

RELIABILITY ISSUES IN ACTIVE CONTROL OF
LARGE FLEXIBLE SPACE STRUCTURES

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Introduction

This is the report of the status of work under NASA Research Grant No. NAG1-126 for the period May 16, 1984 to November 15, 1984. The technology base needed for confident design of the redundancy management system for a large space structure control system is not yet in hand. Compared with previous applications of fault tolerant control system methodology, the large space structure application is different in the order of the dynamic model required, the amount of choice the designer has for the location of sensors and actuators, the amount of model uncertainty or model truncation expected, and the sensitivity of the control system to off-nominal controller behavior. These characteristics of large flexible spacecraft tend to confuse efforts to detect and isolate component failures, and the system has little tolerance for inadequate reconfiguration of the control system following a component failure.

So fundamental work remains to be done to improve our ability to monitor the performance of LSS control systems and to accommodate component failures. And it is important that we make progress in these directions because fault tolerance is an essential feature of control systems for large space structures.

Research Progress

During this reporting period, the work under this grant was directed along three lines: robust failure detection and isolation, control system reconfiguration, and performance evaluation of systems having redundancy management features. The following paragraphs give brief summaries of the progress that has been made in each of these research tasks.

For some time now, we have been studying the problem of designing failure detection filters for improved visibility of the failure signatures in the presence of residuals due to unmodeled dynamics. We have recently broadened our objective to consider the effects of parameter uncertainty in the modeled dynamics in addition to unmodeled dynamics. It is obvious that in the context of large space structure control, both of these types of model mismatch will be important. The effort to make the detection filter more robust has not been strikingly successful to this point. We have shown that the detectability of failures can be changed considerably by varying the free parameters available to the designer of a failure detection filter, but we have not yet produced a systematic design procedure to optimize these choices. Additionally, failure detection sensitivity can be quite different depending on how many failures the filter is designed to detect. This effect can be quite significant, but we cannot predict it in advance of carrying out the design and trying it.

The reason for the difficulty in understanding these phenomena seems to be in the nature of the detection filter itself. The failure detection filter is defined by the property that it holds unidirectional in the output residual space the residuals due to failures of the components it is designed to monitor. The constraints on the filter gain which are necessary to make it detect certain failures give the filter unusual transfer properties in some cases. For instance, in some cases the filter gain becomes unusually large, and this may exaggerate the residual output due to unmodeled dynamics. It is not possible to anticipate in advance of designing the filter what choices of component failures will cause the gain to be abnormally large.

At present, the freedom of choice available to the designer is parameterized in terms of the filter closed loop eigenvalues. The designer can place the poles of the filter where he chooses - but this choice is not easily related to the transfer properties of the filter for component failure signatures nor unmodeled dynamics. Our present thought is to design the filter by a parameter optimization process. The cost function to be optimized would be some measure of the filter transfer properties - for both component failure signatures and for unmodeled mode dynamics if possible. These transfer properties might be characterized by the singular values of the transfer function matrices. The relations which the filter gain must satisfy to make the filter detect the selected set of failures would be

introduced as constraints in the optimization process. The Lagrange multipliers associated with these constraints would then give a measure of the sensitivity of each such constraint to the cost function. Although this approach would be more burdensome computationally than the present design procedure, it would optimize directly the properties we are most interested in whereas the present method of specifying filter eigenvalues cannot easily be related to the transfer properties of most concern.

We are just beginning to develop the details of the approach using parameter optimization with detection filter properties held as constraints. It is hoped that some early results of this method of detection filter design will be ready for presentation at the ACC in June.

The research task on control system reconfiguration has progressed slowly during this reporting period. The graduate student working on this problem, Mohammed Massoumnia, prepared for and passed his doctoral General Examination during this period, and that had a significant effect on his research effort. The thrust of our thinking on this subject continues to be that the effort put into the original design of the control system - whatever the design approach utilized - should be taken advantage of in the reconfiguration procedure. Because of the very sensitive nature of LSS control systems resulting from the omission of lightly damped oscillatory modes from the dynamic model used for system design, it is difficult to say what properties of

the controller make it perform successfully. For example, if the frequency shaped LQG methodology was applied to design the original system, it is not certain that a reconfigured system designed following a failure using the same criterion will even be stable. Of course, the greater the degree of redundancy, the more likely it is that such an approach would work because with extensive redundancy the system, by definition, does not depend critically upon the functioning of any one component. The loss of any one component in that case has only a minor effect on the behavior of the system. Therefore it seems intuitively clear that some simple reconfiguration techniques may work satisfactorily if there is a sufficient degree of component redundancy, and will not work if there is not.

Our initial experience with simple approaches to reconfiguration, as documented in the Proceedings of the June 1984 ACC, has also emphasized the importance of passive structural damping to the success of LSS control system design and reconfiguration. With the dynamics of the real structure having an indefinite number of lightly damped oscillatory modes, characterized by poles very near the j axis, it is inescapable that the controller based on any reduced order model will move some of the unmodeled mode poles to the right - and thus drive them unstable unless there is some degree of passive damping. It seems clear, then, that successful operation of a LSS control system is absolutely dependent upon the presence of some structural

damping - and the more damping there is, the less sensitive the system will be to the effects of parameter uncertainty, truncated dynamics, and imperfect reconfiguration.

Our current work on reconfiguration is addressed to control systems using full estimated state feedback. The properties of the poles and zeros of the system transfer function matrix, for LQG controllers, are being studied as a possible basis for system reconfiguration. The thought is to try to find a revised pair of weighting matrices for the optimal regulator cost function such that the resulting LQ controller will retain the pole-zero structure of the original system. We intend to illustrate any reconfiguration algorithms we may suggest using a model of the dynamics of the experimental grid at LaRC as the example system.

During this reporting period, progress was made on two fronts for the performance evaluation task. The previous Status Report discussed the development of an interactive computer program written in the LISP programming language which evaluated the probabilities of various time histories for the operational state of a fault-tolerant system and the associated performance values. Since that time, an effort was undertaken to analytically predict the growth rate of the number of distinct trajectory classes which must be taken into account in order to accurately compute the performance measure. The evaluation program includes automatic utilities for reducing this number as much as

possible (by "culling" trajectories with very low probability and nearly nominal performance and by "merging" trajectories which yield the same performance values despite differences in their time histories). This makes the analytical prediction very difficult. However, several runs of the program for a seven-state model seem to indicate that the growth eventually becomes linear in the time periods of interest. For extremely long time periods, of course, the number of trajectories which generate different performance values eventually shrinks to zero because the system eventually suffers enough component failures to render it nonoperational. These very long time periods are not really of interest, however, because the mission duration is generally considerably shorter. The phenomenon of linear growth in the time periods of interest was unexpected and will be explored further.

The other area of progress involved the development of two analytical transform techniques for performance evaluation. One is based upon the principles of dynamic programming for controlled Markov processes developed by Howard in the late 1950s. These are Markov processes which involve a reward for achieving a particular system state, much like the Markov model of a fault-tolerant system includes a performance value for each of the system's operational states. Howard has derived an expression from which the time history of the expected reward (or expected value of the performance measure) can be computed given the

initial state of the system. This expression is essentially a time propagation of a vector of expected costs which uses the transition probability matrix as the propagating operator. Using modal decomposition, it is possible to reduce this propagation in time to a scaling by exponential factors related to the eigenvalues of the transition probability matrix of vector-valued terms which depend upon the left and right eigenvectors of this matrix. If the transition probability matrix is triangular (as it frequently is for fault-tolerant system models), its eigenvalues can be found by inspection. This means that in this case the calculation of the expected performance value, even for a model of very large dimension over a very long time period, involves only one difficult operation: that of finding the eigenvectors of the transition probability matrix. The investigation of this problem has just begun and will continue.

The other analytical method involves the definition of a performance transform which possesses properties similar to the z-transform that is used to analyze discrete-time dynamical systems. Suppose that for each possible starting state for the system and each possible terminal state at the end of the mission time one knew all of the possible values the performance measure might take and the probability associated with each value. Let the probabilities be denoted p_j and the performance values be denoted A_j . Now let the "performance transform" be defined for each (initial state,

final state) pair as:

$$M_{ij}(v, \text{mission time}) = \sum_k p_k v^{A_k} \quad i, j = 1, \dots, N$$

Letting v equal unity in the above expression, the result is the exhaustive sum of the probabilities of the various possible performance values for that particular initial state and final state. This is, of course, the multistep transition probability for transitions from the initial state to the final state. Differentiating the above expression with respect to v and setting v equal to unity in the result generates the expected value of the performance under the condition that the system starts in the corresponding initial state and ends in the corresponding final state. The initial state probabilities can then be used to generate the unconditional expected value of the performance (the final state is of no consequence here, hence the results are summed over the final state). Further properties of the performance value can also be derived from the performance transform, and these are being investigated.

Since the performance transform concisely summarizes all of the information on the performance of the system which is of interest in performance evaluation, it would seem to be a very convenient tool for performance evaluation problems. Currently, some attention is being given to the development of methods by which the performance transform matrix (recall that there is a performance transform

expression associated with each combination of initial and final states, hence the expressions can be gathered into a matrix) can be propagated in time. For a single time step, this is relatively easy to do. However, it is hoped that a multistep propagation procedure can be developed which yields the approximate performance transform matrix for long time periods by building it up from those for smaller time periods.

These techniques will be examined for two system models. One is the simple seven-state model alluded to earlier. In addition, work has just begun on the development of a model for the system which is under study in the system reconfiguration task.

Personnel

The Principal Investigator for this grant is Professor Wallace E. Vander Velde who devoted 25% of his time to the program during the last 6 month period. He supervised the work of the following two graduate Research Assistants who worked full time on this research:

Alejandro San Martín - He is a masters degree candidate who is working on the robust FDI task.

Mohammed Massoumnia - He is a Doctoral candidate who is working on the system reconfiguration task.

The second faculty member involved in this research program is Professor Bruce K. Walker. He devoted about 20%

of his time to this work during the reporting period. He supervises the work of the following graduate Research Assistant:

David Gerber - He is a Masters degree candidate who is working on the system performance evaluation research task. He was off during the summer and returned to full time work for the Fall term. He is currently writing a thesis proposal based upon this work.

Publications and Presentations

Vander Velde, W.E.: "Uncertainty Management Methodology for Large Space Structures," Presentation at the NASA Workshop on Identification and Control of Flexible Space Structures, San Diego, California, June 4-6, 1984.

Vander Velde, W.E.: "Control System Reconfiguration," Presentation at the 1984 American Control Conference, San Diego, California, June 6-8, 1984. Also published in the Proceedings of that Conference.

Vander Velde, W.E. and C.R. Carignan: "Number and Placement of Control System Components Considering Possible Failures," Journal of Guidance, Control, and Dynamics, Vol. 7, No. 6, November-December 1984, pp. 703-709.