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, 1985 to November 15, 1985. This research program has been focussed on the various aspects of accommodating the unreliability of sensors and actuators in the design and operation of control systems for complex spacecraft. This is a difficult challenge because of the necessity of working with truncated models of the spacecraft dynamics and the lack of precise knowledge of the parameters associated with the modeled dynamics. But it is essential that this problem be addressed because of the near certainty that component failures will occur during system operation.

Considerable progress has been made in several aspects of the approach to accommodation of component unreliability. These advances have been theoretical to this point with results demonstrated in simulations of spacecraft dynamics. It is appropriate now to begin to demonstrate these techniques in laboratory experiments and to look ahead to demonstrations in space as soon as possible. NASA recognizes the importance of verifying the base of technology needed for active control of large spacecraft and has initiated the COFS program to accomplish this. It is hoped that this program may provide the opportunity to demonstrate in the laboratory and in space some of the techniques for achieving fault tolerance which have been developed or improved in this research program.

Research Progress

Our effort in this reporting period has been centered on four research tasks: design of failure detection filters for robust performance in the presence of modeling errors, design of generalized parity relations for robust performance in the presence of modeling errors, design of failure sensitive observers using the geometric system theory of Wonham, and computational techniques for evaluation of the performance of control systems with fault tolerance and redundancy management features. A brief report on each of these research tasks follows.

Robust design of failure detection filters - The failure detection filter is one method of generating residuals which permits the detection and isolation of component failures. It has the appealing properties that it is applicable to both sensors and actuators and its design and operation do not depend on hypotheses about the modes of component failures. Like all FDI techniques which use analytic redundancy in lieu of massive hardware redundancy, the failure detection filter is based on a model of the dynamics of the spacecraft and therefore is confused by errors in that model. Unfortunately, our initial attempts at use of the failure detection filter showed it to be extremely sensitive to modeling errors. We then initiated a study which continued for two years into ways of designing the filter for improved performance in the presence of these errors.

That study was brought to a conclusion during the past six month period with the completion of the Masters thesis of Miguel San Martin. This is not to say that no further progress can be made, but rather that considerable progress was realized and that we should now direct our limited resources to other ends. The research which is documented in San Martin's thesis has lead to a much improved state of understanding about the design of these filters which, because of the constraint to hold the failure signatures of certain components unidirectional in the output space, often have very peculiar transfer properties. We now have a better appreciation for how the choice of filter poles affects the transfer of failure signatures, which we wish to see in the output, and of unmodelled dynamics, which we would like not to see in the output. We now recognize the importance of the output transformation, used to transform the output residual so the failure signatures appear in single coordinate directions, to the amplification or attenuation of residuals due to modeling error. With these and other modifications, we are now able to design failure detection filters which are vastly improved in their ability to recognize failures in the presence of modeling error.

A complete report on this work was submitted formally to NASA during the reporting period. Some aspects of the work will be presented at the ACC in June. We are now ready to demonstrate this approach to FDI in laboratory experiments - perhaps on the grillage at LaRC.

Robust design of generalized parity relations - In parallel with our work on failure detection filters, we have had a continuing interest in generalized parity relations as a means of generating FDI residuals. This is because this approach to FDI shares the properties of being applicable to both sensors and actuators and not depending on failure mode hypotheses. Our intent has been to study both methods with a view to optimizing their ability to recognize failure signatures in the presence of dynamic modeling errors. Then, when we can design each method to its best advantage, to compare the two as candidates for FDI residual generators for large spacecraft systems.

During this reporting period, we have made good progress in the development of methods to design more robust parity relations. Our initial approach centered on the estimation of the coefficients in the parity relations based on measurements taken in flight. Use of the Kalman filter to estimate these coefficients met with some success in improving the performance of the parity relation but is a computationally intensive procedure. A simpler approach to estimation of the coefficients was also tried - which produced some improvement in performance but not as much as was desired.

Subsequent work centered on procedures for designing generalized parity relations which minimize the variance of the residual due to modeling error or, better yet, which maximize the signal to noise ratio - where the signal is the failure signature and the noise is the residual due to modeling error. These optimization problems have been addressed in two contexts: an analytic statement of the problem which includes a description of the statistics of the modeling errors, and optimum design using data collected in flight. The most effective approach appears to be the design using a sample of data collected in flight which maximizes the signal to noise ratio. This approach is completely independent of an a priori model of the system dynamics. It can be viewed as analogous to system identification from flight measurements, but there is no attempt made to estimate the parameters of a model of the system dynamics. Rather, an optimum parity relation is constructed directly from a sample of actuator commands and sensor outputs collected over an interval of time. The solution procedure involves an eigenvector decomposition of a high dimension matrix, and the feasibility of this method will have to be considered in detail. One might note, however, that there is no specific time constraint imposed on this computation and it may be feasible if done over a long enough period of time. An FDI system of a priori design might be used during the time when improved residual generators are constructed from observations of the actual spacecraft behavior.

This work is documented in the Masters thesis of Jean Dutilloy. A report based on this thesis will soon be submitted formally to NASA.

Failure sensitive observers via geometric system theory - Our doctoral candidate Research Assistant, Mohammad Massoumnia, has continued his work on the application of Wonham's geometric system theory to the design of failure sensitive observers during this reporting period. He is now nearly finished and his report will be ready during the coming six month period.

This is fundamental research of a very high order. The basic theoretical approach is difficult to master, but having mastered it, Mohammad finds it to be a very natural and powerful way to think about linear observers which have transfer properties useful for failure detection and isolation. Because of the design flexibility this affords, FDI residual generators can be designed for some cases where Beard's failure detection filter does not work due to lack of mutual detectability. This approach also provides insights which can lead to reduction of the order of the observer in some cases. With the aid of state augmentation, we now know how to design observers which hold the signatures of sensor failures unidirectional in the output space whereas Beard's failure detection filter only restricts those signatures to a plane. The method also suggests design procedures which utilize more stable numerical algorithms than the method suggested by Beard.

One of the most satisfying results of this work is that when cast in a discrete time setting it unifies the concepts of the failure detection filter and generalized parity relations. They both appear as special cases of a general linear discrete time dynamic observer operating on the actuator commands and sensor outputs of a system. The need to isolate failure signatures can be expressed in terms of the desired transfer characteristics from the inputs to the outputs which are monitored for failure signatures. The geometric theory leads to solvability conditions for the resulting problem statement, and if solvable, to algorithms which can produce the solutions. This constitutes a very comprehensive view of the problem of FDI residual generation, and we are delighted that this quality work is being done as part of our research program.

System performance evaluation

In [1], it was shown that the use of the V-transform led to a simple computational procedure to calculate the statistics of the performance of a fault-tolerant system. In particular, consider a system whose instantaneous performance can be measured by an integer-valued variable J(s), where s is the operational state of the system. As shown in [1], the restriction of J(s) to integer values is merely a problem of selecting a discretization mesh for the cost, if it is real-valued. The cumulative cost for a particular mission that begins with the system in operational state j, ends after k time steps in operational state i, and follows the lth time history among those that begin in j and end in i in k time steps is:

$$J_{ij}(l,k) = \sum_{n=0}^{k} J(s_n)$$

where s_n is the state occupied at time step n. Define the v-transform as:

$$m_{ij}(v,k) \triangleq \sum_{l} p_{ij}(l,k)v^{J_{ij}(l,k)}$$

where the summation is over all distinct trajectories leading from state j to state i in k time steps and where $p_{ij}(l,k)$ is the probability of obtaining the lth such state trajectory. Then if the $m_{ij}(v,1)$ are used to construct a matrix M(v), it is easily shown [1] that $m_{ij}(v,k)$ is the (i,j) element of $[M(v)]^k$. The $m_{ij}(v,k)$ can then be used to construct the probability mass function (pmf) of the cumulative system performance given that it remains operational for k time steps and to calculate the unreliability of the system (see [1] for details).

In [1], a number of algorithms were suggested and tested for calculating the performance pmf in an efficient way. These algorithms relied primarily on successive truncation of the polynomial terms in $[M(v)]^k$ as k was made successively larger.

Nevertheless, the programs which resulted from this work used a lot of CPU time and memory. Therefore, motivation exists for improvement.

The disadvantage of these algorithms lies in the fact that the single step v-transform matrix M(v) must be raised to the kth power, where each element of M(v) is a monomial in v and where k is an integer that can be very large. As an alternative approach, the change of variables v=z+1 defines the "z-transform" matrix M(z). Each element of M(v) is transformed to a polynomial in z in M(z). M(z) can be written as:

$$M(z) = M_0 + M_1 z + M_2 z^2 + \ldots$$

where the M_i are constant matrices.

With the assumption that M_0 is diagonalizable with distinct eigenvalues, the polynomial matrix M(z) can be diagonalized and then can be written as:

$$\begin{aligned} M(z) = &(V_0 + V_1 z + V_2 z^2 + \ldots) \\ &(\Lambda_0 + \Lambda_1 z + \Lambda_2 z^2 + \ldots) \\ &(V_0 + V_1 z + V_2 z^2 + \ldots)^{-1} \end{aligned}$$

or: $M(z) = V(z) \quad \Lambda(z) \quad V^{-1}(z)$

with: V_i constant matrices

Λ_i diagonal constant matrices

Consequently, the computation of M^k can be shortened considerably. It is essentially reduced to the computation of $[\Lambda(z)]^k$ (a diagonal polynomial matrix) because

$$[M(z)]^k = V(z) \quad [\Lambda(z)]^k \quad V^{-1}(z)$$

All the moments of the performance pmf can be found easily by evaluating the derivatives of M^k at $z = 0$, which is equivalent to $v = 1$. The order of the moment to be calculated implies the order of the highest derivative that needs to be computed.

With knowledge of the moments, we should be able to rebuild the performance pmf as accurately as desired. In the examples we have examined so far, the pmf is well-approximated by a distribution of the form:

$$p(x) = e^{A_0 + A_1 x + A_2 x^2}$$

where A_0, A_1 and A_2 are determined such that the pmf is valid and the first two moments of the performance are matched. A Newton-Raphson search routine has been used to find the A_i. We are currently working on approximating the pmf by a distribution of the form:

$$p(x) = e^{A_0 + A_1 x + A_2 x^2 + A_3 x^3}$$

and of the form:

$$p(x) = e^{A_0 + A_1 x + A_2 x^2 + A_3 x^3 + A_4 x^4}$$

In the one example we have examined so far, the latter distributions gave very close approximations to the performance pmf's shown in [1].

Personnel

The Principal Investigator for this research grant is Professor Wallace E. Vander Velde. He devoted 25 percent of his time to this activity during the reporting period. He supervised the work of two Research Assistants and an additional student:

Alejandro San Martin - He is a graduate student Research Assistant. He worked on the robust design of failure detection filters. He completed the requirements for the Masters degree and has left the Institute.

Mohammad Massoumnia - He is a graduate student Research Assistant supported by the program. A candidate for the Doctors degree, he is working on the design of failure sensitive observers using the geometric system theory of Wonham.

Jean Dutilloy - He is a Masters degree candidate who has fellowship support and is doing his thesis research on this program. The grant supports him only with computational needs. He is working on the robust design of generalized parity relations. He has nearly completed his work for the degree.

Bruce K. Walker is another member of the faculty of the Department of Aeronautics and Astronautics who is associated with this research program. He devoted 20 percent of his time to this work during the reporting period. He supervised the work of one student:

Jean-Olivier Missana - He is a graduate student Research Assistant supported by the program. He is a candidate for the Masters degree and has been working on the system performance evaluation task.

References

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