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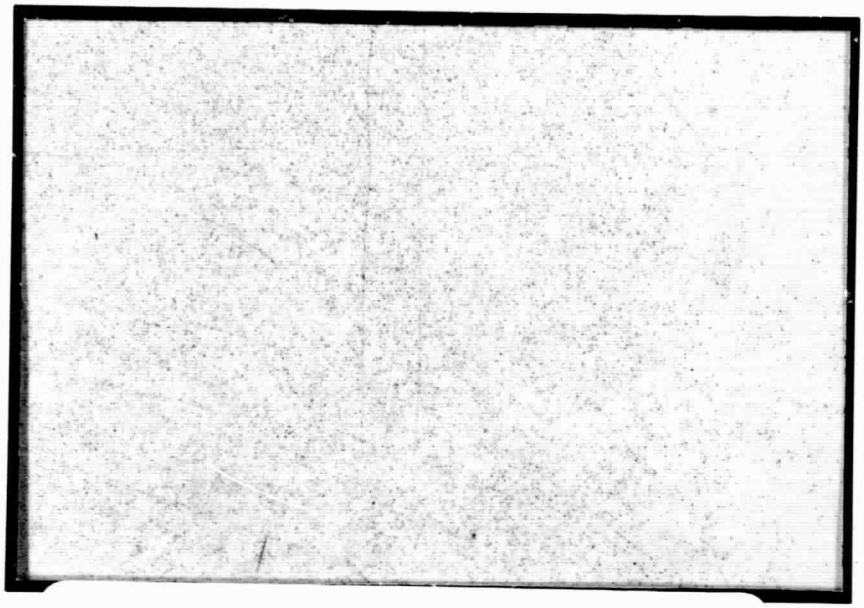

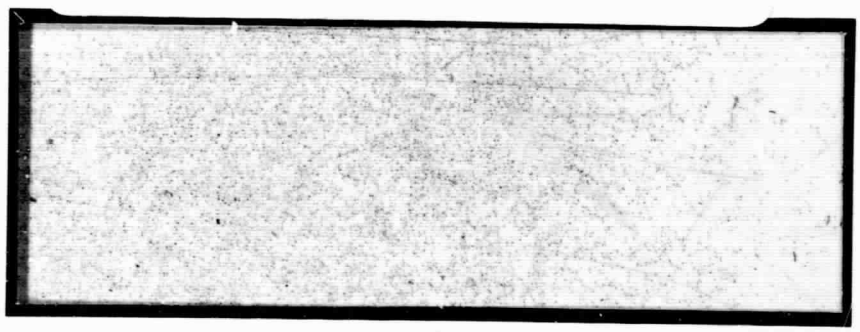

ENGINEERING EXPERIMENT STATION

AUBURN UNIVERSITY

AUBURN, ALABAMA

FINAL REPORT

PREPARED BY

GUIDANCE AND CONTROL STUDY GROUP

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DECEMBER 14, 1970

CONTRACT NAS8-20104
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

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FOREWORD

Auburn Research Foundation submitted a proposal which resulted in Contract NAS8-20104 being awarded on April 6, 1965. The contract was awarded to the Auburn Research Foundation by the George C. Marshall Space Flight Center, National Aeronautics & Space Administration, Huntsville, Alabama, and was active until December 14, 1970.

This report is a summary of the work accomplished by the Electrical Engineering Department, Auburn University, in the performance of the contract.

SUMMARY

Initial work on Project NAS8-20104 involved studies of a display system and of fluid amplification techniques.

Another area of study involved stochastic processes. Probability distributions for propellant utilized for the control of disturbances in limit cycle operation were derived. The application of optimal control and optimal filtering techniques to a fine pointing control system is discussed.

A major area of study was in the analysis of thrust vector control systems and the determination of various non-linear effects such as coulomb friction on the system.

Several aspects of optimal control were investigated. Among those studied were various solutions to the two-point boundary value problem, the use of fuel optimal schemes for the insertion of Saturn type vehicles into conical orbits, parameter optimization techniques for minimum-fuel attitude maneuvers, and the sensitivity of an optimal control solution to various system parameter variations.

Another major area of investigation was in the vehicle guidance area. The Iterative Guidance Mode was investigated along with various techniques for improving its solution. Various other aspects of guidance were investigated such as the characteristics of a four gimbal stabilized platform which is used for determining vehicle

position, the errors associated with a strapdown system, and the errors involved in the numerical integration of the equations of motion of a dynamical system.

Limit-cycle studies were made of missile attitude control systems. Various non-linear elements and their effect in regard to a limit-cycle were investigated. Parameter variations and their effect on a limit-cycle were also studied.

The final area of investigation was the study of momentum exchange control devices. A control moment gyro system was studied in order to determine its closed-loop frequency response and also to evaluate various momentum management schemes. For a system utilizing control moment gyros, a new approach, in which the outer gimbals of the control moment gyros would be clamped, was investigated.

Twenty-five technical reports were submitted during the contract period at the end of the task assignments as well as numerous monthly reports.

PERSONNEL

The following staff members of Auburn University have actively participated in the work of this contract:

C. H. Holmes - Head Professor of Electrical Engineering

C. H. Weaver - Head Professor of Electrical Engineering

J. G. Cox - Head Professor of Industrial Engineering

J. L. Lowry - Professor of Electrical Engineering

C. L. Phillips - Professor of Electrical Engineering

D. W. Russell - Professor of Electrical Engineering

H. M. Summer - Professor of Electrical Engineering

A. R. Barbin - Associate Professor of Mechanical Engineering

G. T. Nichols - Associate Professor of Electrical Engineering

C. L. Rogers - Associate Professor of Electrical Engineering

J. S. Boland, III - Assistant Professor of Electrical Engineering

P. Dyer - Assistant Professor of Electrical Engineering

B. B. Barnes - Graduate Assistant in Electrical Engineering

R. L. Benzer - Graduate Assistant in Electrical Engineering

W. W. Burge - Graduate Assistant in Electrical Engineering

Brij Bhushan - Graduate Assistant in Electrical Engineering

R. W. Cole - Graduate Assistant in Electrical Engineering

S. W. Crigler, Jr. - Graduate Assistant in Electrical Engineering

K. D. Dannenberg - Graduate Assistant in Electrical Engineering

T. W. Daughtrey - Graduate Assistant in Electrical Engineering

D. T. Dobner - Graduate Assistant in Electrical Engineering

W. B. Douglass - Graduate Assistant in Electrical Engineering

N. P. Dwivedi - Graduate Assistant in Electrical Engineering

M. H. Fong - Graduate Assistant in Electrical Engineering

W. C. Hines - Graduate Assistant in Electrical Engineering

W. G. Hopkins - Graduate Assistant in Electrical Engineering

P. M. Julich - Graduate Assistant in Electrical Engineering

L. E. Kendrick - Graduate Assistant in Electrical Engineering

H. H. Plott, Jr. - Graduate Assistant in Electrical Engineering

T. C. Roth - Graduate Assistant in Electrical Engineering

D. W. Sutherlin - Graduate Assistant in Electrical Engineering

L. A. Ward - Graduate Assistant in Electrical Engineering

M. E. Womble - Graduate Assistant in Electrical Engineering

I. INTRODUCTION

This contract was the result of a technical proposal submitted to the George C. Marshall Space Flight Center. The Electrical Engineering Department of Auburn University, under the auspices of the Engineering Experiment Station, proposed to conduct analytical studies on the theoretical aspects of thrust vector control of large space vehicles. The work was closely correlated with in-house efforts at Marshall Space Flight Center.

Areas of effort and priority of work were established by Astrionics Laboratory personnel in conferences with Auburn personnel. As the work progressed, a continuing and close liaison was maintained by making frequent trips to Huntsville for informal discussions and presentations, and by submitting technical reports as each phase of work was completed.

The project was directed by the Electrical Engineering Department. Personnel assigned to the project included faculty members of various departments, graduate students in Electrical Engineering (both PhD and MS candidates), and undergraduate students.

This report is a summary of the work performed under the contract.

II. AREAS OF STUDY

The project studies conducted under this contract are divided into eight areas. In each area the applicable technical reports are listed and the accomplishments briefly summarized.

A. DISPLAY SYSTEMS

Reports: (1) A Stereoscopic Display System.
First Technical Report; 6 April, 1965 to 31 May, 1965.

This technique was devised whereby two two-dimensional systems could be optically combined, via a dual-beam oscilloscope, in order to produce an illusion of a three-dimensional display.

B. FLUIDICS

Reports: (1) A Study of Fluidics.
Second Technical Report; 6 April, 1965 to 31 August, 1965.

Two major areas in fluidics (fluid amplification) were studied. They are:

1. The analogies between fluid and passive electrical components commonly utilized in fluid amplification circuitry and

2. The determination of the transfer function of the open-type proportional fluid amplifier with various loads.

C. STOCHASTIC STUDIES

Reports: (1) Probability Distributions for Propellant Used in the Control of Disturbing Torques. Third Technical Report; 1 May, 1965 to 9 March, 1966.

In non-powered flight, disturbance moments on a vehicle are produced by various system anomalies, which can, in general, be represented by certain probability distributions. This study was performed in order to determine the resulting probability distribution of the total propellant used for the compensation of these disturbance moments.

(2) Filtering and Optimization of Linear Stochastic Systems with Cross-Correlated Noise: An Application to Fine Pointing Control System. Twentieth Technical Report; 14 April, 1969.

A rigorous derivation of Kalman's extension of the Kalman-Bucy filter for a linear stochastic system is presented. It is also shown that the combined problem of filtering and optimization can be resolved into two separate problems of filtering and optimization. The application of these results to a fine pointing control system is discussed.

D. THRUST-VECTOR CONTROL STUDIES

Reports: (1) An Analysis of the S-IVB and the S-IB Thrust Vector Control Systems. Fourth Technical Report; 15 October, 1965 to 15 July, 1966.

The thrust vector control system of the S-IVB and the S-IB were analyzed in order to determine their transient response, frequency response, and steady-state behavior. The effect on system performance of various nonlinearities and a dither force was also determined.

(2) Effects of Coulomb Friction and Dither on the Response of the S-IVB Thrust Vector Control System. Eleventh Technical Report; 18 July, 1966 to 23 February, 1967.

The S-IVB thrust vector control system was studied in order to determine the effects of coulomb friction and a dither force on the frequency response of the system. Two representations of coulomb friction were utilized in the study.

E. OPTIMIZATION STUDIES

Reports: (1) Solutions to the Two-Point Boundary Value Problem with Application to Minimum Fuel Trajectories. Fifth Technical Report; 6 April, 1965 to 12 April, 1966.

A survey of present methods for solving the two-point boundary value problem is given. For one of the methods, a technique, which minimizes computer time while insuring that the truncation error is within specified tolerances, is developed.

(2) An Optimal Guidance Scheme. Ninth Technical Report; 6 April, 1965 to 18 November, 1966.

A unique guidance scheme which conserves fuel while inserting missiles of the Saturn class into any desired conical orbit is developed. Tests were made on the scheme in order to determine the calculation rate requirements of the associated flight computer.

(3) Acceptable Motions of Dynamical Systems. Twelfth Technical Report; 7 February, 1967 to 7 May, 1967.

The concept of acceptable motions of dynamical systems is defined. The relationship of acceptable motions to stability and boundedness requirements is discussed.

(4) Sensitivities of the Optimal Control; An Application to Space Vehicle Guidance. Fourteenth Technical Report; 30 June, 1966 to 30 June, 1967.

A practical way of determining the sensitivities of an optimal control solution to changes in various system parameters is

developed. A discussion of possible applications for the technique is also presented.

(5) Parameter Optimization for Space Vehicle Attitude Maneuvers. Sixteenth Technical Report; 24 January, 1968.

The problem considered here is the expenditure of a minimum amount of fuel by an attitude control system while making large attitude maneuvers during non-powered flight. A parameter optimization scheme utilizing feedback gains is developed to satisfy the minimum fuel requirements.

(6) Optimal Control of Attitude Maneuvers for a Large Orbiting Vehicle. Seventeenth Technical Report; 16 September, 1966 to 19 May, 1967.

The problem considered is the minimization of the amount of fuel used while performing attitude maneuvers with a large orbiting vehicle. The application of two numerical methods for the computation of the optimal control which gives minimum fuel expenditure is discussed.

F. GUIDANCE STUDIES

Reports: (1) Phase I, Guidance Implementation Studies. Sixth Technical Report; 6 April, 1965 to 30 June, 1966.

Some properties of the Iterative Guidance Mode are discussed. Several programs developed for determining the optimum thrust vector control, which minimizes the fuel expenditure for maneuvers, are briefly outlined.

(2) Effect of Update and Rotate on the Iterative Guidance Mode. Tenth Technical Report; 5 September, 1966 to 20 February, 1967.

Update and Rotate, two techniques developed in order to improve the approximate solution provided by the Iterative Guidance Mode, are investigated in order to determine their actual effect on the system performance.

(3) An Alternate Form of the Iterative Guidance Mode with Performance Improvement Techniques. Thirteenth Technical Report; 30 June, 1966 to 24 May, 1967.

An alternate form of the Iterative Guidance Mode is presented. A technique for modifying the alternate guidance scheme in flight so that near optimal performance is achieved is also developed.

(4) Study of a Four-Gimbal Stabilized Platform. Twenty-first Technical Report; 3 June, 1969.

Inertial guidance and navigation may be described as determining a space vehicle's attitude with respect to an inertially fixed

coordinate system and maneuvering the vehicle to some specified location. The most common method of implementing an inertial system utilizes a stabilized platform. This study presents the results of a simulation of a four-gimbal stabilized platform.

(5) Error Analysis of Numerical Integration Schemes. Twenty Third Technical Report; 15 November, 1970.

In a guidance scheme, equations of motion are integrated in order to determine vehicle velocity and position. This study considers the computational errors involved in various numerical integration schemes.

(6) On Error Bounds in the Digital Computation of the Four Parameters for Strapdown Inertial Systems. Twenty Fourth Technical Report; 14 December, 1970.

The strapdown method is one technique for mounting sensing devices in order to obtain the measurements necessary for inertial navigation computations. This report presents the results of a study on the errors associated with the digital computation of the four parameters.

G. LIMIT-CYCLE STUDIES

Reports: (1) Normalization and Limit Cycles of a Relay Control System. Seventh Technical Report; 15 September, 1965 to 7 February, 1967.

Nonlinear missile attitude control systems containing bang-bang elements and which possess a limit-cycle are studied. Switching surface conditions for the system to be asymptotically stable are derived.

(2) The Effects of First-Order Disturbance Parameter Variations on Propellant Consumption. Eighth Technical Report; 9 March, 1966 to 31 October, 1966.

A vehicle in limit-cycle operation experiences disturbance forces due to various system anomalies. This report presents the findings of a sensitivity study made in order to determine the first-order effects of disturbance parameter variations on the vehicle limit-cycle operation.

(3) Determination of Limit Cycles for a Dual-Channel Missile Yaw-Axis Control System. Fifteenth Technical Report; 5 October, 1966 to 31 March, 1967.

The conditions necessary for the existence of a limit cycle and the properties of the limit cycle, if it exists, for a dual-channel yaw axis control system are determined. These conditions are derived considering a system configuration with and without "hard-stop" limiters on the actuators.

(4) Limit Cycles of a Relay Control System with Limiter. Eighteenth Technical Report; 21 February, 1966 to 19 September, 1967.

This report is an extension of Report 1 of this section. Parameter variation effects on the system are investigated.

H. CONTROL MOMENT GYRO STUDIES

Reports: (1) Methods of Dumping Accumulated Momentum Apollo Telescope Mount. Nineteenth Technical Report; 19 April, 1968.

The momentum management system of the Apollo Telescope Mount, which utilizes control moment gyros as momentum exchange devices, is studied. Several schemes, designed to prevent the control moment gyros from saturating, are discussed and evaluated.

(2) A Technique for Frequency Analysis of Systems Containing Multiple Nonlinearities. Twenty Second Technical Report; 15 June, 1969.

A technique utilizing describing functions which gives the closed loop frequency response of a system containing multiple nonlinearities is developed. Results obtained by applying this technique to the inner gimbal of a control moment gyro are presented.

(3) Study of An Improved Attitude Control System.

Twenty Fifth Technical Report; 14 December, 1970.

The investigation of a unique scheme, in which the outer gimbals of a double-gimbaled control moment gyro are rigidly clamped to the frame during specified control periods, is presented. An optimal steering law which virtually eliminates the cross-coupling effects of a control moment gyro is developed.

III. CONCLUSIONS

The technical reports cover the major work conducted under the project. However, for work of temporary interest, several analyses, evaluations and digital computer programs were informally transmitted.

The experience gained by the staff at Auburn in working on this contract should be very valuable in conducting future studies of this nature.

APPENDIX A

LIST OF TECHNICAL REPORTS SUBMITTED UNDER CONTRACT NAS8-20104

1. A Stereoscopic Display System.
   First Technical Report, 31 May, 1965.

2. A Study of Fluidics.
   Second Technical Report, 31 August, 1965.

3. Probability Distributions for Propellant Used in the Control of Disturbing Torques.
   Third Technical Report, 9 March, 1966.

4. An Analysis of the S-IVB and the S-IB Thrust Vector Control Systems.
   Fourth Technical Report, 15 July, 1966.

5. Solutions to the Two-Point Boundary Value Problem with Application to Minimum Fuel Trajectories.
   Fifth Technical Report, 12 April, 1966.

6. Phase I Guidance Implementation Studies.
   Sixth Technical Report, 30 June, 1966.

7. Normalization and Limit Cycles of a Relay Control System.
   Seventh Technical Report, 7 February, 1967.

8. The Effects of First-Order Disturbance Parameter Variations on Propellant Consumption.
   Eighth Technical Report, 31 October, 1966.

9. An Optimal Guidance Scheme.
   Ninth Technical Report, 18 November, 1966.

10. Effects of Update and Rotate on the Iterative Guidance Mode.
    Tenth Technical Report, 20 February, 1967.

11. Effects of Coulomb Friction and Dither on the Response of the S-IVB Thrust Vector Control System.
    Eleventh Technical Report, 23 Fecruary, 1967.

12. Acceptable Motions of Dynamical Systems.
Twelfth Technical Report, 7 May, 1967.

13. An Alternate Form of the Iterative Guidance Mode with Performance Improvement Techniques.
Thirteenth Technical Report, 24 May, 1967.

14. Sensitivities of the Optimal Control; An Application to Space Vehicle Guidance.
Fourteenth Technical Report, 30 June, 1967.

15. Determination of Limit Cycles for a Dual-Channel Missile Yaw-Axis Control System.
Fifteenth Technical Report, 31 March, 1967.

16. Parameter Optimization for Space Vehicle Attitude Maneuvers.
Sixteenth Technical Report, 24 January, 1968.

17. Optimal Control of Attitude Maneuvers for a Large Orbiting Vehicle.
Seventeenth Technical Report, 19 May, 1967.

18. Limit Cycles of a Relay Control System with Limiter.
Eighteenth Technical Report, 19 September, 1967.

19. Methods of Dumping Accumulated Momentum Apollo Telescope Mount.
Nineteenth Technical Report, 19 April, 1968.

20. Filtering and Optimization of Linear Stochastic Systems with Cross-Correlated Noise: An Application to Fine Pointing Control System.
Twentieth Technical Report, 14 April, 1969.

21. Study of a Four-Gimbal Stabilized Platform.
Twenty First Technical Report, 3 June, 1969.

22. A Technique for Frequency Analysis of Systems Containing Multiple Nonlinearities.
Twenty Second Technical Report, 15 June, 1969.

23. Error Analysis of Numerical Integration Schemes.
Twenty Third Technical Report, 15 November, 1970.

24. On Error Bounds in the Digital Computation of the Four Parameters for Strapdown Inertial Systems.
Twenty Fourth Technical Report, 14 December, 1970.

25. Study of an Improved Attitude Control System.
Twenty Fifth Technical Report, 14 December, 1970.

APPENDIX B

LIST OF THESES, DISSERTATIONS AND PUBLICATIONS DERIVED FROM WORK ON CONTRACT NAS8-20104

Master's Theses:

Ray J. Vinson, "Derivation of Fuel Requirement Equations for a Space Vehicle Attitude Control System," December 16, 1965. (Directed by D. W. Russell)

Terrell W. Daughtrey, "The Transfer Function of a Proportional Fluid Amplifier Terminated with Various Loads," June 2, 1966. (Directed by D. W. Russell)

Monroe E. Womble, Jr., "Solutions to the Two Point Boundary Value Problem with Application to Minimum Fuel Trajectories," August 24, 1966. (Directed by D. W. Russell)

Robert L. Benzer, "Frequency Response of a Control System with Coulomb Friction and Dither," March 15, 1967. (Directed by D. W. Russell)

Brij Bhushan, "Error Analysis of Numerical Integration Schemes," December 9, 1970. (Directed by J. S. Boland, III)

Wallace W. Burge, "Analysis of Some Momentum Dumping Schemes for an Asymmetrical Space Vehicle." December 12, 1969. (Directed by C. L. Phillips)

Doctoral Dissertations:

Donald J. Dobner, "An Alternate Form of the Iterative Guidance Mode with Performance Improvement Techniques," August 23, 1967. (Directed by D. W. Russell)

William C. Hines, "Sensitivities of the Optimal Control," August 23, 1967. (Directed by D. W. Russell)

Paul M. Julich, "Acceptable Motions of Dynamical Systems," August 23, 1967. (Directed by D. W. Russell)

Narendra P. Dwivedi, "Filtering and Optimization of Linear Stochastic Systems with Cross-Correlated Noise," June 3, 1969. (Directed by J. S. Boland, III)

Walter G. Hopkins, "A Technique for Frequency Analysis of Systems Containing Multiple Nonlinearities," August 28, 1970. (Directed by J. S. Boland, III)

Michael H. Fong, "Truncation and Roundoff Error Bounds in Numerical Integration Techniques," March 17, 1971. (Directed by J. S. Boland, III)

Publications and Conference Presentations:

N. P. Dwivedi and J. S. Boland, III, "Combined Problem of Filtering and Optimization with Cross-Correlated Noise," Eighth Annual IEEE Region III Convention, Huntsville, Alabama; November 19-21, 1969. Printed in Proceedings of the 8th Annual Region III Convention, pp. 164-171.

M. H. Fong, J. L. Lowry, and J. S. Boland, III, "Quantization Error in Closed Loop Digital Systems Programmed in Canonical Form," Eighth Annual Allerton Conference on Circuit and System Theory, the Allerton House, Conference Center of the University of Illinois, near Monticello, Illinois, October 7-9, 1970. Printed in Proceedings of the Eighth Annual Allerton Conference on Circuit and System Theory.

D. W. Sutherlin and J. S. Boland, III, "On a Clamped Attitude-Control Mode for an Orbiting Space Vehicle," Eighth Annual Allerton Conference on Circuit and System Theory, the Allerton House, Conference Center of the University of Illinois, near Monticello, Illinois, October 7-9, 1970. Printed in Proceedings of the Eighth Annual Allerton Conference on Circuit and System Theory.

M. H. Fong and J. S. Boland, III, "Error Bounds in the Digital Solution of Autonomous Systems," Fourth Asilomar Conference on Circuits and Systems, Asilomar Hotel and Conference Grounds, Pacific Grove, California, November 18-20, 1970. Printed in Proceedings of the Fourth Asilomar Conference on Circuits and Systems.

D. W. Sutherlin, M. T. Borelli, and J. S. Boland, III, "On a New Mode of Gyro Operation for Control of an Orbiting Space Vehicle," Fourth Asilomar Conference on Circuits and Systems, Asilomar Hotel and Conference Grounds, Pacific Grove, California, November 18-20, 1970. Printed in Proceedings of the Fourth Asilomar Conference on Circuits and Systems.

W. G. Hopkins, III, and J. S. Boland, III, "A Technique for Frequency Analysis of Systems Containing Multiple Nonlinearities," Fourth Asilomar Conference on Circuits and Systems Asilomar Hotel and Conference Grounds, Pacific Grove, California, November 18-20, 1970. Printed in Proceedings of the Fourth Asilomar Conference on Circuits and Systems.

M. H. Fong and J. S. Boland, III, "On Round-off and Truncation Error in the Numerical Solution of Autonomous Systems," Mexico International IEEE Conference on Systems, Networks, and Computers, Oaxtepec, Mexico, January 19-21, 1971. Accepted then withdrawn due to lack of travel funds.

D. W. Sutherlin, M. T. Borelli, and J. S. Boland, III, "On the Control of an Orbiting Space Vehicle with a Clamped Gyro Mode of Operation," Mexico International IEEE conference on Systems, Networks, and Computers, Oaxtepec, Mexico, January 19-21, 1971. Accepted then withdrawn due to lack of travel funds.