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A digital motion control system

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A DIGITAL MOTION CONTROL SYSTEM

A Thesis

Presented to

**The Faculty of the Department of Mechanical Engineering
San Jose State University**

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

By

Matthew W. Chin

August, 1990

APPROVED FOR THE DEPARTMENT OF
MECHANICAL ENGINEERING

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Abstract

A DIGITAL MOTION CONTROL SYSTEM

by Matthew W. Chin

This report documents a thesis project that developed a PC based DC motor digital motion control system for San Jose State University's Mechanical Engineering Department. Experiments were conducted to determine the Open-Loop and Closed-Loop characteristics of the system. A theoretical model of the system was developed using the Open-Loop experimental results, and a computer simulation of the system is included in the report.

Acknowledgements

During the development of this report, I have learned that a thesis project demands a substantial amount of effort from various people. I wish to express my sincere appreciation for their help in supporting the development of this thesis project.

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1. Introduction

Since the publication of *A Nation at Risk*¹, a national report that warned of the deterioration of the American Kindergarten through 12 educational system, our educators have been continually concerned with the quality of education in the United States. Specifically in the area of engineering, the growing technology gap between industry and our higher educational system has alerted the engineering community to be proactive in tracking engineering curriculum with the latest technology trends. Technology in our universities vs. industry must be at an equivalent level in order for the student in engineering to successfully make the transition into industry, government, or academia.

In industry today, the technology of using microprocessors (MP) in motion control applications is expanding very rapidly². Early designs for motion control systems were analog in design, but the advantages of replacing analog circuits with digital integrated circuits (ICs) are overwhelming. Recently, a growing number of control systems have incorporated digital control in their designs. The advantages are shown in two main areas: manufacturing and product capabilities.

From perspective of manufacturing, digital circuits are easier to manufacture automatically while analog components must be manually assembled. By increasing the number of components that are automatically assembled, the final product would be reduced in cost and improved in

reliability because of several reasons:

- Automation costs amortized over several years are often less than labor costs per hour when fringe benefits are included.
- Automatic machinery work a larger share of the time at their assigned task.
- Automatic machinery repeat operations with higher percentage of good assemblies because they are not prone to fatigue or lack of attention.

Digital components allow for a control system implementation with fewer components. Again, this would result in reduced cost and improved reliability.

From the perspective of product features, adding the use of MP to motion control systems enhances the system's capabilities. In control applications, the main computer would be free to perform other tasks while the MP handles the motion control task that require fast response. For example, when a vision system is used in conjunction with a pick and place robot the computer must perform several tasks almost simultaneously:

- The vision system must be able to analyze the visual data.
- The robot arm must be moved to a proper location.
- The robot arm must be moved to a proper orientation.
- The part must be picked up.
- The computer must verify that it has picked up the correct part.
- And the part must be placed in the proper location.

These complex tasks demand extensive data processing and signal filtering. A single processor may not be able to provide satisfactory response times in such an application.

The availability of a MP control system also enables the control designer more flexibility in design³. For example, most motion control applications can be fulfilled by the use of position control. With MP control, you can close the position loop and perform the compensation filtering. There is no need for velocity feedback nor for an analog compensation. Other features in MP control systems may include point-to-point positioning, jogging, velocity control, acceleration control, axis coordination, and programmable digital filter parameters. Future trends with MP control systems include the ability to perform complex control algorithms, adaptive control applications, and feedforward control applications.

In summary, digital motion control technology is advancing rapidly, and our engineering school curriculum will need to address these advancements. This report documents the work in developing a digital motion control laboratory. The objectives for this laboratory are as follows:

- Determine the Open-Loop characteristics of the system using the frequency response method.
- Define the Closed-Loop behavior of the system experimentally.
- Develop a computer simulation of the Closed-Loop system using the Open-Loop test results that accurately depicts the behavior of the actual system.

In Chapter 2, the materials list and the experimental setups are fully described should future replication of the tests become necessary. Each of the control system elements are also described to provide an understanding of component limitations. In Chapter 3, the system components are modeled mathematically by the use of transfer functions. The transfer function model

is then used to create a computer simulation of the system described in Chapter 4. Finally, Chapters 5 and 6 presents the data collected from the Open-Loop tests, the Closed-Loop tests, and the computer simulations.

It is expected that this system will be used for hands-on training of future engineering students on the use of digital ICs for position control systems.

2. Materials and Methods

The system components consists of the following components
(see Figure 1):

Hardware:

- IBM PC Compatible Computer with Hercules Video Card Adaptor
- 512K Bytes memory
- GALIL DMC/400-10 IBM PC Motor Controller⁴
- GALIL ICB 930 Interconnect Board
- GALIL AMP 10/75 PWM Servo Amplifier
- GALIL MOTOR 50/1000 50 oz-in DC Motor with Encoder
- GALIL DMM-900 Motion Monitor
- Hewlett - Packard 6002 Variable DC Power Supply
- Hewlett - Packard 7402A Chart Recorder
- Hewlett - Packard 203A Function Generator
- Tektronix Oscilloscope
- Trans-Tek 600-000 angular transducer
- Cables

Software:

- DOS 2.0 system
- GALIL SDK-400-10 Programming Disk

FIGURE 1: Experimental System Setup

The functional elements of the digital control system are described by the block diagram in Figure 2. The main system elements are:

- PC Host Computer
- MP Controller
- Digital-to-Analog Converter (DAC)
- Amplifier
- DC Motor
- Position Feedback Encoder

Description of System Elements⁵

PC Host Computer

An IBM PC Compatible computer is used to interface with the microprocessor controller. Commands can be entered either interactively or programmatically. Running the SDK-400 software on the Host computer, commands are available to:

- Specify profiled motion
- Specify position control
- Specify velocity control (Speed, Direction, Acceleration)
- Specify digital filter parameters for system compensation
- Specify error and torque limits
- Interrogate for position data
- Interrogate for Motor status

FIGURE 2: Block Diagram of the Digital Motion Control System

Included with the software is a guide which steps through the assembly and analysis of a simple servo system. The software also provides a terminal emulator for interactive communications, and a storage scope for displaying snap shots of motion profiles.

Microprocessor Controller

The controller is a GALIL DMC-400 controller card which is installed on the IBM PC Bus inside the host computer. The DMC-400 controls only one axis motion. The output of the card produces a +/- 10 volts analog signal to the power amplifier. The controller performs the following basic functions:

- Receives commands and reports status
- Generates the position profile
- Reads the position feedback and determines the position error
- Performs the digital filtering
- Sends the motor command

Also included with the controller is a hardware input and output protection line for various error and mechanical limit conditions.

Digital-to-Analog Converter

The Digital-to-Analog converter is located on the DMC-400 controller board. Its function is to convert the digital output of the controller to the +/- 10 volts analog signal that drives the amplifier. For the DMC-400, the DAC converts an 8-bit number.

Amplifier

The amplifier is a pulse-width-modulated servo amplifier designed for DC servo motors. The amplifier is fully protected against the following faults:

- Output shorts
- Over/Under voltage
- Wrong supply connection
- Insufficient load inductance
- Over Temperature

A terminal which generates a signal for monitoring motor current is also available on the amplifier.

DC Motor

The motor used is rated as a 50 oz-in DC motor. It has a 200 oz-in peak torque limit and a 3750 RPM maximum speed. The encoder is included with the motor.

Encoder

The encoder is a 1000 pulse per revolution TTL-level incremental encoder. The encoder generates a count which is proportional to the motor's angular position. Because of its quadrature sensing, the position is resolvable to 4000 counts per revolution.

Description of the System Connections

- The GALIL DMC 400-10 motion controller card is installed inside the PC in any PC Bus slot. Two keyed flat ribbon cables connect the controller card to the ICB 930 Interface card and DMM 900 Motion monitor card.
- The motor command pins from the interface are connected to pins 6 and 10 on the 10/75 Amplifier.
- Amplifier output pins 1 and 4 are connected to the motor armature positive and armature negative terminals respectively.
- The power supply is connected to the amplifier input via pins 2 (common) and 3 (positive).

Description of the System Operation

The microprocessor controller receives commands from the PC. These commands are the specific motion control commands. The controller also monitors the position feedback to determine position error. Using the position error information, the controller activates a digital filter and outputs a command to the motor. This command is converted from a digital signal to an analog signal via the Digital-to Analog Converter (DAC). The analog signal is then applied to the amplifier which drives the motor. The motor position is sent back by a feedback signal generated from the motor encoder which generates 4000 counts per revolution. This output returns to the microprocessor via the position decoder and closes the control loop.

Description of Testing Methods

Open-Loop Testing

The Open-Loop test setup is shown in figure 3. Open-Loop testing was performed to determine the transfer function of the amp-motor combination. The experimental determination of the amp-motor transfer function was required because of the unknown nature of the motor system moment of inertia and uncertainty of motor parameters given by the manufacturer's data sheet. With this data and the model of the amp-model transfer function described in Chapter 3, the amp-motor gain constant (K_{mv}) and mechanical time constant (T_m) can be determined to characterized the amp-motor combination. Typical Open-Loop test data collected is shown in Appendix A.

In Open-Loop testing, the input to an open-loop control system is independent of the output of the system. For this experiment, a waveform generator was used to input a sine wave into the amplifier which drives the motor. The angular transducer is coupled to the motor to provide an analog signal output. The input signal and output signal were plotted on a chart recorder. The frequency of the sine wave was varied keeping the input voltage constant, and several sets of input and output signals were recorded.

Given a steady-state response to a sinusoidal input, transient effects will not be seen. Only the amplitude of the output will differ from that of the input, and a phase shift may be present.

FIGURE 3: Open Loop Testing Setup

Closed-Loop Testing

The Closed-Loop test setup is shown in figure 1. Closed-Loop testing was performed to choose the digital filter parameters that yield the best motor response to a given desired position input. The digital filter parameters were also altered and the system's responses were observed

In Closed-Loop testing, the error between the actual response and the desired response of the system is used to alter the system's behavior to achieve better accuracy of a response to a given input. For this experiment, a power supply was connected to the amplifier input, and the signal generated by the amplifier to drive the motor was controlled by the microprocessor. The encoder was connected to the microprocessor to feedback the position error signal for digital filtering. The output signal from the rotary transducer was plotted with the chart recorder. Several step responses were recorded with varied digital filter parameters.

3. System Model

In order to understand the experimental system, a quantitative mathematical system model must be derived. The dynamic nature of motion control systems usually yield descriptive equations in the form of differential equations. These equations can also be represented in a linearized form with the use of Laplace transforms. Once this model is defined, a computer simulation of the system can be easily constructed to analyze the system's behavior.

Given a motor control system driving a load, the system can be characterized and modeled using analytical combined with experimental techniques. First, a sine wave is used to measure the open loop frequency response of the amplifier-motor-load combination. From the results of this testing, a Bode plot showing the frequency response of the system can be generated. Matching the theoretical amplifier-motor-load transfer function to the experimental results, the gain constant (K_{mv}) and the mechanical time constant (T_m) are determined by curve fitting. This curve fit is accomplished by mapping the magnitude of the amplifier-motor transfer function in the following equation to the experimental data expressed in the Bode plot.

$$|G(\omega)| = \frac{K_{mv}}{\omega (1 + (\omega T_m)^2)^{1/2}} \quad (1)$$

where

K_{mv} = The gain constant for the Amp and Motor combined

T_m = Mechanical time constant in seconds

$\omega =$ Frequency in radians/seconds

$|G(\omega)| =$ Magnitude Contribution.

The results of this mapping is shown in Chapter 4, figure 5. Subsequently, all component transfer functions are then known, and the complete system transfer function can be determined for either open loop or closed loop analysis/simulation.

The system components in Laplace transform notation are shown in figure 4. Using Laplace transformations, the system is reduced to a linear approximation which variables of interest are easily solvable. Each of the individual component transfer functions are derived as follows⁶:

Digital Filter

Internal to the Galil motion controller is a digital filter in Z-transform notation.

$$D(z) = \frac{G_n (z - Z_r)}{(z - P_l)} \quad (2)$$

where

$G_n =$ The Gain programmable term.

$Z_r = ZR/256$ The Zero programmable term.

$P_l = PL/256$ The Pole programmable term.

FIGURE 4: Digital Motion Control System Transfer Function

Zero Order Hold

The zero order hold term is included to model the update delay in a digital system when the output amplitude is held constant during the sampling period (T). The signal is then said to be held constant by a zero order hold. Typical sample time: T = 0.0005 sec.

$$Z(s) = \frac{1 - e^{-sT}}{s} \quad (3)$$

Digital to Analog Converter

The digital to analog converter (DAC) converts the 8 bit motor command word from the DMC 400 into an analog voltage signal. The gain (Kd) of the DAC is determined as follows.

$$\text{Gain} = \frac{\text{Voltage range (volts)}}{2^N \text{ (bits or counts)}} \quad (4)$$

$$\begin{aligned} K_d &= \frac{-10 \text{ to } +10 \text{ volts}}{-128 \text{ to } +128 \text{ cts}} \\ &= 20/256 \\ &= 0.0781 \text{ volts/ct.} \end{aligned} \quad (5)$$

Amplifier - DC Motor

Frequency response measurements were taken on the Amplifier and Motor combination. Therefore, the model depicts a transfer function that includes the amplifier, motor, load, and position contributions to the system.

$$M(s) = \frac{K_{mv}}{s(s T_m + 1)} \quad (6)$$

where

K_{mv} = The gain constant for the Amp and Motor combined (K_a & K_{mc}).

T_m = Mechanical time constant in seconds.

Note: Contribution of the electrical time constant to the system is neglected since $T_e < T_m$ ⁷.

$$\begin{aligned}T_e &= L/R \\&= .0025 / 1.59 \\&= .00159 \text{ seconds} \\T_m &= .0236 \text{ seconds (see CH 5)}\end{aligned}$$

where

L = Armature Inductance (henries)

R = Armature Resistance (ohms).

Using the equation (5), the phase angle and magnitude of the amp-motor combination can be derived to yield⁸:

$$\phi(\omega) = -\pi/2 - \tan^{-1}(\omega T_m) \quad (7)$$

$$|G(\omega)| = \frac{K_{mv}}{\omega (1 + (\omega T_m)^2)^{1/2}} \quad (8)$$

where

ω = Frequency in radians/seconds

ϕ = Phase Angle Contribution

$|G(\omega)|$ = Magnitude Contribution.

From the experimental data, the magnitude at each frequency can be determined by the ratio of the voltage amplitudes. The phase shift between the input and output sine waves will display the phase shift.

$$|G(\omega)|_{\text{exp}} = 20 \log (A_{\text{out}}/A_{\text{in}}) \quad (9)$$

where

$$|G(\omega)|_{\text{exp}} = \text{Magnitude in decibels.}$$

$A_{\text{out}} =$ Output Sine wave voltage amplitude (equivalent to radians)

$A_{\text{in}} =$ Input Sine wave voltage amplitude.

Incremental Encoder

The incremental encoder is a 1000 line density encoder with quadrature sensing. Therefore, the feedback gain is equivalent to:

$$\begin{aligned} K_p &= \frac{4 * 1000}{2 \pi} & (10) \\ &= 636.6 \text{ counts/radians.} \end{aligned}$$

4. Computer Simulation Model

A computer simulation model is derived to approximate the closed loop behavior of the motor control system with digital filter compensation. This simulation is useful to investigate the behavior of the system. Assuming that the model and simulation are relatively accurate, the computer simulation can be used to:

- Analyze system performance under different conditions.
- Analyze the system to help with future design decisions.
- Evaluate the system without the need of real experimentation that may be costly. For the purposes of this report, the simulation will be used to analyze the system under different digital filter values. The simulation results are then compared to the actual system response.

First, the system model must be transformed from the s -domain to the z- domain, a discrete-time approximation of the system. Once transformed into the z domain, the system can be represented by state equations in matrix notation⁹.

$$\dot{\underline{x}} = [\underline{A}]\underline{x} + [\underline{B}]\underline{u} \quad (11)$$

The discrete-time approximation divides the time axis into small increments and the state variables are evaluated at the successive intervals.

Taking the s - domain model, the terms are combined into two component blocks.

$$D(z) = \frac{K(z - Z_r)}{(z - P_l)} \quad (12)$$

and

$$G(s) = K_d K_p Z(s) M(s) \quad (13)$$

Transforming G(s) into the z-domain,

$$G(z) = K_d K_p [1 - z^{-1}] Z[M(s)/s] \quad (14)$$

$$= \frac{K_d K_p K_{mv} [(aT - 1 + e^{-aT})z + K_o]}{a(z - 1)(z - e^{-aT})} \quad (15)$$

where

$$a = 1/T_m$$

T = Sampling time interval (ts)

K_o = Combined for the simplification of the equation $(1 - aTe^{-aT} - e^{-aT})$.

Combining G(z) with the digital filter D(z), the closed loop transfer function is represented by

$$\frac{Q_c(z)}{U(z)} = \frac{D(z) G(z)}{1 + D(z) G(z)} \quad (16)$$

Substituting D(z) and G(z) into the equation (15),

$$\frac{G_n (z - Z_r) K_d K_p K_{mv} [(aT - 1 + e^{-aT}) z + K_o]}{a \{(z - P_l) (z - 1) (z - e^{-aT}) + G_n (z - Z_r) K_d K_p K_{mv} [(aT - 1 + e^{-aT}) z + K_o]\}} \quad (17)$$

Simplifying and equating to Mason's gain formula¹⁰,

$$\frac{b_2 z^2 + b_1 z + b_0}{z^3 + a_2 z^2 + a_1 z + a_0} \quad (18)$$

yields

$$b_2 = G_n K_{mv} K_d K_p T_m (aT - 1 + e^{-aT})$$

$$b_1 = G_n K_o K_{mv} K_d K_p T_m - b_2 Z_r$$

$$b_0 = -K_o G_n K_{mv} K_d K_p Z_r T_m$$

$$a_2 = b_2 - P_l - 1 - e^{-aT}$$

$$a_1 = b_1 - P_l + (1 - P_l) e^{-aT}$$

$$a_0 = b_0 - P_l e^{-aT}.$$

Thus, in matrix form,

$$X_{(k+1)} = \begin{bmatrix} -a_2 & 1 & 0 \\ -a_1 & 0 & 1 \\ -a_0 & 0 & 0 \end{bmatrix} X_{(k)} + \begin{bmatrix} b_2 \\ b_1 \\ b_0 \end{bmatrix} U_{(k)} \quad (19)$$

$$\Theta_{c(k)} = [1 \quad 0 \quad 0] X_{(k)} \quad (20)$$

where

$X(k)$ = state variables

$U(k)$ = input commands.

Appendix B shows a program written using the previous equations to simulate the motor control system.

5. Experimental and Simulation Results

Open-Loop Test Results

Data was obtained at six different frequencies. A Bode diagram plotting the results is shown in figure 5. Using the previously described theoretical transfer function,

$$|G(\omega)| = \frac{K_{mv}}{\omega(1 + (\omega T_m)^2)^{1/2}}$$

values for the mechanical time constant (T_m) and amp-motor gain constant (K_{mv}) were chosen by trial and error to best fit the experimental data.

Table 1 Open-Loop Test Results

Frequency (radians/sec)	$ G(\omega) _{\text{experimental}}$ (radians/volt db)	$ G(\omega) _{\text{theoretical}}$ (radians/volt in db)
9.8	13.52	15.68
13.07	11.13	13.01
18.85	9.83	9.44
31.42	3.41	3.89
62.83	-6.2	-5.28
128.49	-15.7	-16.53

$T_{m\text{fitted}} = 0.0236$ seconds

$K_{mv\text{fitted}} = 61.2$ (see Appendix D for a sample verification calculation).

The empirical curve fit was done on a Microsoft Excel™ spreadsheet. Values for $|G(\omega)|_{\text{theoretical}}$ were calculated at various values of T_m and K_{mv} . With each trial of $|G(\omega)|_{\text{theoretical}}$ values, the standard deviation of the absolute values of the difference between $|G(\omega)|_{\text{theoretical}}$ and $|G(\omega)|_{\text{experimental}}$ over the frequency range was then calculated.

Figure 5: Bode Diagram - Open-Loop Test Results

Trials were performed with efforts on minimizing this standard deviation of the differences. The value for this standard deviation of differences at the fitted K_{mv} and T_m values resulted in a value of 0.26 rads/v db over the range of frequency . It should be noted that 0.26 rads/v db translates to 1.03 radians/volt which represents a potentially significant magnitude error.

Closed-Loop Test Results

The digital filter parameters were initially chosen by trial and error experimentation on the closed-loop test setup. The values were chosen on the basis of trying to find the combination yielding a minimum overshoot response. The digital filter parameters for this stable response were chosen at

$$GN = 8 \quad ZR = 247, \quad PL = 0.$$

The position input U (P_r) chosen was set at 0 to 20 counts in a square wave pattern. The resulting response is shown in figure 6. Subsequently, system response data was collected when the Gain value was increased to 20, and when the Zero value was decreased to 150. The results are shown in figures 7 and 8, respectively.

Computer Simulation Results

Using the Open-Loop fitted values for T_m and K_{mv} , simulated closed loop response data were taken with the digital filter parameters set for a stable system, increased gain value = 20, and decreased zero value = 150. The results are shown in figures 9, 10, and 11, respectively.

CASE A

GN 8
ZR 247
PL 0

Figure 6: Closed-Loop Test Result - Stable system

CASE B

GN 20
ZR 247
PL 0

Figure 7: Closed-Loop Test Result - Increased Gain

CASE C

GN 8
ZR 150
PL 0

Figure 8: Closed-Loop Test Result - Decreased Zero

Figure 9: CASE A Simulation - Stable System

Figure 10: CASE B Simulation - Increased Gain

Figure 11: CASE C Simulation - Decreased Zero

6. Discussion

Open-Loop Test Results

From the Open-Loop test results, the theoretical motor transfer function appears to fit the experimental results reasonably well. The only exception is the non-linear behavior observed at the low frequency range of 10 to 15 radians per second. Perhaps at the lower frequencies, friction effects may dominate the system's behavior. Note that since the basis of the computer simulation model is based upon the amp-motor transfer function obtained from the open loop testing, correlation of low frequency simulation results to actual system response may be invalid.

It is also interesting to note that the mechanical time constant T_m , which takes into account the motor's load inertial and frictional characteristics, experimentally is seen to be an extremely sensitive system parameter. While varying T_m , the Bode plot changes drastically. Over time, the behavior of a motor control system may alter significantly if frictional characteristics or load variations change.

Closed-Loop Test Results

Examining the closed-loop test results, the effect of increasing the Gain value (CASE B) or decreasing the Zero value (CASE C) can be evaluated when compared with the system's response to the set of stable filter parameters (CASE A). Increasing the Gain shows a response which exhibits an overshoot of the desired position setpoint, but demonstrates a potentially

quicker settling time. Intuitively, this overshoot behavior may be undesirable depending on the system application. Moreover, the vertical slope of the response towards the setpoint is seen to be steeper with the increased Gain value. A faster rise time is observed for the system to first reach the setpoint position.

Decreasing the Zero value appears to decrease the damping of the system as shown by the longer settling time of the response. Again, the slope of the vertical rise is slightly steeper depicting a faster response, but a decrease in stability as shown by the overshoot and underdamped behavior.

Computer Simulation Results

Comparing the Simulation responses with the actual closed loop data, observations of the effects on increasing Gain and decreasing Zero values are identical. However, the faster rise response is shown to be more pronounced in the simulated response than the actual closed loop response. The resolution of the time axis or position axis seen in the simulated response data may not be resolvable for the purposes of a detailed accurate comparison to the actual system. Other exceptions include encoder position hunting or pulse-width-modulated amplifier ripple caused by effects of nonlinear switching. The computer model has not been implemented to simulate these behaviors.

7. Conclusions

This report provides a specific example of a microprocessor motion control system that is commercially available in the industry today. A test setup has been implemented to demonstrate classical closed loop control behavior. With open-loop frequency response testing, experimental system characteristics were obtained to be used in a computer simulation of the system. The simulation appears to predict the behavior of the system's response quite well. The only exceptions to the behavior prediction are the lack of resolution of the obtained response time data from the experimental system, and the lack of resolution of the discrete response data because of its finite nature. With more precise recording methods, the simulation time response data could be compared with the actual experimental system data. Other errors were not addressed in this paper. The errors include equipment calibration error, measurement noise, system environment noise, and component resolution.

Overall, this control system demonstrates a typical application of a digital control system which allows the engineering student to vary coefficients of a digital filter to tune the system to a particular motor/load condition. With the advent of lower cost computers, the engineering student will find such systems becoming prevalent in today's control industry applications. The advantages of affordable flexible control systems cannot be overlooked.

8. Recommendations

For further studies, the motion control system described in this report may be enhanced in many ways. More specifically, the system model can be extended to evaluate:

- Disturbance rejection
- Adaptive control
- Integrator digital filter compensation
- Alternative control algorithms
- Simultaneous motion applications
- Robotic or Automation applications

If the system is integrated to perform control tasks for a specific application, it is also highly recommended that limit switches are installed on the system for safety considerations. Unforeseen system behaviors while operating any control system may cause damage to equipment or even jeopardize user safety if limit switches are not installed.

Appendices

- A. Open-Loop Testing Response Data**
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Appendix A: Open Loop Test Response Data

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Appendix B: Closed-Loop Simulation Program

program Matrix;

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{First Release 5/14/90}

{This program simulates the closed loop behavior of a motor }
{position control system w/ inertial using system parameters derived }
{from experimental results. The discrete-time evaluation of the time }
{response is derived from first taking the Z-transform of the system }
{transfer function, and then relating the constants to Mason's gain }
{formula in Matrix notation. }

var

A: array[1..3, 1..3] of real;

xnew, xold, B, C, D: array[1..3] of real;

n, m, i: integer;

Ko, Kd, Kp, ts, tm, t: real;

Kmv, Pi, Ct: real;

Gn, Zr, Pl, Pr: real;

temp: real;

begin{main program}

{Initialize Gain & Digital Filter Parameters}

Gn := 8;

{Gain Value}

Zr := 247;

{Zero Value}

Pl := 0.0;

{Pole Value}

Pr := 20.0;

{Position Relative in Counts}

{Initialize Transfer Function Constants Derived From Experimental Results}

Kmv := 61.2;

{Gain Constant of Amp-Motor-Inertial System}

tm := 0.0236;

{Mechanical Time Constant}

Appendix B: Closed-Loop Simulation Program

{Constants}

Kd := 0.0781;

{X'fer Fcn for D/A}

Pi := 3.1415926;

{Value for π }

Ct := 4000.0;

{Encoder Quadrature Counts}

ts := 5.0E-4;

{Sampling Time}

Kp := Ct / (2.0 * PI);

{Gain constant for Encoder}

{Derive Zero & Pole Filter Parameters}

Zr := Zr / 256.0;

Pl := Pl / 256.0;

{Clear Matrix Values Before Setting Initial Values}

i := 1;

for n := 1 to 3 do

begin

for m := 1 to 3 do

begin

A[n, m] := 0;

end;

B[n] := 0;

C[n] := 0;

D[n] := 0;

xold[n] := 0;

xnew[n] := 0;

end;

{Calculate Simulation Matrix Numerator Parameters}

Ko := (1 - (ts / tm) * exp(-ts / tm) - exp(-ts / tm)) * tm;

B[1] := (Gn * Kmv * Kd * Kp * tm) * ((ts / tm) - 1 + exp(-ts / tm));

B[2] := ((Ko * Gn * Kmv * Kd * Kp) - B[1] * Zr);

B[3] := -Ko * Gn * Kmv * Kd * Kp * Zr;

Appendix B: Closed-Loop Simulation Program

{Calculate Simulation Matrix Denominator Parameters}

```
A[1, 1] := -B[1] + P1 + 1 + exp(-ts / tm);  
A[2, 1] := -B[2] + P1 + exp(-ts / tm) * (P1 - 1);  
A[3, 1] := -B[3] + exp(-ts / tm) * P1;  
A[1, 2] := 1.0;  
A[2, 3] := 1.0;
```

{Set Step Response Matrix}

```
for n := 1 to 3 do  
  begin  
    D[n] := B[n] * Pr;  
  end;
```

{Calculate the values of the state variables at the successive time intervals of ts}

```
while i <> 50 do  
  begin
```

{Clear C Matrix for Next Calculation}

```
  for n := 1 to 3 do  
    begin  
      C[n] := 0;  
    end;
```

```
  for n := 1 to 3 do  
    begin  
      for m := 1 to 3 do  
        begin  
          temp := A[n, m] * xold[m];  
          C[n] := C[n] + temp;  
        end;  
      end;
```

{Save Xold = Xnext for Next Iteration}

```
  for n := 1 to 3 do  
    begin  
      xold[n] := C[n] + D[n];  
      xnew[n] := C[n] + D[n];  
    end;
```

Appendix B: Closed-Loop Simulation Program

{Output Current Position & Increment to Next Time Step}

```
writeln(xnew[1], xnew[2], xnew[3]);
```

```
i := i + 1;
```

```
end
```

```
end.{main program}
```

Appendix C: Sample System Operation Instructions

1. Make sure the system is first in the power-off condition. While power is not applied, check all connections as described in the *Materials and Methods* portion of this report.
2. Establish communications with the controller by first powering up the IBM PC compatible. Enter the directory named, C:\MATTC and startup the command file named SDK.COM.
3. Once the software is loaded, you can easily follow the menus to start the terminal emulator/scope portion of the system. Type the command:

OE1 <return>

4. Next, power up the power supply to the motor amplifier. For best results, the gain of the amplifier should be set as low as possible. The power supply should be set to deliver no more than 19.7 volts.
5. When the control loop is closed, there is a 50% chance that the polarity of the system is wrong. This condition is indicated by a red lit LED. If this condition exists, reverse the motor wires or encoder channels. Once the polarity has been corrected, reset the system by typing the command:

RS <return>

6. Now you can begin to apply the following sample applications to the motor control system:

Appendix C: Sample System Operation Instructions

Set Compensation Parameters:

GN 8	<return> set Gain value
ZR 247	<return> set Zero value
PL 0	<return> set Pole value

Profiled Move:

PR 10000	<return> set relative position
SP 20000	<return> set speed
AC 100000	<return> set acceleration
BG	Begin Motion

Absolute Position

PA 7000	<return> set absolute position
BG	Begin Motion

Step Response Motion:

PR 20	Move 20 encoder counts
WT 200	Wait 200 ms between steps
AC 1000000	Set max acceleration limit
RR	Repeat Motion
BG	Begin Motion

To Interrogate Position:

TP	Tell Position of the encoder
----	------------------------------

To Change Sampling Time:

TM n	where $n > 500 \mu\text{sec}$
------	-------------------------------

To Repeat Motion:

RR	repeats move indefinitely
----	---------------------------

To Stop Motion:

ST	Stops Motion
----	--------------

Appendix D: Sample Calculation: Verification of Tm and Kmv values

From Chapter 3, equations (7) and (8)

$$|G(\omega)| = \frac{K_{mv}}{\omega (1 + (\omega T_m)^2)^{1/2}} \quad (D1)$$

$$\phi(\omega) = -\pi/2 - \tan^{-1}(\omega T_m) \quad (D2)$$

From Appendix A page 43, we read from the graph:

$$\omega = 62.83 \text{ rads/sec (10Hz)}$$

$$\phi(\omega) = -144^\circ$$

$$\text{Input volts} = 0.05$$

$$\text{Output volts} = 0.1406$$

Substituting these values into equation (D2), and solving for Tm,

$$-144^\circ = -90^\circ - \{\tan^{-1}(\omega T_m)\}$$

$$54^\circ = \tan^{-1}(\omega T_m)$$

$$\tan 54^\circ = \omega T_m$$

$$\tan 54^\circ / 62.83 = T_m$$

$$T_m = 0.0219$$

Converting the Output/Input ratio to units of radians/volt,

$$|G(\omega)| = \frac{2\pi/360^\circ}{100\text{mv}} \times \frac{0.1406}{0.05}$$

$$|G(\omega)| = 0.49 \text{ radians/volt}$$

Appendix D: Sample Calculation: Verification of Tm and Kmv values

Substituting $|G(\omega)|$, Tm, and ω into equation (D1), and solving for Kmv,

$$0.49 = \frac{K_{mv}}{62.83 (1 + (62.83 \times 0.0219)^2)^{1/2}}$$

$$K_{mv} = 52.37$$

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