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11. SUPPLEMENTARY NOTES

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13. ABSTRACT (Maximum 200 words)

Designing controllers for which selected system (input and output) variances are constrained have practical applications to a variety of problems, including control design for flexible structures. This research has demonstrated that a fuzzy algorithm developed by the investigators allows the design of reduced-order, H_2 optimal controllers that satisfy bounds on selected system variances. This is the first time that an algorithm has been developed and demonstrated for weight selection in the design of ***reduced-order*** controllers. In addition, this research developed a fuzzy algorithm for choosing weights in single-input, single-output H_∞ loop shaping control design with multiple time-domain and frequency-domain objectives. As a theoretical extension of the fuzzy weight selection algorithms, this research also developed a fuzzy algorithm for solving inexplicit and underdetermined nonlinear systems of the form $F(x)=0$, where F: $R^n \rightarrow R^m$. An inexplicit system is one for which there is no analytical expression for the function $F(x)$. An undetermined nonlinear system is one for which $m<n$. These results have wide applicability since zero-finding problems are prevalent in engineering and science.

14. SUBJECT TERMS	15. NUMBER OF PAGES
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1. STATEMENT OF THE PROBLEM STUDIED

Attack helicopters, air defense missiles, and multiple launch rocket systems are examples of the many military systems whose accurate operation depends on proper tuning of their control systems. The tuning process for any control system involves selection of controller parameters to satisfy prescribed performance constraints. Control engineers or technicians using trial and error almost always accomplish the tuning process manually, which can be tedious and time consuming and leads to solutions that vary widely according to the expertise, time commitment, or fatigue of the engineer or technician. The aim of this research is thus to demonstrate that fuzzy logic may be used to utilize human expertise to automatically tune modern control systems, which can lead to higher performing control systems and savings in the time devoted by the control engineer.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

This section briefly summarizes some of the most important results obtained in this research. The details are found in the publications listed in the next section.

2.1 H_2 Optimal Reduced Order Control Design Using a Fuzzy Logic Methodology With Bounds on System Variances

It is well known that there are practical reasons for constraining the variances of selected system inputs and outputs. One way of designing control laws that achieve these objectives is by using a linear quadratic Gaussian (LQG) (or optimal H_2) control design method with an appropriate choice of the input and output weighting matrices. Since the LQG controller is of the same order as the plant being controlled, its practical implementation tends to be very difficult for higher order plants unless the controller order is reduced. This research considered the design of H_2 optimal reduced-order controllers to meet a set of variance constraints. This problem also involves the proper choice of the weighting matrices in the cost function. The fuzzy algorithm previously developed for the full-order variance constrained control problem is shown to be applicable to the reduced order variance constrained problem. Three reduced order design schemes are developed and compared. Two schemes involve direct reduced order design and one scheme involves reduced order design using modified balanced truncation. The three schemes are compared using numerical experiments. The results clearly demonstrate the feasibility of reduced order H_2 optimal design that satisfies variance constraints on the system.

2.2 Facilitating SISO Design of Multiobjective H_∞ Loop Shaping Control Systems

The H_∞ loop shaping design method is an effective way to design robust controllers. One of the main limitations in the design of H_∞ loop shaping controllers is that the design method is based on frequency domain specifications that do not precisely represent the underlying time domain performance requirements. Even if the time response constraints were not present, the approach is based on trial and error selection of the frequency dependent weights that are used in the design. Selection of these weights becomes more difficult if time response constraints must be satisfied. This research developed a systematic way of selecting the loop parameters for the frequency-dependent weights and develops a fuzzy algorithm that selects these parameters so that the resulting H_∞ loop shaping controller yields a closed loop system that satisfies the time response characteristics for a SISO system. It is seen that although most of the time response characteristics of the system can be improved by changing any of the loop parameters, the frequency domain constraints normally set limits on some of these loop parameters in such a way that they cannot be changed further to improve the time response characteristics of the system. The only loop parameters that can be varied freely in order to satisfy constraints on both the time domain and frequency domain criteria are the low frequency and high frequency loop gains. The developed algorithm uses fuzzy logic to imitate the actions of a human designer in adjusting this low frequency loop gain to satisfy each of the time response constraints.

2.3 Solution of Inexplicit Systems of Nonlinear Algebraic Equations by Fuzzy Logic

A derivative of the development of fuzzy algorithms for weight selection in modern control design, is the development of a fuzzy logic approach for solving a consistent system of algebraic equations $F(x) = 0$ in which either the function $F(\cdot)$ is not explicitly defined or there are more variables than the number of independent equations or both. Such systems arise frequently in many engineering design problems where design parameters must be chosen using qualitative information to meet a set of desired performance constraints. It is seen that this method works quite well for such problems, although when employed to consistent, explicit nonlinear equations, it tends to be slower than Newton's method.

3. LISTING OF ALL PUBLICATIONS SUPPORTED UNDER GRANT

3.1 Papers Published in Peer-Reviewed Journals

M. F. Selekwa and E. G. Collins, Jr., "H_2 Optimal Reduced Order Control Design with Bounds on System Variances Using a Fuzzy Logic Methodology," *IEEE Transactions on Control Systems Technology*, Vol. 11, No. 1, pp. 153-156, January 2003.

3.2 Papers Published in Conference Proceedings

E. G. Collins, Jr., A. Sivaprasad and M. Selekwa, "Insights on Reduced Order, H_2 Optimal Controller Design Methods," *Proceedings of the 2003 American Control Conference*, Denver, Colorado, pp. 5357-5362, June 2003.

M. F. Selekwa and E. G. Collins, Jr., "Solving Inexplicit and Undetermined Nonlinear Systems of Equations Using Fuzzy Logic," *Proceedings of the American Control Conference*, Anchorage, Alaska, pp. 3258-3263, May 2002.

3.3 Papers Presented at Meetings, But Not Published in Conference Proceedings

NONE

3.4 Manuscripts Submitted, But Not Published

M. F. Selekwa and E. G. Collins, Jr., "Solution of Inexplicit Systems of Nonlinear Algebraic Equations by Fuzzy Logic," submitted to *Fuzzy Sets and Systems*.

M. F. Selekwa and E. G. Collins, Jr., "Facilitating SISO Design of Multiobjective H_∞ Loop Shaping Control Systems by Fuzzy Logic," submitted to the *International Journal of Contrl and Intelligent Systems*.

3.5 Technical Reports Submitted to ARO

Only the required interim reports.

4. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL

Dr. Emmanuel G. Collins, Professor

Dr. Majura Selekwa, Post-doctoral Associate

5. REPORT OF INVENTIONS

NONE

6. BIBLIOGRAPHY

NONE

7. APPENDICES

NONE