm is applied to design a full-order dynamic controller based on the reduced-order design model. The alternating convex projection (ACP) algorithm is applied to find a feasible state covariance matrix satisfying all performance requirements. Using this covariance matrix, a covariance controller with minimal control effort is constructed to satisfy the design objectives. Finally, the finite-wordlength effects on the controller implementation are considered and evaluated. A workstation environment has been created in which these and other algorithms are used in an iterative procedure for identification, modeling, and control design. The resulting designs are evaluated in the 83rd-order truth model as is the SAGA-II controller.

Dual-Mode Disturbance-Accommodating Controller Design

Developed by C. D. Johnson of the University of Alabama in Huntsville (UAH), DAC is particularly well suited for problems of this nature.[9] The design team from UAH employed DAC to develop two strategies for coping with the unexpected solar array disturbances, the total isolation (TI) and the array damping (AD) strategies.[21] The DAC method is naturally applied to a problem such as the thermally induced structural vibration disturbances imparted on the HST PCS by the solar arrays. These disturbances have a distinguishable damped-oscillation-type waveform character, which may have varying initial conditions but is generally smooth and well behaved. DAC theory is based on the assumption that an unknown disturbance for which compensation is to be designed has this type of waveform behavior and is triggered only occasionally, as opposed to being erratic or random in nature.

To accomplish the TI and AD DAC designs, a planar model of the HST dynamics was developed. The motivation for the development of a new model, rather than the use of the models and simulations provided by NASA, was the technological necessity of having a mathematical model of the HST that is based on "first principles" of dynamics. In particular, the ability to derive a controller that accomplishes the TI model of disturbance accommodation requires starting with a model of the HST that embodies the actual dynamic equations of motion for the main body and for the interface dynamics associated with each of the attached solar arrays. Alternative mathematical models based on modal decompositions or transfer function methodologies, such as the ones NASA provided, might not provide such detailed information and may actually obscure some novel control possibilities such as the TI mode of control. In fact, the manner in which the NASA linear and nonlinear simulations are used for verification, that is, playing the flight data back through the model to determine the performance of a new controller design, does not adequately reflect the true dynamics of the system. It does, however, provide a fair approximation of the system, as is demonstrated by the fact that the working SAGA controllers were designed and verified in this fashion.

The planar model includes all the main body and solar array interface dynamics of the HST. It was derived using the method of Kane's equations[22] as implemented in a computer-aided modeling program. Although the model is a "simple" planar model, the equations of motion for the system are quite complex. The details of the model development and the full equations of motion are presented in Ref. 21. The TI and AD control strategies, briefly described below, were verified in a simulation based on the planar dynamic model. HST masses, stiffnesses, inertias, and dimensions were used in the planar simulation employed to evaluate the controllers. Both the 0.11- and 0.65-Hz modes were simulated as in-plane modes. It should be pointed out that the 0.11-Hz mode is an out-of-plane mode.

The solar array structural vibrations impart disturbance torques on the main body of the HST, causing it to deviate from the desired direction. Thus, it is clear that those persistent disturbances, which degrade the pointing performance of the platform, directly imply that the primary goal of the HST PCS, with respect to accommodating those disturbances, should be to generate opposing control torques that automatically adapt to and cancel out the persistent disturbance torques and their upsetting effects in real time. Under this mode of control, the main body of the HST remains effectively isolated from the vibrational disturbances. This is the TI mode of DAC for the HST PCS.

In the TI mode, no effort is made to mitigate the vibrations of the solar arrays, which do eventually damp out due to natural structural damping effects. In some situations, it may be desirable to employ the HST controller to hasten the natural damping out of the solar array oscillations. This can be accomplished by designing the HST controller to create strategic rocking motions of the main body that are timed and phased so as to accomplish active damping of the solar array vibrations. This is the AD mode of DAC as designed for the HST PCS. The technical details of the development of the TI and AD controllers and the composite observers that produce the state and disturbance-state estimates are presented in Ref. 21.

Results Summary

In this section, the performance of each control design will be considered on its own merits in a qualitative fashion with no attempt made to compare one design to the other. It should be noted that no format was specified for presentation of the results from the study, making direct comparisons of the modern control methods difficult. Furthermore, no attempt is made to identify the controller with the best performance, as this was not the intent of the study. The intent was to investigate the feasibility of applying advanced control theory to a "real-world" problem and to explore the potential improvements that might be achieved in doing so.

The ROM-based DAC and the ROM/RMF controllers were evaluated in the linear MIMO simulation provided by NASA. Both controllers developed by the University of Colorado design team produced very promising results in the linear simulation with pointing errors well below the prescribed requirement. Technical difficulties with the nonlinear simulation precluded the use of that simulation as an evaluation tool.

The performance of the Harris Corporation LQG-based HST PCS design provided performance comparable to that of the SAGA-II compensator. Examination of the frequency response and power spectral density(PSD) plots in Ref. [13] show that the tracking properties of the LQG controller are improved over those of the original PID controller. The LQG design meets the HST specification for rms error.

Recall that the development of a noncomposite 90 deg MIMO modal model was required to derive an H_∞ controller for this method. This simulation, the NASA linear, and NASA nonlinear simulations were all used to evaluate the performance of the MADCADS-redesigned SAGA-II controller. The controller designed using the H_∞ method worked only for the model with which it was designed and no other. The SAGA-II was the initial controller used with the MADCADS program that uses H_∞ constraints to improve the controller stability characteristics and performance. Improvement in performance in terms of peak and rms attitude errors is seen in all simulation results with the errors falling within the specified requirements.

The covariance control design results were evaluated using the 83rd-order truth model, derived as described in the previous section. The OCC and COV controller performances are comparable to that of SAGA-II. The dramatic improvement that these control techniques manifest is in control energy. The energy required for the covariance control designs is significantly less than that required by the SAGA-II controller.[19] The effect of wordlength was also evaluated. The OCC, COV, and SAGA-II controllers meet the pointing specifications when implemented in 24-bit arithmetic.

The TI and AD controllers were evaluated in the planar simulation developed by the UAH design team. These controllers were evaluated in neither of the NASA MIMO simulations. The results indicate that the TI controller is very effective in maintaining pointing stability in the face of the disturbance torques imparted by the vibrating solar arrays. The AD controller uses the HST controller torques to strategically maneuver the angular rotations of the platform main body to actively damp the solar array oscillations. It was discovered that the AD mode of control has a relatively small domain of stability and a relatively high sensitivity to system parameter variations, apparently due to the nonlinear terms in the plant model. For dynamically symmetric solar panels, the closed-loop response was good; however, the solar array oscillations continue undamped. A redesign of the AD controller should mitigate this feature.

Lessons Learned

Conducting a study of this type is both a rewarding and frustrating exercise. A number of important "lessons learned" and general rules for conducting a good study are presented here for those who may consider leading or becoming involved in a similar study at some future time. These are not listed in any particular order of importance, as all are very important to remember. Probably many others could be listed. Here are the most notable ones.

1) The study manager must be intimate with any simulation code used in the study. He or she must be allowed the time to learn the models and simulations used "inside out"! If the study manager is not intimately familiar with the codes, then he or she must have direct influence over the performance appraisal of those individuals responsible for the simulations.

2) The study manager should not depend on others who are not directly associated with the project or who do not report directly to him or her for the success of the study effort. (See 1.)

3) A user-friendly, proven, error-free simulation should be provided that is configured so that the new design algorithms can be "plugged in" using a standard format.

4) Ample, clear, concise, and thorough documentation on all aspects of the project should be provided to the design teams. Lack of good documentation forces researchers to spend an inordinate amount of time sorting out details of the simulation codes, reducing the time spent on the design effort.

5) When time permits, the study manager should personally test the software with one of their own designs. Or a trusted colleague should test the code.

6) The study manager should be as responsive as possible to requests for information from the design teams. When they are forced to wait for information, no progress is made.

7) There should be a standard format defined for presentation of the performance results to facilitate comparison. Because no format for the performance results was specified in this study, results were presented in many different ways, including frequency responses, time responses, PSDs, plots of covariance, singular value plots, and pole-zero plots. No two researchers presented their results in the same way.

8) There should be a concrete set of performance specifications, e.g., gain and phase margins, time response, etc.

9) There should be a plan as far ahead as possible; years would be good. Counting on "streamlined" procurement procedures is not recommended because they do not work even when existing contract or grant vehicles are in place. Planning ahead also allows the study manager and the team to familiarize themselves with the data, models, and simulations to be used.

10) Every participant should understand the problem, the results expected, and how the results will be used.

11) The goals set should be reachable in the time provided. The study manager should allow for unforeseen time delays and remember that studies of this type are learning exercises. Part of the knowledge gained is how efficiently a method can be applied to a particular problem.

12) At the initiation of the study, the study manager and all the design team leaders should come together for an official project kickoff meeting to ensure that everyone starts from the same point and at the same time. The study funding should allow for travel to the kickoff meeting. This would reinforce point 10 above.

13) Study participants should begin work immediately after the kickoff meeting, before if possible. They should not wait until the last minute to begin work and try to finish up just at the deadline. (See also 11.)

Conclusion

The HST PCS design improvement study afforded five research groups a unique opportunity to test the merits of their control system design methodologies on an existing system using actual flight data. Based on the results of the studies, much was learned regarding the design of controllers using advanced modern control methodologies on a real-world problem. In addition, there were many lessons learned regarding the organization and execution of a study of this type. The HST PCS study was the final funded effort in the MSFC CSI Program. Funding for the MSFC CSI Program was abruptly terminated at the end of fiscal year 1992. Unfunded in-house and cooperative efforts do, however, continue in the laboratories.

On a more positive note, the HST was visited by a crew of astronauts in December 1993. Because of their skill and the noble efforts and perseverance of thousands of engineers and scientists, "the trouble with Hubble is over," noted Senator Barbara McCulsky of Maryland. The troublesome solar arrays were replaced with a more well-behaved set and the world's largest contact lens was installed. The latest reports from Art Bradley of the Goddard Space Flight Center indicate that the HST PCS is now meeting the modified original pointing specifications without the use of the SAGA-II controller. Great things are expected in the near future, as evidenced by the crystal clear photographs that are now being returned from the observatory.

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