MASSACHUSETTS INSTITUTE OF TECHNOLOGY

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Principal Investigators: L. R. Young
Y. T. Li

June 1969

Status Report on
NASA Grant NsG 22-009-025

MAN-VEHICLE LABORATORY
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Status Report on NASA Grant NsG 22-009-025
for the period July 1968-June 1969

June 1969

Principal Investigators: Professor L. R. Young
Professor Y. T. Li

Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
Man-Vehicle Laboratory
Center for Space Research

STUDIES OF HUMAN DYNAMIC SPACE

ORIENTATION USING TECHNIQUES OF CONTROL THEORY

ABSTRACT

The Man-Vehicle Laboratory has pursued a wide variety of research areas associated with dynamic space orientation during the academic year 1968-69. It has in addition been led to the consideration of several other practical instrumentation problems of interest primarily to medical or aviation fields, but related to the central subject of man sensing his environment and controlling his orientation in it. Research was carried out by thirteen research assistants, three graduate fellows, a post doctoral research associate, and a full time research staff member, under the supervision of Professors Young and Meiry. Six of the students are working toward doctoral degrees, two toward engineer's degrees and the remainder toward masters degrees. During this past year, three masters degrees and one degree of engineer were awarded based on research supported by this grant. To put the research sponsored by this grant in the context of the overall laboratory effort, the following list of the thirty-eight research topics treated during the past year is included. Those topics marked with an asterisk were supported wholly or in part from the subject grant.

A. Manual Control Modeling*
   1. Adaptive characteristics
   2. Development of an "aided driven" force control stick
   3. Separation of effects of linear and angular motion
   4. Multi-loop characteristics and instrument scanning rules

5. Aircraft landing and "backside of power curve" approach

B. Display Research*
   1. Audio localization for collision warning
   2. Perspective glide slope display and evaluation
   3. VTOL "bottom window" integrated display
   4. "Anti-vertigo" display
   5. 3-D display

C. Vestibular Research
   1. Development of model for adaptation
   2. Low frequency otolith stimulation
   3. Directional preponderance in semicircular canals
   4. Habituation to rotating environment
   5. Unified model of vestibular function*

D. Eye Movements*
   1. Stochastic eye tracking model
   2. Visual vestibular interaction
   3. Effects of voluntary limb motion (efferent copy) on pursuit movements
   4. Nonlinear aspects of compensatory eye movements

E. Cybernetics*
   1. Self reorganizing systems
   2. "Learning automata" based on physiological principles
   3. On-line identification
   4. Circadian rhythms
   5. Information processing in human reading
   6. Speech recognition

F. Postural Control
   1. Balance reflex experiments
   2. Neuromuscular models
   3. Extravehicular stabilization from postural signals*

G. Life Support
   1. Atmospheres for spacecraft and extravehicular activity
   2. Contaminant monitoring
   3. Effects of ionization radiation and magnetic fields on the CNS
   4. Water recovery systems
   5. Cardiovascular deconditioning in weightlessness

H. Medical Applications
   1. Electromyogram processing and display for orthopedic surgeons*
   2. Postural control diagnostics
   3. Eye movement (nystagmus) processing program
   4. Intraocular pressure measurement
   5. Diabetes diagnosis and insulin-glucose modeling*

Brief descriptions of these projects, and abstracts of relevant theses and publications are given in the remainder of this report.

MAN-VEHICLE LABORATORY PERSONNEL 1968-69

Faculty

Y. T. Li
L. R. Young
J. L. Meiry

Research Associate

A. V. Phatak

Research Staff

H. L. Galiana

Research Assistants

J. Allum
N. Goto
D. Mathur
P. Mirchandani
L. Nashner
C. Oman
C. Ormsby
J. Tole
N. Van Houtte
L. Von Renner
S. Yasui

Graduate Fellows

P. B. Dinsdale
G. Kemp
P. L. Noggle

Secretaries

M. Kulash
A. Wasserman
A. Markowitz

I. MANUAL CONTROL MODELING

Modeling of the human operator in his role as a pilot, particularly in complex multi-loop adaptive systems, remains a challenging and important research area. We have continued some of our earlier work on adaptive models and the effects of motion cues, completed an important set of experiments on "aided driven force control" and branched into the new area of multi-loop characteristics and instrument scanning rules.

1.1 Manual Adaptive Control Characteristics

The entire topic of modeling man as an adaptive control element was explored preparatory to an invited paper by L. Young entitled "On Adaptive Manual Control." This paper, to be presented at the IEEE-ERS International Symposium on Man-Machine Systems, Cambridge, England, September 1969 and published in Ergonomics, September 1969, points out some of the answers but many more of the questions about what information man uses in his adaptive process. In the course of this research some preliminary experiments were carried out by L. R. Young and D. Mathur to discriminate among different schema for manual adaptive control. The experimental situation is shown schematically in Figure 1. Three tracking situations were explored. One operator controlled a compensatory display and was asked to recognize and correct a sudden change in plant dynamics. The second operator was given the same situation as the first with the exception that, without his knowledge, his control stick was disconnected and the error he observed was that generated by the first operator. The third operator merely observed the error display. Each indicated the time when he detected a change in the plant dynamics. Whereas the first operator could act as a model reference adaptive control system based on an internal model of the plant, the second could operate only on the basis of an internal model of the entire forward loop and the third could adapt only on the basis of error pattern recognition. The preliminary data shows that the first operator has shorter detection times than the second, and both detected the plant failures much more rapidly than the third, thus strengthening our belief in some type of model reference control rather than error pattern recognition adaptive control.

The abstract of the paper is given below.

<u>On Adaptive Manual Control</u>

by
Laurence R. Young, Sc.D.

IEEE-ERS International Symposium on Man-Machine Systems
Cambridge, England, September 1969;
Ergonomics, September 1969

<u>Abstract</u>

Experimental studies and control descriptions of the human operator in recent years have extended the knowledge of adaptive behavior in manual control from vague generalities about his versatility to quantitative descriptions. Considerable data have been gathered on the ability of the human to adapt to changes in input spectra, controlled element gain, polarity and dynamics, display modality, and the limits of controllability under a variety of situations. These results have indicated a greater adaptation versatility than expected from some earlier descriptions, but have also pointed out some of the restricted training conditions under which the rapid human adaptation may be expected to be demonstrated.

When it comes to explaining <u>how</u> the human manages his remarkable adaptation abilities, less progress has been made. Improvement in the techniques for dynamic measurement of the adaptive process have been helpful in this regard but still fall short of what is required to observe the change in control law. Some appealing suggestions for detection models, model reference control analogs and statistical decision theory pattern recognition algorithms have been put forth but are in no sense "proven." Primarily as a result of the measurement limitation and the lack of sufficient knowledge about adaptive control systems in general, the development of models for human adaptive control has been limited to general "schema" at this time.

Guidance in the performance of our experiments on manual adaptive control was given by Dr. Anil V. Phatak, who spent the year as a Research Associate in our laboratory. Dr. Phatak in conjunction with Dr. George Bekey of the University of Southern California, wrote a paper entitled "Decision Processes in the Adaptive Behavior of Human Controllers," which was presented at the Fifth Annual Conference on Manual Control, March 1969, and is to appear in the IEEE Systems Science and Cybernetic transactions, October 1969. This paper was based on research performed at the University of Southern California last year.

1.2 Development of an "Aided Driven" Force Control Stick

The use of a force control stick has been of growing interest for a number of applications including the control of unstable vehicles, the linking of a human pilot to an autopilot, and control under severe vibration and high g environments. We have concentrated on ways of using a servo-driven force control stick for stability augmentation while retaining the reliability associated with having the human directly in the control loop. The development and testing of the system was the topic of an engineer's thesis written by Major Philip

Noggle, the abstract of which is given below.

Manual Control of Unstable Vehicle
Using Kinesthetic Cues
by
Philip L. Noggle

Engineer of Aeronautics and Astronautics
Thesis, March 1969

Abstract

A control stick was constructed which sensed the operator's force but moved only in response to an external electrical signal, giving the operator kinesthetic cues. First and second order plants were used in experiments which compared human operators' ability to control instabilities with the force sensing stick fixed, driven by plant position, and driven by plant velocity. Great improvement in human control capability were found in controlling first order plants with the stick driven by plant position and in controlling second order plants with the stick driven by plant velocity. The large improvement was due to a reduction in lead required of the operator and a reduction in operator delay time. The necessity for lead was reduced by providing the operator with a signal, in the form of stick motion, with the proper phase for stabilization. The delay time was reduced by enabling the operator to transmit the stabilizing signal to the plant by stick reaction forces determined by muscle tensing instead of voluntary action.

1.3 Separation of Effects of Linear and Angular Motion Cues On the Human Operator

A major phase of our research on the quantitative effect of motion cues on manual control has been brought to a close by the successful completion of two projects. The theses of Richard Shirley and Peter Dinsdale on roll motion cues and the differential effect of roll and yaw motion cues, respectively, were summarized in a previous status report. During the current reporting period, two papers based on this work were presented. The abstracts are given below.

Motion Cues in Man-Vehicle Control

Effects of Roll-Motion Cues on Human Operator's Behavior in Compensatory Systems with Disturbance Inputs

by

R. Shirley and L. Young

IEEE Transactions on Man-Machine Systems
Vol. MMS-9, No. 4, December 1968

Abstract

The human operator's use of roll-motion cues is investigated for man-vehicle control in a compensatory tracking task with a disturbance input. Extensive data for the human operator's describing function are taken for a wide range of vehicle dynamics under conditions of visual cues only, roll-motion cues only, and simultaneous visual and roll-motion cues. Addition of roll-motion cues to visual cues permits the human operator to increase his phase lead at frequencies above 3 rad/s. This allows him to increase the system open-loop gain without a loss of system stability, and thus to reduce the system tracking error. Experimental results indicate that in a compensatory system with a disturbance input, any condition in which additional human operator lead at frequencies above 3 rad/s would be useful is a condition in which roll-motion cues would aid.

Contributions of Roll and Yaw Motion Cues in Manual Control

by

L. R. Young and P. B. Dinsdale

Fifth Annual NASA-University Conference on
Manual Control, M.I.T., March 1969

Abstract

Previous communications concerning the effects of roll motion cues on pilot characteristics emphasized the increase in low frequency gain and the phase lead contributed at higher frequencies. To determine the relative contributions of semicircular canal and otolith responses, experiments were performed in yaw and roll control of a K/s^2 vehicle on a moving base rotation simulator. Comparison of human operator describing functions shows that rotation with respect to the g vector (roll) leads to higher gain than rotation in a horizontal plane, although no significant difference in phase lag appears.

1.4 Multiple Loop Characteristics and Instrument Scanning Rule

In the increasing literature on multi-loop and multi-axis systems, the assumption is generally made that the pilot receives information from his displays (be they integrated or separated) on a continuous basis. In only a few studies does the discontinuous sampling behavior exhibited by the human operator come to the fore; and for these situations a periodic switching hypothesis which predicts the number of fixations or the amount of time spent on each display is used. In a new study in our laboratory, N. Goto investigated analytically and experimentally the operator's sampling strategy in deciding when to look away from one display and observe a second one in a coupled multi-loop tracking task. A switching hypothesis led to a scanning rule which predicts the length of time a subject spends on each display and the times at which he switches from one display to the other, based upon the observed state of the system and its predicted state during a succeeding fixation. The particular application chosen for this study was the problem of aircraft landing on the back side of the power curve in which the pilot controls altitude deviation from the glide slope and air speed by means of two controls, the throttle and the elevator. This work is reported in full in a forthcoming laboratory report, the abstract of which is given below.

An Experiment on the Human Operator's Scanning Rule for Two Displays

by
Norihiro Goto

Abstract

An experiment was conducted to investigate the scanning rule and control characteristics of the human operator in a multi-loop task.

The task was that of controlling the glide slope in a landing approach condition. The operator was given two separately located displays, glide slope indicator and air speed indicator.

The human operator's eye movements were measured as well as the actual output data and performance in terms of mean-squared error and mean-squared control movements.

The human operator's scanning rule was found to be neither periodic nor constant. The human operator set his permissible error region in each indicator and controlled the system in reference to the permissible error region.

The human operator's control characteristics were such that he tried to maintain the performance of the command loop by changing his control technique. Task difficulty was shown most clearly in control movements.

II. DISPLAY RESEARCH

Over the past two years, we have devoted an increasing amount of our effort to research in displays for current and future vehicles, emphasizing basic studies of the essential features of displays which enable a pilot to sense his orientation with respect to the earth and with respect to other obstacles in the environment. The practical application of most of this display research is in the area of aircraft rather than spacecraft, especially general aviation and VTOL.

2.1 Displays for Pilot Warning Indicators (PWI)

We have been concerned with the problem of localizing other objects in the airspace without distracting the private pilot from his primary task of maintaining control of his airplane. Our discussions with NASA Electronics Research Center about their optical PWI program have emphasized to us the need for development of a warning indicating system which clearly informs the pilot as to other aircraft in the area which may be on a collision course, assists, and yet does not involve an excessive amount of cross checking between visual search and instrument readings. Several types of heads-up displays are being considered, and in particular we plan to investigate the combination of audio-visual localization using our Link GAT-1 as a test bed. A small grant from NASA ERC will support our research in this area (NGR 22-009-444).

2.2 Perspective Glide Slope Display and Evaluation

A natural outgrowth of our earlier work on perspective and three dimensional displays is an application to the aircraft landing situation. A new form of contact analog display using perspective vertical bars for glide slope indication is under development and evaluation by Noel Van Houtte as part of his doctoral thesis. The display and the method of evaluation are designed to emphasize the ease of learning to land a tilt-engine VTOL on different steepness glide slopes.

Mr. Van Houtte's present work will integrate several aspects of display information, pilot performance and handling of V/STOL aircraft from cruise to final touchdown, including transition, hover and landing.

The purpose of the study is an evaluation of display information presentation and human pilot performance. It concentrates on a novel contact analog display (perspective view of runway or landing site and glide path). The investigation of the display will examine:

1.a. information available in a perspective display, giving the pilot a real outside world picture of runway and transition path.

b. examination of the display elements, each giving some information, e.g. - horizon for roll cue

- intensity for depth cue

c. examination of components used for integrated display, superimposed on the contact analog display,

e.g. - angle of attack

- velocity vector

d. other display parameters, such as

- effect of screen size

- display gain

2.a. pilot performance while landing, using a compensatory display overcoming common optical illusions

b. ability of pilot to get familiar with a given display (learning curve for that display)

The basis for analysis of this portion is a measure of integrated weighted deviation from desired path. This figure will be plotted as history of the number of trials. The number of trials will be determined by the asymptote of the learning curve, i.e. steady state in the performance.

3. The piloting technique for controlling the aircraft in the different phases of landing. A study of the pilot describing

function will be done for the variables of interest. The quantities which will be recorded and will be available for study are: forward speed, rate of climb, angle of attack, position, attitude, thrust, engine tilt angle.

4. Work load measurements will be done by giving the pilot a secondary task. This task will be either an arithmetic task or a test for alertness.

Certain aspects have been studied in a limited sense. Integrated displays, containing the state of many variables have been tested, and were compared with pilots' comments. The tendency has been to 'improve' the picture by adding more and more 'available' information with the result of a cluttered map. Effects of adding this information in a more convenient way have also been studied: scales at the sides and bottom of the contact analog display, moving pointers along these scales, and finally stationary pointers with moving tapes.

Furthermore, studies have been carried out for evaluation of director symbols, display alteration and presentation of secondary flight information.

Work Plan

The main point of interest is the quality of information transfer to the pilot about the actual situation of the flight: state variables for the aircraft. This study will examine the display and pilot transfer function as a whole.

The pilot will be presented with a display, representing a runway and prescribed glide path. To add other "necessary" information: poles will be drawn to give the impression of velocity, the horizon will give roll information, intensity modulation as well as size and perspective provides range information.

2.3 VTOL "Bottom Window" Integrated Display for Hover and Landing

One of the fundamental problems in a VTOL integrated display is a combination of the vertical plane information (artificial horizon) with the horizontal situation indication. A new approach to this problem is the subject of the research of Major Gordon Kemp, CAF, who is developing a "bottom window" VTOL display in which pitch and roll are indicated by projections of aircraft planes on the ground plane. This display is being simulated and evaluated on the Adage AGT-30 display computer in the M.I.T. Electronic Systems Laboratory.

As shown in Figure 2, the display is basically an inside-out "bottom window view" with the face of the display mounted horizontally. The C.R.T. displays a grid painted on the ground. The grid moves aft along the display face to indicate forward velocity and sideways to indicate sideslip. Increasing altitude is indicated by decreasing grid size as compared to a reference square or "window" which is drawn on the lower half of the display face. When the grid size is identical to the window size, the aircraft is at zero altitude. The origin of the grid is at the center of the window. Locations of interest (e.g. landing sites) will be marked on the grid with a prediction line showing computed future position. Heading will be displayed alpha-numerically at the top of the display with a prediction line showing computed future heading.

The attitude display will not be the normal horizon line type display but rather will show the direction of the z axis of the aircraft. Thus roll will be indicated by displacement of a force and aft line on the screen and pitch by displacement of a lateral line. When the aircraft is straight and level, the intersection of the two lines will be in the center of the screen. Predicted pitch and roll will be indicated by a line emanating from the intersection of the pitch and roll lines.

The prediction times for the attitude indications will be different from the prediction times for lateral indications but both will be computed using a much simplified set of equations as compared to the equations which will be used for the vehicle dynamics simulation.

2.4 Anti-Vertigo Display

In recent months, laboratory efforts to develop valid mathematical models for the semicircular canals and otoliths using the techniques of control theory have been reviewed in an attempt to define and investigate the etiology of vertigo, and the interaction between visual and vestibular motion cue inputs. We conclude that a conflict arises as a man attempts subconsciously to continue the process of establishing a conception of his dynamic orientation in space in the presence of contradictory visual and vestibular cues.

Our research in developing a "psuedo-stable" peripheral display to reduce the onset of vertigo under unusual motion was reviewed in a previous status report. The basic idea was to create a moving peripheral display which would appear to the subject viewing it as consistent with the motion he senses through the stimulation of his vestibular system, and thus eliminate the visual vestibular conflict so important in the onset of vertigo. The prototype display was constructed and tested for one-axis stimulation as part of the master's thesis of Charles M. Oman.

Experiments were undertaken to investigate visual and vestibular motion cue interaction. The laboratory's rotating chair was modified to include a rotating drum projector to produce a moving stripe display on a screen inside the cab. Subjects were seated in the closed cab and stimulated so as to experience a simple form of vertigo, "dizzyness", which results from lingering sensation of rotation after a cessation of angular velocity. A non-rational-parameter computer model for human vestibular response to angular acceleration in a horizontal plane was used to control the moving bar display, thus creating a visual input which could be made to agree or to disagree with the theoretical subjective sensation of motion relative to the outside world.

Preliminary experiments involving four types of tests on five subjects were performed. Subjects were asked to indicate the onset of sensation of rotation in a given direction by pushing a bi-directional switch, and to signal each ninety degrees of subsequent rotation in that particular direction. In addition, subjects were told to indicate directly when they felt confused in that they could no longer determine their angular velocity. No confusion was reported when the display was driven so that the visual cue was sympathetic to the theoretical subjective angular velocity profile, even though it was not identical with the actual chair velocity. However, every subject reported confusion either when the display was anti-sympathetically driven or when the visual input was driven so that it was stabilized with respect to the outside world.

The apparent success of our preliminary experiments in the single axis have encouraged us to extend this work to the more complex two axis stimulation and to attempt to find some reasonable feedback scheme for allowing a subject to voluntarily or involuntarily control the display in order to avoid vertigo or motion sickness.

2.5 3-D Display

Most of the original 3-D display program was concluded by the beginning of this reporting period, having explored the full range of depth cues which could be made available using a single cue and the kinetic depth effect, hidden-line removal, brightness variation, and perspective. Any more complex display of this type including the use of interposition would not be possible on our hybrid computer while retaining real-time flicker-free operation. Consequently, our future 3-D display research is being shifted to the Adage AGT-30 computer. The VTOL bottom window display, referred to above, is one of these applications.

The three previous areas, 3-D display, VTOL bottom window display, and the anti-vertigo display were summarized in a paper presented to the Fifth Annual NASA University Conference on Manual Control, M.I.T., March 1969 and scheduled for publication in the NASA special publication on this meeting. The abstract of that paper is given below.

Three Display Techniques at the Man-Vehicle Laboratory

by

Laurence R. Young, Charles M. Oman, Robert M. Vircks
Noel A. J. Van Houtte, and Gordon G. Kemp

Fifth Annual NASA-University Conference on
Manual Control, M.I.T., March 1969

Abstract

Three display techniques designed to reduce man's uncertainty about his spatial orientation are presented:

1) A 3-D display system is described in which a simple computer generated C.R.T. contact analog system is controlled by movement of the observer's head, as well as by vehicle motion.

2) A prototype VTOL guidance and control display is being developed. All attitude and guidance cues are presented on an integrated horizontal situation display in which pitch and roll angles appear as vehicle axis projections, and predictive display of attitude and position is used.

3) An "Anti-Vertigo" research display is being developed in which visual-vestibular conflict is reduced by driving a rotating visual field at rates determined by a mathematical model for vestibular function.

III. VESTIBULAR RESEARCH

Research on the functioning and importance of the vestibular system continues to be central to the laboratory and to the research on this grant in the area of dynamic spatial orientation. Our vestibular research effort falls under the following broad areas:

1. quantitative dynamic modeling of vestibular function, including responses to linear and angular acceleration and the interaction with visual stimuli

2. behavioral correlates of vestibular responses, i.e. the effects of motion cues on pilot's performance and vertigo

3. the underlying physiological and neurophysiological mechanisms responsible for observed and modeled vestibular responses

4. clinical applications of our research on vestibular function.

3.1 Development of a Model for Adaptation to Sustain Semi-Circular Canal Stimulation

Aircraft and especially spacecraft permit subjects to experience sustained angular velocities and even sustained angular accelerations of the type which were not normally explored in early laboratory studies. Our research on the adaptation present in association with horizontal semi-circular canal stimulation led to a revision of the classical second order description. The results are summarized in a paper accepted for publication in Aerospace Medicine, the abstract of which appears below.

A Model for Vestibular Adaptation To Horizontal Rotation

by

Laurence R. Young, Sc.D.
Charles M. Oman, S.M.

Abstract

Short-term adaptation effects are seen in subjective sensation of rotation and vestibular nystagmus. The mathematical model for semicircular canal function is improved by the addition of two adaptation terms (approximately one-half minute time constant for sensation and two minute time constant for nystagmus) to the overdamped second order description. Adaptation is represented as a shift of reference level based on the recent history of cupula displacement. This model accounts for the differences in time constants between nystagmus and subjective cupulograms, secondary nystagmus, and decreased sensitivity to prolonged acceleration.

3.2 Low Frequency Otolith Stimulation

We have attempted to extend the body of data on low frequency sinusoidal stimulation of the linear acceleration sensors to below our previous limit of 0.1 rad/sec, which represented the limitation on the thirty-two foot length of our acceleration track. In a series of experiments conducted by Lonnie C. Von Renner subjects were oscillated at very low frequencies about the roll axis in our NE-2 simulator in an attempt to introduce sinusoidal stimulation to the y-axis of the otoliths while maintaining the angular acceleration and angular velocities below canal thresholds. Although the subjective phase lag data (phase of subject's indication of velocity reversal with respect to actual velocity reversal) did indeed show the low frequency phase peak predicted by the model, the data did not overlap or tie in with the previous experimental data taken on the linear acceleration cart. A number of possible explanations for this phenomenon have been considered, including the non-uniformity of the NE-2 rotation and the inherent canal stimulation associated with a rotating specific force vector. We plan to repeat these experiments with the smoother control in the new Link GAT-1 simulator. Further details of this experiment are given in the June 1969 status report on NASA grant NGR 22-009-156, which concentrates on the biophysical vestibular studies in our laboratory.

3.3 Directional Preponderance of the Semicircular Canal

The directional preponderance associated with the semicircular canal indicates the direction and magnitude of spin that a subject "feels" in the absence of any average angular velocity. The nature of this directional preponderance is of considerable interest clinically and in screening and matching certain dynamic displays to individual pilots. We explored a "natural stimulation" psychophysical method as an alternative to the caloric testing usually used for directional preponderance studies. Seven subjects were tested in our servo-driven single axis yaw chair (subject to zero mean random disturbances.) Subjects all had eyes open in the dark. They tried to control the chair to keep it stationary while we recorded the resulting drift of the chair in one direction or the other. In the experiments conducted by Mr. Pitambar Mirchandani all subjects showed a tendency to rotate in a preferred direction without being aware of this fact. Of the seven subjects tested, three always drifted in one preferred direction and the rest drifted in a preferred direction at least eighty per cent of the time. It was further noticed that each subject tended to drift in his preferred direction at an approximately constant angular acceleration. The mean average of angular acceleration of the subjects in their preferred direction of rotation was 0.16 rad/sec^2. The subjects were also given a thorough vestibular examination by Dr. A. D. Weiss of the Massachusetts Eye and Ear Infirmary. The "reduced vestibular response" (sensitivity of one ear as compared to the other on the basis of caloric responses) were obtained with eyes open and eyes closed. The clinical directional preponderance (preponderance in one direction of nystagmus as compared to the other direction) in duration and slow phase velocity, of the subjects were also calculated, both with eyes closed and with eyes opened.

Although high correlation was not observed between Dr. Weiss' tests and those run on the rotating chair, there seemed to be significant binary correlation between the reduced vestibular response, with eyes opened, and the directional preponderance as measured with the rotating chair. Five of the six subjects tested by Dr. Weiss showed reduced vestibular response in the ear corresponding to the preferred direction of rotation. This would mean that the subjects whose left ear was more sensitive to caloric testing usually tended to drift to the left.

Further tests are essential before more inferences can be made. Other tests must be conducted which would distinguish whether the bias was psychological or physiological in nature. Once the cause of the bias has been established our method of testing subjects may also prove to be a useful diagnostic tool even though it may not differentiate between sensitivity in the two ears.

3.4 Habituation to a Rotating Environment

Having made significant progress in modeling at least one of the adaptation phases of vestibular response, we began to consider the more challenging problem of habituation to specific or general classes of motion stimuli. The kinds of habituation to be considered eventually include the pilot's ability to subjectively ignore and in fact to inhibit nystagmus as a result of motion, the "sea legs" phenomenon, the skater's or acrobat's habituation to "bizarre stimulation" such as is experienced in moving about in a rotating spacecraft or habituating to the long-term weightless condition. There is a relative paucity of firm data in these areas and the performance of experiments is difficult. Nevertheless, using behavioral tests on human subjects, especially the results of Dr. A. Graybiel's slow rotating room experiments at Pensacola, and a number of fine habituation experiments on nystagmus in cats, we hope to be able to develop a theory for habituation of vestibular responses which will at least allow prediction of disorienting situations. Our basic notion at the moment consists of a model for habituation which involves an internalized model of the environment against which all vestibular responses are compared, with only deviations from the expected stimuli transmitted.

3.5 Unified Model of Vestibular Function

Our total modeling effort of vestibular function is aimed at a unified input-output model which will be able to relate any combination of specific force and angular acceleration, with or without visual stimuli, to perception of orientation and nystagmus. Although considerable success has been had in the semicircular canal modeling, and to a lesser extent in the otolith, we are just beginning to understand some of the cross coupling effects between these angular and linear acceleration sensing channels, and are at the very beginning of the visual-vestibular interaction problem. The status of vestibular models from the point of view of a unified model was reviewed in a series of papers of varying lengths given during the past year. The most complete of these was "On Biocybernetics of the Vestibular System" by L.R. Young which appeared as a chapter in Biocybernetics of the Central Nervous System (L. Proctor (ed.), Boston, Little Brown, 1969.) A control engineering oriented paper on this subject entitled "A Control Model of the Vestibular System" was presented at the International Federation of Automatic Control, Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, September 1968. A paper based on this presentation, entitled "Current Status of Vestibular Models" by L. R. Young is scheduled to appear in Automatica July, 1969.

The Current Status of Vestibular Models

by

Laurence R. Young, Sc.D.

(In Automatica, Vol. 5, Pergamon Press, Great Britain, 1969)

Abstract

The human vestibular system for dynamic space orientation is described mathematically, using the identification methods of control theory. The analysis by several investigators at the M.I.T. Man-Vehicle Laboratory, building on the available data, has led to a biocybernetic model which is useful in predicting man's perceived orientation in space, postural reactions, nystagmus eye movements, and piloting actions based on motion cues. The semicircular canals, which act as angular velocity sensors, have been subjected to a fluid dynamics analysis. The limitations of the torsion pendulum model of Van Egmond, Groen and Jongkees are examined, and a quantitative description of adaptation in·proposed. An otolith model, responding to linear acceleration forces, is presented and shown to agree with perception of tilt and translation, eye counterrolling, and electrophysiological data. Cross-coupling effects are discussed, including the influence of linear acceleration on the semicircular canal.

An electrical-mechanical analog of this mathematical model was reported by L. R. Young at the AGARD Symposium on Bionics, Brussels, 1968, abstract given below:

Functions of the Vestibular System

In Human Guidance and Control

Abstract

A physical analog model of the vestibular system was developed for research purposes. The model consists of a three gimbal "head" containing three rate gyroscopes and six linear accelerometers, and a special purpose analog computer simulating the dynamics and nonlinearities of the non-auditory labyrinth.

The vestibular package can be rotated through normal head movements by the machine and mounted on a centrifuge or flown to measure actual motion inputs. The distance between the "ears" is adjustable, as well as the orientation of the sensitive direction of each canal and otolith axis. The computer console permits adjustment of the important gains, nonlinearities, and time constants of the vestibular system system for utility in refining models, training phy-

siologists, predicting orientation perception or nystagmus, and for aids in design of moving base simulators or artificial g platforms.

Finally, specialized papers on certain aspects of the vestibular models were presented briefly in the following two papers:

Young, L.R., "Motion Cues and Vestibular Models," presented at NEREM '68 in November, 1968

and

Young, L.R., "Vestibular Models," presented at 1969 Joint Automatic Control Meeting, University of Colorado, Aug.'69.

IV. EYE MOVEMENTS

4.1 Model for Eye Tracking Movements

Our hybrid model for eye tracking movements, described in a previous status report, has undergone further development and appears to explain most of the human eye responses observed to fixed head tracking of moving targets. The implications of the effect of open loop pursuit tracking in terms of neurophysiological function are being explored. The current hybrid model is shown in Figure 3 . A report on this model was given in the paper entitled "A Hybrid Model for Eye Tracking Movements" by Young, Van Houtte and Forster at the 21st Annual Conference on Engineering in Medicine and Biology, Houston, Texas, November 1968.

4.2 Visual Vestibular Interaction

We are beginning a program to determine the effects of simultaneous visual and vestibular stimulation on the eye tracking system. Questions which will be explored are the effects of nystagmus resulting from head movement on fixation ability and the relative advantages in terms of static and dynamic visual acuity for space-stabilized versus vehicle-stabilized displays.

4.3 Effects of Voluntary Limb Motion on Pursuit Eye Movements

A new form of input to the eye movement system, depending upon neither visual nor vestibular cues, has been the subject for study in the M.I.T. Psychology Department. In our laboratory, Dilip Mathur has extended the experiments on the limb movement input to the oculomotor system.

Steinbach has shown that tracking is more precise when the target is moved by the subject rather than if it is moved independently of his control, indicating that the oculomotor system has access to the efferents that moves the target, and that the useful information in the efferent signal is concerned with the self-moved target's absolute velocity and acceleration. He further has shown that the pursuit eye movement system has a proprioceptive input from the arm. To determine whether it is hand velocity or force that drives the pursuit system, a comparison was made between tracking performances under two conditions: the first, where the information available to the oculomotor system was proprioceptive and efferent velocity information (the target was controlled by a subject-moved position stick), and the second, where the information available was proprioceptive and efferent force information (the target was controlled through a fixed force stick.) It was clear from the eye movement records that tracking performance, judged on the basis of latency and saccades, was considerably superior in the first case, indicating that force information is a poor drive for the pursuit system. To determine if force information is used at all, the experiment with the force stick was repeated with the visual information available reduced to a marginal level by displaying a stroboscopic target. In this situation there was no pursuit tracking, thus delineating that it is hand velocity and not force that drives the pursuit system. The control experiment of displacement stick control and stroboscopic display has not yet been performed.

4.4 Non-Linear Aspects of Compensatory Eye Movements

A number of interesting non-linearities in the eye movement system have been observed but not treated in detail. For example, it has been shown that the peak velocity of saccadic eye movements is greater when moving from a secondary to a primary position than vice-versa over the same angular travel. Similarly, in discussing the anti-compensatory flicks associated with a rapid head movement, Jones suggested that these occur to stretch the compensating muscles for fast vestibulo-ocular compensation and early fixation. If the stretching of an agonist extra-ocular muscle serves to deliver higher force and consequently greater velocity to the eye in the forthcoming eye motion, then this should also be apparent in optokinetic nystagmus. Dilip K. Mathur performed some preliminary experiments in this area. The method used was to compare optokinetic nystagmus records under conditions which stretched the compensating muscles to varying degrees: with the head turned away from the target screen at different angles.

Jones' results show that when the angular velocity step is large enough to produce a fifteen degree stretch in the leading direction, vestibular nystagmus has high, slow phase velocity and the sweep of the eyes is large. However, when the angular velocity step is so large as to produce a stretch of approximately 45 degrees, nystagmus is inhibited for several seconds. It was therefore expected that if stretching is conducive to fast compensation, then at low stretch, approximately 15 degrees, optokinetic nystagmus performance would improve over that at no stretch, and that at high stretch angles it would again decline. Given a situation where a pulse train was moving across a screen at a speed he was barely able to follow, the subject's optokinetic nystagmus records showed that tracking performance (in terms of picking up a pulse and following it across the screen) improved as the stretch angle increased from 0 to 20 degrees.

V. CYBERNETICS

Under the general term cybernetics we include a number of investigations of basic problems of manual control, human behavior, and man-machine systems, which are not immediately applicable to the manual control problem.

5.1 Self-Organizing Systems

Self-organizing systems are systems which change their structure when the input or plant changes under the conditions where the controller has never previously experienced this change (this latter is in contrast to self-adaptive systems.) Some of the important properties of these systems, also known as self-learning systems and systems with a teacher, are involved with the concept of its hierarchy.

Pitambar B. Mirchandani has begun investigations in this area, considering at first the concept of multi-level performance indices and coordinability. At each level of the controller hierarchy a performance index is available which dominates the lower level performance indices. Coordination is defined as the decision problem of a control unit imbedded in the self-organizing system. A system is said to be coordinable if the lower level control problem can be influenced so that the overall objective is achieved. More simply, a two level system is coordinable if the satisfaction of the sub-goal (lower level performance index maximized) also satisfies the primary goal (higher level performance index.) The study of self-organizing systems both from the point of view of advances in control and understanding the human self-organizing control nature is a new departure for us at this time.

5.2 "Learning Automata" Based on Physiological Principles

Syozo Yasui has begun looking into the problem of automata based on extremely large numbers of essentially identical neuron-like elements in hope of making some progress in the study of primitive intelligent functions such as memory, learning, adaptation, and decision-making that can be observed in the behavior of animals. This approach is in contrast to the artificial intelligence approach of specific well-defined functional elements and decision-making elements such as considered above in 5.1. The organizing ability resulting from large numbers of spatially and temporarily integrated field effects of neural activities in which each element in some way affects nearly every other element in the space is to be considered. The motivation for this work is three-fold: to attempt to understand some aspects of brain function, to consider the possibility of building artificial field effect learning automata, and finally to study some very interesting and complex non-linear systems. The obvious advantages in terms of reliability and self repair of this type of network automata have been dealt with in the past. Mr. Yasui is also investigating some properties of neural networks and their relationship to visual illusions.

5.3 Rapid Systems Identification

Rapid reliable identification of changes in control systems is an important problem which plagues the adaptive control field as well as the manual control area. A study of improved techniques to get rapid identification in a sufficiently constrained situation, in which the allowable post-failure dynamics were limited to a small number was studied. Charles C. Ormsby has been investigating the applicability of a method of modulating functions introduced by J. Loeb and G. Cahen (IEEE Transactions on Automatic Control, July 1965, pg. 359).

Very briefly, the method of modulating functions consists of the following:

Given the unknown plant and a record of the input and the output of the plant over an interval $[T_1, T_2]$ assume that the input y and the output x are related by

$$\Theta_o X(t) + \Theta_1 \dot{X}(t) + \ldots + \Theta_n X^{(n)}(t) = y(t) \qquad \text{(I)}$$

To find the values of the coefficients Θ_i a set of modulating functions $\phi_j(t)$ are generated with the property that ϕ_j and (n-1) derivatives, when evaluated at T_1 and T_2, have the value zero. Multiplying equation (I) by each of the $\phi_j(t)$'s and integrating from T_1 to T_2 yields:

$$\Theta_o \int_{T_1}^{T_2} \phi_j(t) X(t)dt + \Theta_1 \int_{T_1}^{T_2} \phi_j(t)\dot{X}(t)dt + \ldots$$

$$+\Theta_n \int_{T_1}^{T_2} \phi_j(t) X^{(n)}(t)dt = \int_{T_1}^{T_2} \phi_j(t)y(t)dt$$

Integrating by parts and using the fact that,

$\phi_i(T_1)=\phi_i(T_2)=\dot{\phi}_i(T_1)=\dot{\phi}_i(T_2)=\ldots=\phi_i^{(n-1)}(T_1)=\phi_i^{(n-1)}(T_2)=0$ we find that

$$\Theta_o\int_{T_1}^{T_2}\phi_j(t)X(t)dt-\Theta_1\int_{T_1}^{T_2}\dot{\phi}_j(t)X(t)dt+\ldots+\Theta_n(-1)^n\int_{T_1}^{T_2}\phi_j^{(n)}(t)X(t)dt=$$

$$\int_{T_1}^{T_2}\phi_j(t)y(t)dt \quad \text{or}$$

$$\sum_{i=0}^{n}\Theta_i(-1)^n\int_{T_1}^{T_2}\phi_j^{(n)}(t)X(t)dt=\int_{T_1}^{T_2}\phi_j(t)y(t)dt$$

If our set of modulating functions consists of m functions $[m \geq (n+1)]$ then we are left with a set of m linear equations in (n+1) unknowns which for the case m=n+1 can be solved by matrix inversion and for the case m>n+1 can be solved in a least squares sense.

The most promising feature of the method is that no knowledge of the derivatives of X(t) or y(t) are assumed. It is a well known fact that when derivatives are taken of signals that are corrupted by noise (as we suspect the records of X(t) and y(t) will be) the effect is to greatly magnify the noise. On the other hand, when the integral is taken of a signal corrupted with noise, as we can consider $\phi_j^{(n)}(t)X(t)$ or $\phi_j(t)y(t)$ to be, the effect of the noise is greatly decreased.

For the purposes of the present research the following relationship between X(t) and y(t) was assumed

$$\Theta_o X(t) + \Theta_1\dot{X}(t) + \Theta_2\ddot{X}(t) = y(t)$$

in which Θ_o,Θ_1 and Θ_2 may undergo a step change in the parameters. Results indicate that the occurrence of some failure (change in parameters) could be detected with about .25 seconds of data and a very good estimation of the actual plant parameters could be made with between .50 and .75 seconds of data.

To translate this feasibility into a more practical and challenging application, the roll dynamics of the Bell X-14A VTOL aircraft in the hover mode were selected as a basis for the study of this method of identification. The system is the same as used by Phatak, (USCEE Report 277, On the Adaptive Behavior of the Human Operator in Response to a Sudden Change in the Control Situation, by Anil V. Phatak). The following four parameter model of the human operator dynamics was chosen:

$$\frac{\text{stick output}}{\text{error displayed}} = K\left(\frac{s + z}{s + p}\right) e^{-s\tau}$$

where for the steady state configuration the following parameters were used:

$$K = 8.0 \qquad \tau = 0.4$$
$$z = 3.0 \qquad p = .05$$

The input to the plant consisted of the sum of six non-harmonic sine waves at .157, .262, .393, .602, .969, and 1.49 radians/sec.

In the steady state situation the plant can be approximated as a gain, K_0. There are three basic post failure configurations. The first can be approximated as K_1/s and occurs when the attitude augmentation fails to zero feedback. The second can be approximated by K_2/s^2 and occurs when both attitude and rate feedback fail to zero. The third failure is the same as the first except the attitude feedback fails to a constant non-zero value.

The system described above has been simulated using the IBM System/360 Continuous System Modeling Program (CSMP). Initial difficulties were encountered in identification of the plant dynamics due to the fact that the plant being identified was of higher order than the assumed model. This problem has finally been resolved very simply by modeling the higher order dynamics as a delay. Identifications have been made with .75 seconds of data. An "identification" in this program consists of four numbers which correspond to the thetas in the following expression:

$$C(t) + \Theta_4 = \Theta_1 m(t) + \Theta_2 \dot{m}(t) + \Theta_3 \ddot{m}(t)$$

where Θ_4 identifies the degree of "hard" failure in the third failure configuration described.

A perfect identification in the case of attitude and rate augmentation failure (case number two) would be:

$$\Theta_1 = 0.0,\ \Theta_2 = 0.0,\ \Theta_3 = .0218,\ \Theta_4 = 0.0$$

The worst deviation from the above over 3/4 seconds of data is given below:

$$\Theta_1 = .001,\ \Theta_2 = .0004,\ \Theta_3 = .0215,\ \Theta_4 = .0022$$

Current research is centered on identification of the other modes of failure which will probably be accomplished in a similar way by modeling the higher order dynamics with a delay.

Research this summer will center on an evaluation of the effects of noise, the effect of errors in the entries of a matrix on the entries of its computed inverse (matrix inversion is needed in this identification scheme), and on the implementation of this identification routine in an adaptive system which will change the autopilot configuration or the controlling strategy of the human operator model to that which is appropriate to the new post failure dynamics of the plant.

5.4 Speech Recognition

D. K. Mathur worked on a speech recognition scheme that is a variation of the "distinctive feature" philosophy commonly applied to individual phonemes. An attempt was made to identify the distinctive features of entire words and not just their constituent phonemes. This kind of speech recognition system would be capable of selecting a word from a limited lexicon. This scheme envisaged applications such as providing a command vocabulary for an astronaut maneuvering in space outside his vehicle, or, more generally, a command vocabulary for a computer.

5.5 Circadian Rhythms

Dr. Anil Phatak has begun a study of circadian rhythms, characterized by cycles which are present in a "constant" environment with an "almost" 24 hour period. The understanding of circadian rhythms is of interest not only from a scientific point of view, but also for several practical aerospace problems. To name but two, the jet transport pilot crossing many time zones each flight and the astronaut in a space capsule or on another body lose their normal endogenous synchronizer to a daily cycle.

In circadian rhythms the periodic environment only operates as a synchronizing agent which entrains an almost 24 hour period cycle to an exact 24 hour period. Any periodic environmental agent which serves to entrain a circadian periodicity has been termed a "Zietgeber".

Models developed to explain circadian phenomenon have primarily used variations of the Vander Pol equation with a forcing function of the form:

$$\ddot{y} + f(y)\dot{y} + g(y)y = h(x,\dot{x},\dot{x})$$

where y(t) is the variable whose periodicity is being monitored and x(t) is the environmental entraining agent.

The mathematical analysis goes into determining the nature of self-sustained oscillations and the frequency of entrainment. Effects of input intensity have also been studied.

The principal criticism of these models is that even though they explain qualitatively the general phenomenon of entrainment of a non-linear oscillator by an external forcing function there is no attempt to compare model predictions with actual data quantitatively. Also the model is a black box equivalent to a multivariable physiological system - hence any insight into the underlying biological mechanism is hard to achieve.

Unfortunately, too much effort in the past has gone into studying and analyzing circadian rhythms of behavioral variables such as running activity of rats and macro variables such as temperature. It would be more valuable to study the periodicities of a group of variables in a given metabolic activity as has been done of late on the effects of light on the contents of the Pineal gland in rats. Also the effects of food intake on rhythms has not received as much attention as it deserves.

VI. NEUROMUSCULAR AND POSTURAL CONTROL

6.1 Balance Reflex Experiments

We have for some time performed experiments on and analyzed manual control situations in which a man stabilizes a vehicle using combinations of visual, tactile, and vestibular cues. We have turned to a study of man's stabilization of his own body based on these same cues, but using his own musculature to provide the appropriate torques. The doctoral thesis work of Lewis M. Nashner in this field is described at length in a separate progress report under NASA Grant 22-009-025, June 1969. To summarize briefly, Mr. Nashner's thesis seeks to define a model which consistently describes posture control responses in human subjects, considering primarily control actions about the ankle joints. Particular emphasis will be placed on:

1. determining the basic sensory-motor feedback loops and their properties
2. describing the modes of interaction among these feedback loops and describing how they adapt to disturbances and varied posture control tasks
3. suggesting possible correlations between the resulting model and the actual physiology

The research will be primarily experimental. A platform, capable of measuring posture responses and initiating probes and disturbances, will be used to observe human subjects under varied posture control tasks. Analytical techniques will be developed to determine the sources of the measured responses and to begin to define the properties of the sensory feedback loops.

In order to explore the physiological modes of controlling posture, the experiments will observe both normal subjects and those with pathologies affecting posture control. As an important product of the research, applications of the results to clinical diagnosis and treatment of these pathologies will be considered.

6.2 Neuromuscular Models

It has become increasingly evident that many problems of theoretical and practical interest in manual control and manipulation require a fuller understanding of the control characteristics of the human neuromuscular system in tracking tasks. We are interested particularly in the dual role of postural control (regulation against disturbances) and closed loop manual tracking tasks. John Allum has been devoting his efforts to improvements of the neuromuscular models consistent with the known physiological data.

Neuromuscular physiology was extensively investigated in order to analyze critically past efforts in neuromuscular modeling and provide a basis for extending the work of the Man-Vehicle Laboratory in this area. The emphasis in the present work is to describe the peripheral motor system in its:

1. general structure,
2. modes of adaptation within the general structure,
3. control loops activated by higher level commands,
4. criteria by which control is allocated among the control loops.

The area of the model is constrained to be inclusive of the motoneuron pool in the spinal column and peripheral to it; that is, the muscle system. The model control loops are closely related to the function of actual nervous tracts.

A major purpose of the model will be to provide a control analog for human tracking responses and responses to transient inputs during tracking. The model will, it is hoped, provide valuable insights into the functional significance of motor system nervous tracts.

The model has been defined with three types of control patterned by switching operations in the motoneuron pool. These control modes are:

1. a quasi-linear stage, corresponding to a minor tracking error reduction phase,

2. an adaptation among quasi-linear phases,

3. a non-linear phase representing control in cases of large random excursions of the musculature.

The object of the current research is to determine how the nervous system uses incoming sensory signals from limbs and the visual system to structure its commands to spinal reflex centers for each of the three control modes defined above.

The components considered in a simplified model of neuromuscular dynamics consist of:

1. The force transducer - the extrafusal fibers, the limb and stick dynamics,

2. The muscle length, and a muscle length and muscle velocity feedback system - the muscle spindle system.

3. The muscle feedback system - the Golgi tendon organ feedback system.

4. The joint angle feedback system - joint proprioception,

5. A switching and gain setting area - the interneuronal and Renshaw cells in the spinal cord.

Allum has postulated a new model of the muscle spindle which he intends to simulate and test its sensitivity to model parameters given in the literature. A series of human tracking experiments for the "critical task" $[k/(s-\lambda)]$ are planned using free, restrained and force sticks. In addition to the normal tracking of the pseudo-random signal, the sticks will be subject to pseudo-random signal, the sticks will be subject to pseudo-random pertubations in position or force. It is hoped to obtain the postural reaction parameters of the arm in a situation of active tracking by these experiments.

6.3 Extravehicular Stabilization From Postural Signals

The variety of postural control signals which have been proposed for use in a free and "natural" attitude control system for extravehicular activity have been reviewed in connection with our life support work. L. C. Von Renner has been studying one particular new concept for attitude stabilization and control of an astronaut outside his space vehicle. Experiments are currently in progress to determine the feasibility of using the astronaut's head motion as an actuator for a portable attitude control system. The concept for this system stems from our work on the human vestibular system and space orientation, in which it is clear that all the postural control loops act to stabilize the head and body in space. Thus a system which would drive the astronaut's trunk to a given position with respect to his head should be quite satisfactory. The astronaut could command a turn by turning his head in the desired direction.

Two approaches to this "head tracking" EVA attitude control system are being considered. The first relies upon the voluntary muscle contraction in the neck corresponding to head movement. Muscle activity detected by surface electrodes yields an electromyogram of the type used in prosthetic devices to achieve more natural input response characteristics for an amputee. We are currently studying electromyogram processing and have been filtering the records on our hybrid computer. We plan to experiment with control of pseudo-random disturbances, first in a fixed base experiment and then using our moving base simulators to approach the EVA situation with the exception of weightlessness. The principal problems in this approach are the separation of neck muscle recordings into roughly uncoupled pairs and the choice of the control mode among proportional, rate or some combination thereof. The second approach is the direct measurement of head movements with respect to the neck using potentiometers or resolvers linked to the helmet. This system is obviously feasible but would have the disadvantage of requiring additional hardware.

VII. LIFE SUPPORT IN UNUSUAL ENVIRONMENTS

Under a separate grant, (NGR 22-009-312), the Man-Vehicle Laboratory has been studying a number of life support projects, emphasizing those promising areas of biotechnology which are appropriate for future university research projects. During this past year a summary of the research needs in the area of radiation and magnetic field effects on the nervous system was produced (Man-Vehicle Laboratory Report MVLS 69-1). The other areas which received considerable attention are trace contaminant monitoring, extravehicular propulsion, water reclamation, and particularly regenerative atmospheric control systems. The status of these reports is reviewed in MVLS 69-2, the February 1969 status report on the above grant. Of these areas it is only the project on extravehicular propulsion which ties in very closely to the dynamic space orientation work which is the major theme of this grant.

VIII. MEDICAL APPLICATIONS

It is inevitable that in a close cooperation among engineers and life scientists, particularly in problems of understanding human behavior, that medical problems and medical applications of our research appear regularly. We have been encouraged both to examine the direct medical applications of our NASA research and to explore some new clinical areas.

8.1 Electromyogram Processing and Photographic Displays for Orthopedic Surgeons

The application of hybrid computer displays in clinical studies has been investigated. Specifically, in the study of pathological movements, the orthopedic surgeon requires accurate information on limb movements and associated muscular activities (EMG's). With this in mind it is thought useful to provide the surgeon with a film of the subject's limb with a measure of EMG superimposed directly over each muscle of interest, in each frame of the movie film. Thus for continuous viewing or frame-by-frame analysis, the surgeon can see exactly which muscle group is active at every phase of a complex motion such as walking, and decide upon appropriate remedies.

To achieve this result, Mrs. H. L. Galiana has worked out a three step process.

1. The subject is filmed, with a 16mm movie camera, while a signal synchronous with the frame rate and the EMG signals broadcast from a telemetry pack around his waist are

tape recorded.

2. The film of the subject is scanned to store on DEC Tape the relative positions of the muscles in each frame. This was done by projecting each frame onto the screen of an oscilloscope to cover an area 6x8cm, and with the aid of a joy stick and a contact switch and suitable hybrid programming (PDP-8/GPS-290T), storing each (x, y) coordinate on DEC Tape.

3. The hybrid computer system was programmed to generate a display of vertical vectors on the CRT, covering an area 6x8cm. The length of each vector is proportional to its associated full-wave-rectified/low-pass-filtered EMG (on the tape recorder) and its lower point is positioned according to the stored coordinates on DEC Tape. The choice of coordinates and EMG analysis are synchronized in time using the frame sync signal on the tape recorder. Simultaneously, the changing display is recorded on film with the 16mm camera, where the camera sync now triggers the beginning of each displayed frame, at the same frame rate as in step 1.

The films of the subject and display are sent to a photographic laboratory for superimposition, to produce a film of synchronized data and movement. We are working in collaboration with Dr. Donald Peirce of the Massachusetts General Hospital in evaluation of this technique.

8.2 Postural Control Diagnostics for Neurology

The efforts of L. Nashner to develop a model for nervous system processing of information and adaptation involved in postural control has been discussed above. Once having achieved a model for normals in the simple task of control about the ankle joint, it will of course be of considerable interest to observe the variations of the model parameters in patients with various neurological diseases. We also plan to investigate the effect on the postural control system measured by our compliant servo-driven platform of remaining visual or vestibular sensory modalities.

8.3 Diagnosis of Diabetes Mellitus

In research sponsored principally by the National Institutes of Health, Dr. Anil Phatak has been investigating the etiology of the disease diabetes mellitus from the system theory point of view.

Diabetes is a disease characterized by a gradual deterioration of the endocrine apparatus that maintains glucose regulation. There are widespread biochemical abnormalities in metabolism but the fundamental defect to which most of the abnormalities can be traced is an impairment of the mechanism which controls the rate of insulin release and synthesis by the beta cells of the pancreas. The key features of insulin deficiency are:

1. decreased peripheral utilization of glucose and
2. increased hepatic gluconeogenesis and glycogenolysis (or decreased net hepatic uptake of glucose)

The resulting symptoms are hyperglycemia, polyuria, polydipsia, weight loss despite polyphagia, glycosuria, ketosis, acidosis, coma and eventual death. The only way to reverse this trend known at the present time is the administration of exogenous insulin.

Both oral and intravenous glucose tolerance tests indicate that the principal difference between normal and diabetic subjects is in their pancreatic beta cells -- that normal cells respond instantly to a glycemic stimulus, whereas diabetic cells react sluggishly. Thus diabetes mellitus is fundamentally the result of deficient insulin secretion, but one of rate rather than magnitude in the initial stage of the disease. Early diabetes progressively becomes worse over the years and results in chronic diabetes where the endogenous source of insulin gets depleted.

If diabetes is detected at an early stage, then it can be controlled by treatment with exogenous insulin. In recent years it has been suggested that in a hereditary disease like diabetes mellitus, the manifest stage of the disorder ought to be preceeded by a phase unrevealed by the conventional oral or intravenous glucose tolerance tests. This"silent" stage which covers the period from birth to the moment when intolerance to glucose can be demonstrated, has been termed "prediabetes" or "diabetes premellitus".

Recently a new type of glucose tolerance test called the glucose infusion test (GIT) has been developed in which a prolonged glucose infusion rather than a single dose of glucose is given to sustain a more or less constant hyperglycemia in order to stimulate the beta cells strongly. This was based on the general principle in clinical endocrinology that decreased or impaired secretory capacity of a gland is best demonstrated if the gland is heavily stimulated and in the case of the pancreas this stimulus is obviously glucose. Using this procedure it was demonstrated that diabetes had a slow, delayed and decreased insulin response to glucose infusion in contrast to the rapid and marked response in most of the healthy subjects. However, a small number of the latter with a normal intravenous glucose tolerance had an insulin response similar to that of the diabetic subjects. It was therefore suggested that these apparently healthy subjects might be prediabetics.

A computer model has been built at the Research Institute of National Defense, Stockholm, to model the glucose-insulin relationship in a glucose infusion test. A change in certain dynamic parameters from the normal ranges is used as an indicator of prediabetes. The model, however, is not physiologic in detail; hence, any predictions using such a model must be interpreted with care. The model is obtained by making analytic assumptions on the form of the dynamics of the pancreas, hepatic uptake, glucosuria, etc., and making a least-squares fit to data.

A major criticism of all the three glucose tolerance tests is that they are no more than physiologic equivalents of black box model concepts. One may be able to design many such tests which show significant differences in response between normal and diabetic subjects; however, no insight is gained in the physiological apparatus and its imbalance that causes diabetes mellitus. Also the emphasis in all these studies is, perhaps rightly so, on the single hypoglycemic-hormone insulin. The remaining hyperglycemic hormones namely, growth hormone, glucagon, epinephrine, corticosteroids and thyroid hormone have been neglected, with the exception of some studies on insulin-growth relationship. (No mention has been made here of proinsulin, the precursor to insulin as that opens up a whole new set of questions. Any detailed study of the etiology and pathogenesis of diabetes mellitus cannot ignore this aspect.) Recently a theoretical framework of a non-linear model for glucose regulation incorporating six hormones and carbohydrate, protein and fat metabolism has been proposed.

In Dr. Phatak's opinion such a task is ultimately desirable and worth attempting experimentally. Unfortunately, with the present state of the art in measuring physiological variables one is forced to study simpler though constrained models. It would be desirable to quantify the differences between insulin responses to oral versus intravenous glucose inputs and the reasons therefore, such as the presence or absence of enteric hormones such as "gut" glucagon. Above all it would be interesting to experiment with perfused pancreas and try to model the dynamics of insulin synthesis and release to glucose stimulus. If one insists on continuing with the glucose tolerance tests then the use of manual or automatic feedback control techniques should be made to give a repeatable and known glucose input at the plasma glucose level, such as a step or ramp change in plasma glucose. One may then be able to use existing control theory background for system identification.

8.4 Vestibular Diagnostics

With the addition of neurologist Dr. Alfred Weiss to the laboratory staff, we expect to apply some of our vestibular testing procedures to the problem of diagnosing vestibular disorders. In particular, we would like to concentrate on the use of "physiological stimuli" available by any variety of motions in our several moving base simulators, to augment and in some cases supplant the caloric tests which are frequently used.

IX. PUBLICATIONS AND THESES OF THE MAN-VEHICLE LABORATORY, 1968-69

1. Dinsdale, P. B., "Relative Effects of Roll and Yaw Motion Cues in Manual Control," S.M. Thesis, M.I.T., September 1968

2. Forster, J. D., "A Stochastic Revised Sampled Data Model for Eye Tracking Movements," S.M. Thesis, M.I.T., June 1968

3. Li, Y. T., "Digital Controller for Feedback and Adaptive Control Systems," in press

4. Meiry, J. L., "Skill Organization and Human Learning Behavior," presented at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, USSR, Sept. 1968

5. Meiry, J. L., "Stochastic Modelling of Human Learning Behavior," IEEE Trans. on Man-Machine Systems, June 1968

6. Noggle, P. L., "Manual Control of Unstable Vehicles Using Kinesthetic Cues," Engineer Thesis,March 1969

7. Oman, C. M., "Influence of Adaptation on the Human Semi-circular Canals and the Role of Subjective Angular Velocity Cues in Spatial Orientation," S.M. Thesis, M.I.T., September 1968

8. Shirley, R. S., and L. R. Young, "Motion Cues in Man-Vehicle Control," IEEE Trans. on Man-Machine Systems, December 1968

9. Vircks, R. M., "Investigation of Head Movement and Intensity as Depth Cues in a Perspective Contact Analog Display," S.M. Thesis, September 1968

10. Young, L. R., Dinsdale P., "Contributions of Roll and Yaw Motion Cues in Manual Control," 5th Annual NASA-Univ. Conf. on Manual Control, M.I.T., March 1969

11. Young, L. R., "A Control Model of the Vestibular System," presented at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, USSR, September 1968

12. Young, L. R., "The Current Status of Vestibular Models," Automatica, Vol. 5, Pergamon Press, Great Britain, (in press)

13. Young, L. R., "Functions of the Vestibular System in Human Guidance and Control," AGARD Bionics Symposium, Brussels, Belgium, September 1968

14. Young, L. R., and Oman, C. M., "A Model for Vestibular Adaptation," presented at the 4th Symposium on the Role of the Vestibular Organs in Space Exploration, Pensacola, Florida, September 1968; Aerospace Medicine, (in press 1969)

15. Young, L. R., "Motion Cues and Vestibular Models," presented at NEREM 68 in November 1968

16. Young, L. R., "Recording Eye Position," chapter for McGraw Hill Book Co., to appear in Medical Electronics and Engineering

17. Young, L. R., and J. L. Meiry, "A Revised Dynamic Otolith Model," Aerospace Medicine, Vol. 39, No. 6, June 1968

18. Young, L. R., C. Oman, R. Vircks, N. Van Houtte, and G. Kemp, "Three Display Techniques at the Man-Vehicle Laboratory," 5th Annual NASA-University Conference on Manual Control, M.I.T., March 1969

19. Young, L. R., "Vestibular Models," presented at 1969 Joint Automatic Control Conference, University of Colorado, August 1969

X. FACILITIES

Three major research facilities were added during this year:

A general purpose experimental apparatus for studies of postural control was designed and built. This device permits simulation of any type of active or passive restraint against the feet while measurements of ankle angle, torque, and muscle activity are recorded.

A Link GAT-1 moving base flight simulator was purchased and is being integrated with our hybrid computer to permit three axis angular motion simulation of any vehicle. It will be used for control and display evaluation, manual control, and vestibular testing, and complements our existing simulators.

We have been using the Adage AGT-30 Computer Graphics Terminal in the Electronic Systems Laboratory for VTOL display research. We plan to install a remote console to permit "flying" the displays in the simulators in our laboratory.

Our hybrid computer system has been somewhat expanded.

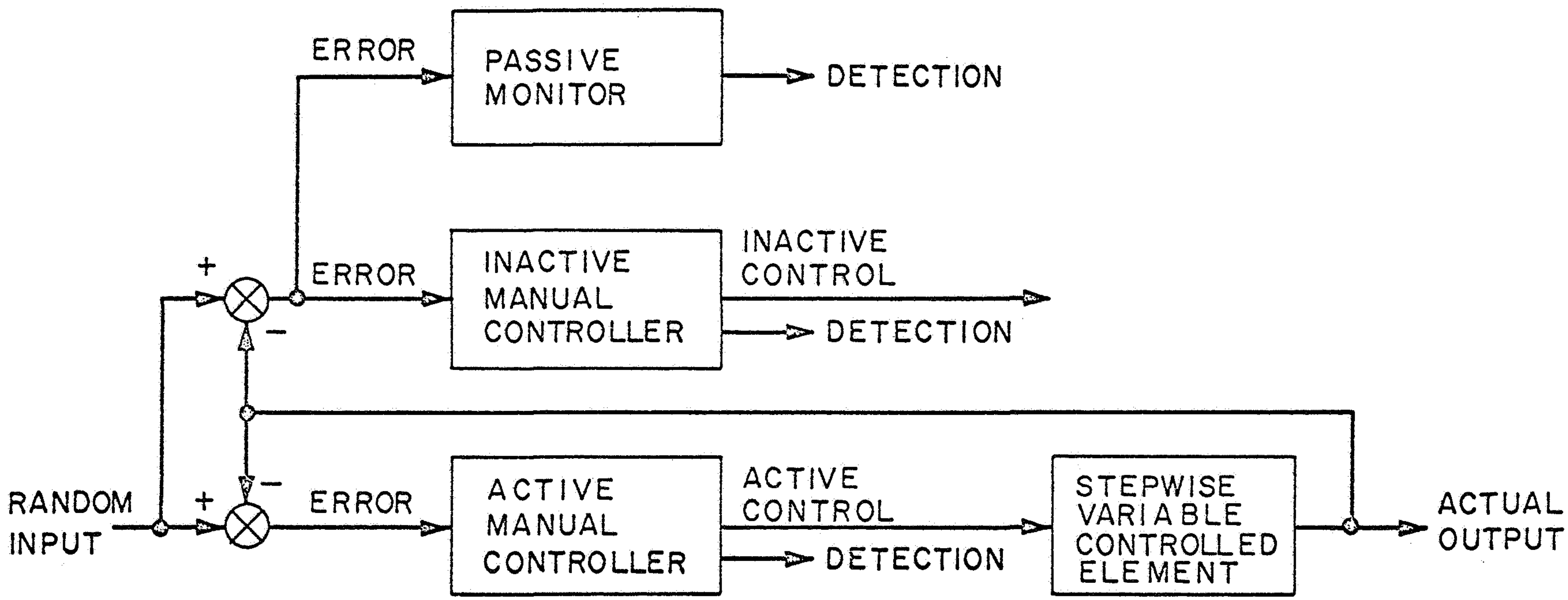


Figure 1. Experimental conditions for test of models for manual adaptive control.

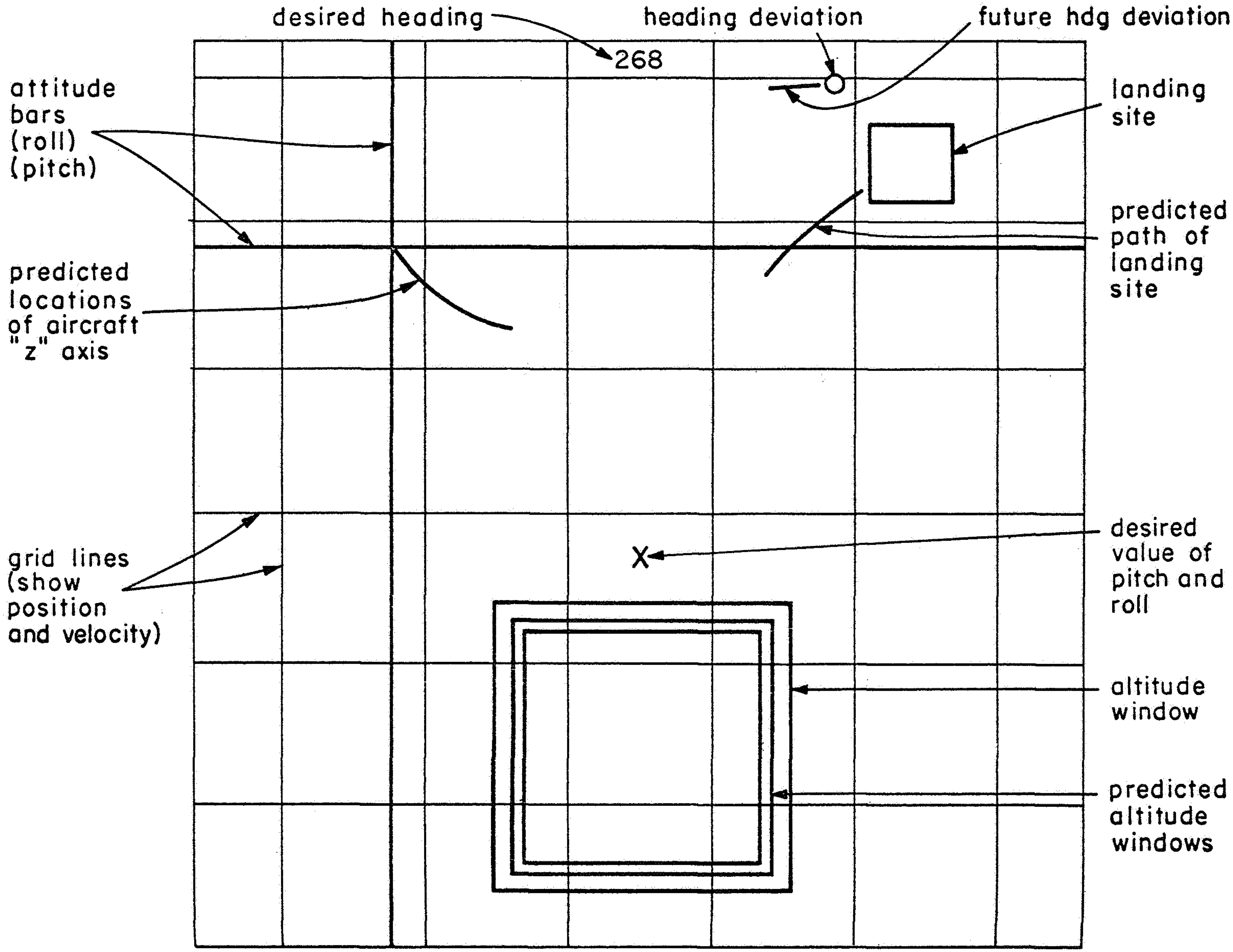
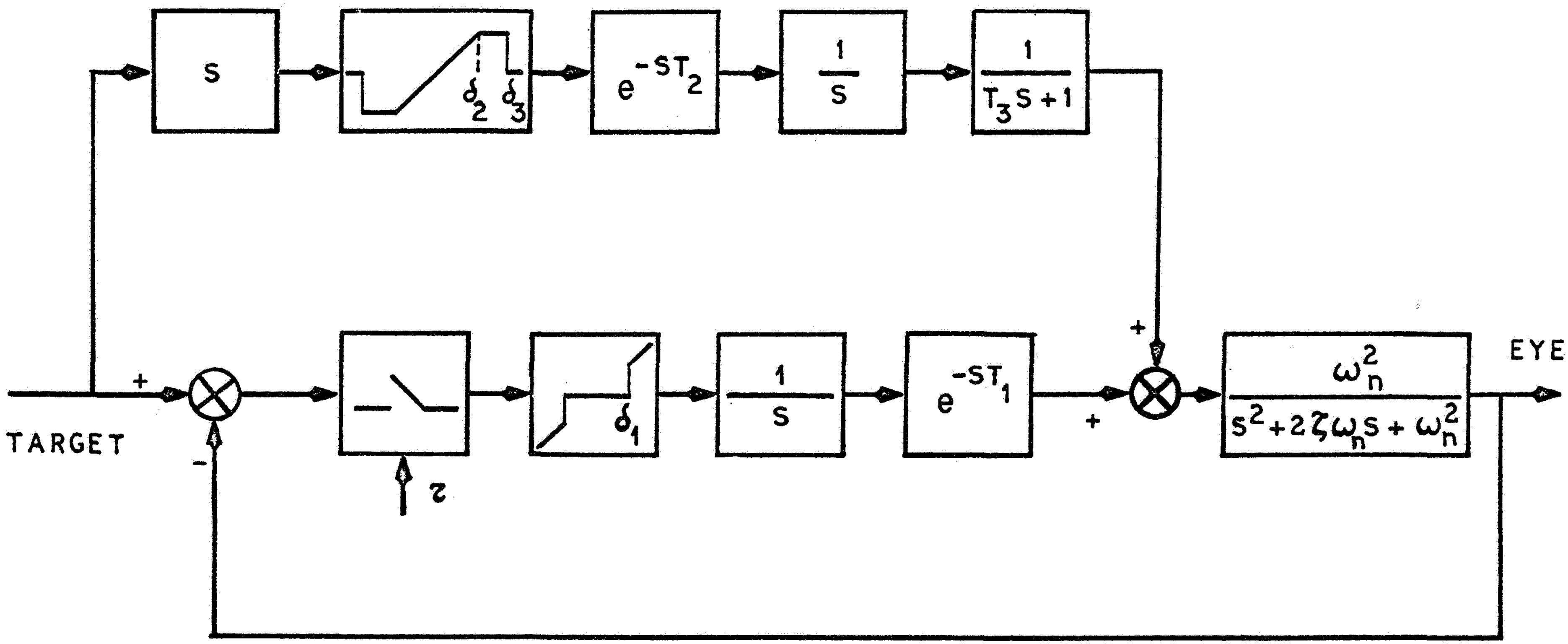


Figure 2 Proposed Display



SACCADIC DELAY	$T_1 = 150$ ms	DEAD ZONE	$\delta_1 = .3$ deg	$\tau = 200$-240ms
PURSUIT DELAY	$T_2 = 134$ ms	SATURATION	$\delta_2 = 30$ deg/s	$\zeta = .7$
PURSUIT LAG	$T_3 = 40$ ms	CUTOFF	$\delta_3 = 100$ deg/s	$\omega_n = 120$ rad/s

Figure 3 Eye Tracking Movement Model