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Subject: Final Report of Work under Contract No. NASr-54(06) for the period 1 March 1964 to 30 June 1969

N69-80688

Gentlemen:

This Final Report covers work from 1 March 1964 to 30 June 1969 under Contract No. NASr-54(06), Man-Machine Performance Measurement. Under this contract an interdisciplinary program of research has been conducted between the Department of Aerospace Engineering and the Department of Psychology concerning the analysis and synthesis of manual control systems. The work has included development of system simulation techniques, manual control system measurement techniques, and many empirical studies of fundamental characteristics of manual control system performance.

In the paragraphs that follow abstracts of the major efforts under the contract are presented together with the reference to the published document. Following the abstracts a complete bibliography of work published under the contract is provided.

A significant output of a sustained research effort such as this one is the training of students for work on manual control problems. A list of the students who have participated and their present positions is documented at the end of this report.

In addition to the substantive research studies that have been accomplished, the project has accumulated a substantial library of manual control literature and has served as host to the 1965 and 1968 NASA-University Conferences on Manual Control Systems.

Abstracts of Major Research Studies

Fogarty, L. E., & Howe, R. M. Space trajectory computation at the University of Michigan. Simulation, April 1966, 220-226.

Extensive investigation of methods of real-time and fast-time computation of earth orbits and reentry trajectories has been conducted for both analog and digital computers. Integrator drift and multiplier errors in the case of analog computers preclude the use of direct computation in inertial frames or geocentric coordinate systems. Such coordinate systems can also lead to serious digital computer problems due to truncation and roundoff errors. Introduction of a vehicle-centered rotating coordinate system with variables referred to a nominal orbit permits greatly improved

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computer scaling which, in turn, very substantially improves the absolute computational errors. In addition, the use of angular momentum and energy constraints is shown to reduce greatly the effect of integrator drift on the in-plane motion. Analog solutions to orbital and reentry problems have been obtained in real-time, fast-time, and high-speed repetitive operation using the above coordinate system.

Pew, R. W. Performance of human operators in a three-state relay control system with velocity-augmented displays. IEEE Transactions on Human Factors in Electronics, HFE-7, 2, June 1966, 77-83.

A one-dimensional three-state relay control task in which human operators served as the active switching and equalization element was employed to compare performance in three display conditions and to derive measures of performance that might prove useful for further development of models of human tracking behavior. Two displays which provided explicit velocity information in the form of a unidimensional error-velocity vector superimposed on a compensatory error display and two-dimensional phase-plane display of error velocity vs. displacement were shown to enhance learning over that produced by the usual compensatory display of error, but only with the highest value of system gain, 30 cm/second. An analysis of subjects' initial transient response represented as mean switching points in the phase-plane revealed remarkably little variability and switching performance close to that of an optimal minimum-time controller. Finally, in this and two subsidiary experiments, a measure of time to process visual feedback about the ongoing response process was derived that may provide a first step toward linking discrete reaction-time results to continuous manual-control performance.

Fogarty, L. E. Computer generation of arbitrary functions. Simulation, August 1966, 7(2), 80-89.

Two schemes for generating functions of several variables on a computer are described. It is shown that both schemes are practical, but both have limitations. The first scheme is capable of reproducing a data matrix without error, but the amount of equipment required may become very large. The second scheme provides a series approximation to the data matrix which usually converges very rapidly. This second method requires precomputation to determine the terms of the series. In many cases this is not a serious penalty to pay in view of the modest amount of equipment required for acceptable accuracy.

Fogarty, L. E. Survey of flight simulation computation methods. Proceedings of SAE Third International Simulation and Training Conference, New York, April 1967.

An historical review of developments in flight simulator computation methods

indicates that the computation load has been increasing by about a factor of ten every ten years for the last thirty years. From a brief analysis of computation methods used on a typical modern digital flight simulator it is concluded that these methods are more than adequate for the simulation task as presently defined. Additional new simulation requirements such as computer-aided instruction methods and computer-based navigation techniques apparently will require very large additional simulator computer capacity in the near future.

Pew, R. W., Duffendack, J. C., & Fensch, L. K. Sine-wave tracking revisited. IEEE Transactions on Human Factors in Electronics, HFE-8, 2, June 1967, 130-134.

A study of sine-wave tracking is reported which illustrates the extent to which the predictability of the input and of the control device dynamics can be utilized with extended practice. Analysis of the error power spectra establishes the presence of a stable source of noise power in the operator's output that has implications for deriving models of manual tracking performance.

Jackson, G. A. Measuring human performance with a parameter tracking version of the crossover model. NASA Contractor Report, NASA CR-910, October 1967.

The purpose of this research is the evaluation of a particular parameter tracking system for use in measuring the performance of human operators in low order compensatory manual control systems. The system is based on a "crossover model" proposed by Duane McRuer, which assumes that the entire forward loop of the compensatory control system can be represented by a gain, an integration and a pure time-delay.

A continuous parameter tracking system is developed using an approximate version of the crossover model as the basic system model. The approximation involves the use of a first-order Pade time-delay in place of the pure time-delay. The parameter tracking system is designed to adjust automatically the gain and time-delay parameters so that the instantaneous value of the square of the error between the model output and the compensatory system output is driven toward zero. The tracking method is similar to those developed by George Bekey and Hans Meissinger, except a nonlinear parameter adjustment technique has been added to give smoother performance.

The parameter tracking system is tested on subjects controlling single and double integrator plants, with input signals of bandwidth limited Gaussian noise. The gain and time-delay parameters are found to change significantly with training and with the bandwidth of the input signal. The parameters also vary between subjects and with the order of the plane being controlled.

Using spectral analysis, the parameter values determined by the parameter tracking system are confirmed. Also, the crossover model is shown to represent the compensatory

system nearly as well as the best linear time-invariant model.

In addition to the experimental testing of the parameter tracking system, a theoretical analysis of the system is undertaken. It is shown that the convergence properties of the parameters can be calculated when the input signal is sinusoidal and the system is tracking a known constant coefficient system. The theoretical analysis is based on the method of Kryloff and Bogoliuboff. The extension of this analysis to the random input case is indicated.

It is concluded that, as long as the input bandwidth is properly chosen, the parameter tracking system developed is an excellent method for measuring human performance in certain low order compensatory control systems.

Fogarty, L. E., & Howe, R. M. Trajectory optimization by a direct descent process. NASA Contractor Report, NASA CR-1070, April 1968.

The problem considered is that of trajectory optimization using step-by-step descent to minimum cost along the direction of the cost gradient with respect to the control. Using a hybrid computer, the gradient is computed directly as the response to nearly impulsive control perturbations. A method is presented for computing the gradient when several terminal constraints are enforced. Examples of application of the method are presented. It is concluded that the direct gradient computation method has some significant advantages over other methods.

Pew, R. W. The speed-accuracy operating characteristic. Acta Psychologica, 1969, 30, 16-26.

In a search for parallels between performance in manual tracking tasks and performance in discrete reaction time tasks, the relationship between speed and accuracy of performance was examined under a wide variety of discrete task conditions. It was found that regardless of the number of alternative stimuli employed, the level of discriminability of the stimuli presented, the method of response coding utilized, or the method by which the relevant emphasis on speed versus accuracy was manipulated, a linear relationship between log odds in favor of a correct response and reaction time was maintained. The slopes and intercepts were variable, but the linearity remained. This result is consistent with the conceptual logic of a statistical decision model of choice reaction time and suggests that it is possible to define a speed-accuracy operating characteristic analogous to the receiver-operating characteristic in signal detection analysis. The analog of this operating characteristic in continuous tracking tasks concerns the trade-off between response lag and level of error that the operator will tolerate. The relationship between these two properties of tracking performance has never been studied quantitatively in the case of manual control systems.

Howe, R. M. Computer mechanization of reentry equations with four degrees of freedom. NASA Contractor Report, NASA CR-1249, December 1968.

An effective method for controlling the flight path of a vehicle during reentry into the atmosphere is to utilize aerodynamic lift forces. By controlling the bank angle of the vehicle the lift force vector can be directed upwards or downwards to effect the down-range impact point, or sidewards to effect the cross-range impact point. In computing trajectories for such vehicles there are fundamentally four degrees of freedom which must be represented. These are the three translational degrees of freedom and one rotational, namely the roll motion.

In solving the translational equations for reentry there are sizable computing advantages in using a modified flight-path axis system called the H-frame. The purpose of this report is to add the fourth degree of freedom to these equations in order to allow the trajectory computation for lifting vehicles with controlled bank angle.

Powers, W. F. On the generation of ideal coordinate systems for the analysis of optimal trajectories. NASA Contractor Report, NASA CR-1250, December 1968.

A relatively well-known property of continuously thrusting optimal trajectories is that there exists a vector constant of the motion which is linear in the Lagrange multipliers. Since the relationship between the corresponding Lagrange multipliers for different sets of state variables is linear, the possibility exists that there is an ideal coordinate system such that three of the associated Lagrange multipliers are constants of the motion. It is shown that such a situation is impossible for more than one of the three constants of the motion. However, a method due to Whittaker is applicable to the problem of generating sets of state variables such that one of the corresponding Lagrange multipliers is a constant of the motion. It is shown that the system of variables generated by cylindrical coordinates possesses this property and, for a large class of problems, the remaining constants of the motion are used effectively to reduce from twelve to nine the number of differential equations which define three-dimensional, optimal trajectories.

Robb, Margaret, & Pew, R. W. Skill training for the production of a memorized movement pattern. NASA Contractor Report, NASA CR-1251, December 1968.

Many skilled tasks require execution of a movement pattern directed toward a specific goal. However the individual performing the movement lacks information about how well he is doing until the movement pattern is completed; instantaneous error information is not available along the way. Although this kind of task has not frequently been studied in the laboratory, it is very common in practical situations. A golfer perfecting his swing, a pilot executing a procedural turn under

VFR conditions, and an astronaut performing extra-vehicular maneuvers are typical examples. The question to be attacked in this report concerns the evaluation of several possible procedures for training human operators in the execution of this class of memorized movement pattern.

Five training methods were administered over a period of 5 one-hour daily sessions to five different groups of subjects. On the sixth day the groups were all tested on their performance of the required movement pattern from memory. The training conditions consisted of (1) pattern memory condition in which the subjects were shown the desired pattern but were given no cues about how to make the movement while it was in progress, (2) pursuit tracking condition, (3) alternating pattern memory training and pursuit tracking training in ten-trial blocks, (4) alternating pursuit tracking and passive watching of the movement pattern traced out in time in ten-trial blocks, and (5) alternating pursuit tracking at half speed in ten-trial blocks.

Passive watching trials and slow speed trials contributed nothing to the training process. Alternating pattern memory and pursuit tracking appeared to improve pattern memory performance about equally to all pattern memory trials. After transferring to the test conditions, the full speed--half speed practice produced significantly worse pattern memory performance, but the other conditions were not reliably different. This study has broken ground for the study of memorized movement patterns but did not discover training conditions that were any more effective than direct practice of the task as it was to be performed.

Herzog, J. H. Proprioceptive cues and their influence on operator performance in manual control. NASA Contractor Report, NASA CR-1248, January 1969.

Control engineers and psychologists have jointly participated in research intended to investigate the unique characteristics of control systems which contain a human operator. A class of tracking problems known as compensatory tracking is of special interest due to its similarity to manual control problems such as flying an aircraft.

In this research the neuromuscular control system of the human upper limb was investigated as an auxiliary source of sensory information. Analysis of a functional block diagram of the human operator indicated that a control system with interesting characteristics could be devised if the control stick were constructed to be a mechanical analog of the plant being controlled. This is called the matched manipulator control technique. The torque applied by the operator to the control stick was sensed and used as the control input to the plant. For stable plants the plant output and the control stick position were placed in correspondence. This correspondence

allowed the physiological force and position feedback paths of the upper limb to furnish information to the operator concerning the state of the plant.

When the matched manipulator technique is used, the control force applied to the plant is a scalar multiple of the reaction force experienced by the operator. The operator is in a particularly advantageous position to formulate control strategies to emphasize either accurate control performance or minimum use of control effort.

In order to investigate the matched manipulator technique and other questions associated with the relationship of control stick "feel" to performance in manual control a special control stick was constructed. Known as the Variable Dynamics Control Stick, this device utilized a torque motor to provide operator reaction force as specified by functions generated on an analog computer. Using voltage signals related to the control stick position, velocity and acceleration, the analog computer formed functions of these variables. A closed loop control system allowed these functions to be accurately converted to torque by a torque motor. By simulating mechanical reaction forces with this apparatus it was possible to produce a wide range of control stick characteristics including time variations, instabilities, and nonlinearities.

Experimentation conducted utilizing the matched manipulator technique with several human operators indicated that performance with the matched manipulator technique was consistently superior to control of the same plants with position type control sticks. The experimentation included linear plants, nonlinear plants, time varying plants, unstable plants, and linear plants with time delay. Describing function representations of the combined open loop characteristics of the operator and the plant indicated a uniformity of performance when using the matched manipulator technique.

The matched manipulator technique seems to offer an interesting and useful means of altering the interface between the human operator and his electro-mechanical surroundings in order to improve the system performance. This technique when properly applied can result in extremely high compatibility between the human and the plant with corresponding improvements in control performance.

Burgett, A. L. A study of human operator performance using regression analysis. NASA Contractor Report, NASA CR-1259, January 1969.

The purpose of this research is twofold: the development of a parameter identification technique which can be used with intervals of data which are on the order of 20-seconds and shorter in length and secondly, the use of this technique in a study of various aspects of human operator performance in low order compensatory control tasks.

As developed here, the parameter identification technique is a modification of the

classical statistical regression analysis, modified in the sense that integrals of continuous functions of time are used to obtain the desired parameter estimates instead of sums of discrete data samples. In addition to the integral formulation, a technique proposed by A. I. Rubin is used to implicitly invert the correlation matrix which is part of any regression analysis formulation. This makes the entire technique amenable to implementation on an analog computer. In the present research the parameters being estimated appear as elements of a dynamical system. The estimates of the system parameter values are obtained by first constructing a model of the system for which the parameter values are known. The system parameter estimates are then obtained by combining the known model parameter values with estimates, obtained with the regression analysis technique, of the difference between the corresponding model and system parameters.

The regression analysis technique is used to analyze the performance of human operators in low order compensatory manual control systems. This study is based on two experiments in which the subjects controlled single and double integrator dynamical systems with an input which was low frequency noise. In modeling the human operator system the "crossover model" proposed by D. T. McRuer is used. This model expresses the entire forward-loop of the compensatory control system as a series of operators: a gain L, a time-delay τ, and a single integration. The study takes the form of obtaining estimates of the parameters K and τ for twenty-five 20-second intervals for each day of testing. From an analysis of these parameter values, inferences are made about the performance of the human operators.

A novel approach which is taken in the analysis of the parameters is to divide the variance of both K and τ, based on 20-second data intervals, into a within-subject component and a between-subject component for each day of testing. On the basis of the components of variance for K and τ the following characteristics of the human operator when controlling low order dynamical systems are inferred.

(1) The human operator adopts a more consistent "signal processing path" as he learns the tracking task.

(2) The subjects are more uniform in control strategy for the double integrator system than for the single integrator system.

(3) The variance of τ is a more sensitive indicator of learning than is the average value of either K or τ.

(4) There appears to be an inherent variability in the human operator gain on which training has little effect.

Warner, J. D. A fundamental study of predictive display systems. NASA Contractor Report, NASA CR-1274, February 1969.

This report presents the results of a fundamental study of the predictive display technique. It is intended to provide a basis for understanding some of the advantages and limitations of predictive displays in man-machine systems, and a starting point for both future research and eventual applications. The particular predictive technique considered in this report utilizes a repetitive, fast-time, on-line computation scheme developed by H. Ziebolz which provides a predicted response of the controlled element to the human operator based on certain assumptions about future control inputs and disturbances. It is apparent from previous studies which have been concerned with specific applications that there is a need for clarification of applicable terminology as well as a need for general investigations into the effects of certain inherent characteristics of predictive display systems.

On the basis of a review of the known literature on the subject, an in-depth discussion is provided on the various characteristics that are important in any predictive display application. In addition, the problem of performance measurement is discussed. A discussion of several potential applications is provided to point out the possible advantages of a predictive display and those characteristics which might be important.

An experimental investigation on the effects of controlled element dynamics on performance with three display forms (exploratory prediction, on-line prediction, and no prediction) in a time vs. error format is reported. A minimum-time terminal control task for a pure inertia system driven by a fixed three-state relay controller was chosen for the study. The system is described by several independent parameters which are hypothesized as being important in a variety of manual control situations. These paramters are varied systematically to determine their effect on performance with the three display forms. Several new performance measures are developed for use in minimum-time terminal control tasks.

It is found that the human operator performs with consistent control timing accuracy using exploratory prediction, independent of the various system parameters and the effective display gain. Performance variations in terms of the system and task-oriented criteria are found, however, which are explained through an analysis of the sensitivity of the criteria to constant timing errors in the application of control changes. On-line prediction yields nearly the same level of performance as exploratory prediction. Performance with the normal display on the other hand is more variable, and generally becomes worse as the required mental prediction time spans of the operator increase.

A general conclusion from this research effort is that predictive displays are potentially useful whenever the information processing requirements are severe and required mental prediction time spans are not short, but that additional studies are needed comparing predictive displays to semi-automatic systems using command displays and fully manual systems using advanced integrated display forms. Additional specific conclusions from the experimental effort are: (1) exploratory prediction and on-line prediction result in nearly the same level of performance as long as the required decision times are not short, and (2) performance measure selection is critical to the evaluation of advanced display systems and of the effect of different system parameters.

Pew, R. W., & Chananie, J. D. Subjective scaling of springs, shock absorbers, and fly wheels. Proceedings of the 5th Annual NASA-University Conference on Manual Control, Cambridge, Massachusetts, March 1969.

In an attempt to examine a human operator's sensitivity to the dynamic feel characteristics of a physical control stick, observers were asked to provide, on the basis of feel alone, subjective ratings of the relative magnitude of spring restoring torques, frictional or damping characteristics, and inertial effects in an attempt to develop scales of subjective response as a function of the physical magnitude of these variables. For example, if we doubled the physical magnitude of damping in a control device, would the observer perceive that twice as much damping was present? Physical dynamic stick characteristics were presented to the observers with a variable dynamics control stick.

When the relationship between perceived magnitude and actual physical magnitude is plotted in double logarithmic coordinates, the resulting curves for spring constant, for coefficient of viscous damping, and for moment of inertia are adequately described by linear functions. Thus, it appears that these data may be represented by a power function similar to that which has been found to be appropriate for other sensory dimensions. It is of interest, then, to examine the slope of these power functions. A slope equal to 1.0 implies a one-to-one correspondence between the physical dimension and the perceived effect. Slopes less than one imply a loss of sensitivity as the magnitude of the physical dimension increases, while slopes greater than one imply increasing sensitivity with increasing physical magnitude. The slopes obtained were spring constant: 1.05, coefficient of viscous damping: 0.89 and 1.04 for two different groups of subjects, and moment of inertia: 1.27 and 1.82 for two different measurement groups. Thus springs and viscous friction appear to be judged relatively accurately, while observers tend to be more sensitive to changes in moment of inertia with increasing stimulus magnitude.

When moment of inertia was judged in the presence of three levels of damping and coefficient of viscous damping was judged under three levels of inertia, it was found that the increasing level of the secondary dimension tended to mask the observer's sensitivity to the primary dimension. In both cases the value of the power function exponent decreased as the level of the secondary dimension increased. That is, the observer's sensitivity to the judged dimension was decreased in the presence of increasing amounts of the secondary dimension.

In addition to the demonstration of a methodology for evaluating the perceived effect of dynamic dimensions of a control stick, the most important practical result appeared to be the demonstration that the perceived massiveness of the control device grows more rapidly than does its corresponding physical magnitude. This result provides further reason for minimizing control stick inertia as well as suggesting that when the inertia is relatively large, small changes in the level of the inertia are more likely to be noticed by the operator.

Fogarty, L. E., & Howe, R. M. Computer mechanization of six-degree of freedom flight equations. NASA Contractor Report, NASA CR-1344, May 1969.

Some of the six-degree-of-freedom flight equations for aircraft and missiles represent one of the most important application areas for analog, hybrid, and digital computer systems. Important computer requirements such as accuracy and speed are dependent very much on the choice of axis system for the translation equations of motion. In this connection it is well known that the flight-path axis system makes much lower accuracy and speed demands on the computer than does the body-axis system. Computations of Euler Angles and vehicle position for both the flat earth and the spherical earth cases are considered as well as the computation of aerodynamic forces and moments. The purpose of this paper is to point out again the advantages of flight path axes and to summarize the overall equation requirements for solving the six-degree of freedom flight equations.

Sincerely yours,

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Below is a bibliography of the published articles and reports in chronological order under Contract NASr-54(06) from inception March 1964 to termination June 1969:

Pew, R. W., Duffendack, J. C., & Fensch, L. K. Summary of sine wave tracking studies. Proceedings of 2nd Annual NASA-University Conference on Manual Control, NASA SP-128, Boston, Massachusetts, March 1966.

Fogarty, L. E., & Howe, R. M. Space trajectory computation at the University of Michigan. Simulation, April 1966, 220-226.

Robb, Margaret. Feedback and skill learning. (Doctoral dissertation, The University of Michigan) Ann Arbor, Mich.: University Microfilms, 1966. No. 66-14,580.

Pew, R. W. Performance of human operators in a three-state relay control system with and without explicit velocity information. IEEE Transactions on Human Factors in Electronics, HFE-7, June 1966, 77-83.

Fogarty, L. E. Computer generation of arbitrary functions. Simulation, August 1966, 7(2), 80-89.

Gilson, R. P. Some results of amplitude distribution experiments on shift register generated pseudo-random noise. IEEE Transactions on Electronic Computers, EC-15, 6, December 1966, 926-927.

Herzog, J. H., & Pew, R. W. Force feedback compensation: A new concept for improved manual control system performance. Proceedings of 3rd Annual NASA-University Conference on Manual Control, NASA SP-144, Los Angeles, California, March 1967.

Fogarty, L. E. Survey of flight simulation computation methods. Proceedings of SAE Third International Simulation and Training Conference, New York, April 1967.

Pew, R. W., Duffendack, J. C., & Fensch, L. K. Human operator output noise: Central vs. peripheral performance limitation. Technical Digest of 8th Annual IEEE Symposium on Human Factors in Electronics, May 1967 (Abstract).

Pew, R. W., Duffendack, J. C., & Fensch, L. K. Sine-wave tracking revisited. IEEE Transactions on Human Factors in Electronics, HFE-8, 2, June 1967, 130-134.

Jackson, G. A. Measuring human performance with a parameter tracking version of the crossover model. (Doctoral dissertation, University of Michigan), Ann Arbor, Mich.: University Microfilms, 1967. No. 67-17,783.

Fogarty, L. E., & Howe, R. M. Trajectory optimization by a direct descent process. Proceedings of XVIIIth Congress of the International Astronautical Federation, Belgrade, Yugoslavia, September 1967.

Jackson, G. A. Measuring human performance with a parameter tracking version of the crossover model. NASA Contractor Report, NASA CR-910, October 1967.

Herzog, J. H. Proprioceptive cues and their influence on performance in manual control. (Doctoral, dissertation, University of Michigan) Ann Arbor, Mich.: University Microfilms, 1968. No. 68-7626.

Warner, J. D. A fundamental study of manual control system performance with predictive displays. (Doctoral dissertation, University of Michigan) Ann Arbor, Mich.: University Microfilms, 1968. No. 68-13,426.

King-Smith, E. A. Predictive compensation in time delay manual control systems. Proceedings of 4th Annual NASA-University Conference on Manual Control, Ann Arbor, Michigan, March 1968.

Warner, J. D. Manual control system performance with predictive displays. Proceedings of 4th Annual NASA-University Conference on Manual Control, Ann Arbor, Michigan, March 1968.

Robb, Margaret. Feedback and skill learning. The Research Quarterly, 39:1, March 1968.

Fogarty, L. E., & Howe, R. M. Trajectory optimization by a direct descent process. NASA Contractor Report, NASA CR-1070, April 1968.

Jackson, G. A. On the stability of continuous parameter tracking systems. Simulation, July 1968.

Herzog, J. H. Manual control using the matched manipulator control technique. IEEE Transactions on Man-Machine Systems, MMS-9, 3, 1968, 56-60.

Howe, R. M., & Fogarty, L. E. Computer mechanization of six-degree of freedom flight equations. Simulation, October 1968, 11(4).

Howe, R. M. Computer mechanization of reentry equations with four degrees of freedom. NASA Contractor Report, NASA CR-1249, December 1968.

King-Smith, E. A. Time delay in closed-loop systems with special reference to the human operator. (Doctoral dissertation, University of Melbourne) Melbourne, Australia, December 1968.

Powers, W. F. On the generation of ideal coordinate systems for the analysis of optimal trajectories. NASA Contractor Report, NASA CR-1250, December 1968.

Robb, Margaret, & Pew, R. W. Skill training for the production of a memorized movement pattern. NASA Contractor Report, NASA CR-1251, December 1968.

Burgett, A. L. A study of human operator performance using regression analysis. (Doctoral dissertation, University of Michigan) Ann Arbor, Mich.: University Microfilms, 1969. No. 69-12,062.

Pew, R. W. The speed-accuracy operating characteristic. Acta Psychologica, 1969, 30, 16-26.

Herzog, J. H. Proprioceptive cues and their influence on performance in manual control. NASA Contractor Report, NASA CR-1248, January 1969.

Burgett, A. L. A study of human operator performance using regression analysis. NASA Contractor Report, NASA CR-1259, January 1969.

Warner, J. D. A fundamental study of manual control system performance with predictive displays. NASA Contractor Report, NASA CR-1274, February 1969.

Burgett, A. L. A study of the variability of human operator performance based on the crossover model. Proceedings of 5th Annual NASA-University Conference on Manual Control, Cambridge, Massachusetts, March 1969.

Jackson, G. A. A method for direct measurement of crossover model parameters. IEEE Transactions on Man-Machine Systems, MMS-10, 1, 1969, 27-33.

Pew, R. W., & Chananie, J. D. Subjective scaling of springs, shock absorbers, and fly wheels. Proceedings of 5th Annual NASA-University Conference on Manual Control, Cambridge, Massachusetts, March 1969.

Fogarty, L. E., & Howe, R. M. Computer mechanization of six-degree of freedom flight equations. NASA Contractor Report, NASA CR-1344, May 1969.

Summary of Student Participation

on Contract NASr-54(06)

The following students received their Ph.D. in connection with their contribution to the Contract:

Margaret Robb, Associate Professor, Department of Physical Education, Cortland State University, Cortland, New York. "Feedback and Skill Learning", Ph.D. dissertation, University of Michigan, April 1966.

Glenn A. Jackson, Assistant Professor, Division of Engineering, Oakland University, Rochester, Michigan. "Measuring Human Performance with a Parameter Tracking Version of the Crossover Model", Ph.D. dissertation, University of Michigan, August 1967.

James H. Herzog, Department of Electrical Engineering, Oregon State University, Corvallis, Oregon. "Proprioceptive Cues and thier Influence on Performance in Manual Control", Ph.D. dissertation, University of Michigan, December 1967.

John D. Warner, Boeing Aircraft Company, Seattle, Washington. "A Fundamental Study of Manual Control System Performance with Predictive Displays", Ph.D. dissertation, University of Michigan, December 1967.

August L. Burgett, Assistant Professor, Department of Electrical Engineering, University of Southern Florida, Tampa, Florida. "A Study of Human Operator Performance Using Regression Analysis", Ph.D. dissertation, University of Michigan, December 1968.

Eric A. King-Smith, NIH Special Fellow, Bioengineering Program, University of Michigan, Ann Arbor, Michigan. "Time Delay in Closed-Loop Systems with Special Reference to the Human Operator", Ph.D. dissertation, The University of Melbourne, Melbourne, Australia, December 1968. (Research completed under the contract.)

Students who received their Master of Science degrees are:

Kirby J. Thomas, Martin Marietta Corporation, Denver, Colorado. M.S., August 1968.

Christopher D. Wickens, U. S. Navy. M.S., April 1969.

Students who contributed to the contract but who left before completing their degrees are:

J. David Chananie, Bell Laboratories, Whippany, New Jersey.
Rodman Gilson, Bendix Systems Division, Ann Arbor, Michigan.
John Frait, Veda Inc., Ann Arbor, Michigan.
John C. Duffendack, Comshare Inc., Ann Arbor, Michigan.
Roger Zauel, Ford Motor Company, Dearborn, Michigan.

Students who contributed to Contract NASr-54(06) and are continuing related work toward their Ph.D. degrees are:

Terry R. Armstrong	Gary Rupp	Vicki Cohen
Brian Repa	John Ware	Richard Jagacinski