A
VESTIBULO-OCULAR REFLEX
DATA ACQUISITION
SYSTEM

by

NEIL JOSEPH KELLY

A thesis submitted to the
Faculty of Graduate Studies
of the
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ABSTRACT

The Vestibulo-Ocular Reflex (VOR) generates eye movements in response to head motion to keep an image fixed on the retina as the head moves. Researchers at the University of Manitoba required a system that could produce head movement and monitor the resulting eye position to continue investigation of VOR behavior.

This dissertation describes the design and construction of this system, the VOR Data Acquisition System (VORDAS).

The VORDAS consists of a computer controlled, motor driven, rotating chair and Electro-Oculogram (EOG) data collection system. The EOG is a recording of eye position made by sensing the corneal-retinal potential of the eye.

The VORDAS is capable of generating arbitrary chair velocities and recording one channel of EOG data. The chair has a top speed of 300 degrees/sec, and top acceleration of 300 degrees/sec/sec, for frequencies of dc to 0.5 Hz.

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I would like to acknowledge and thank EG&G Torque Systems for permission to reprint sections of their S-1201 Serial Input Module manual in this dissertation.

I would like to thank the Manitoba Health Research Council and the Natural Sciences and Engineering Research Council for their funding to support this project.

To my wife and children,

who have endured and sacrificed much for this work.

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GLOSSARY

General abbreviations used in this glossary are:

abbr	abbreviate(d); abbreviation
SI	International System of Units
wrt	with respect to

Acronyms and abbreviations used in this dissertation are:

aliasing the effect of creating non-existent frequencies caused by sampling a waveform at a rate lower than the Nyquist rate.

acceleration profile the angular acceleration wrt time of the subject over the duration of the run.

bit abbr of **b**inary dig**it**; a single binary digit, ie a "1" or a "0".

byte a binary number made up of 8 bits.

CW abbr of clockwise.

CCW abbr of counterclockwise.

D/A acronym of **D**igital to **A**nalog.

DAC acronym of **D**igital to **A**nalog **C**onverter.

EDAC acronym of **E**OG **D**ata **A**cquisition **C**ontroller.

EOG acronym of **E**lectro-**O**culo**g**ram; **E**lectro-**O**culo**g**raphy. Recording of eye position made by sensing the corneal-retinal potential of the eye.

EPROM acronym of **E**rasable **P**rogrammable **R**ead-**O**nly **M**emory. A computer memory device that can be programmed with electric pulses, retains its information without power, and can be erased by exposure to ultraviolet light.

FIFO acronym of **F**irst-**I**n-**F**irst-**O**ut. A FIFO is a memory device used to store data similar to a stack. When read, the FIFO outputs the first datum it received.

Hz abbr of cycles per second.

k abbr of SI kilo-. Represents 10^3.

K abbr in computer terminology to represent 2^{10}, or 1024 decimal.

latch a device that maintains an output signal after the input signal has changed or disappeared.

m abbr of SI milli-. Represents 10^{-3}.

M abbr in computer terminology to represent 2^{20}, or 1048576 decimal.

MIT acronym of **M**assachusetts **I**nstitute of **T**echnology.

PIA acronym of **P**eripheral **I**nterface **A**dapter. An 8 bit programmable interface device manufactured by Motorola Semiconductors. An 8 bit interface to a microprocessor's data bus, the PIA's input output characteristics are determined by the way it is programmed.

PLA acronym of **P**hase **L**ock **A**dvance. A term used by EG&G Torque Systems to identify the input of their S-1201 position controller that accepts digital pulses that each cause the motor being controlled to advance one position unit.

PPI acronym of **P**arallel **P**eripheral **I**nterface. An 8 bit programmable interface device manufactured by Intel. See PIA above.

PWM acronym of **P**ulse **W**idth **M**odulation.

quadrature a term meaning 90 degrees out of phase.

real time a computer term used to indicate that a computer must complete its task within a specified period of time. An example is a computer being supplied with data once every second. If the computer is busy when the data is supplied to it, the data is lost.

RAM acronym of **R**andom **A**ccess **M**emory. General use memory of a computer. It can be programmed and erased electrically, but loses the information stored in it when power is turned off.

researcher the person operating the VORDAS.

RPM acronym of **R**evolutions **P**er **M**inute.

run or **examination run** the period of time when the chair is in motion.

servo controller a device used to control the velocity of a servo motor. It is also referred to as servo amplifier or servo drive.

servo motor an electric motor designed to generate high accelerations.

subject the person being examined.

tachogenerator a linear device that generates an output voltage proportional to its angular velocity.

μ abbr of SI micro-. Represents 10^{-6}.

velocity profile the angular velocity of the subject wrt time over the duration of the run (spelled with lower case letters).

Velocity Profile the disk file storing the data to control the VORDAS during the run (spelled with capital letters).

VOR acronym of **V**estibulo-**O**cular **R**eflex. The VOR changes eye position in response to head motion to keep an image fixed on the retina.

VORDAS acronym of **VOR** **D**ata **A**cquisition **S**ystem, the subject of this thesis and dissertation.

Chapter 1

INTRODUCTION

1.1 Objective

The objective of this thesis was to design and build a system to record a human subject's eye position in the horizontal plane as the subject's head experiences angular acceleration about the vertical axis. The system was to consist of a computer controlled, motor driven, rotating examination chair and an Electro-Oculogram (EOG) data acquisition system. The EOG is a recording of eye position made by sensing the corneal-retinal potential of the eye [1].

1.2 Background

Doctors Ireland, Jell, Onyshko, and Shwedyk of the University of Manitoba are conducting ongoing research to develop a more accurate mathematical model of the human Vestibulo-Ocular Reflex (VOR) system. The goals of the research are to advance the knowledge of the function of the human VOR and, ultimately, to develop a clinical tool for non-invasive diagnosis of VOR system dysfunction.

The Vestibulo-Ocular reflex, literally meaning the Ear-Eye reflex, is generated by the VOR system which consists of the semi-circular canals of the inner ear, neural pathways in the brain, and the eye muscles. The function of the VOR is to keep an image fixed at the center of the retina as the head moves [2]. It is the VOR that makes it possible for objects to be seen unblurred when driving over a bumpy road.

The dual pathway model of the VOR reported by Arbez [3] was developed at the University of Manitoba largely using parameters from existing literature. For the most part the parameters in the existing literature were based on data from animal experiments. They were modified to reflect the results of rotational tests done using a clinical chair at the Health Sciences Center in Winnipeg, Manitoba, but the limited capabilities of that examination chair prevented further research.

More accurate determination of the model parameters requires human EOG data obtained in response to a wider range and greater variety of inputs than were possible with the clinical chair available to the the University [4]. Therefore, to continue the research it was necessary to design and build the VOR Data Acquisition System (VORDAS).

This thesis set out to achieve the VORDAS specifications listed in Table 1. The original specifications for maximum acceleration and velocity, stated in the Manitoba Health Research Council proposal [4], were 200 degrees/sec^2 and 255 degrees/sec respectively. The target values of these two parameters were increased to 300 degrees/sec^2 and 300 degrees/sec respectively to maximize the range of input stimuli the VORDAS could produce.

1.3 Outline Of Dissertation

This dissertation describes the design and construction of the VOR Data Acquisition System defined by the specifications in Table 1. A detailed description of the theory, design and equipment of the VORDAS required so much space it could not all be included in this dissertation. Therefore, this dissertation is an overview of the work done and the results achieved.

The detailed technical information of the VORDAS, including circuit diagrams, device specifications, flowcharts, and software listings, are contained in two University of Manitoba Department of Electrical Engineering reports. These reports are the VORDAS Hardware Manual, Report Number 88-1 and the VORDAS Software Manual, Report Number 88-2. These manuals are listed in the bibliography for those readers interested in further detail.

TABLE 1

Specifications of the Vestibulo-Ocular Reflex Data Acquisition System

Rotation:

Acceleration	-Maximum acceleration of 300 deg/sec^2 and a resolution of 1 deg/sec^2. -Arbitrary acceleration profiles. -Sinusoidal profiles of 0.01 to 0.5 Hz. -Triangular profiles of 0.01 to 0.5 Hz. -Random disturbance with frequencies of 0.01 Hz to 0.50 Hz.
Velocity	-Maximum velocity of 300 deg/sec with a resolution of 1 deg/sec.

Trim:

Pitch	-Fixed velocity of 10 deg/sec from upright to supine.
Vertical	-Fixed velocity of 3 in/sec over a 20 inch range.
Head tilt	-Fixed velocity of 10 deg/sec over a 50 degree range.

Safety features:

-Hardware acceleration limit at 400 deg/sec^2.
-Hardware velocity limit at 330 deg/sec.
-Software limits on velocity and acceleration.
-Pressure mats for proximity detection.
-Operator/subject "panic" buttons.
-Hardware interlocking of chair motion.

Data acquisition:

-Able to digitize and store EOG data from the test run on floppy disk.

The body of this dissertation describes the work done during this thesis in the following order:

1) An overview of the VORDAS.
2) A discussion of the VORDAS hardware and its considerations.
3) A discussion of the VORDAS software and its considerations.
4) A discussion of the theory of the rotation control system. This discussion focuses on the key parameters and considerations that effect the operation and selection of the system. The discussion was not included in the description of the VORDAS hardware because it is somewhat involved and would constitute a confusing digression that would make it difficult for the reader to follow the interconnections of the system hardware.
5) The results of this study.
6) Recommendations.

The reader should be aware that the material in this dissertation was arranged so that its presentation would be easy to follow and understand and does not necessarily reflect actual chronological progression of the work done.

A discussion of the EOG and of dipole generation has been included in appendix D for completeness.

Chapter 2

VORDAS SYSTEM OVERVIEW

A block diagram of the VORDAS is shown in Figure 1. It consists of a motor driven examination chair, a Velocity Control computer, EOG conditioning electronics, a Data Acquisition computer, a Main computer, and Emergency-stop (E-Stop) electronics.

The Examination Chair:

1) Is rotated by a dc servo motor through a right angle worm-gear transmission.
2) Has three ac motors that provide the trim functions of elevation, pitch, and head tilt.
3) Uses slip rings to get EOG data, control signals, and power to and from the chair.

The Velocity Control Computer:

1) Controls chair motion and EOG data collection during the run.
2) Monitors system status and sends status information to the Main computer.

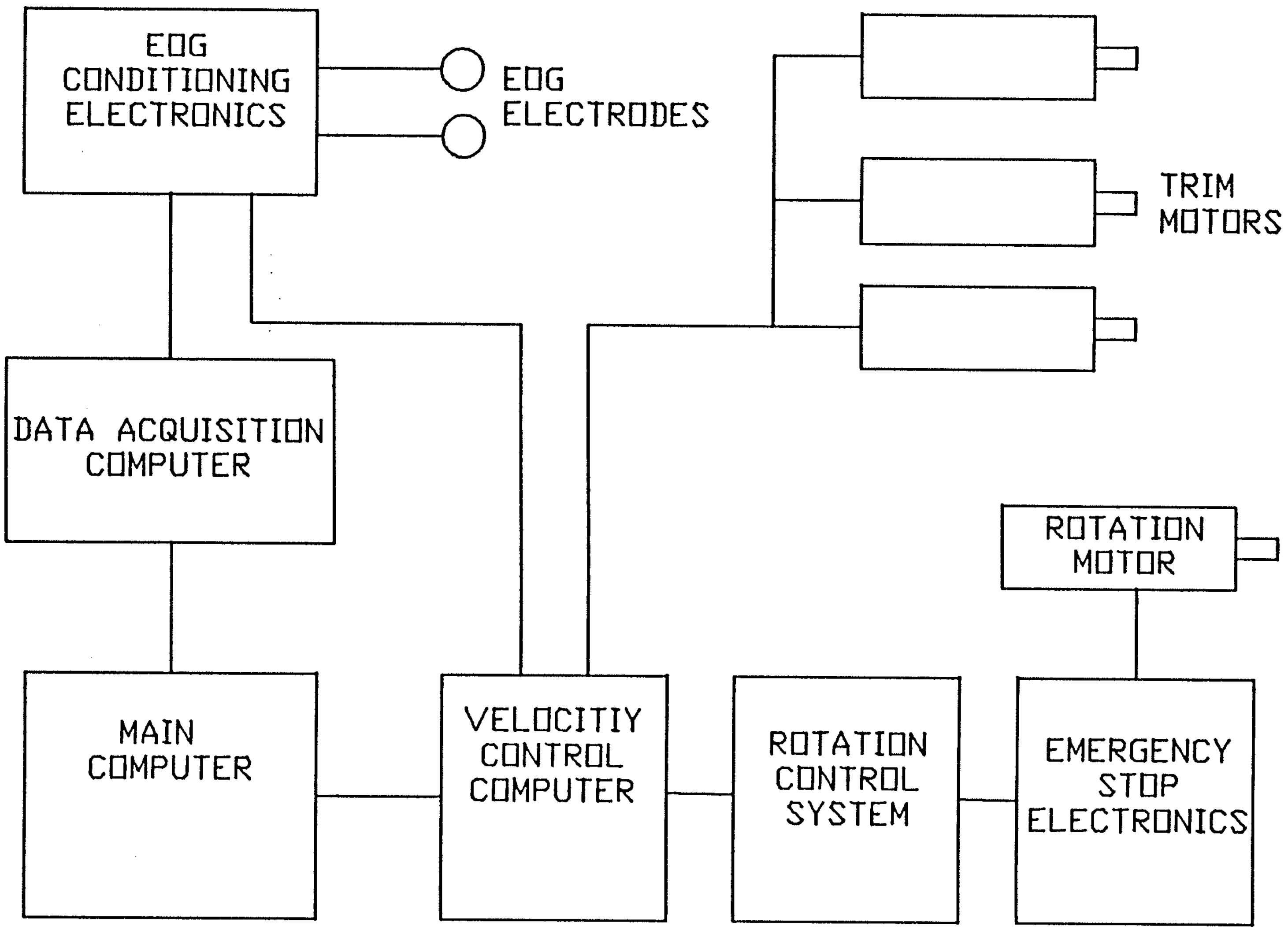

FIGURE 1: BLOCK DIAGRAM OF THE VORDAS.

The EOG Conditioning Electronics:

1) Amplify and filter the EOG signal.
2) Sample the analog EOG signal and convert it into a binary number for transmission to the Main computer.

The Data Acquisition Computer:

1) Controls wall mounted Light Emitting Diodes (LED's) to perform calibration samples of the subject's EOG.
2) Compacts and buffers EOG data.

The Main Computer:

1) Is used to create data files, called Velocity Profiles, from the mathematical description of the acceleration the researcher wants the subject to experience.
2) Allows the researcher to input commands.
3) Displays system status information to the researcher.
4) Sends the data needed to control the chair motion to the Velocity Control computer.
5) Stores the EOG data in a disk file for later use.

The E-Stop Electronics:

1) Detect emergency conditions.
2) Shut down the system in the event of an emergency.
3) Allow the system to be reset after an emergency.

Chapter 3

HARDWARE DESIGN

3.1 Chair/Frame

There were three main considerations in selecting a chair for the VORDAS. First, the chair had to have built-in motors capable of producing trim motions of elevation, pitch, and head tilt to the specifications in Table 1. Second, the chair had to weigh as little as possible to minimize the load inertia. Third the chair should have an open type of frame so that any changes or additions for subject safety, structural strength, and control would be easy to make.

Study of a similar system, designed and built at the Massachusetts Institute of Technology (MIT) and reported by Tole et al [5], led to the selection and use of an examination chair manufactured by Surgical Mechanical Research, Inc [6]. The SMR MAXI III weighs approximately 80 kg, and three constant speed ac motors provide the required trim functions. An AUTORETURN function activates the pitch and elevation motors to return the chair to an upright, unelevated position. Head tilt is not affected by the autoreturn function. Solid state relays, mounted on the base of the chair, allow computer control of the trim functions without audible mechanical relay noise.

Figure 2 shows the mounting arrangement of the chair. The chair is mounted so that, when the subject is sitting upright, the axis of rotation is approximately through the axis of the subject's spine where it intersects the skull. In this way the angular motion generated by the chair is the same as the motion generated by the subject turning his head from side to side. However, this mounting arrangement means that the subject experiences radial acceleration OUT of the chair rather than INTO the chair, a sensation that tends to be somewhat discomforting.

Restraints were added to insure that the subject would be both safe and able to relax comfortably during the run. The restraints consist of a lap belt, two shoulder belts. The lap and shoulder belts are three inches wide and fully adjustable for maximum comfort.

A subject panic button insures that a subject that feels uncomfortable can stop the run.

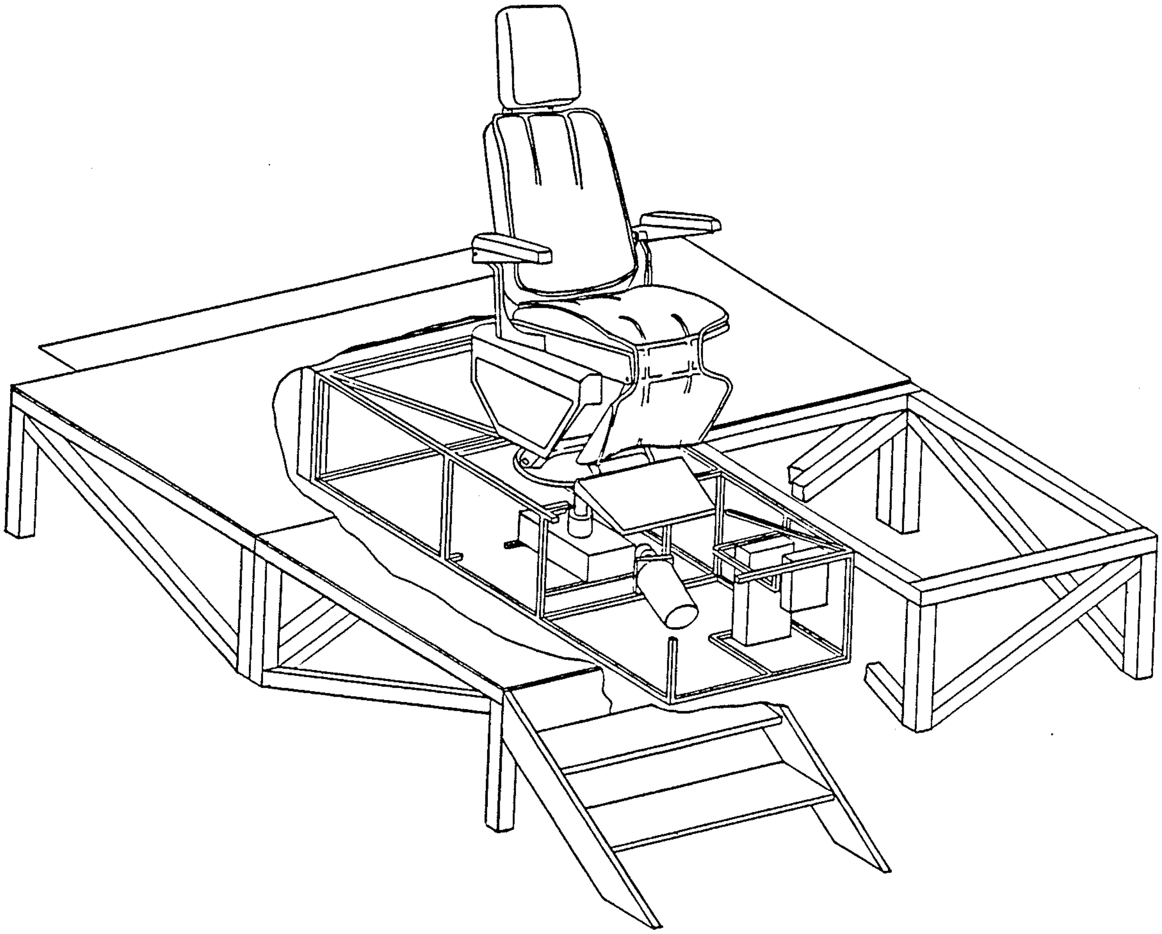

FIGURE 2: Chair mounting arrangement

The chair, and all of its drive components, are mounted on a movable frame in a sub-floor. The sub-floor was required to provide enough room under the chair for the drive components. Mounting the chair and drive components on a movable frame allows removal of the chair from the sub-floor for service. The frame has levelers at six points for support and leveling of the frame.

3.2 Drive Components

Chair rotation is provided by a dc servo motor through a torque limiting clutch and a transmission. Factors considered in selecting the components to drive the chair were:

1) All of the mechanical components must be smooth and quiet so that the subject would not have any external stimulus that could interfere with the normal VOR stimulus.
2) A right angle transmission should be used to minimize the overall height of the chair/drive combination.
3) The transmission should have little or no backlash because the feedback sensors are directly connected to the motor, not the chair.
4) The transmission should not have any belts in it that could stretch under acceleration.
5) There must be some way to stop the chair quickly, but in a controlled manner, in an emergency.
6) There must be some way of getting power, data, and control wiring to the chair.
7) There should be some device incorporated into the chair drive train to limit chair acceleration in the event of equipment failure.
8) The motor must be matched to the transmission to provide the torque required to accelerate the chair over the speeds of the dc motor.

A worm-gear transmission was selected for the VORDAS because:

1) Worm-gear transmissions can operate with zero backlash.
2) Worm-gear transmissions can be self-locking, that is, they cannot be driven from the gear side [7]. In practice even self-locking worm-gear transmissions can be driven from the gear side but doing so is very inefficient. This means that a self-locking worm-gear transmission will act as a brake if power is removed from the motor. Therefore, a quick, controlled stop can be effected in an emergency simply by disconnecting the power to the motor without the need to install any additional braking device.
3) Worm-gear transmissions are smooth and quiet.

The driven shaft of the transmission was bored to allow data and control cabling to be routed to the chair.

A low noise, multi-contact slip ring package mounted under the transmission was used to route data and control signals to the chair. Two power slip rings, mounted on the drive shaft above the transmission, provide 120 Vac power to the chair.

Slip rings are, at best, electrically noisy devices. At worst, dirt and contact surface imperfections can cause complete, momentary loss of the signal. Multi-contact slip rings help reduce and eliminate complete loss of signal, but noise is still present. For example, the signal slip ring package used in the VORDAS has a maximum noise level of 100 mV. This noise would become part of and corrupt analog signals transmitted through the slip rings. On the other hand digital signals will not be affected by the noise provided they have a high enough noise margin. One way to increase the noise margin of any digital signal is to increase its signal level. Therefore, to achieve maximum noise immunity, 12V digital signals are transmitted through the slip rings.

The motor is connected to the transmission through a mechanical torque limiting clutch to prevent high accelerations that could injure the subject. The clutch disconnects the motor from the transmission when the input torque is greater than the trip limit of the clutch. The trip limit is adjustable, and has been set to meet the specifications of Table 1. Note that the clutch does not cause the motor to shut down, and re-engages if and when the input torque drops below the trip limit of the clutch.

A dc servo motor was selected based on the chair inertia, the required maximum chair acceleration and the transmission gear ratio (14:1). The inertia of the chair and a 90 kg subject was reported by Tole et al [5] as 203.5 in-lb-sec^2. The maximum torque required to accelerate the chair and subject was calculated using this value. The torque calculations are shown in detail in Appendix B.

A servo motor was selected because servo motors are designed for higher acceleration rates than other types of motors.

Power is supplied to the motor through a contactor that is used to shut down the motor in an emergency. The contactor has normally open contacts and is energized through the Emergency-stop circuits. This technique insures any emergency, including a power failure, will reliably shut down the motor.

3.3 Rotation Motor Control Equipment

A rotation control system was required to power and control the rotation motor. The VORDAS rotation control system was patterned after a system used at MIT [5], consisting of a commercially available position control system and binary Bit Rate Multiplier (BRM).

BRM's are devices that accept a constant frequency digital pulse train and a number called the multiplier, and generate an output digital pulse train with a frequency proportional to the multiplier. A binary BRM accepts a binary multiplier, as opposed to a multiplier coded in some way such as Binary Coded Decimal (BCD).

For any motor attached to a fixed load, acceleration is proportional to the motor torque. For a dc motor, torque is proportional to armature current. Therefore, a current control system is needed to control the acceleration of the examination chair directly. Such systems are not common and do not have a high degree of accuracy.

An alternative is to use a velocity control system. Velocity control systems for dc motors are common and fairly accurate. Typical systems require an analog input voltage as a velocity reference signal and use a tachogenerator connected to the motor for a velocity feedback signal. Velocity accuracy of 1% is common.

Since acceleration is the time rate of change of velocity, a velocity control system generates acceleration in response to a time-varying analog voltage.

A third way of controlling acceleration is to use a position control system. Position control systems are easily connected to computers because they accept digital pulses as their input. They are also very accurate, with velocity accuracy of 0.1% being common.

A typical position control system block diagram is shown in Figure 3. It has both velocity and position feedback loops. The velocity loop is not apparent to any external device, but requires a tachogenerator attached to the motor for velocity feedback. Feedback for the position loop is typically provided by a two-channel quadrature optical encoder attached to the motor. Use of a quadrature (in which each channel is 90 degrees out of phase with the other) encoder allows the position control system to determine motor direction as well as position. Inputs to the position control system are a direction bit and an advance bit. Each advance pulse sent to the control system causes the motor to rotate until the control system receives a corresponding pulse from the optical encoder.

Each pulse received by the position control system causes the motor to move a fixed angular distance, determined by the resolution of the encoder. Therefore a constant frequency digital pulse train causes the motor to rotate at a constant angular velocity proportional to the pulse train frequency. Specifically, the motor would rotate at a constant angular velocity given by:

$$V=360*(f/N) \text{ deg/sec} \qquad 1)$$

f = frequency of the advance pulse train, in Hz.

N = number of pulses required for one revolution of the motor, in pulses/revolution. Note that in many systems N is the number of lines of the encoder.

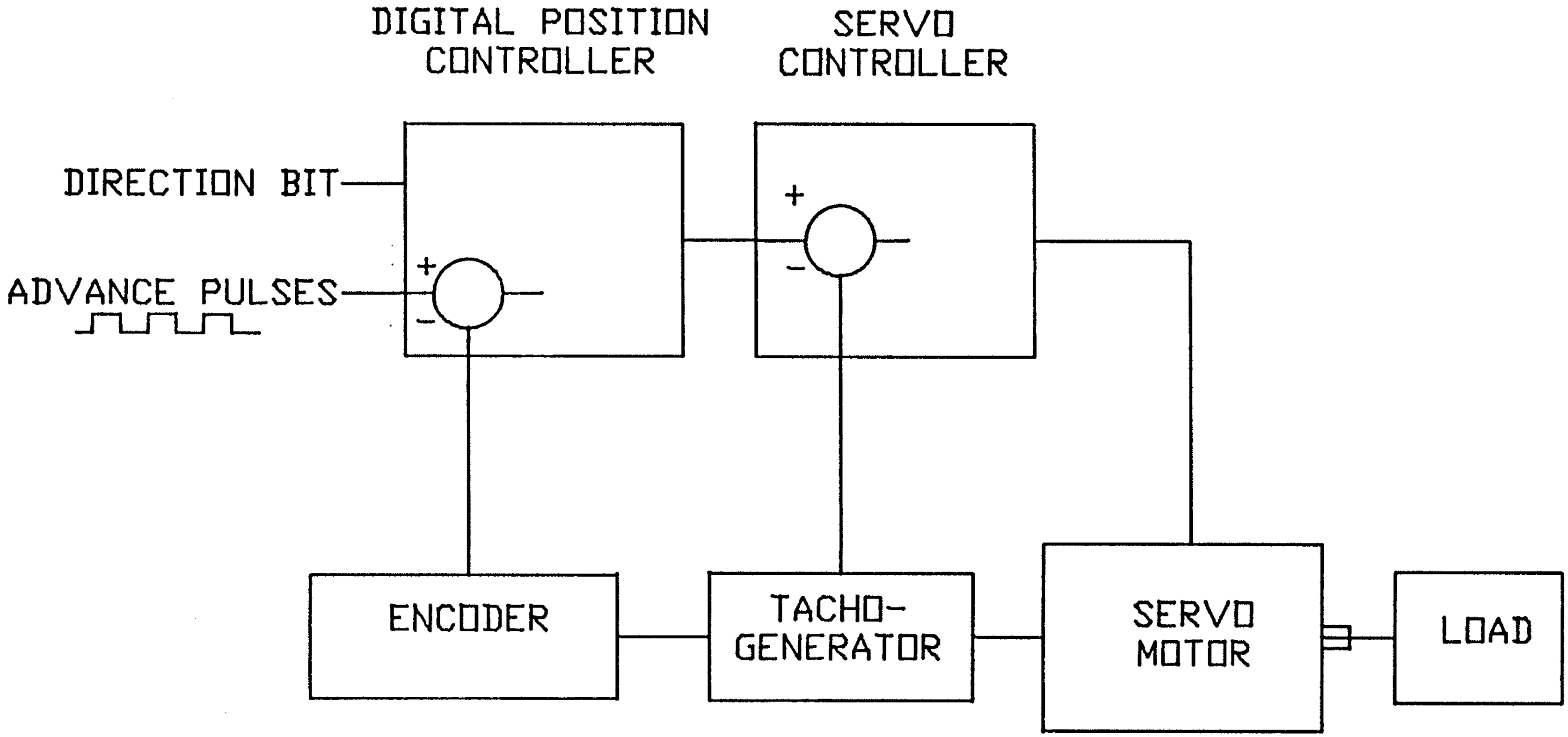

FIGURE 3: BLOCK DIAGRAM OF TYPICAL POSITION CONTROL SYSTEM.

Acceleration is the time rate of change of velocity. Therefore a position control system generates acceleration in response to a digital pulse train with a time-varying frequency.

This technique was chosen for the VORDAS because it is accurate and simple to interface to a computer system. A binary BRM generates the digital pulse train which is sent to a commercially available position control system. The BRM's used in the VORDAS have the following relationship:

$$f = f_0 * M / 120 \quad \text{Hz} \qquad 2)$$

where: f_0 = a constant frequency input, selected by the circuit designer, in Hz.

f = is the output frequency, in Hz.

M = is the multiplier, a 9 bit binary number.

Using 1) and 2), f_0 was calculated such that an input multiplier value of M would result in an actual chair velocity of M degrees/sec. A 9 bit multiplier was chosen to allow a one degree/sec velocity resolution.

It is impossible for a computer to generate a number that is continuously changing with time. All a computer can do is send a number to the BRM then, some time later, send another number; and continue to do so until the run is complete. Therefore, to generate these numbers the continuous velocity function of the chair must be sampled periodically with time. This requires that a sampling rate be chosen, and that the same sampling rate be used to sample the continuous velocity function and to update the numbers sent to the BRM.

The Nyquist criterion states that the highest frequency component of a sampled function that can be reproduced is one half the frequency used to sample the function. Therefore, in selecting a sampling rate, consideration must be given to the frequency of the velocity signal to the chair, and the frequency response of the position control system as well as the control of any other chair functions.

Theoretical analysis showed that the bandwidth of the position control system was the limiting factor in selecting the upper frequency limit. However, a sampling rate several times higher than the Nyquist rate required for the position control system was selected to provide better control of the trim functions than would be possible with lower sampling rates. This is discussed in greater detail in the sections dealing with the design considerations of the position control system and the design of the Velocity Control computer software.

3.4 EOG Conditioning Electronics

The EOG conditioning electronics consist of an EOG amplifier and an analog to digital (A/D) converter. Together they amplify and digitize the subject's EOG signal so that it can be transmitted through the slip rings and stored by the Main computer. Figure 4 shows a block diagram of the EOG Conditioning Circuits.

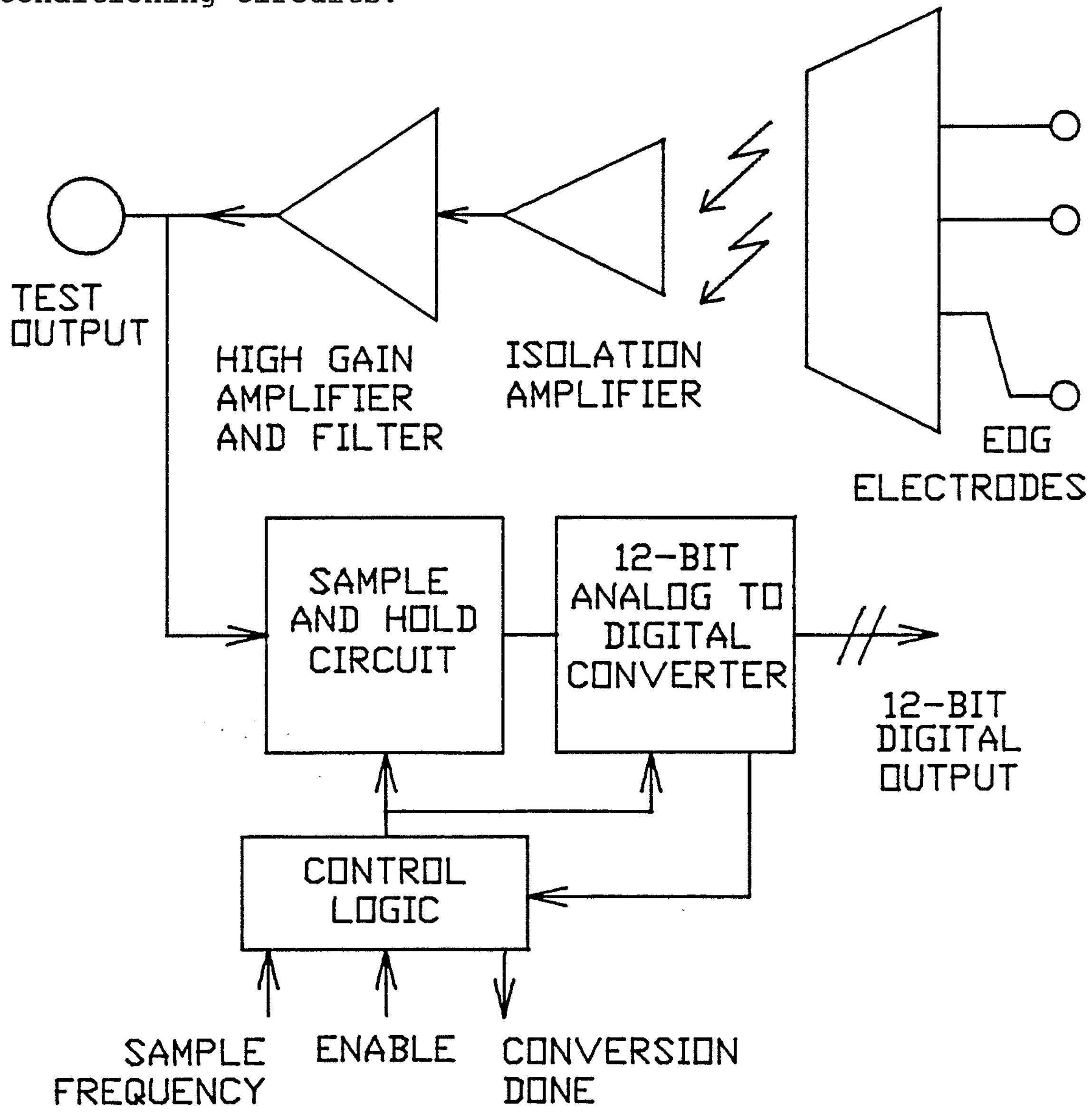

FIGURE 4: Block Diagram of EOG Conditioning Circuits

3.4.1 EOG Amplifier

The function of the EOG amplifier of the VORDAS is to condition the EOG signal so that it can be digitized. The following factors were considered in the design of the EOG amplifier used in the VORDAS:

1) The EOG signal is characterized by having an amplitude of 50 to 3500 µV and a frequency range of dc to 50 Hz [8].
2) The amplifier must be electrically isolated from all external power supplies to insure subject safety.
3) The amplifier must have high input impedance to minimize loading and polarization of the electrodes.
4) The galvanic action that occurs when an electrode is placed on the skin must not be allowed to saturate the amplifier.
5) The amplifier must amplify the signal to the level required by the A/D converter.
6) To prevent aliasing the amplifier must have a filter to remove frequency components above the Nyquist limit determined by the sampling rate of the A/D converter.
7) The amplifier must have low noise and a high Common Mode Rejection Ratio (CMRR). The CMRR is a measure of the ability of an amplifier to cancel input signals that appear on both of its input terminals, such as 60 Hz signals generated by lighting and residential power supplies.

The EOG amplifier designed for the VORDAS meets all of the requirements. It is a linear, high gain, multistage, isolation amplifier capable of amplifying the EOG signal to the point where it has a range of +/-5 Vdc.

A band pass filter is built into the amplifier. The lower cutoff frequency prevents the dc voltage generated by the galvanic action of the electrode and skin from saturating the amplifier. The upper cutoff frequency prevents aliasing when the EOG signal is digitized.

The lower cutoff frequency not only removes the dc voltage generated by galvanic action, but also removes the dc component of the EOG. This cannot be helped, but it can be minimized by choosing a very low cutoff frequency. The lower cutoff frequency used for the VORDAS is 0.1 Hz, high enough to filter the dc component, but low enough to achieve good eye position accuracy.

The upper cutoff frequency must be high enough to allow reproduction of the EOG waveform by passing the significant higher harmonics, yet low enough to prevent frequencies greater that the Nyquist rate from being digitized. Based on this, a cutoff frequency of 100 Hz was chosen. The filter also minimizes the effect of unwanted signals from muscles in the proximity of the electrodes and any unwanted high frequency noise from electromagnetic interference (EMI).

The first stage of the EOG amplifier is a dc coupled, high impedance, linear isolation amplifier with a gain of 25. This stage isolates the subject electrically from the rest of the equipment and the primary power supply for maximum subject protection. The stage has some gain, to increase the common mode rejection ratio (CMRR) and lessen the effect of any noise introduced in the later stages, but not enough gain to cause the stage to saturate as a result of electrode galvanic action. The stage is dc coupled to the electrodes to minimize electrode polarization and provide good low frequency response.

The output of the first stage is passed through a high pass filter with a cutoff frequency of 0.1 Hz to remove any dc component that could be introduced by the skin-electrode interface. This is absolutely necessary as there will always be a galvanic potential generated at the skin-electrode interface and there is no way to insure that both electrodes will have exactly the potential across them. Since the potential difference could easily be in the order of millivolts, the EOG amplifier could become saturated without this filter.

The second stage of the EOG amplifier is a simple inverting amplifier with a fixed gain of 100.

The third stage of the EOG amplifier is a non-inverting summing amplifier with a gain adjustable from 1 to 100. An adjustable bias voltage is added to the EOG signal at this stage so that the output voltage range is 0 to 10 Vdc, making the output directly compatible to the A/D converter.

At the output of the third stage a low pass filter with a cutoff frequency of 100 Hz prevents aliasing that could result from sampling the signal. The output of the low pass filter is sent to the A/D converter and to a BNC connector on the back of the chair. The BNC connector allows the researcher to connect an oscilloscope to the output of the EOG amplifier for adjustment of the gain and bias.

3.4.2 Analog To Digital Converter

The function of the Analog to Digital (A/D) converter is to sample the EOG signal periodically and convert the analog sample into a binary number for transmission and storage. Considerations in the design of the A/D converter were:

1) The selection of the sampling rate for the EOG signal.
2) The resolution of the A/D converter.
3) The speed of the A/D converter.
4) The signal to the A/D converter must not change during conversion.

The Nyquist rate defines the theoretical upper frequency that can be reproduced from a sampled continuous function. However, in practice, sampling rates above the Nyquist rate result in better reproduction of a frequency. For this reason a rate of 500 Hz, five times the Nyquist rate, was chosen.

The resolution of the A/D converter should be as high as possible to minimize the quantization error associated with digitizing any signal. The A/D converter used in the VORDAS performs a 12 bit conversion in 100 µs, using the technique of successive approximation. It samples the EOG signal continuously every 2 ms independently of any control inputs. A DONE bit indicates when the conversion is complete and an ENABLE bit masks the DONE to the recording device.

A sample-and-hold amplifier insures that the input to the A/D converter does not change during the digitizing process.

3.5 Chair Interface

Up to this point the design of the motion control systems and the EOG monitoring system have been described. The motion control systems require only a binary number representing the instantaneous angular velocity of the chair and a trim control code to function. The EOG monitoring system requires only a bit to tell it when to sample and digitize the subject's EOG signal and something to store the data it generates.

The Main computer was to provide the functions of generating the chair motion data, storing the EOG data, and providing an interface between the researcher and the VORDAS. In fact, additional circuitry had to be used to connect the Main computer to the motion control system and the EOG monitoring system. Therefore, the Main computer is discussed next so that the reader will understand the need for the circuits that follow: The Velocity Control computer and the Data Acquisition computer.

3.6 The Main Computer

Several considerations for the Main computer affected the design of the entire VORDAS hardware:

1) There must be some type of interface between the researcher and the VORDAS. The interface must provide the researcher with VORDAS status information and allow entry of VORDAS instructions.
2) The Main computer should be as inexpensive as possible.
3) To minimize costs the Main computer should handle as much of the control and computation requirements of the VORDAS as practical.

As with most design criteria there are conflicting requirements. In this case they were 2) and 3) above. By choosing a small microcomputer of the type commonly called "personal computers" the cost of the Main computer can be kept very low, but a small "personal computer" does not have the computational power or memory needed to collect data or do computation in real time.

The main problem with "personal computers" is that they were never intended to operate in real time. As long as the computer can do what is asked of it and not keep the operator waiting too long, its speed of operation is acceptable. In addition some computer tasks, such as storage and retrieval of information on a disk, have their own real time considerations and cannot be interrupted to collect external data.

The solution to this dilemma was to implement a system made up of a small, inexpensive personal computer and external data buffers that could temporarily hold data to and from the Main computer. The type of buffer required is known as a First In First Out (FIFO) buffer. Because large hardware FIFO's are expensive, microprocessors with RAM were programmed to create the required FIFO's.

These "software FIFO's" are actually small computers, so in addition to buffering data to and from the Main computer they could be programmed to perform data manipulation, decoding, and control functions. The result is a system that is not directly dependent on the speed and computation power of the Main computer. Virtually any personal computer could be used for the Main computer.

The VORDAS Main computer was assembled at the University of Manitoba. Features of the Main computer are:

1) 64K bytes of RAM, 1K = 1024 bytes.
2) Two 8 bit parallel input ports, two 8 bit parallel output ports, two RS-232 serial ports and a SASI I/O bus that can be used to connect it to other devices.
3) Two double sided, double density, 8 inch floppy disk drives configured as four single sided, double density disk drives capable of storing 680K bytes of information on each side of the disk.
4) Digital Research CP/M operating system.

The 8 bit parallel ports are used to connect the Main computer to the Velocity Control computer and the Data Acquisition computer to minimize communication time. These ports are not standard computer communication ports, such as a Centronics parallel port, but were chosen because they can achieve higher data rates than the RS-232 port and SASI I/O bus.

The Main computer is used to generate a data file containing the instantaneous velocity of the chair and control commands for the trim motors and data acquisition controller for every 0.01 sec interval of the run.

3.7 The Velocity Control Computer

The Velocity Control computer is a small microprocessor based computer connected between the Main computer and the control electronics of the VORDAS. Its functions are:

1) To work in real time updating data and control signals every 0.010 sec to insure accurate control of the VORDAS.
2) To buffer data from the Main computer to the VORDAS control circuits.
3) To monitor VORDAS status, act on it if necessary, and report it to the Main computer for information to the researcher.

Two different Velocity Control computers were built, programmed, and used during the course of this thesis. The first Velocity Control computer was built using printed circuit technology. It was based on a Motorola 6802 microprocessor and had 3K bytes of data buffer, large enough to store data for 15.3 sec of VORDAS operation. It worked well, but the Main computer could not update the buffer fast enough meaning a larger buffer was needed.

The problem was how much larger to make the new buffer. If the buffer was large enough to hold all the data to control the chair motion for the entire run, the Main computer would not have to spend any time updating the Velocity Control computer's buffer during the run. This would increase the EOG data collection rates, simplify the programming of the Main computer, and allow a number of different options, such as sending the data to the Velocity Control computer once and using it for several runs, to be implemented in the future.

The software used to generate the chair motion data is capable of creating data files up to 128K bytes long, enough data for runs up to 655 sec in duration. Although it is highly unlikely that any examination run would last 10 minutes, it was decided that if the Velocity Control computer was going to be designed to store the data required to control the chair for the entire run, it should be capable of at least storing the largest file that could be currently created. However, the Motorola 6802 can access only 64K of memory directly.

Therefore a second Velocity Control computer was built, using wire wrap technology, based on an Intel 8088 microprocessor, with a 128K byte buffer. The Intel 8088 was chosen because it has the capability to directly address 1M (1,048,576) bytes of memory.

To insure that the data needed to control the VORDAS are updated every 0.01 sec, a crystal clock generates an accurate 0.010 sec time base used as an interrupt to the Velocity Control computer. Between data updates, the Velocity Control computer monitors the VORDAS and relays its status to the Main computer.

During the run the Velocity Control computer controls the ENABLE bit of the EOG A/D converter. This allows runs to be made without collecting EOG data and for data collection to be stopped and started at different times during the run according to the researcher's requirements.

3.8 The Data Acquisition Computer

The Data Acquisition computer is a small microprocessor based computer connected between the Main computer and the EOG A/D converter. Its functions are:

1) To collect data from the EOG A/D in real time. One 12 bit sample is generated every 2 ms during the run.
2) To compact the 12 bit data and buffer it for the Main computer.

The Data Acquisition computer, built using printed circuit technology, is based on a Motorola 6802 microprocessor and has 3K bytes of data buffer, large enough to store 4 sec of EOG data. The A/D converter signals the Data Acquisition computer that the conversion of EOG data is done through an interrupt to insure that data is not missed because the 6802 was busy with some other task.

Samples of the subject's EOG corresponding to known angular eye displacement must be taken for use as a reference to interpret the data collected during the run. This process is called calibration.

To collect calibration data, the Data Acquisition computer is connected to three Light Emitting Diodes (LED's) and the ENABLE bit of the A/D converter. The three LED's are mounted at fixed angular distances of 0 and +/- 20 degrees in front of the subject when the chair is in the home position. Calibration samples are taken by turning on each LED and recording the subject's EOG in response. The calibration sequence is started by pressing the CALIBRATION button mounted on the back of the chair.

3.9 The Emergency-stop Hardware

The Emergency-stop (E-stop) hardware has one very important function: It MUST bring the chair to a quick controlled stop in the event of an emergency.

Conditions that are considered an emergency in the VORDAS are:

1) Excessive velocity: the angular velocity greater than 10% of the specified maximum.
2) Subject panic: the subject feeling uncomfortable with the run.
3) Proximity: anyone being close enough to the chair to be hit by it as it rotates.
4) Researcher E-stop: anything that the researcher does not feel is safe.

Figure 5 shows a block diagram of the Emergency-stop hardware.

Any system that remains safe, even if the system itself fails, is a fail safe system. To achieve fail safe operation, the E-stop system of the VORDAS uses a holding circuit to close the armature contactor and energize the rotation motor. Therefore any disruption of the holding circuit, loss of power, or failure of the contactor coil will shut down the power to the rotation motor. Power to the chair trim motors is not shut off directly by the E-stop

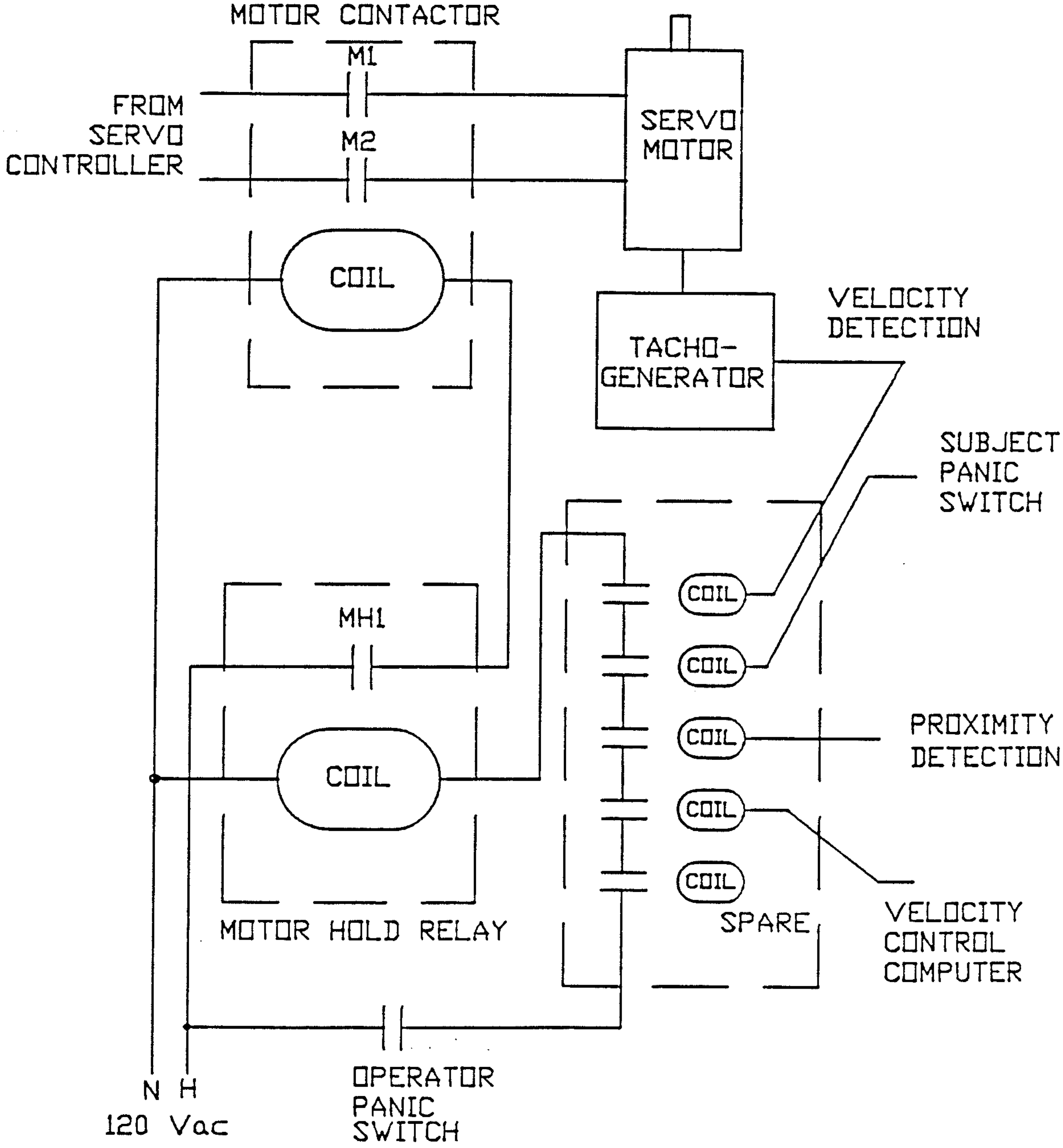

FIGURE 5: Block diagram of Emergency-stop hardware

system. This is not considered to be hazardous because the motions of the trim motors are slow. (Note that, in the event of an emergency, the Velocity Control computer will attempt to shut down the chair trim motors. However, this technique is not fail safe because failure of the Velocity Control computer or the solid state relays may mean that the trim motors will not shut down.)

Solid state relays are used in the velocity limiting, subject panic, and proximity detection parts of the holding circuit. They were chosen because they are quiet and small. However, the possibility exists that a solid state relay can fail in its closed position. To insure that there is always some way to shut down the rotation motor, the E-stop switch for the researcher is wired directly into the holding circuit.

3.10 System Interconnection

All of the circuits of the VORDAS are electrically isolated from each other using optical isolators. This was done to minimize the influence of electrical noise, and eliminate the possibility of ground loops.

Chapter 4

DATA FILE FORMATS

The VORDAS computers must store and manipulate two sets of data: the data specifying the motion of the examination chair, and the EOG data being collected. These two sets of data are stored in disk files.

4.1 The Velocity Profile

The term "velocity profile" refers to both the velocity of the chair as a function of time and the disk file that contains the data used to control the motion of the chair during the examination run. Throughout this dissertation the phrase "Velocity Profile" (spelled with capital letters) refers to the data file, and the phrase "velocity profile" (spelled with lower case letters) refers to the velocity of the chair as a function of time.

The Velocity Profile is made up of 16-bit Motion Control Words. One Motion Control Word is required for every 0.01 sec of the run. Each Motion Control Word contains a 4-bit Trim Control Code used to control the chair Trim functions and data collection. Figure 6 shows the Motion Control Word format, and Table 2 lists the Trim Control Code functions.

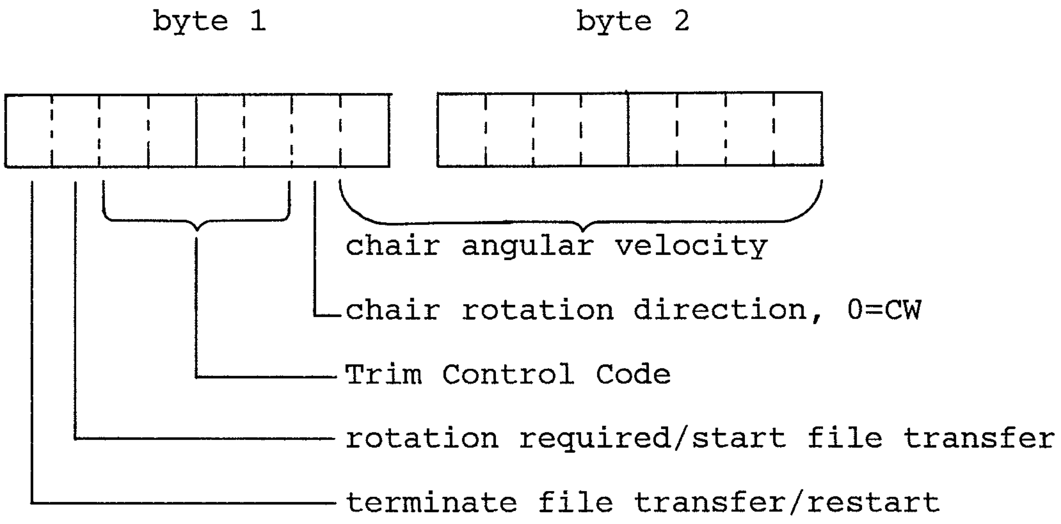

FIGURE 6: Motion Control Word Format

TABLE 2

Trim Control Codes

0000 ... stop everything/run complete
0001 ... rotate with data acquisition
0010 ... tilt headrest forward
0011 ... tilt headrest backward
0100 ... pitch chair forward
0101 ... pitch chair backward
0110 ... raise chair
0111 ... lower chair
1000 ... rotate without data acquisition
1001 ... stop headrest tilt
1010 ... stop chair pitch
1011 ... stop elevation
1100 ... return to home position
1101 ... unused, set to continue without change
1110 ... unused, set to continue without change
1111 ... continue without change

Implementing the Trim functions with a control code uses fewer bits than would have been needed for individual control of each function. The only potential drawback to this technique is that multiple trim functions cannot be executed at exactly the same time. Only one trim function can be executed every 0.01 seconds.

Using this technique in the VORDAS posed no problems for two reasons. First, many of the functions are mutually exclusive. Second, all three chair Trim functions can be executed in a space of only 0.03 sec by placing one Trim Control Code in each of three successive Motion Control Words, close enough together that the subject cannot detect that they did not start at the same time.

It should be noted that the first 4 bytes of the Velocity Profile do not contain valid chair motion data and are ignored by the program that takes the Velocity Profile from disk during an examination run. The program that creates the Velocity Profile uses the first 4 bytes of data in the file to store file information it requires.

4.2 The EOG Data File

The disk file used to store the EOG data is simply referred to as the EOG Data File. Each EOG sample is 12 bits long, but data is transmitted to the Main computer and stored on the disk in 8-bit bytes. Therefore, to minimize the transmission rates and the disk space required to store the EOG data, the data from two consecutive samples of the EOG are compressed into 3 bytes by the Data Acquisition computer before being transmitted to the Main computer. The only exceptions are the three calibration samples taken before the run, which are stored in 6 bytes at the beginning of the file.

The format of the EOG data file is shown in Figure 7.

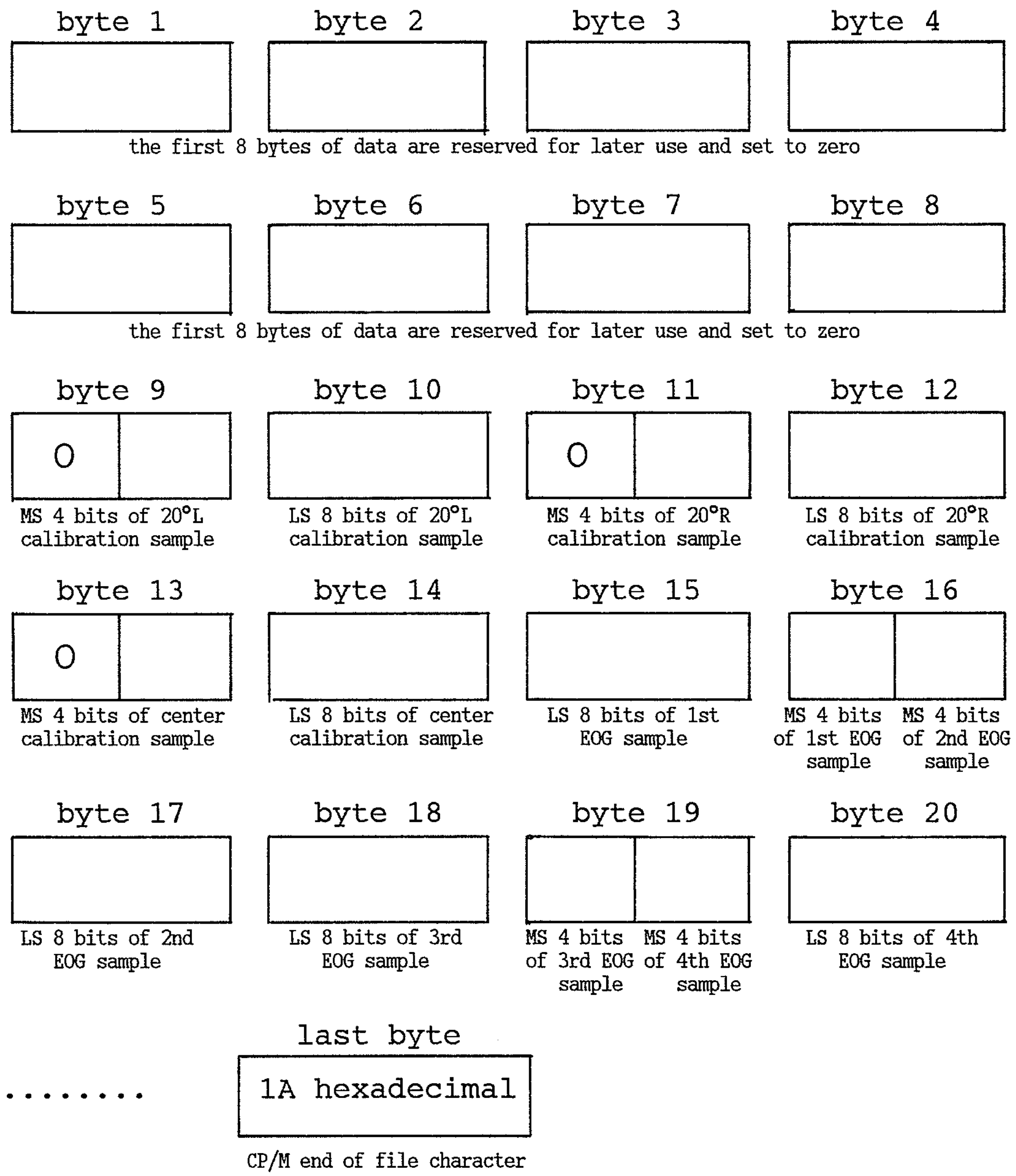

FIGURE 7: EOG Data File Format
The first 8 bytes of the EOG data file are presently not used and are set to zero. They were left so that there would be room at the start of the file for future developments such as inserting file length. Abbreviations used above are: right (R), left (L), most significant (MS), least significant (LS)

Chapter 5

SOFTWARE DESIGN

5.1 Background

The Main computer used in the VORDAS is a small personal computer. Any computer is made up of hardware such as the keyboard, video monitor and electronic devices, and software, i.e. the programs.

A computer requires programs to tell it what to do when the power is turned on, where to get information it needs, and how to respond to commands from the user. One of these programs is the disk operating system or simply the operating system of a computer.

A computer's operating system provides the user and the programmer with a standard method of accessing the resources of a computer, i.e. the memory, disks, keyboard and video monitor. This standard access is the same for any computer using that operating system regardless of the type of computer. This means that, for example, any computer that uses Microsoft's MS-DOS operating system will run programs designed for use with MS-DOS regardless of who made the computer or the programs.

Operating systems are able to provide standard functions because they are made up of several parts, two of which are called the Basic Disk Operating System (BDOS) and the Basic Input Output System (BIOS). The BDOS is the standard part of the operating system and is supplied by the manufacturer (of the operating system). It offers specific functions, such as "write to disk", that are always the same command regardless of the computer. As long as the program being developed uses these commands it will run on any computer using that operating system. The BIOS is the part that is written for each computer by the computer manufacturer. The BIOS is passed a set of standard parameters by the BDOS and executes them in a way unique to its own computer. The only criterion for the BIOS is that it implement the functions as defined by the manufacturer of the operating system.

The operating system of the Main computer is CP/M by Digital Research, and is structured as described above. Programs being developed to work in a CP/M environment should use standard CP/M BDOS functions to access the hardware of the computer for two reasons. First, so that the program could be used on any computer with a CP/M operating system. Second, so that a lot of time does not have to be spent writing routines to communicate with devices such as disk drives and video monitors. This was the initial approach taken to develop the program for the Main computer.

The CP/M disk routines are very reliable but have several features that make them too slow to operate in real time:

1) The routines do a lot of error and format checking.
2) The routines attempt to execute a command several times in the event of an error before returning to the program that called the routine.
3) The routines do not keep the disk head "loaded", i.e. on the disk, but load it as necessary. This does save both the disk and the head, but takes a lot of time.

Therefore, custom disk handling routines had to be written.

The end result is that the CHAIRCON program works well, but it cannot be used on any other computer without reasonably extensive modification and a thorough understanding of the computer hardware involved.

5.2 Introduction

From the hardware description it is clear that the VORDAS has three separate computers in it. Five programs were written for the VORDAS computers over the course of this thesis. They are:

1) CHAIRCON: the chair control program for the Main computer.
2) VELCON: the velocity control program for the original Velocity Control computer.
3) VELCON88: the velocity control program for the current Velocity Control computer.
4) DATACON: the data acquisition program for the Data Acquisition computer.
5) The Velocity Profile generation programs for the Main computer.

Programs 1 to 4 were written in the native language of the microprocessors, known as machine language, for the fastest possible operation and the greatest amount of control over the resources of the computers. Only program 2, written for the Motorola 6802 version of the Velocity Control computer, is not currently used.

The Velocity Profile generation programs were not part of this thesis. The original programs were written by Mr. Johnson Way on the Main computer in Borland International's version of the PASCAL language, TURBO PASCAL.

5.3 CHAIRCON

The functions provided by CHAIRCON are:

1) Communicates with the Data Acquisition computer to collect EOG data and store it on disk during the run.
2) Communicates with the Velocity Control computer to transfer the Velocity Profile from disk to, and receive system status from, the Velocity Control computer.
3) Reports system faults and errors.
4) Allows the researcher to:
    - i) make a run with or without collecting EOG data.
    - ii) adjust the chair trim from the Main computer before the run.
    - iii) send the chair to its HOME position.
    - iv) exit to the CP/M operating system.

CHAIRCON is a menu driven program; that is, the researcher picks the desired operation from a list that appears in a menu on the video monitor. In addition, errors, faults, and instructions are displayed on the video monitor. In this way there are no commands to be memorized; the researcher simply reads the screen.

Figure 8 shows a functional flow chart of CHAIRCON. Complete program listings and flow charts are contained in the VORDAS Software Manual.

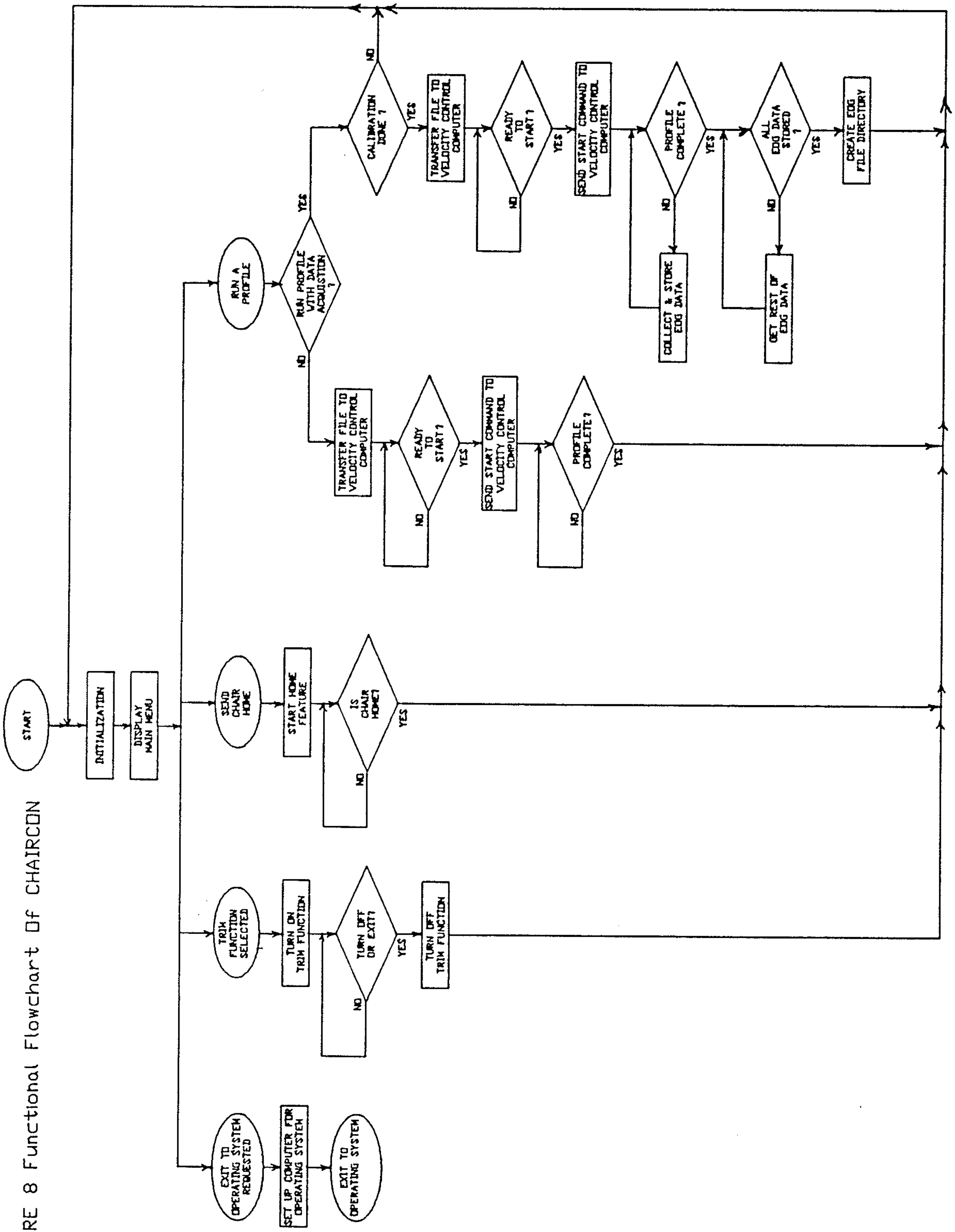

FIGURE 8 Functional Flowchart Of CHAIRCON

Three versions of CHAIRCON were written. The first version used the disk handling routines built into the BDOS of the CP/M operating system to store and retrieve data on the disks. It communicated with the original 6802 based Velocity Control computer, sending the Velocity Profile to it while the run was in progress. The program was functional, but unfortunately the CP/M disk routines were not fast enough to keep the Velocity Control computer from running out of data during the run.

The second version of CHAIRCON uses custom disk handling routines to speed up data transfer to and from the disk. The routines communicate directly with the disk controller, the device in the computer that actually stores and retrieves data to and from the disk. The routines check for faults and report them, but attempt a command only once because there is not enough time to attempt a command more than once without losing EOG data. This means that in the event of a disk error EOG data will be lost but the researcher will know that data was lost.

In addition to the custom disk routines the interrupts of the Main computer were modified so that only the disk controller interrupts are active while the run is taking place. This technique gives CHAIRCON complete, uninterrupted control of the Main computer during the run.

The second version of the CHAIRCON program communicated with the original 6802 based Velocity Control computer. It was fast enough to keep the Velocity Control computer supplied with Velocity Profile data, but only if EOG data collection was not taking place.

The CHAIRCON program was completely rewritten to achieve the third, and present version for use with the 8088 based Velocity Control computer. It has improved error reporting and recovery, and uses macros to increase the speed of the program. Macros are similar to subroutines except that, on compilation of the program, each time a macro is called its code is actually reproduced at that point in the program. The result is a program that has the advantages of readability, ease of understanding, and ease of programming that result from modular programming, and the speed of in line machine code.

In addition to the use of macros, the following were done to insure the fastest possible disk operation:

1) The file transfer routines were rewritten to allow complete transfer of the Velocity Profile to the Velocity Control computer before the run started.
2) The custom disk routines used to store the EOG data were optimized.
3) A disk format was selected for the EOG data storage disk such that the disk head would never have to be moved to a

new track during data storage. The disk format is 9 sectors per track, 1K bytes per sector, single sided. (Note that CHAIRCON assumes the disk used to store EOG data is in disk drive B, is blank, and is formatted correctly. Any data on the disk in drive B is destroyed by the new EOG data and the new directory that is written over it.) If a disk with an incorrect format is used, a disk error results and the EOG data is lost.

4) Two areas in the memory of the Main computer were set up to store the incoming EOG data. While one area is being filled the other area is written to the disk. The size of the areas is 3K bytes each and was selected to correspond to the disk format.
5) The Main computer must check the system status during the run. Checking the system status continuously would seriously slow down the data collection. Therefore, CHAIRCON checks the system status periodically only after a predetermined number of bytes of EOG data have been stored or an equivalent amount of time has elapsed. This technique maximizes the data transfer rates while still being able to monitor the system. The technique relies on the fact that any real world problem is both slow and, in this case, does not have to be reacted to, only reported by, the Main computer.
6) A CP/M compatible directory entry is created after the run is complete. Creating the directory during the run

could result in long delays as the disk head moves from the data storage area of the disk to the directory area of the disk. By creating the directory after the run is complete, the furthest the disk head ever has to travel during the run is one track.

The final CHAIRCON program is capable of collecting and storing the subject's EOG data during the run. The only disadvantage of the program is that it is unique to the Main computer of the VORDAS and cannot be used on any other computer without modification.

5.4 VELCON88

The functions provided by VELCON88 are:

1) Control of chair motion.
2) Control of data acquisition.
3) Storage of the entire Velocity Profile.
4) Monitoring of system status.
5) Communication with The Main computer to receive the Velocity Profile from, and send system status to, the Main computer.

The operation of VELCON88 is completely transparent to the researcher. Figure 9 shows a functional flow chart of VELCON88. Complete program listings and flow charts are contained in the VORDAS Software Manual.

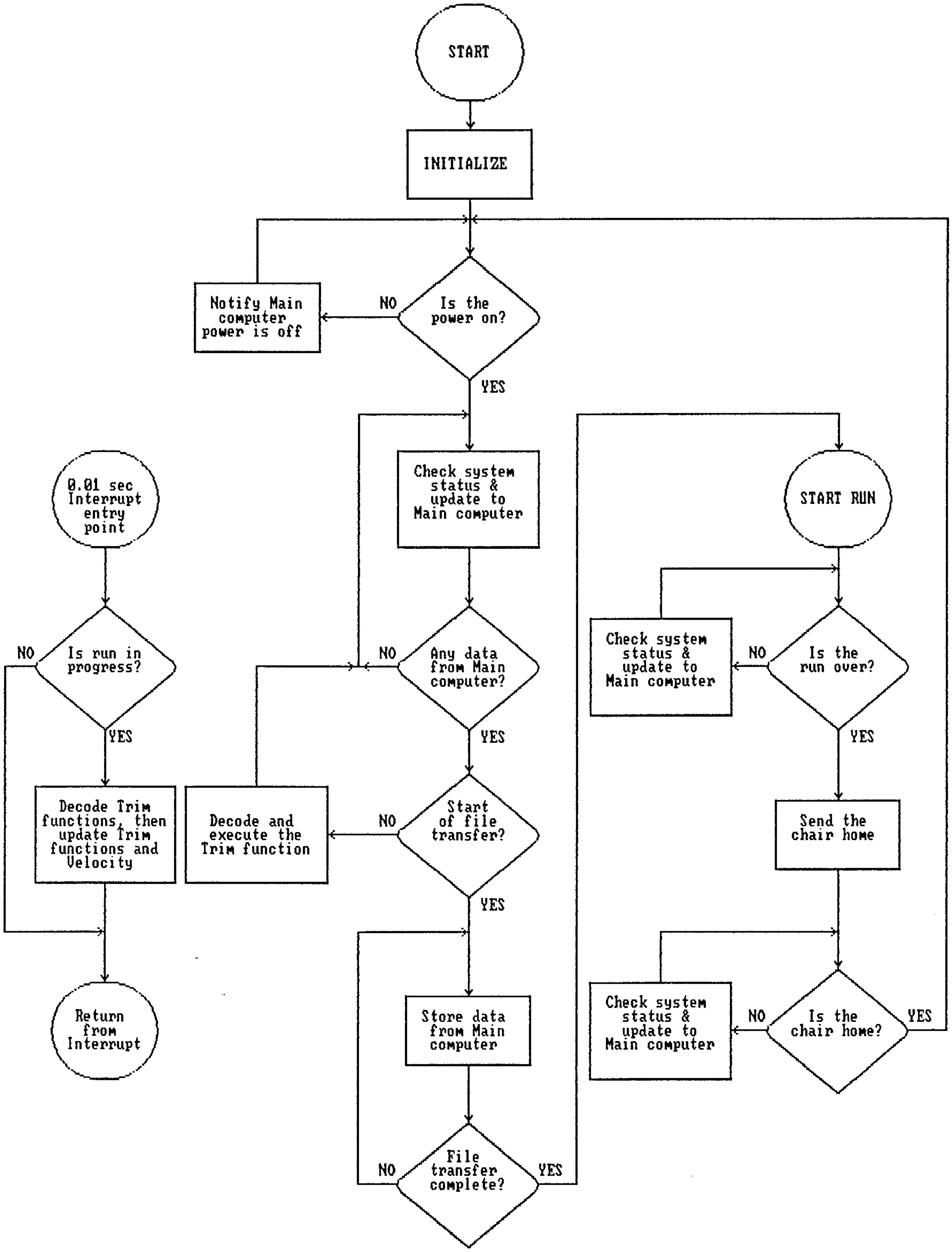

FIGURE 9: Functional flowchart of VELCON88

The most important function of VELCON88 is to decode and send out a new Motion Control Word every 0.01 seconds. A hardware clock generates an interrupt to the 8088 to signal that it is time for the next word to be sent out. Interrupts are the fastest way to have a microprocessor respond. When one occurs, the microprocessor completes its present instruction then immediately starts to execute the instructions in the interrupt subroutine. The important consideration for the interrupt subroutine is that the time from the start of the subroutine until the control system commands are actually updated must be the same regardless of the subroutine path taken. As a result the subroutine paths were minimized and timing loops were installed where necessary to insure the time between updates was as close to 0.01 seconds as possible.

The chair trim functions are decoded and latched, or held, by VELCON88 to allow simultaneous operation of the chair trim functions. This means that once a function has been turned on it remains on until another trim control code is issued to turn the function off. It should also be noted that there is no feedback from the trim functions, therefore VELCON88 does not know if they are actually working or what position the chair is in.

5.5 DATACON

DATACON is the simplest of the three programs. Its functions are:

1) To get the digitized EOG data from the A/D converter.
2) To compact two 12 bit EOG samples into three 8 bit bytes.
3) To take calibration samples of the subject's EOG before the run begins.
4) To buffer the EOG data for the Main computer.
5) To communicate with the Main computer to send the calibration status and EOG data to it.

With the exception of the calibration procedure, the operation of DATACON is completely transparent to the researcher. Figure 10 shows a functional flow chart of DATACON. Complete program listings and flow charts are contained in the VORDAS Software Manual.

With the chair in the home position the researcher presses the calibration button on the back of the chair. DATACON turns on three Light Emitting Diodes (LED's) mounted at -20, 0 and +20 degrees to the subject and records the subject's EOG in response. From these samples the researcher can generate a scale factor to be used in analyzing the EOG data.

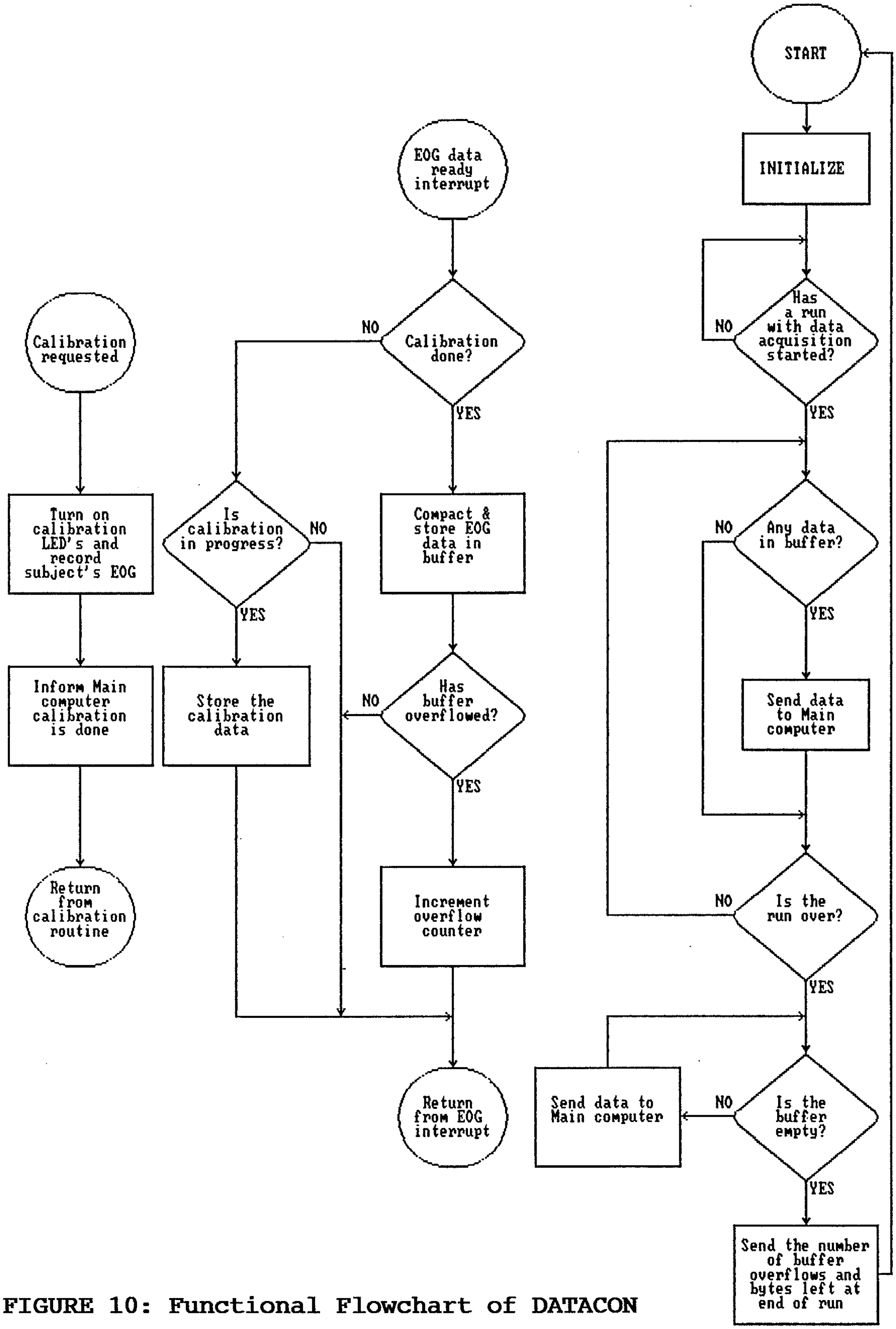

FIGURE 10: Functional Flowchart of DATACON

Chapter 6

THEORY OF POSITION CONTROLLER OPERATION

The position control system used in the VORDAS was purchased from EG&G Torque Systems Inc of Watertown, Massachusetts. A block diagram of the system was shown earlier, in Figure 3. The position controller used in the VORDAS is the EG&G Torque Systems Inc model S1201 Serial Input Module (SIM).

The S-1201 SIM manual has an excellent discussion of the theory of operation of this type of position control system [9]. That discussion is reprinted in Appendix A, with the permission of EG&G Torque Systems.

In summary, the position control system is a first order control system as long as it remains linear. However, there are several factors that can cause non-linear operation of the control system. The following discussion considers these factors to determine the theoretical limits to the linear operation of the VORDAS position control system. These factors were not discussed under hardware considerations for clarity but must be considered in designing such a system.

6.1 Application To VORDAS

Determining the limits of linearity is the first consideration in analyzing the VORDAS position control system. Causes of non-linear operation are:

1) Overflow of the counter, or position register.
2) Saturation of the Digital To Analog (D/A) converter (DAC).
3) Current limit of the servo motor controller.

The position control system uses a counter to determine the position error of the system. Input pulses cause the counter to count in one direction (up or down depending on the direction of the motor being commanded), and feedback pulses from the encoder cause the counter to count in the opposite direction. The output of the counter is position error, and is converted to an analog signal using a digital to analog (D/A) converter (DAC).

Both the counter and the DAC have fixed length; that is, there is a limit to the number of pulses the counter can count before it overflows and the DAC has a value that will cause it to saturate and generate its maximum output voltage.

If the DAC saturates, any further increase in position error has no effect on the output of the DAC and the system becomes non-linear. If the counter overflows, position information is lost. The system is designed so that the DAC will saturate before the counter overflows. In this way, if the DAC saturates, the system may be able to keep track of position even though it is no longer linear.

A motor must generate torque to accelerate the load attached to it. The acceleration of the load is directly proportional to the torque generated by the motor. For a dc motor torque is directly proportional to the armature current. Therefore, for a load attached to a dc motor the acceleration of the load is directly proportional to the armature current.

The armature current is supplied by the servo controller. If the output current of the servo controller is high enough, either the armature winding or the electronics of the servo controller, or both will be damaged. The servo controller has built-in current limits to prevent such damage. Once the servo controller is in current limit, any further increase in the acceleration being requested does not result in an increase in the output current and the system becomes non-linear.

Therefore, for the control system to be suitable for the application requires that it operate within its linear region and that it be capable of generating the response required by the application.

To determine the limits of linear operation requires that the system characteristics and response requirements be known. Therefore, the motor, servo controller, and position controller characteristics and motor load inertia must be known. Appendix B shows the calculation of the motor load inertia and Appendix C lists the motor and controller characteristics.

The motor load inertia was calculated to be 20.717 oz-in-sec^2 with a 90 kg subject. The torque sensitivity of the motor is 69.9 oz-in/A. The encoder used in the VORDAS has 1000 lines/revolution. The servo controller is configured so that 12 V input results in a motor velocity of 700 RPM. The S-1201 position controller is set to provide 0.029V/bit output.

Using equation A.2, the system time constant and bandwidth were calculated to be 35.5 ms and 4.49 Hz, respectively.

Equation A.11 defines the maximum step input frequency that the position control system can accept without saturating the DAC register. For the VORDAS the frequency is 14.42 kHz. The frequency required for a chair velocity of 300 degrees/sec is 23.33 kHz. Therefore the DAC register of the VORDAS will saturate and cause non-linear operation if the input velocity step is 185 deg/sec or greater. However, the worst case acceleration is 300 deg/sec^2 which results in a 3 deg/sec velocity step. Therefore, the DAC register does not overflow and cause loss of position information.

Equation A.19 defines the maximum step acceleration that the position control system can achieve without reaching current limit. By manipulating A.19 the current required to achieve a given step acceleration can be determined. For the VORDAS it was determined that 21.6 A would be required to achieve 300 deg/sec^2 accelerations with a 90 kg subject.

Equation A.24 defines the maximum step velocity the system can achieve without overshoot. For the VORDAS this number works out to 1.67 kbits/sec which corresponds to approximately 21 degrees/sec.

Therefore the VORDAS should operate as a linear first order control system with a time constant of 35.5 ms, a bandwidth of 4.5 Hz, and no velocity overshoot provided accelerations of 300 deg/sec^2 or velocity steps of 21.3 deg/sec are not exceeded.

Chapter 7

RESULTS AND CONCLUSIONS

The VORDAS worked as designed. It is capable of generating arbitrary chair Velocity Profiles and recording one channel of EOG data. The chair has a maximum velocity of 300 deg/sec, and maximum acceleration of 300 deg/sec^2. The VORDAS has already been successfully used by Xiao to continue VOR research [10].

7.1 Testing Of The VORDAS

Testing of the VORDAS was done to verify the operation of system hardware, communications, and programs. Once the system operation was verified, tests were conducted to determine frequency response of the EOG amplifier and the performance of the rotation control system.

7.1.2 Testing Of The EOG Amplifier

The EOG amplifier was designed according to the recommendations of the manufacturer of the isolation amplifier, Burr-Brown. Based on the specifications provided by Burr-Brown [11], the input impedance of the amplifier is 10^{11} ohms and the electrical isolation is 2000 V continuous, 5000 V peak.

Common mode and differential frequency responses of the finished amplifier were measured. All frequency response tests were made with the amplifier adjusted to produce a differential gain of 5000. From the tests it was found that the EOG amplifier has a bandwidth of 0.1 Hz to 100 Hz, a CMRR of 83 dB at 60 Hz, and about 100 mV of output noise with the inputs tied together.

7.1.3 Testing Of The Rotation Control System

The rotation control system was evaluated to determine its frequency response and maximum acceleration and deceleration. The test frequency range was dc to 3 Hz.

The rotation motor armature current and the tachogenerator output were monitored during all tests.

Because the rotation motor is coupled to the chair via gears, the tachogenerator output is directly proportional to the chair velocity. The tachogenerator output voltage is 15V/1000 RPM of the motor. The chair velocity is 1/14 of the motor velocity.

The motor armature current was monitored for two reasons. First, to see if the system was becoming non-linear as a result of current limiting by the servo controller. Second, to provide an indication of control system instability.

Frequency response was evaluated with sinusoidal velocity profiles of different frequencies at the limit of the design specifications of the VORDAS. The maximum acceleration was determined by subjecting the rotational control system to velocity steps that caused the servo controller to produce maximum output current.

The VORDAS frequency response was evaluated at the maximum possible accelerations. The VORDAS was designed to accelerate a 86 kg subject at a maximum angular acceleration of 300 deg/sec^2 with a maximum angular velocity of 300 deg/sec. Accelerations of 300 deg/sec^2 cannot be attained over the entire design frequency range of the VORDAS because of the maximum velocity limit. Therefore, the test profiles were chosen so that either maximum acceleration or maximum velocity were generated.

The acceleration required to produce a sinusoidal velocity is given by:

$$A = A_o \cos(2\pi f t) \text{ deg/sec}^2 \qquad 3)$$

where: A_o = the maximum acceleration in deg/sec^2
f = the frequency in Hz
t = time in seconds

The resulting velocity can be found by integrating 3) with respect to time. It is:

$V = V_O \sin(2\pi ft)$ deg/sec 4)

where: $V_O = A_O/2\pi f$ = the maximum velocity in deg/sec 5)

f = the frequency in Hz

t = time in seconds

From 5) the frequency at which $|A_O| = |V_O|$ is found to be $1/2\pi$ Hz, or approximately 0.159 Hz.

Therefore, for frequencies below 0.159 Hz, the acceleration of the chair and subject are limited by the maximum velocity the VORDAS and the test velocity profile was: $V = 300 \sin(2\pi ft)$ 6)

For frequencies above 0.159 Hz, the velocity of the chair and subject are limited by the maximum acceleration of the VORDAS and the test velocity profile was:

$V = (300/2\pi f) \sin(2\pi ft)$ 7)

7.2 Results Of Control System Tests

The VORDAS frequency response tests showed that the system has a gain of unity for frequencies up to 1 Hz with subjects ranging in weight from 36 to 86 kg. Figures 11 and 12 show a sample of the results. The response of the system was not considered above 1 Hz because the response becomes progressively more distorted as the frequency increases.

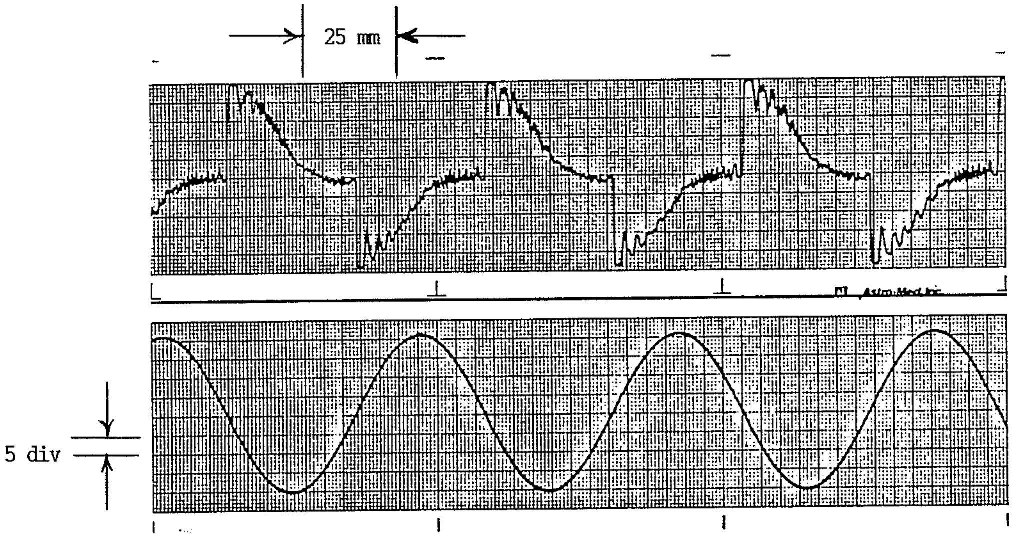

Fig 11a: 86kg subject, 0.15 Hz, 0.5V/div, chart speed 10mm/s

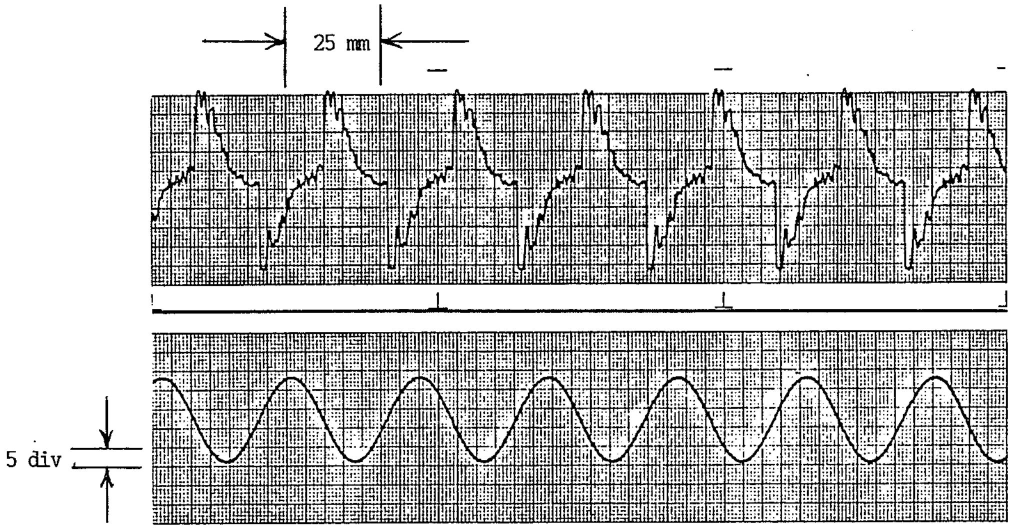

Fig 11b: 77kg subject, 0.30 Hz, 0.5V/div, chart speed 10mm/s

FIGURE 11: Samples of Test Velocity Profiles

Upper trace of both charts is motor armature current. The scale is 0.2V/div, 0.2V=1A. The lower trace of both charts is motor velocity. The scale is listed under each chart, 15V=1000 RPM of the motor. The chair velocity is 1/14 of the motor velocity.

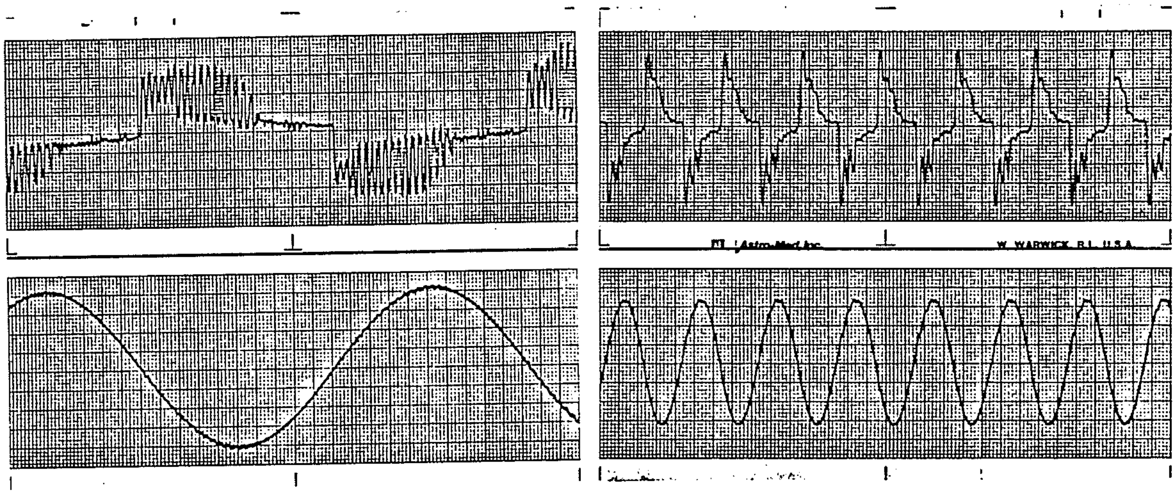

Fig 12a: 36kg subject
0.10 Hz, 0.5v/div
chart speed 10mm/sec

Fig 12b: 36kg subject
0.50 Hz, 0.2V/div
chart speed 10mm/sec

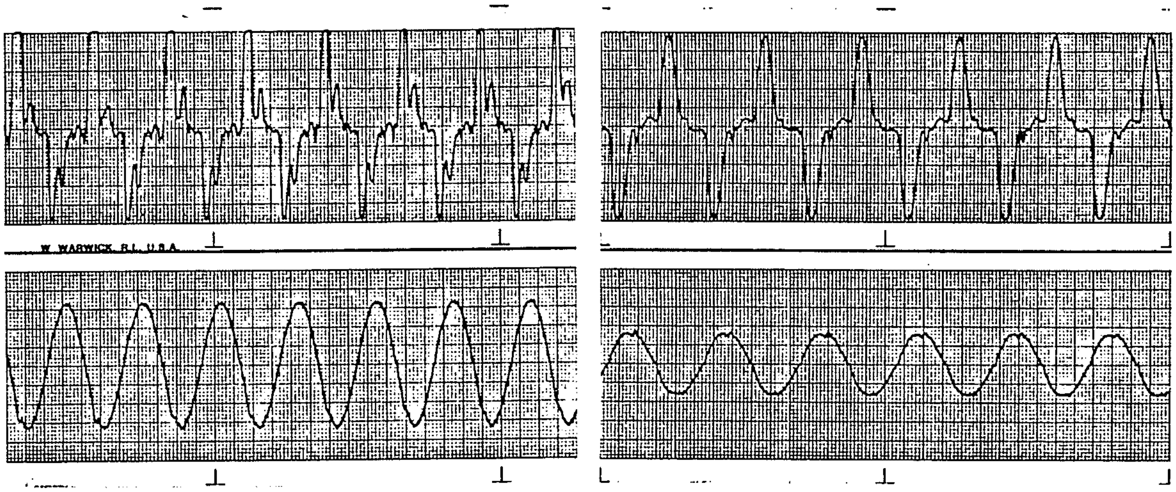

Fig 12c: 77kg subject
0.50 Hz, 0.2V/div
chart speed 10mm/sec

Fig 12d: 77kg subject
1.00 Hz, 0.2V/div
chart speed 25mm/sec

FIGURE 12: Samples of Test Velocity Profiles

Upper trace of all charts is motor armature current. The scale is 0.2V/div, 0.2V=1A. The lower trace of all charts is motor velocity. The scale is listed under each chart, 15V=1000 RPM of the motor. The chair velocity is 1/14 of the motor velocity.

It was observed that the ability to accelerate the chair and subject as a single unit has a marked effect on the ability of the system to produce an undistorted response. Also, as the frequency of the chair increases, it becomes increasingly difficult for the subject to hang on to the chair and move with it. This results in distorted velocity waveforms, and non-linear operation of the servo controller. Figure 13 shows the results of 1.5 Hz and 2.0 Hz sinusoidal velocity profiles. During the periods marked as P5 for the 1.5 Hz, and P3 for the 2.0 Hz waveforms the subject tried to hold himself rigid and move with the chair. During the other periods, the subject simply relaxed.

To determine how much current was required to generate a 300 deg/sec^2 acceleration, the VORDAS was subjected to a velocity step severe enough to drive the servo controller into current limit. It was found that approximately 22 A of armature current was required to produce a 300 deg/sec^2 acceleration with a 77 kg subject. As a result the current limits were set to allow peak values of 25 A, the maximum of the servo controller.

Therefore, 300 deg/sec^2 accelerations could be realized with an 86 kg subject without the servo controller going into current limit. However, a current limit of 25 A is beyond the natural convection cooling limits of the servo controller, and fan cooling is recommended.

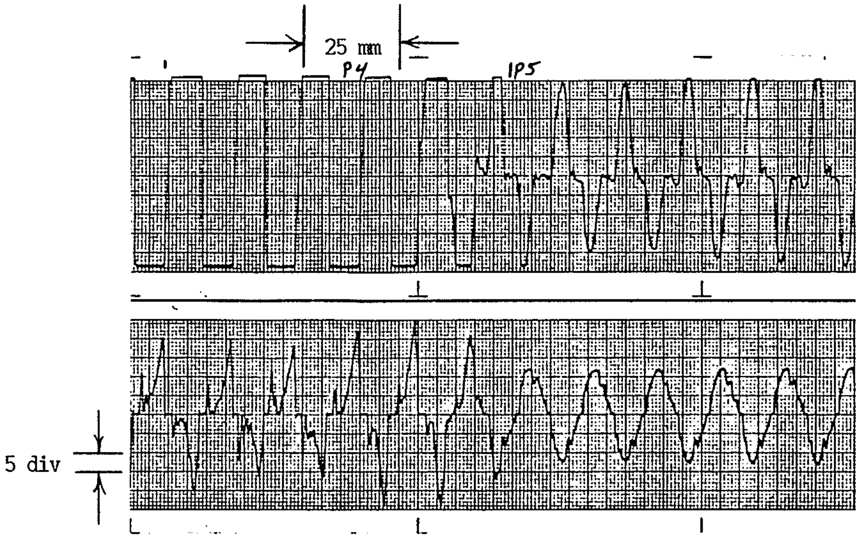

Fig 13a: 77kg subject, 1.50 Hz, 0.1V/div, chart speed 25mm/s

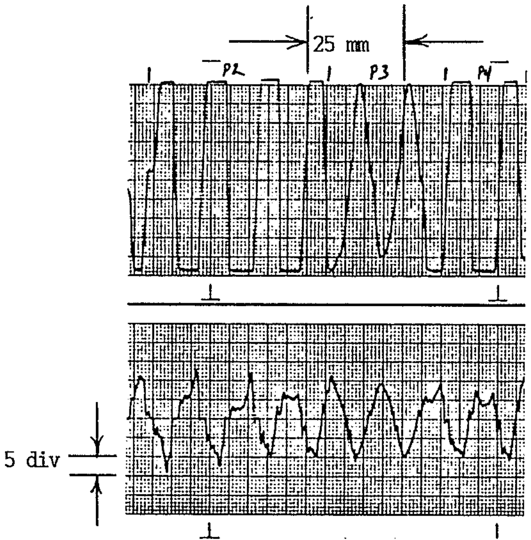

Fig 13b: 77kg subject, 2.00 Hz, 0.1V/div, chart speed 25mm/s

FIGURE 13: Samples of 1.5 & 2.0 Hz Profiles

Upper trace of both charts is motor armature current. The scale is 0.2V/div, 0.2V=1A. The lower trace of both charts is motor velocity. The scale is listed under each chart, 15V=1000 RPM of the motor. The chair velocity is 1/14 of the motor velocity.

Emergency stop deceleration was measured and found to be 230 deg/sec^2 with a 77 kg subject from a velocity of 300 deg/sec. Figure 14 shows a chart of the result.

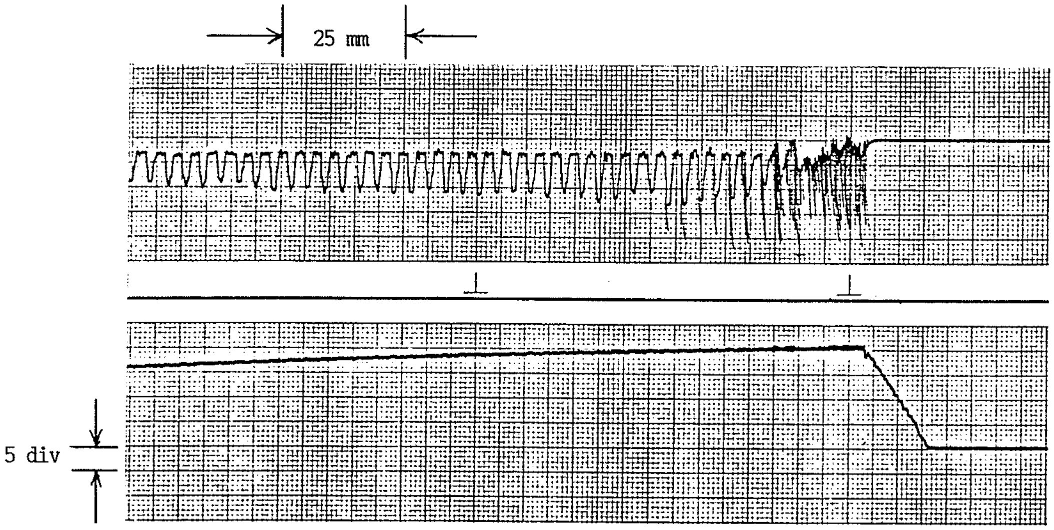

FIGURE 14: E-stop from 300 deg/sec

Upper trace is motor armature current. The scale is 0.2V/div, 0.2V=1A. The lower trace is motor velocity. The scale is 0.5V/div, 15V=1000 RPM of the motor. The chair velocity = 1/14 of motor velocity. 77 kg subject. Chart speed 10 mm/sec.

It was observed that the control system required some tuning between subjects to achieve optimum performance with subjects ranging from 36 kg to 86 kg. Figure 12a shows a test response with a 36 kg subject when the servo controller was adjusted for a 86 kg subject. The rotation control system was designed to be used in industrial equipment where the load inertia does not change significantly. Under such conditions the response of the control system can be optimized. However, the load inertia of the VORDAS is not constant, rather it varies with the weight of the subject, making tuning necessary.

It was found that the chair is tilted about 0.5 degrees from vertical. This tilt does result in slightly more torque being required to accelerate during one half of a chair revolution than during the other half of a chair revolution. The effect becomes noticeable as frequencies become high enough that the chair rotates through less than 180 degrees. In addition the motor is not perfectly aligned with the transmission input shaft.

7.3 Conclusions

The VORDAS is a fully functional system that can generate angular accelerations and record a human subject's EOG as specified by Table 1. In addition, frequencies up to 1.0 Hz may be possible if the subject is adequately secured in the chair.

At present the upper frequency of the VORDAS is limited by the ability to hold the subject securely in the chair. As frequencies increase the subject moves in the chair. Therefore, the subject is no longer experiencing a known acceleration, and is presenting a changing load to the control system.

Chapter 8

RECOMMENDATIONS

Added leg and head support should be installed. The first consideration is the safety of the subject, and added support would minimize risk of injury to the subject. The second consideration is insuring the subject moves with the chair at all times so that the acceleration the subject is experiencing is known. Added supports would allow the subject to relax completely and still move with the chair during higher frequency examinations. The supports should consist of both secure straps and padding to insure the subject is held rigidly in the chair.

The mechanical drive system of the VORDAS should be adjusted to align the chair vertically, and align the motor with the input shaft of the transmission. A flexible motor coupling could be installed to compensate for any slight motor misalignment.

A cooling fan for the servo controller should be added to the VORDAS. There have not been problems of servo controller overheating to date, however addition of the cooling fan would insure damage to the servo controller due to overheating does not occur.

Tuning of the servo controller is necessary to achieve optimum performance with subjects of widely varying weights. Tests should be conducted to determine the optimum setting of the servo controller parameters for various weight ranges of subject. Once the settings have been determined, the variable potentiometers used to make the servo controller adjustments can be replaced with switch selectable fixed resistor values. The researcher can then select the range to match the weight of the subject.

To maximize the service life of the VORDAS, the wire wrap version of the Velocity Control computer should be replaced with a printed circuit version. Technology advances have made possible a second option which is to replace both the existing Main computer and Velocity Control computer with a single more powerful Main computer. To do so would require rewriting the Main computer software, however it would result in a more reliable system that would be less dependent on a specific computer.

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Appendix A

THEORY OF POSITION CONTROLLER OPERATION

The following discussion of position controller operation was reprinted with the permission of EG&G Torque Systems. It is a concise, general discussion applicable to the EG&G S-1201 Serial Input Module (SIM) and to similar equipment commonly used in industry.

The reader should note that equation A.6 is not of a general nature, rather it applies specifically to the S-1201 SIM. The general form of the equation is:

$$\Theta = \Phi/Q \qquad \text{[revolutions]} \qquad (A.6.1)$$

where: Q = number of input pulses/motor revolution

$Q = 2N$, For the S-1201 SIM

The S-1201 SIM passes the signals from the two quadrature optical encoder channels, A and B, through an Exclusive-OR (XOR) gate. The XOR gate generates two pulses for each pulse from the optical encoder, see Figure A-0. This has the effect of doubling the optical encoder resolution, and means that the number of input pulses to the S-1201 SIM required to produce one revolution of the motor is twice the number of optical encoder lines. Thus the factor of two in the denominator of equation A.6.

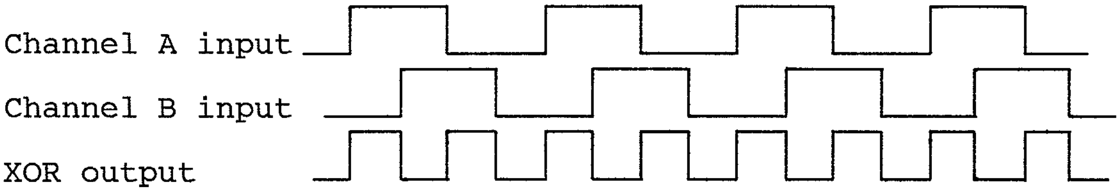


Figure A-0: XOR of two quadrature inputs

DIGITAL POSITION SERVO SYSTEM
ANALYSIS USING SIM

Reprinted with permission of EG&G Torque Systems,
from EG&G Torque Systems SIM Model S1201 Instruction Manual

A.1 General

The components which comprise the functional digital control servo system include:

1) a DC servo motor/tachometer coupled to a load,
2) an incremental encoder attached to the motor shaft,
3) a servo controller (amplifier plus power supply), and
4) a SIM digital control module.

(The functional digital control servo system diagram is given in Section 1 of this manual.)

In general, this system may be used as: (1) a point-to-point control system where a load is moved to a particular position, and stops within a given time, and (2) a "phase-locked servo system" to control velocity by locking the system to a defined input pulse rate.

Regardless of other system constraints and requirements, the functional digital control servo system will accelerate a load to some velocity, decelerate, and stop. This will result in a position displacement.

A.2 System Operation

Figure A-1 is a block diagram of the digital position control system. This model can be treated in several ways to determine system performance.

As shown, the input and output parameters are frequency. However, the summation (or integral) of input frequency is position input, and the summation of output pulses is position displacement. By considering the output parameter before the encoder, the output parameter would be velocity, and the encoder would be a feedback element.

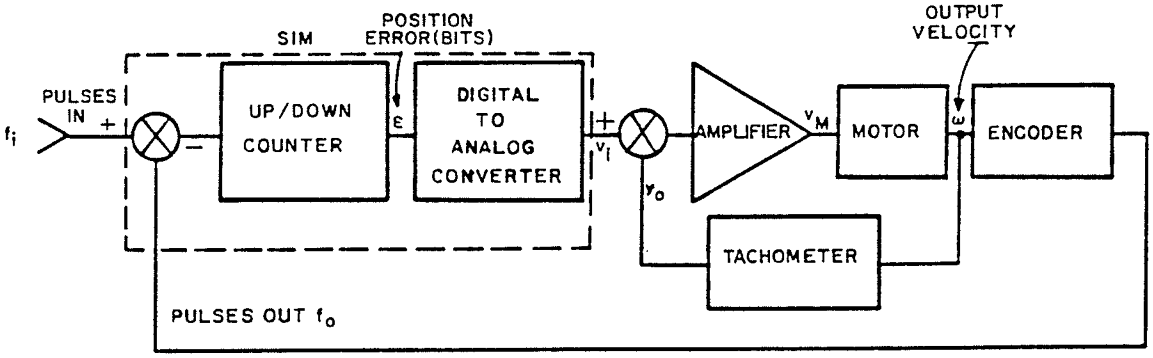


Figure A-1. Digital position control system, block diagram.

A.3 Transfer Function

Figure A-2 is a simplified block diagram of the digital servo system. Each element is replaced by its transfer function as follows:

1) The U/D counter is, in effect, an integrator, which in the frequency domain has a transfer function of $\left[\frac{1}{S}\right]$.

2) The DAC has a transfer function (K_1) of [volts/bit].

3) The velocity loop composed of the amplifier, motor, and tachometer has a transfer function (K_2) of [RPM/volt]. (This assumes that the bandwidth of the velocity loop is much higher than the position loop.)

4) The encoder has a transfer function (K_3) of [bits/sec/RPM].

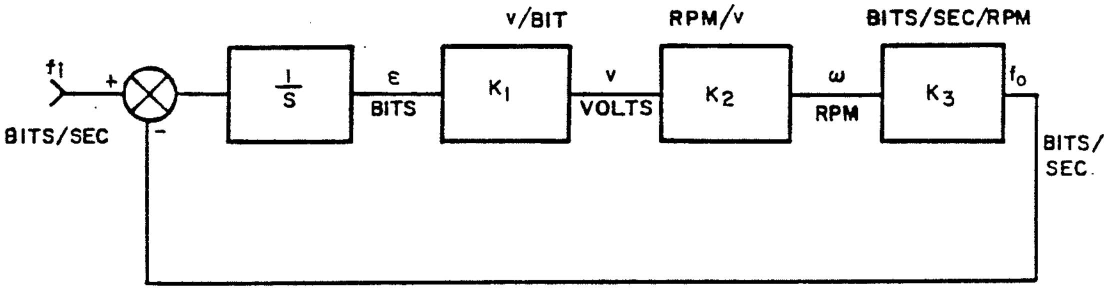


Figure A-2. Digital servo system, simplified block diagram.

Therefore, the transfer function of the position control loop is:

$$\frac{f_o}{f_i} = \frac{\frac{1}{S} K_1 K_2 K_3}{1 + \frac{1}{S} K_1 K_2 K_3}$$

$$= \frac{K_1 K_2 K_3}{S + K_1 K_2 K_3}$$

$$\frac{f_o}{f_i} = K_1 K_2 K_3 \frac{1}{\frac{1}{K_1 K_2 K_3} S + 1} \qquad \text{(A.1)}$$

This is a first order system of the form $\frac{1}{\tau S + 1}$; therefore its time constant is:

$$\boxed{\tau = \frac{1}{K_1 K_2 K_3}} \qquad \text{(A.2)}$$

Bandwidth (-3 dB)

$$\boxed{BW = \frac{1}{2\pi\tau}}$$

A.4 Input Functions

In general, the input to the position control system will be either a pulse train at a constant frequency or a pulse train which starts at a low frequency, increasing linearly to a higher frequency.

In the frequency domain, a constant input frequency represents a "step-function" and the linearly increasing frequency is a "ramp-function."

A.5 System Non-Linearities

As long as the system remains linear such that its response can be described by the transfer function of Equation A.1, analysis is relatively simple. However, there are limits in various parts of the system which must be taken into account. These limits and their effect on system performance will be considered where appropriate in the following discussion.

A.6 Natural Response of System to a Step-Function

Figure A-3 shows the natural response of the first order linear system of Figure A-2 to a step function (i.e., constant) input frequency (f_i), starting at $t = 0$ and ending at $t = t_2$.

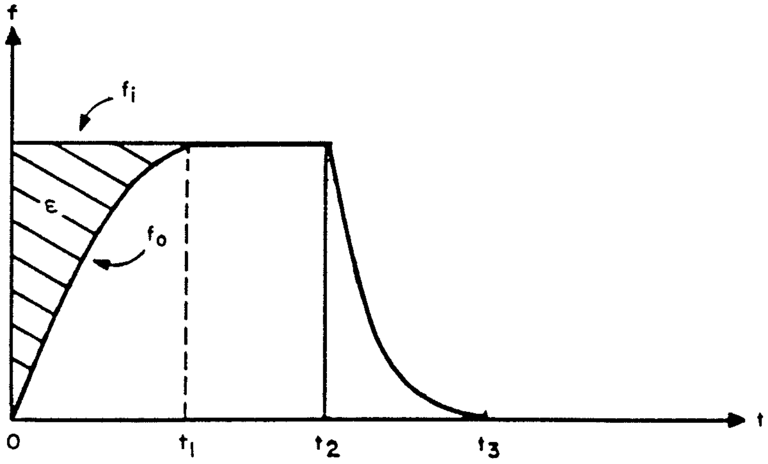


Figure A-3. Natural response of system.

From 0 to t_2:

$$f_{o_{0\to t_2}} = f_i \, (1 - e^{-t/\tau}) \tag{A.3}$$

From t_2 to t_3:

$$f_{o_{t_2\to t_3}} = f_i e^{-\frac{t - t_2}{\tau}} \tag{A.4}$$

The total displacement in terms of encoder pulses is:

$$\phi = f_i \, t_2 \qquad \text{[bits; pulses/sec, sec]} \tag{A.5}$$

In terms of displacement at the motor shaft it is:

$$\theta = \frac{\phi}{2N} \quad \text{[revolutions]} \quad (A.6)$$

where N is the encoder line count.

The acceleration (or deceleration) is the slope of f_o:

$$\alpha(t) = \frac{df_o}{dt} = \frac{f_i}{\tau} e^{-t/\tau} \quad (A.7)$$

Maximum acceleration occurs at $t = 0$;
Maximum deceleration occurs at $t = t_2$ and is:

$$\alpha(t)_{MAX} = \frac{f_i}{\tau} \quad (A.8)$$

The position error (input to DAC) is:

$$\varepsilon = \frac{f_o}{K_1 K_2 K_3} = f_o \tau \quad \text{[bits]} \quad (A.9)$$

During phase lock ($t_1<t<t_2$), $f_o = f_i$, so:

$$\varepsilon_{t_1 \rightarrow t_2} = \frac{f_i}{K_1 K_2 K_3} = f_i \tau \quad (A.10)$$

A.7 DAC Saturation Effect on Natural Response

The maximum range in terms of error (ε), of the DAC (K_1) is ±512 bits at a position gain setting of 0.02 volt per bit. The maximum ε decreases proportionately with increasing position gain.

When the DAC saturates there will be no further increase in output voltage and therefore no further increase in motor speed, as shown by Figure A-4.

The frequency at which saturation occurs may be derived from Equation A.9.

$$f_{SAT} = \varepsilon_{SAT} K_1 K_2 K_3 = \frac{\varepsilon_{SAT}}{\tau} \qquad \text{[bits/sec; bits, sec] (A.11)}$$

where $\varepsilon_{SAT} \leqq 512$

Therefore, for any input frequency (f_i) higher than f_{SAT}, the natural response will be as shown in Figure A-4.

Even though the DAC range is 512 bits, the U/D counter range is +32,767 to -32,768. Therefore, if the U/D counter range is not exceeded, there will be no resultant position error and the final displacement will still be: $\phi = f_i \ t_2$.

Since the U/D counter is represented by the integrator, clearly the content of the counter at any time is equal to the area under f_i minus the area under f_o, so:

$$\varepsilon = \int_0^t f_i \, dt - \int_0^t f_o \, dt \qquad \text{(A.12)}$$

By inspection of Figure A-4, the error is increasing continually until f_i stops at t_2 and then it decreases continually until it is zero at t_3. Obviously, therefore, the maximum error is at $t = t_2$, and it cannot exceed approximately 32,000 bits if there is to be no displacement error.

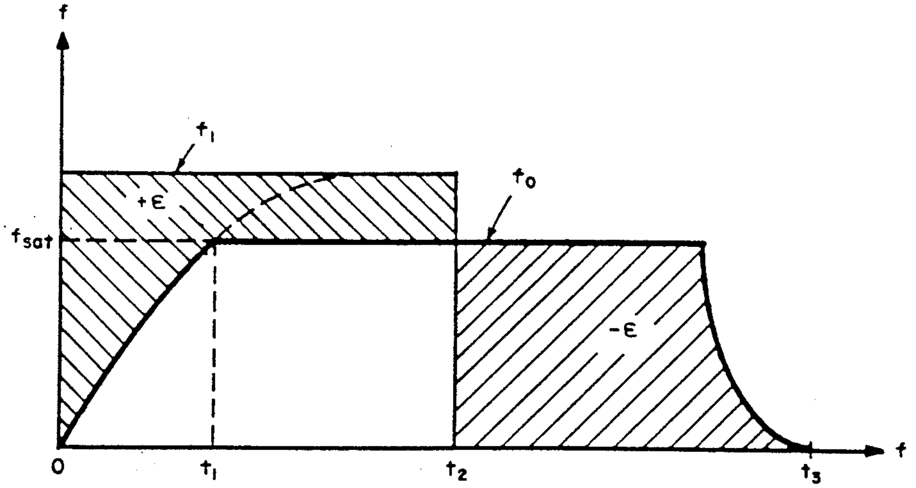


Figure A-4. Response with DAC saturated.

Since the area under f_0 from 0 to $t_1 \leqq 512$ bits, which is small compared to 32,000, the error at t_2 can be approximated by:

$$\varepsilon = (f_i - f_{SAT})\ t_2 \tag{A.13}$$

so, for any given input frequency the maximum duration without loss of position is:

$$t_{2MAX} = \frac{32{,}000}{f_i - f_{SAT}} \tag{A.14}$$

A.8 Amplifier Current Limiting

As stated previously the system must accelerate the motor to a given velocity and decelerate it to zero velocity. Acceleration or deceleration of an inertia requires torque input, as defined by the following:

$$T = J\alpha \qquad [\text{oz-in; oz-in-s}^2\text{, rad/sec}^2] \tag{A.15}$$

The torque delivered by a motor is directly proportional to its input current according to the following relationship:

$$T = K_T I \qquad [\text{oz-in; oz-in/A, A}] \tag{A.16}$$

Therefore, the acceleration or deceleration (α_L) during current limit (I_L) referred to the motor shaft is:

$$\alpha_L(\omega) = \frac{K_T\ I_L}{J} \qquad [\text{rad/s}^2\text{; oz-in/A, A, oz-in-s}^2] \tag{A.17}$$

Relating this to output frequency (i.e., encoder output) and converting rad/s to RPM:

$$\alpha_L(f) = \alpha_L(\omega) \times K_3 \times \frac{1\ \text{RPM/s}}{0.105\ \text{rad/s}^2}$$

where

$$K_3 = 2 \times \frac{N}{60} \qquad [\text{bits/sec/RPM; lines}] \tag{A.18}$$

so:

$$\alpha_L(f) = \alpha_L(\omega) \times \frac{1}{0.105} \times \frac{2N}{60}$$

$$\alpha_L(f) = 0.32 \frac{K_T I_L N}{J} \quad [\text{bits/s}^2;\ \text{oz-in/A, A, lines, oz-in-s}^2] \quad (A.19)$$

The effect on the system shown in Figure A-2 will be that the output frequency will follow a linear ramp as defined by Equation A.19 during current limiting, rather than the natural response. The system will be in current limiting whenever the natural response calls for an acceleration greater than that allowed by the current limit value. During acceleration, this could cause an overshoot in velocity. During deceleration, current limiting can cause the output to overshoot the desired position. Even though the output will reverse and return to the correct position with no loss of position information, this overshoot is often undesirable.

To achieve maximum acceleration without velocity overshoot as shown on Figure A-5, the position error (ε) must be equal to that value required for f_i when $f_o = f_i$. The position error as stated previously is the difference in area under f_i and f_o, so:

$$\varepsilon(t_1) = f_i t_1 - \frac{\alpha_L t_1^2}{2} \quad (A.20)$$

where for no overshoot

$$\varepsilon(t_1) = \frac{f_i}{K_1 K_2 K_3} \quad (A.21)$$

so:

$$\frac{f_i}{K_1 K_2 K_3} = f_i t_1 - \frac{\alpha t_1^2}{2} \quad (A.22)$$

and from Figure A-5,

$$t_1 = \frac{f_i}{\alpha_L} \quad (A.23)$$

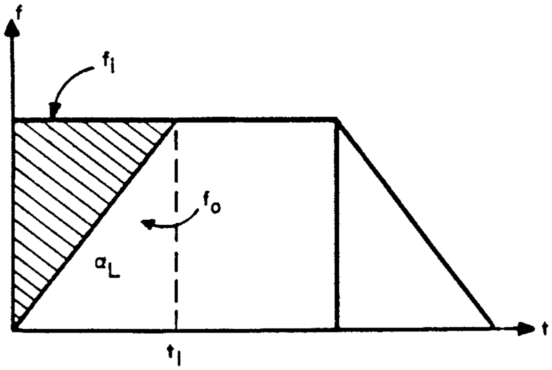


Figure A-5. Frequency response with current limiting.

from Equation A.2,

$$K_1 K_2 K_3 = \frac{1}{\tau}$$

Substituting this and Equation A.23 into Equation A.22

$$f_i\tau = \frac{f_i^2}{\alpha_L} - \frac{f_i^2}{2\alpha_L}$$

$$\tau = \frac{f_i}{2\alpha_L}$$

$$f_i = 2\alpha_L\tau \text{ (maximum for no overshoot) [bits/sec; bits/s}^2\text{, sec]} \quad (A.24)$$

It can be shown that deceleration follows the same trajectory with the same required error change as acceleration, so that Equation A.24 is also valid for no overshoot during deceleration.

A.9 Ramping

As noted previously, the effect of current limiting is to limit the maximum input frequency that can be applied without loss of position information or overshoot.

In order to attain higher frequencies, it is necessary to ramp the input frequency up and down such that the maximum acceleration of the motor shaft requires a current below the current limit value of the amplifier.

The response of the system of Figure A-2 with a ramp input is a ramp output having a following error that equals τ for $t \gg \tau$.

From Figure A-6, the acceleration and deceleration are given by

$$\alpha = \frac{f_{iMAX}}{t_1} \tag{A.25}$$

and this must be less than the α with current limiting, α_L, so:

$$t_{1MIN} = \frac{f_{iMAX}}{\alpha_L} \qquad \text{[sec; bit/sec, bits/sec}^2\text{]} \tag{A.26}$$

which is the minimum time that can be used to ramp the frequency to f_{iMAX} and, as before, f_{iMAX} must be a frequency achievable without saturating the DAC.

Substitute Equation A.19 into Equation A.26.

$$t_{1MIN} = \frac{f_{iMAX} J}{0.32\ K_T\ I_L\ N} \tag{A.27}$$

This frequency ramp could be generated by an analog method and therefore be a truly linear ramp, or it could be generated by a digital technique, in which case it would be a succession of discrete steps of frequency.

Recalling from Equation A.24 that the maximum frequency without overshoot is $f_i = 2\alpha_L \tau$, then the maximum incremental discrete frequency step is

$$\Delta f_{iMAX} = 2\alpha_L \tau \tag{A.28}$$

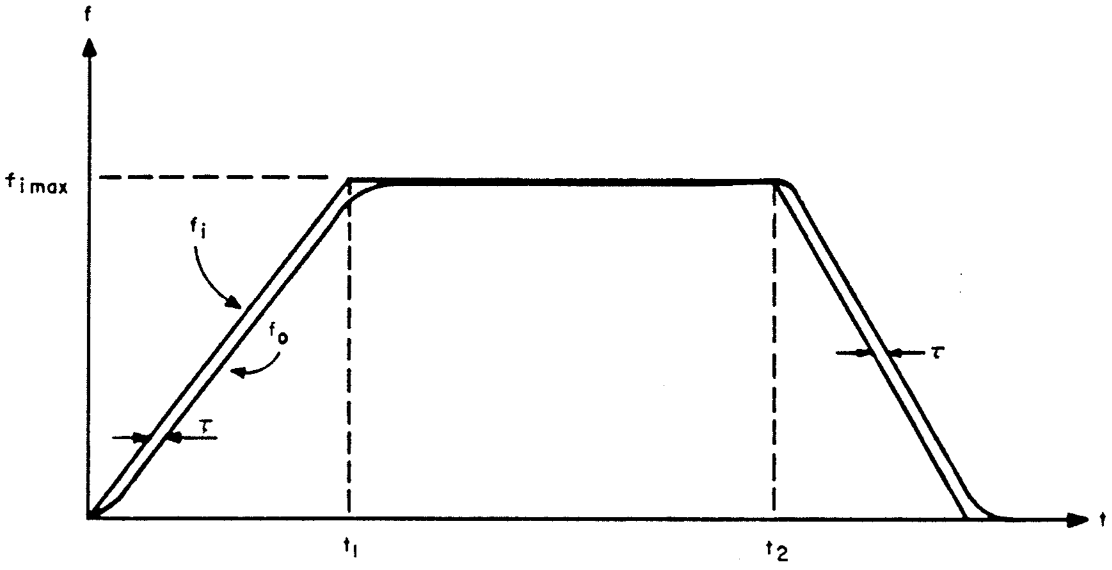


Figure A-6. System response with ramping.

Appendix B

CALCULATION OF MOTOR LOAD INERTIA

The motor load inertia is the total inertia seen by the motor resulting from the load, the motor armature, the transmission, and the torque limiting clutch.

The inertia of the chair and a 90 kg subject was used as reported by Tole et al [5] at 203 in-lb-sec^2. The resulting inertia seen by the motor is:

$$I_{cm} = (203)/G^2, \qquad \text{B.1)}$$

where G = the gear ratio of the transmission.

Therefore, the inertia seen by the motor due to the chair and subject is 16.571 oz-in-sec^2.

The inertia of the torque limiting clutch was approximated by measuring the dimensions of the clutch, and approximating its weight as 75% of steel to account for the internal components of the clutch. In this way the inertia of the clutch was approximated as the inertia of a cylinder.

The clutch has a diameter of 5.6 inches, a depth of 2" and weighs approximately 10 lb. The inertia of a cylinder about its central axis is given by : $I = mr^2/2$ B.2)

where: m = mass of the cylinder
r = radius of the cylinder

From B.2 the inertia of the torque limiting clutch was estimated to be 1.704 oz-in-sec^2.

The inertia of the motor armature is specified by the manufacturer as 0.240 oz-in-sec^2.

The inertia of the transmission could not easily be estimated, and manufacturers data was not available. Therefore, an estimate of 1.3 times the inertia of the torque limiting clutch was made. The estimate was based on the worm being somewhat smaller in diameter, but heavier than the clutch.

The result was a total estimated load inertia of 20.717 oz-in-sec^2 seen by the motor.

Appendix C

SELECTED SERVO MOTOR
AND
CONTROLLER CHARACTERISTICS

ROTATION MOTOR CHARACTERISTICS

Peak torque	350 in-lb
Continuous torque (TENV)	48 in-lb
Torque sensitivity	4.37 in-lb/Amp
Moment of inertia	0.015 in-lb-sec^2

SERVO CONTROLLER CHARACTERISTICS

	w/o fan mounted with fins vertical	fan cooled (30 cfm)
Continuous output current	12A	20A
Peak current (5 sec)	30A	30A
peak current (1 min)	20A	25A

Note: TENV stands for Totally Enclosed Non-Ventilated.

Appendix D

BIOPOTENTIAL OF THE HUMAN EYE AND THE EOG

The human eye generates a corneal-retinal electric dipole, the cornea being positive with respect to the retina. The dipole has both a constant component and a component that varies with light intensity the eye is exposed to. The Electro-Oculogram, or EOG, is a recording of the magnitude of the dipole as the eyes move in their sockets. The magnitude of the voltage measured by a pair of orthogonal electrodes placed around the eye is given by:

$$V = V_O \sin A \qquad \text{D.1)}$$

where: V is the voltage measured by the electrodes

V_O is the magnitude of the dipole

A is the angle between the line of sight and directly ahead

The EOG is useful for monitoring eye position, however factors such as noise from brain, nerve, and muscle activity, and the environment limit its accuracy to 1 to 2 degrees of eye movement. In addition, preparation of the electrode site, choice of electrodes, and ambient light effect the results. Therefore, care must be exercised in preparing the subject and establishing the test environment.

DIPOLE THEORY

(Extracted from [12], as reported by Xiao)

Since active tissue is electronegative with respect to an inactive or recovered area, a boundary exists. The boundary between active and inactive tissue can be represented by a dipole, and because environmental tissues and fluids can conduct current, potential fields will be established, as in Fig. D-1.

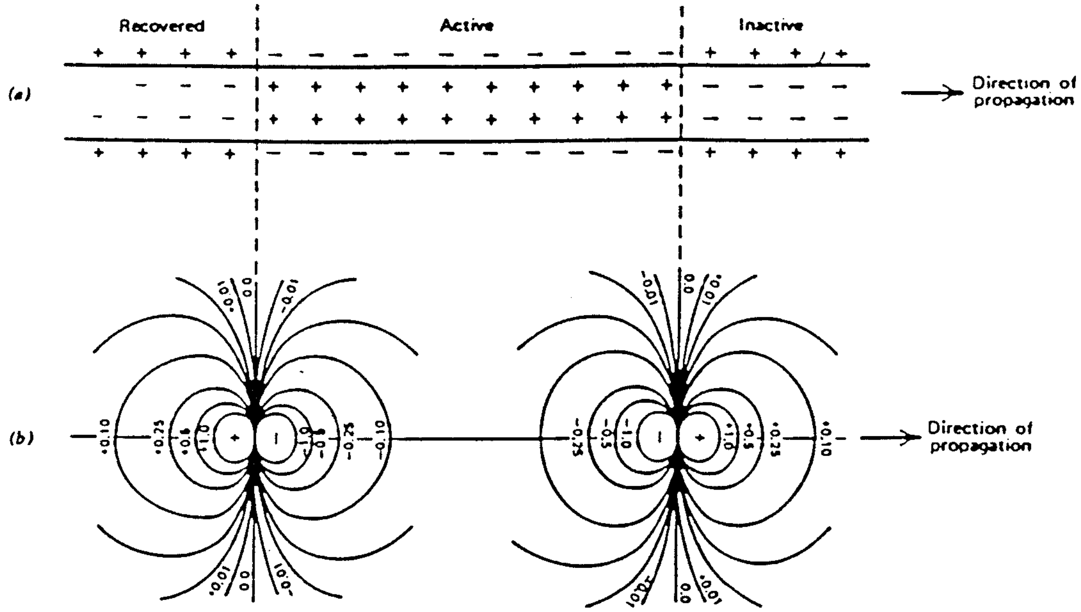
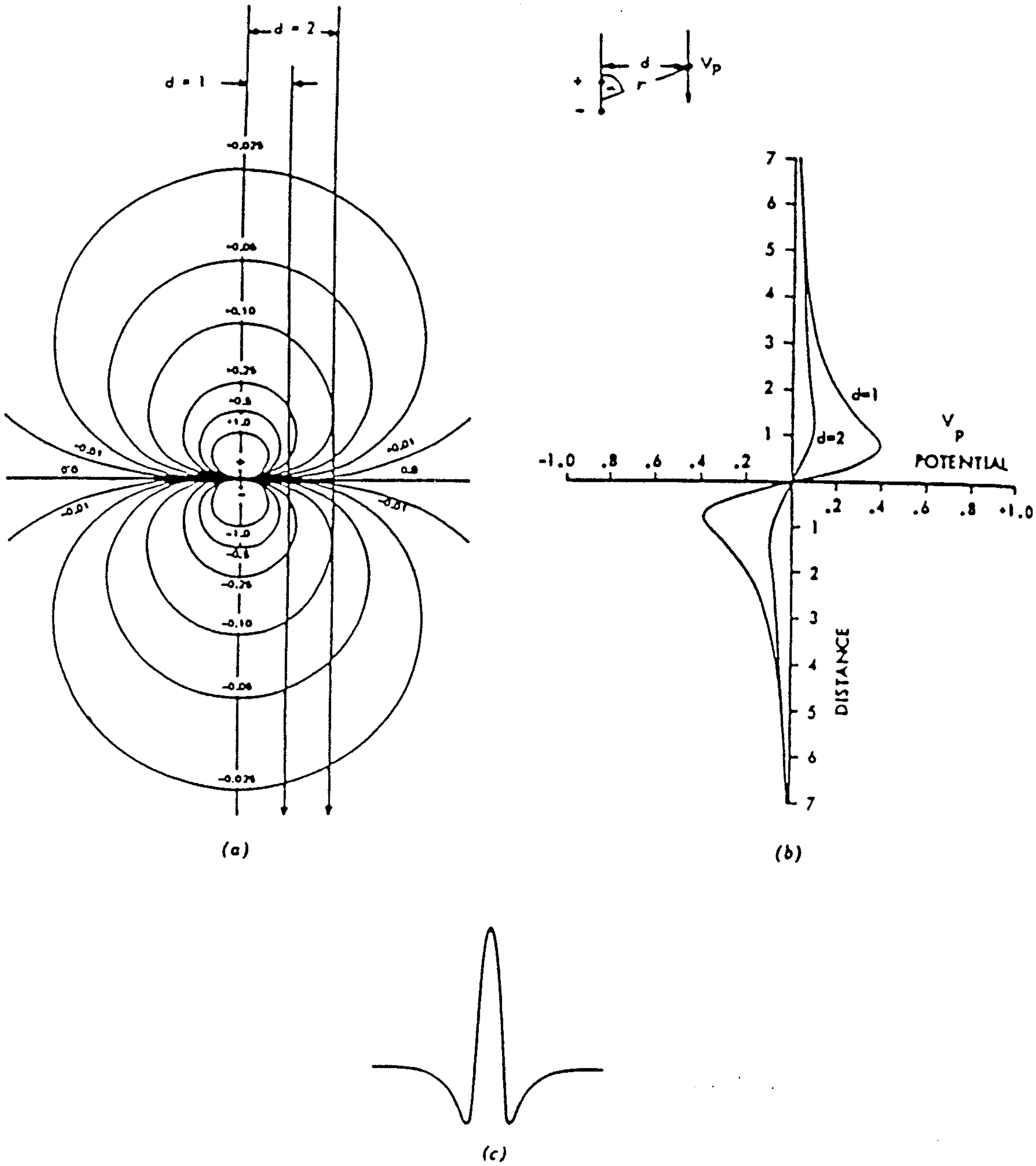


Figure D-1: Application of the concept to represent excitation and recovery.

The potential field surrounding a current dipole in an infinite volume conductor is represented in Fig. D-2. If the dipole moves along its axis, its field will accompany it, and the potential (Vp) at a nearby point will start to rise, then fall to zero, increase in the negative direction, then decrease as the dipole moves further away. Thus, a positive-negative biphasic wave will be described as in Fig. D-2 (d=1) as the dipole passes the measuring point. If the point is more distant, (d=2), the potential excursion will be in the same direction, but decreased in amplitude. This sequence of events describes what is obtained with 'monopolar' recording; that is, one electrode is near active tissue, the other is at a distance in a region of no potential change.

According to the dipole concept, propagated excitation is equated to a dipole traveling with its positive pole facing the direction of propagation. Thus, a nearby electrode will detect a positive-negative biphasic potential as excitation passes. Recovery (repolarization) is equated to a dipole with its negative pole facing the direction of propagation. Therefore, at a nearby point, the passage of recovery will be signaled by a negative-positive biphasic potential. If excitation occupied only a small amount of tissue, the potential waveform will be obtained in Fig. D-2 (c).



(a)

(b)

(c)

Figure D-2: The dipole and its potential field.
(a): potential distribution.
(b): potential encountered by exploring electrode moving along lines (d=1, d=2) parallel to the dipole axis.
(c): the waveform frequently encountered with monopolar recording.