An analysis of Cartesian deviations in robot work cycles
by Anand Adkoli

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial & Management Engineering
Montana State University

Abstract:
Robots have proven to be extremely useful in performing a variety of tasks, especially those that are repetitive in nature. Most applications require good accuracy and repeatability, therefore positioning errors need to be minimized to enhance any practical application. Information concerning the source of positioning errors and their influence on the work cycle is inherently useful in the study of robotics.

The Teachmover is a five-jointed Robot arm that is widely used for educational purposes. The robot does not have a built-in feedback system and therefore does not have a high repeatability, which limits its usefulness to classroom learning. This project attempted to identify alternatives to correct deviations from the programmed points in a Teachmover's routine. A comprehensive analysis of the variables affecting position errors is presented. A strategy to locate a repeatable home position (starting point) was defined, together with a detailed methodology to analyze the deviations. This methodology included statistical tests which are common to a similar class of problems.

The results indicated that the load on the robot and the working speed were the main causes of the deviations. It was found that neither the area of execution in the working envelope nor the number of cycles of execution affect the error. Linear relationships were found to exist between load and speed with the positioning error. It was established that there was no correlation between load and speed.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Robots have proven to be extremely useful in performing a variety of tasks, especially those that are repetitive in nature. Most applications require good accuracy and repeatability, therefore positioning errors need to be minimized to enhance any practical application. Information concerning the source of positioning errors and their influence on the work cycle is inherently useful in the study of robotics.

The Teachmover is a five-jointed Robot arm that is widely used for educational purposes. The robot does not have a built-in feedback system and therefore does not have a high repeatability, which limits its usefulness to classroom learning. This project attempted to identify alternatives to correct deviations from the programmed points in a Teachmover's routine. A comprehensive analysis of the variables affecting position errors is presented. A strategy to locate a repeatable home position (starting point) was defined, together with a detailed methodology to analyze the deviations. This methodology included statistical tests which are common to a similar class of problems.

The results indicated that the load on the robot and the working speed were the main causes of the deviations. It was found that neither the area of execution in the working envelope nor the number of cycles of execution affect the error. Linear relationships were found to exist between load and speed with the positioning error. It was established that there was no correlation between load and speed.

INTRODUCTION

Robot Manipulators

A precursor to robots were the teleoperators designed for use in radioactive surroundings. Manipulators such as these are common, and they utilize an operator who controls the master unit with a "slave" manipulator that duplicates the movements. Advances made in the field of electronic technology made it possible to link the master-slave systems by using electric motors and potentiometers. The use of electrical linkage led to the development of more sophisticated teleoperators. As sensor technology advanced, feedback in the teleoperator systems became more accurate and sensitive, and the ground work for robotics was laid. Once manipulators were shown to be feasible in the laboratory, the industrial versions were developed. Robots are often put to work in factories on highly repetitive, monotonous, and/or dangerous tasks. The field of robotics is important to many of the engineering disciplines and prominent learning institutions are involved in many phases of design, application and analysis.

Description of the Teachmover Robot

The Teachmover robot is microprocessor controlled with a five-joint mechanical arm designed to provide dexterity at low cost (Figure 1). It is used in the Computer Integrated

Manufacturing laboratory (CIM) in the Department of Industrial & Management Engineering to support laboratory training for several classes.

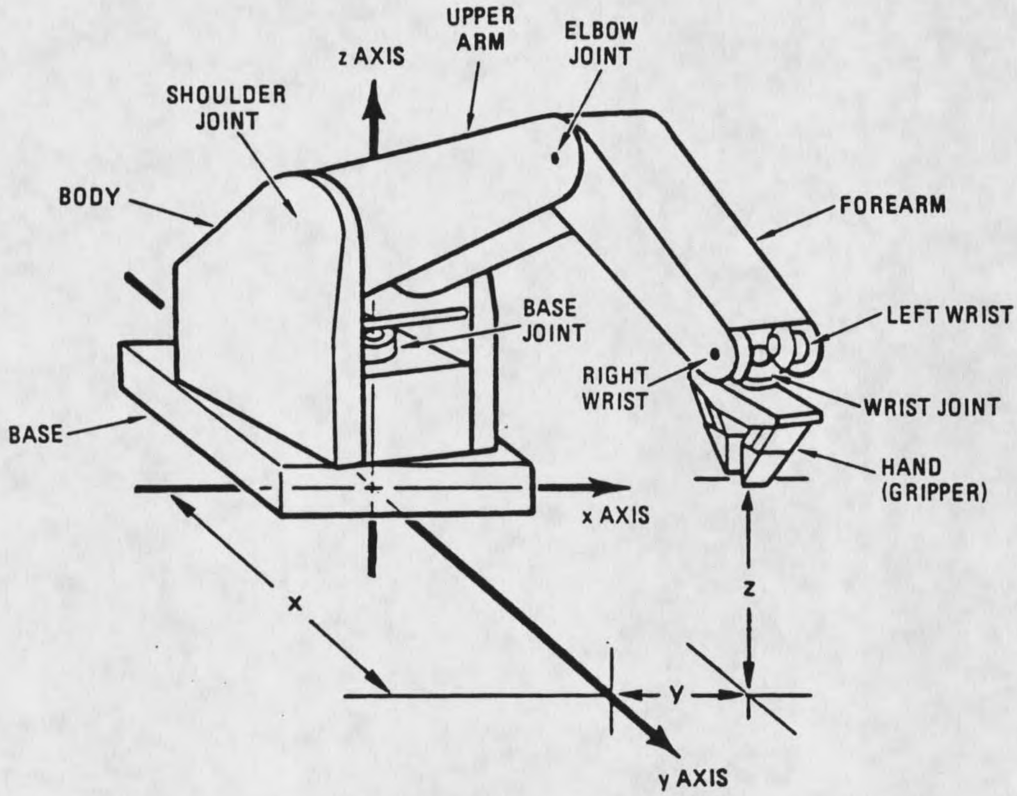

Figure 1. Schematic of the Teachmover [13]

The Teachmover can be used in teach-control mode or in the serial-interface mode. The serial interface mode permits off-line control with a host personal computer through RS-232 serial data transfer. The Teachmover does not have a built-in feedback system which would enhance the performance.

The robot can be integrated with miniature physical production systems for purposes of physical simulation. This enables students to analyze various plant layouts and production schemes for productivity improvement.

Definition of the Problem

Deviations from taught points have been experienced when playing back a program due to the limited accuracy and repeatability of the Teachmover. Reducing positioning errors enhances the robot's ability and allows students to utilize their time more effectively.

Identifying the source of deviations from the programmed points in typical Teachmover routines is a major step in reducing positioning errors. A related problem is to devise a strategy to define a home (starting point) position which is repeatable and reachable through hardware.

In order to address the problem, a methodology to analyze the deviations from home must be developed. Variables which affect the error must be isolated and a standard procedure which can be applied to a similar class of problems must be described.

Hypotheses to be tested

1. The load carried by the robot does not affect the error. The robot performs at the same level of precision at all loads.
2. The speed of execution of the robot does not affect the error. The error does not vary with changing speeds.
3. The error is not cumulative. The magnitude of the error is not dependent on the number of cycles executed.
4. The area of execution in the working envelope has no affect on the error. The behavior of the robot is similar in the entire working envelope i.e., the type of routine (movement vectors in the work envelope) has no affect on the error.
5. The sequence of taught points does not affect the error. The robot routines can be chained in any order.

Limitations of the Problem

This project examined the behavior of the robot with respect to three degrees of freedom: base rotation, shoulder pivot, and elbow pivot. The other two degrees of freedom are related to the wrist, and were not considered in this project due to time restrictions. Theoretically, there can be several positions for the end-effector, but the manner in which experimental data were collected eliminated the position effects of the end-effector.

Feeler gauges used to measure the errors presented another limitation. More sophisticated measuring equipment was available, but only at a cost greatly in excess of the budget of the CIM laboratory.

The experimental factors were assumed to fairly represent a wide spectrum of working conditions. Due to the restricted time available and almost boundless possibilities, it was not possible to analyze all combinations of factors that influence robot performance.

Goals of the Project

This project had the following goals:

a) Analyze the variables affecting errors in the Teachmover.

b) Develop a strategy for a repeatable home in the Teachmover work envelope.

c) Create a body of knowledge on methods to help solve similar problems.

d) Illustrate a comprehensive procedure for data analysis and statistical validation.

Definition of Common Terms

1. ROBOT OR TEACHMOVER

The problem was defined for the Teachmover brand of Robot. The terms ROBOT and TEACHMOVER will be used interchangeably.

2. HOME

The HOME position is a fixed starting point for the execution of every routine of the Robot. It is reached by executing a homing routine devised as a part of this project.

3. WORK VOLUME

The WORK VOLUME (work envelope) is defined as the space within which the robot can manipulate the end of its wrist. The Teachmover has a partial sphere as its work volume.

4. ERROR OR DEVIATION(S)

The ERROR or DEVIATION (used interchangeably) is defined as the difference in the location of the end-effector with respect to a fixed home position after the execution of the robot program.
ERRORn (n = X, Y or Z) will be used to denote the deviation along the X, Y or Z axes.

5. LOAD

LOAD will be used to denote the load carried by the Robot.

6. SPEED

SPEED will denote the programmed velocity during execution.

7. CYCLES

CYCLES will denote the number of repetitions of execution before the cumulative error was measured.

CYCLES will normally be preceded or succeeded by an integer to designate the number of repetitions.

8. ROUTINE

Three different routines (ROUTINE) were used in this project. The first routine was entirely executed in the left portion of the working envelope, the second routine was executed in the right portion, and the third routine in the entire working envelope (left and right).

9. SEQUENCE

SEQUENCE will be used to represent the sequence of joint movements used. Eight separate sequences were used in the left portion of the working envelope (one ROUTINE).

Need for the Study

Deviations in robot programs significantly affect the efficiency and the effectiveness of simulated industrial operations in laboratory projects. Considerable time is lost in re-programming the robot until all the routines can be combined and merged into a system. It is possible for the robot to miss the part to be moved completely. The robot is unable to repeat the programmed routines for more than a few cycles. Thus data collected in this manner could lead to the wrong conclusions since sufficient data points required for statistical procedures may not be available.

The more general need for this study is to establish a body of knowledge which can be used for a similar class of problems. The techniques demonstrated in this project can be applied to the analysis of numerical control machines and other automation equipment. A detailed standard procedure has been established to greatly reduce the time required to solve similar problems.

Organization of the Report

The "LITERATURE REVIEW" section provides an overview of the literature surveyed during the course of this project.

The section "DESIGN AND CONSTRUCTION OF HARDWARE" discusses the construction of the homing routine and problems encountered in obtaining feedback to reset the robot for a repeatable home. The electronic circuitry is also described.

The next section, "THE EXPERIMENT", describes the iterative process of designing the experiment and analyzing the results.

The results obtained are presented in the section titled "ANALYSIS OF DATA AND SUMMARY OF RESULTS" including both graphs and tables. An attempt has been made to enable understanding by minimizing obfuscation.

The conclusions made, and suggestions for future research in this area are included in the section "CONCLUSIONS".

LITERATURE REVIEW

Manipulators and Drive Systems

The manipulator of a robot is constructed of a series of joints and linkages. A joint in a robot is similar to a joint in the human body. It provides relative motion between two parts of the body. "Each joint provides the robot with a degree of freedom (d.o.f.) of motion. A typical robot manipulator can be divided into two sections: a body-and-arm assembly, and a wrist assembly. There are usually three d.o.f. associated with the body-and-arm, and two or three d.o.f. associated with the wrist. The actions of the individual joints must be controlled in order for the manipulator to perform a desired motion cycle" [1]. Common drive systems used in robotics are electric drive, hydraulic drive, and pneumatic drive. Electric drive systems are becoming more prevalent in commercially available robots.

The type of drive system, actuators, position sensors, and feedback control systems for the joints determine the dynamic response of the manipulator. The speed with which the robot can achieve a programmed position and the stability of its motion are two important characteristics of dynamic response in robots [2].

Accuracy and Repeatability

The capacity of the robot to position and orient the end of its wrist with accuracy and repeatability is an important control attribute. Accuracy is a measure of the robot's ability to position the end of its end-effector at a desired location in the work volume (working envelope). Repeatability is a measure of the robot's ability to return to a previously taught point in the work volume.

Sensors used in robots are classified as internal and external. Internal sensors form a feedback control loop with the robot controller. These are used for controlling the position and velocity of the various joints. External sensors are used to coordinate the operation of the robot with other equipment in the cell.

Various devices can be used to measure spatial parameters necessary to describe a robot position. Such devices use dial gauges [3], eddy current probes [4], laser interferometry [5], and position sensitive detectors [6]. The advantages and disadvantages of each of these types of sensors is given by Colson and Perreira [6]. The primary reason for not adopting any of the available methodologies in this project was the budget constraint.

"There are no current standards for robot calibration. The ability to uniquely determine the pose information will aid in determining the accuracy, repeatability and resolution for any robot" [7]. Inverse kinematic procedures help to deduce the cause for performance error. System parameters in a robot vary with load and the position, and the most effective method for designing motion control systems for robots is the use of adaptive control [8]. The general operation of a motion control system and the common approaches to adaptive control are discussed by Tal [8].

Scientific Experiments

An experiment may be defined as a study in which certain independent variables are manipulated. Their effect on one or more dependent variables is then observed at random relative to the experimental units in the study [9].

Proper design of the experiment can minimize the experimental error when such factors are anticipated. A basic principle in such experimentation is referred to as the max-min-con principle [10]. The goal is to maximize the effect of the independent variables of interest, minimize the error variance, and control some of the variables at specified levels.

"Designing an experiment simply means planning an experiment so that information will be collected that is relevant to the problem under investigation" [11].

The terms replication, confounding, and randomization are frequently used in experimental design. Replication may be defined as a repetition of the basic experiment. It provides an estimate of experimental error for the assessment of the significance of observed differences. A more precise estimate of the effect of any factor (synonymous with the independent variable), can be obtained by replicating. Experimental errors include errors of experimentation, errors of observation, and combined effects of extraneous factors that could influence the study.

Confounding is a phenomenon wherein two or more effects in an experiment are mixed together. "Randomization permits us to proceed as though independence is a fact "[11]. It helps to reduce the correlations between errors associated with experimental units adjacent in time.

The analysis of variance (fixed effects) model reflects only fixed treatments present in the experiment. This model does not look at the entire population, but is concerned with only the fixed number of treatments.

Computation of test statistics is an integral part of any analysis. Once the test statistics have been computed, decisions can be made. The decisions should be expressed in graphical or tabular form for clarity.

DESIGN AND CONSTRUCTION OF HARDWARE

Capabilities of the Robot

The Teachmover can currently be operated either through a hand-held teach control or a series of instructions from a host computer. Most of the routines are integrated with miniature Fischertechnik components into work cells, and hence require operation through a host computer to coordinate the entire operation. The instructions are down-loaded to the robot through a serial port on the host computer and are processed by a 6502 microprocessor on the robot circuit board. These instructions consist of a sequence of steps through which the robot should move. Each instruction consists of six numbers, each number corresponding to either one of five joints, or the gripper. The six numbers represent the absolute positions of the six stepper motors associated with each joint and the gripper. The following example will illustrate a typical instruction (Figure 2).

Assume that Point A has the absolute stepper motor values 100,-50,200,25,0,0. These six numbers correspond to the six motors (base, shoulder, elbow, pitch, yaw and gripper). Assume that Point B corresponds to the values 200, -100, 20, 0, 0, 0.

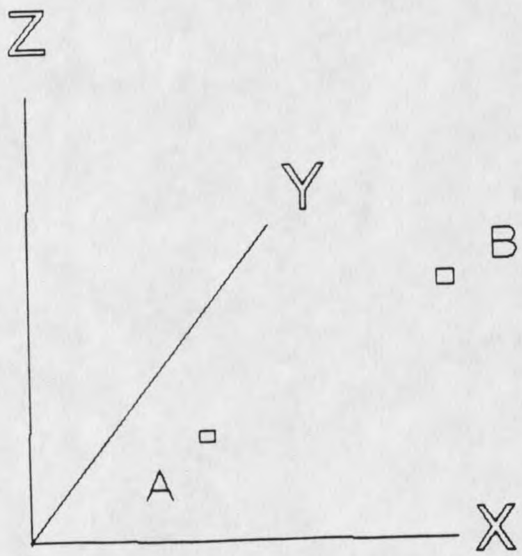

Figure 2. Illustration of Programmed Points

The following instruction (in BASIC) will program the robot to move from Point A to Point B:

```
PRINT#1, "@STEP", (SP), 200, -100, 20, 0, 0, 0,INPUT AS#1
```

(SP) is the speed of the movement.

When this instruction is executed, the robot starts to move from Point A (the current point) to Point B. While it is executing, the microprocessor in the host computer is in a "wait" state. When point B is reached, the robot returns a handshaking signal to the host computer which informs the microprocessor in the computer that the previous instruction has been completed. Thus it is impossible to stop the robot during execution with the current setup. This problem was overcome through additional hardware.

The Teachmover is designed to execute all routines from a programmed home (usually 0,0,0,0,0,0). This home position has to be defined by the user by aligning a fixed point on the robot with a fixed point in the working envelope. This is currently done through visual inspection. The robot movements are broken down into elements, and each of these elements is programmed as a separate routine. This allows for more flexibility in the robot movements between work stations. An attempt is made to program all these routines with reference to the same home. Since there is no strategy (other than visual examination) to reach this home, errors creep in when these routines are used together.

Strategy to Define Home Position

The obvious solution to the problem of defining the home was to incorporate some kind of a feedback within the constraints. This hardware had to interactively communicate with both the robot and the host computer.

There are several types of commercial sensors available that can be adapted to this situation. Some of the common ones are photo-sensors, acoustic sensors and induction sensors. These sensors are fairly expensive and were not feasible for this project because of the relatively low resolution of the Teachmover. A simple electrical signal feedback circuit was adequate for the required purposes here.

Three metal plates were placed orthogonal to each other. Each of these plates corresponded to one axis in the Cartesian system (X, Y or Z). These plates were fixed at a specific location in the working space in Figure 3. A

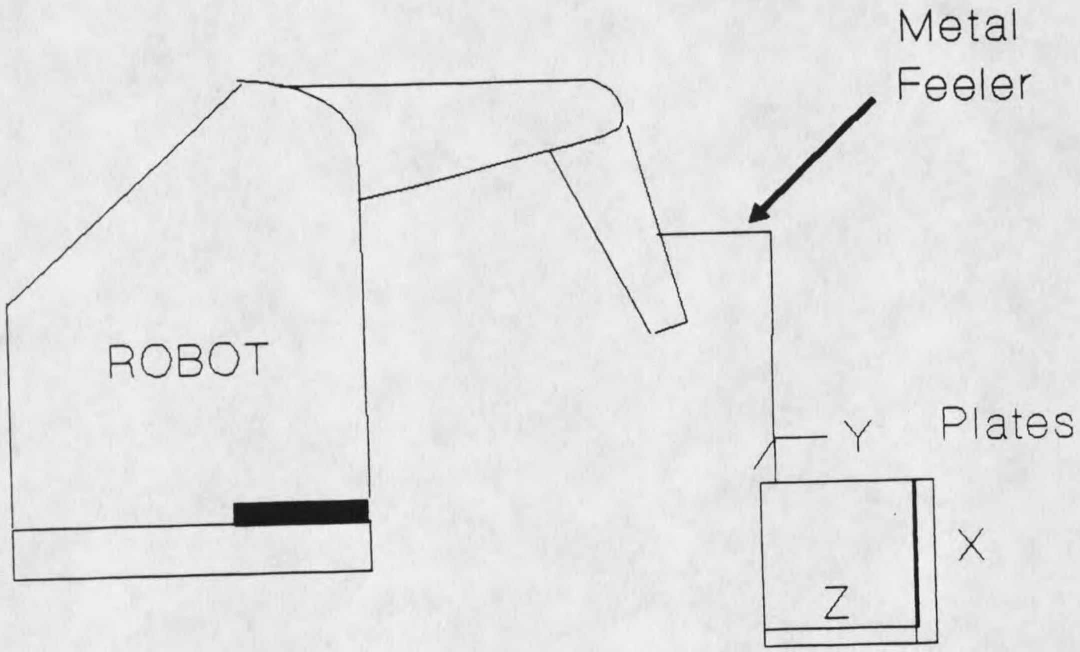

Figure 3. Teachmover Robot with Feeler

potential was applied to each of the three plates. The robot body was at zero potential (grounded). A metal feeler was attached to the end of the robot elbow. When the robot moved towards a plate and the feeler made contact with it, the potential across the plate dropped to zero. This was used as the signal to reset the robot along one axis. The robot was then made to touch the other two plates which enabled the resetting of the other two axes.

Strategy to Reset the Robot

As mentioned earlier, the robot does not release the microprocessor on the host computer until it completes the execution of an instruction. A methodology to generate a hardware interrupt had to be devised to overcome this problem.

The signal generated when the robot made contact with a plate (a low signal) was used as the input for a hardware reset on the microprocessor of the robot. This reset the robot and simultaneously released the microprocessor on the host computer. The computer was now free to execute the next instruction in the program which enabled it to direct the robot to the next plate in sequence. Thus the robot was reset three times in sequence on making contact with the three metal plates.

Another problem surfaced when the above method was implemented. As the robot made contact with one of the plates, the microprocessor received a reset and the computer was freed to execute the next instruction. But the microprocessor remained in this interrupted mode until the robot was in contact with the current plate. This did not permit the robot to execute the next instruction. Additional circuitry was designed to solve this problem.

The signal from the plate was used as an input to the host computer through a Peripheral Interface Adapter (PIA) board. This signal was pre-processed through a timer and an inverter for convenience (see Appendix A). Additional software was written to generate an output signal which was used in conjunction with the original plate signal, through an OR gate, as the hardware interrupt to the robot.

The following example will illustrate the functioning of the hardware:

A digital low signal (0) generated by the computer was initially used as one of the inputs to the OR gate. The other input was from the plate. This signal from the plate was a digital high (1) when the robot was not in contact with the plate and a low when the robot was in contact with the plate. When the robot was not in contact with the plate the output signal of the OR gate was high, which was used as input to the robot microprocessor. When the robot made contact with the plate the output of the OR gate was low, which reset the microprocessor. Simultaneously the computer signal to the OR gate was changed to a digital high which allowed the robot microprocessor to come out of the reset mode. This process was repeated for the other two plates in sequence. All robot movements were pre-programmed and incorporated into software (Appendix B).

THE EXPERIMENT

Preliminary Design of the Experiment

A five-factor experiment was initially designed to model the effect of load, speed, number of cycles, the area of execution in the work envelope (ROUTINE), and the sequence of joints on the positioning error. The following model was developed:

$$
\begin{aligned}
\mathrm{ERROR}_{ijklmn} = {} & U + \mathrm{LOAD}_i + \mathrm{SPEED}_j + \mathrm{CYCLES}_k \\
& + \mathrm{ROUTINE}_l + \mathrm{SEQUENCE}_m \\
& + \mathrm{LOAD} \times \mathrm{SPEED}_{ij} + \mathrm{LOAD} \times \mathrm{CYCLES}_{ik} \\
& + \mathrm{LOAD} \times \mathrm{ROUTINE}_{il} + \mathrm{LOAD} \times \mathrm{SEQUENCE}_{im} \\
& + \mathrm{SPEED} \times \mathrm{CYCLES}_{jk} + \mathrm{SPEED} \times \mathrm{ROUTINE}_{jl} \\
& + \mathrm{SPEED} \times \mathrm{SEQUENCE}_{jm} + \mathrm{CYCLES} \times \mathrm{ROUTINE}_{kl} \\
& + \mathrm{CYCLES} \times \mathrm{SEQUENCE}_{km} + \mathrm{ROUTINE} \times \mathrm{SEQUENCE}_{lm} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{CYCLES}_{ijk} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{ROUTINE}_{ijl} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{SEQUENCE}_{ijm} \\
& + \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{ROUTINE}_{jkl} \\
& + \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{SEQUENCE}_{jkm} \\
& + \mathrm{CYCLES} \times \mathrm{ROUTINE} \times \mathrm{SEQUENCE}_{klm} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{ROUTINE}_{ijkl} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{SEQUENCE}_{ijkm} \\
& + \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{ROUTINE} \times \mathrm{SEQUENCE}_{jklm} \\
& + \mathrm{LOAD} \times \mathrm{SPEED} \times \mathrm{CYCLES} \times \mathrm{ROUTINE} \\
& \times \mathrm{SEQUENCE}_{ijklm} + \mathrm{REPLICATION}_n + E_{ijklmn}
\end{aligned}
$$

i = 0, 0.0326, or 0.1137 lb.

j = 0, 141 or 360 half-steps per second

k = 2, 4 or 6 cycles

l = routine executed in the left portion of work envelope, right portion of work envelope, and the entire work envelope.

m = sequence number 1,2,3,4,5,6,7 or 8

n = 1 to 2 replications

U = Mean

E_{ijklmn} = experimental errors (assumed to be normal, independent, with homogeneous variance

The variable name SEQUENCE was assigned to the sequence of joint movements used in a particular routine. A robot routine consists of several steps. Each step corresponds to the movement of the joints from one point to the next. The sequence in which the joints are moved can vary from routine to routine. There are innumerable ways in which sequences can be arranged, so a preliminary analysis of the effect of the factor SEQUENCE on error was necessary.

Measurement of Error

The error was defined as the positional difference (separately on X, Y, and Z axes) between the home point defined through hardware, and the home point reached after the execution of a robot routine through software. This positional difference was measured by using feeler gauges.

Analysis of the Effect of SEQUENCE on the Error

A single factor, one-way classification ANOVA with zero-extraneous sources of variation was performed on the errors measured after executing eight typical joint sequences in the left portion of the robot work envelope. The model used for this purpose is shown in the next section. This model was used separately on each of the X, Y and Z axes to define the dependent variable $ERROR_{ij}$:

$$ERROR_{ij} = U + SEQUENCE_j + E_{ij}$$

U = Mean

i = 1,2 observations

j = 1,2,..,8 treatments

The corresponding ANOVA table is shown in Table 1.

Table 1. ANOVA Table for Effect of SEQUENCE on Error

Source of Variation	d.o.f	Sum of Squares	Mean Square	F
$Sequence_j$	7	SS(Tr)	SS(Tr)/7	$\frac{MS(Tr)}{MSE}$
Error	8	SSE	SSE/8	
Total	15	SST		

The experiment was totally randomized with two replications. The sampling scheme used is shown in Appendix C. The null hypothesis tested was:

$$H_o: \text{SEQUENCE}_j = 0 \text{ for } j = 1,2,..,8$$

The summary of results for the one-way classification ANOVA are shown in Tables 2, 3, and 4 (complete results are shown in Appendix D).

Table 2. One-way ANOVA of SEQUENCEX on ERRORX

Source of Variation	F-ratio	Significance Level
SEQUENCEX	0.224	0.9681

Table 3. One-way ANOVA of SEQUENCEY on ERRORY

Source of Variation	F-ratio	Significance Level
SEQUENCEY	1.291	0.3615

Table 4. One-way ANOVA of SEQUENCEZ on ERRORZ

Source of Variation	F-ratio	Significance Level
SEQUENCEZ	0.685	0.6843

The results indicated that the sequence of joints used in executing a routine does not have a significant effect on

X, Y, or Z axis error. The variable SEQUENCE was eliminated from all further analysis.

Further Analysis of the Data

The next step was to explore the possibility of excluding other independent variables from the model. This would further simplify the rather complex nature of the problem.

Errors were again measured separately for the X, Y and Z axes at three loads, for three speeds, for 2, 4 and 6 cycles of execution in the left portion, right portion and the entire working envelope. The errors were measured in random order based on the sampling scheme shown in Appendix E.

A correlation analysis was performed. Correlation matrices were determined separately for the X, Y and Z axes. The summary is shown in Table 5.

Table 5. Correlation Matrix

Axis		LOAD	SPEED	CYCLES	ROUTINE
X	$ERROR_X$	-0.3361	-0.2672	0.0400	0.0098
Y	$ERROR_Y$	0.1644	-0.2822	0.1926	-0.0414
Z	$ERROR_Z$	0.1805	-0.1096	-0.2606	-0.0010

The correlation matrix shows relatively higher correlations between load and error, speed and error, cycles and error, as compared to the correlations between routine and error (values of 0.0098, -0.0414 and -0.0010 on the X, Y and Z axes respectively). The variable ROUTINE was further examined for elimination.

A discriminant analysis was performed with the variable ROUTINE as the discriminant. Separate codes were assigned for error values obtained in the left region of the work envelope, the right portion and the entire working envelope. High canonical correlations were found between the error data between the three types of routines. The results were similar and consistent among all three axes. The high canonical correlations indicated that there was no significant difference between the error data collected in the three different areas of the working envelope (results in Appendix F). A summary is shown in Table 6.

Table 6. Correlations from Discriminant Analysis

Axis	ROUTINE
X	0.9414
Y	0.9236
Z	0.8965

A partial correlation analysis between error and ROUTINE yielded similar results (Table 7). Very low partial correlations were determined between error and the area of execution.

Table 7. Partial Correlations Between ROUTINE and ERROR

Dependent Variable	ROUTINE
$ERROR_X$	0.00982
$ERROR_Y$	-0.04137
$ERROR_Z$	-0.00103

Based on the results obtained from the above procedures, the variable ROUTINE was eliminated from all further analysis.

Some Comments on Multivariate Procedures

Multivariate procedures are not often applied to the kind of data seen in this problem. Multivariate procedures are traditionally considered more useful in interpreting data which are qualitative in nature. There is some subjectivity involved, however multivariate procedures can also give consistent results when the data collected is quantitative [13]. The following section will illustrate this point.

The procedures used in the earlier section (correlation analysis and discriminant analysis) give a clear indication that the factor ROUTINE does not have an effect on the error. To substantiate this, an ANOVA was also performed with the four factors (load, speed, number of cycles, and the area of execution) with the results shown in Appendix G. It is clear from ANOVA that the factor ROUTINE does not have an effect on the error, which supports the results of the multivariate procedures.

Revised Design of Experiment

The model was revised as a three-factor ANOVA with fixed effects. Errors were measured for three load conditions at three speeds, and for two, four and six cycles of operation in the left portion of the work volume. Following the practice cited in numerous examples in the literature, the 3-way interactions were neglected, thus increasing the d.o.f. for Residuals by 8. The d.o.f. for two replications is shown in Table 8.

Sampling Scheme and Randomization

The experiment was designed to be completely randomized, that is, each observation had an equal chance of being assigned a given treatment. Randomization was necessary to take into account the effect of uncontrollable factors such as, variance in performance of the robot due to heating, voltage fluctuations, joint sequence differences, etc..
The sampling scheme adopted is shown in Appendix H.

Table 8. D.O.F for Three-Factor Experiment

Source of variation	d.o.f
Main effects	
Load	2
Speed	2
Cycles	2
2-Factor interactions	
Load x Speed	4
Load x Cycles	4
Speed x Cycles	4
Load x Replications	2
Speed x Replications	2
Cycle x Replications	2
Replications	1
Residuals	28
Total	53

Risk Tolerance

Hypotheses testing is always subject to errors since it is based on sample statistics. Probabilities can be assigned for the possibility of rejecting a true hypothesis (Type I error), and the possibility of accepting a false hypothesis (Type II). These probabilities are also referred to as the risk of making an incorrect decision. The level of significance was chosen as 5% (Type I error) due to standard interpretation.

Values for Independent Variables

The following values were chosen for the three independent variables:

Load - 0, 0.0326, 0.1137 lb.

Speed - 28, 141, 360 half-steps per second

Cycles - 2, 4, 6 cycles

Thus the number of observations for error on each axis was 54 (3*3*3 and 2 replications) for the experiment.

The model shown in the next section was separately used to define position error on the X, Y, and Z axes for this portion of the experiment.

Revised Model

The model adopted for the three factor experiment was (Interactions of the three factors with replications do not exist physically and were ignored):

$$\begin{aligned} ERROR_{ijkn} = U &+ LOAD_i + SPEED_j + CYCLES_k \\ &+ LOAD \times SPEED_{ij} \\ &+ LOAD \times CYCLES_{ik} \\ &+ SPEED \times CYCLES_{jk} \\ &+ LOAD \times SPEED \times CYCLES_{ijk} \\ &+ REPLICATION_n + E_{ijkn} \end{aligned}$$

i = 0, 0.0326, or 0.1137 lb.

j = 0, 141 or 360 half-steps per second

k = 2, 4 or 6 cycles

U = Mean

n = 1,2 replications

E_{ijkn} = experimental errors (assumed to be normal, independent, with homogeneous variance)

<u>Null Hypotheses Tested</u>

(a) H_o: $LOAD_i = 0$, for all i

Load has no effect on position error

(b) H_o: $SPEED_j = 0$, for all j

Speed has no effect on position error

(c) H_o: $CYCLES_k = 0$, for all k

Number of cycles has no effect on position error

(d) H_o: $(LOAD \times SPEED)_{ij} = 0$

Load & speed interaction has no effect on position error

(e) H_o: $(LOAD \times CYCLES)_{ik} = 0$

Load & cycles interaction has no effect on position error

(f) H_o: $(SPEED \times CYCLES)_{jk} = 0$

Speed & cycles interaction has no effect on position error

(g) H_o: $(LOAD \times SPEED \times CYCLES)_{ijk} = 0$

Load, speed & cycles interaction has no effect on position error

(h) H_o: $REPLICATION_n = 0$

Replications have no effect on position error.

Data Collection and Processing

This portion of the experiment was conducted in the following manner: 1) The observation type was determined from the sampling scheme. 2) The robot was made to execute the homing routine, which ensured that the robot would return to the same starting point before each observation. 3) The chosen routine was then executed for the given number of cycles under the specified load and speed conditions. 4) The error was measured as defined earlier. The data were recorded in specially designed data sheets shown in Appendix I.

ANALYSIS OF DATA AND SUMMARY OF RESULTS

Analysis of Variance

An analysis of variance was performed with axis-error specified as the dependent variable; load, speed, and number of cycles were specified as independent variables. The complete results of the analysis of variance are shown in Appendix J.

The results of the ANOVA suggested that the variable CYCLES had no significant affect on the error. LOAD and SPEED were seen to be the main effects. A summary of the results is provided in Tables 9, 10, and 11 for the X, Y and Z axes, respectively. The F-ratio and the level of significance are shown in the two right hand columns.

Table 9. Analysis of Variance for ERRORX

Source of variation	F-ratio	Sig. level
Main effects		
$LOAD_X$	29.528	.0000
$SPEED_X$	23.321	.0000
$CYCLE_X$	1.240	.3049
2-Factor Interactions		
$LOAD_X$ $SPEED_X$	11.007	.0000
$LOAD_X$ $CYCLE_X$	0.531	.7138
$SPEED_X$ $CYCLE_X$	3.202	.0276

Table 10. Analysis of Variance for ERRORY

Source of variation	F-ratio	Sig. level
Main effects		
$LOAD_Y$	14.192	.0001
$SPEED_Y$	47.628	.0000
$CYCLE_Y$	1.300	.2885
2-Factor Interactions		
$LOAD_Y$ $SPEED_Y$	35.568	.0000
$LOAD_Y$ $CYCLE_Y$	2.131	.1034
$SPEED_Y$ $CYCLE_Y$	1.113	.3701

Table 11. Analysis of Variance for ERRORZ

Source of variation	F-ratio	Sig. level
Main effects		
$LOAD_Z$	4.835	.0157
$SPEED_Z$	65.216	.0000
$CYCLE_Z$	0.212	.8105
2-Factor Interactions		
$LOAD_Z$ $SPEED_Z$	2.140	.1022
$LOAD_Z$ $CYCLE_Z$	3.732	.0148
$SPEED_Z$ $CYCLE_Z$	0.551	.6997

A few of the 2-factor interactions were also shown to be significant.

Relation between Load, Speed and Error

A secondary analysis was performed to determine the relation between load, speed and error. A correlation matrix was formed as shown in Appendix K. Summarized results in Table 12 indicate no correlation between load and speed.

Table 12. Correlation Matrix for Main Effects

Variable	ERROR	LOAD	SPEED
ERRORX	1	0.3083	-0.4107
LOADX	0.3083	1	0
SPEEDX	-0.4107	0	1
ERRORY	1	-0.1462	0.4944
LOADY	-0.1462	1	0
SPEEDY	0.4944	0	1
ERRORZ	1	0.2125	-0.7101
LOADZ	0.2125	1	0
SPEEDZ	-0.7101	0	1

A partial correlation analysis was performed and the results tallied. It was apparent that load and speed had no affect on each other.

The correlation matrix showed a high correlation between load and error, and speed and error as expected. A regression analysis was done on the data available. The following linear relationships were found to exist between load and error, and speed and error (complete results are shown in Appendix 12).

$ERROR_X = 0.1179 + 0.0072*(LOAD_X)$

$ERROR_X = 0.1515 - 0.00982*(SPEED_X)$

$ERROR_Y = 0.1582 - 0.00319*(LOAD_Y)$

$ERROR_Y = 0.1302 + 0.01085*(SPEED_Y)$

$ERROR_Z = 0.1292 - 0.00994*(LOAD_Z)$

$ERROR_Z = 0.2155 - 0.03322*(SPEED_Z)$

These relationships can be used to provide an indication of the expected deviations from the programmed points. Correction factors can be established based on these relationships. Plots of the regression of load and speed on error for the X,Y, and Z axes are shown separately in Figures 4 through 9. Plots of the residuals are shown in Figures 10 through 15.

The results of the regression analysis indicate the presence of a quadratic term in the model. Inclusion of these terms could provide a better model.

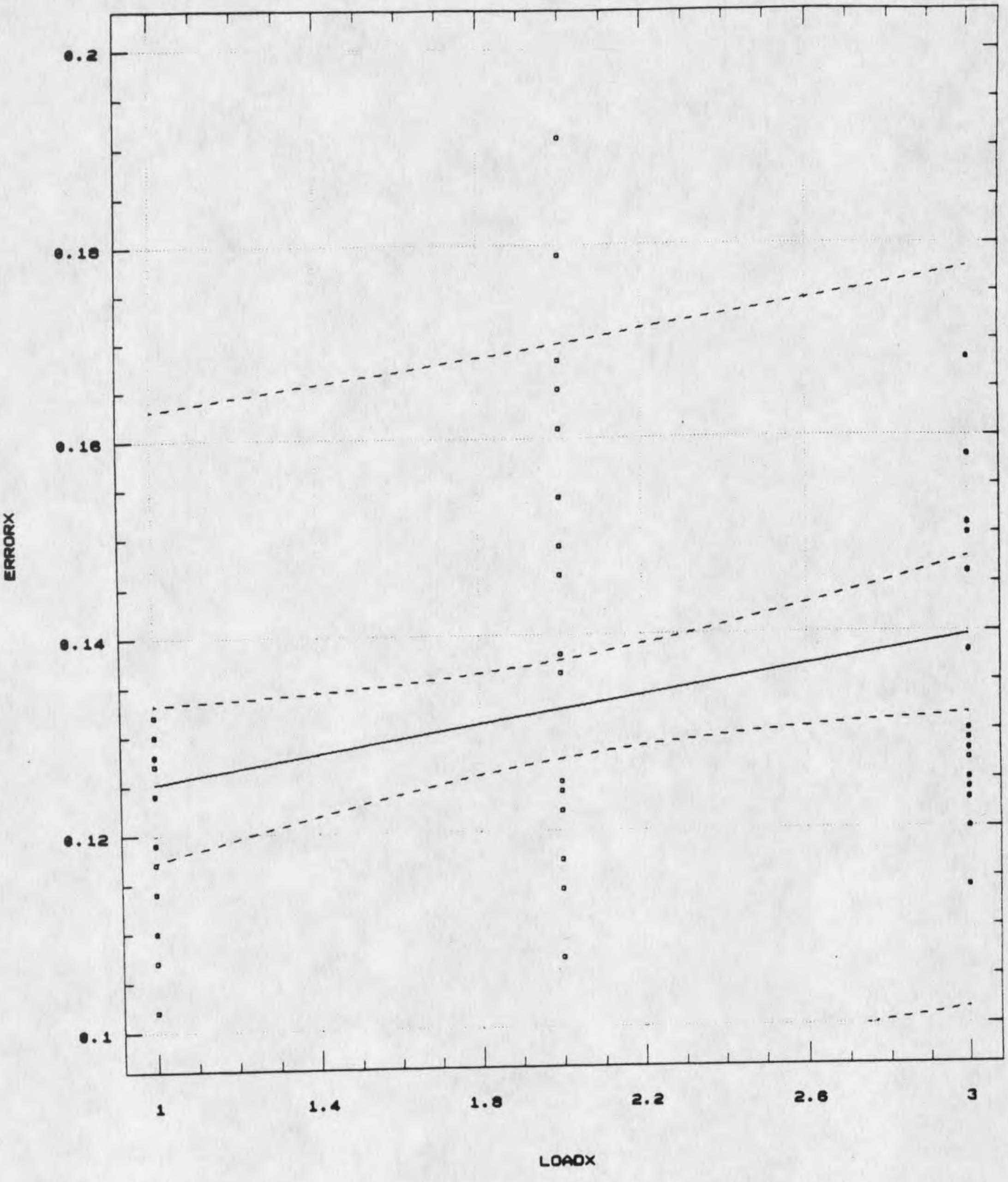

Figure 4. Regression of ERRORX on LOADX

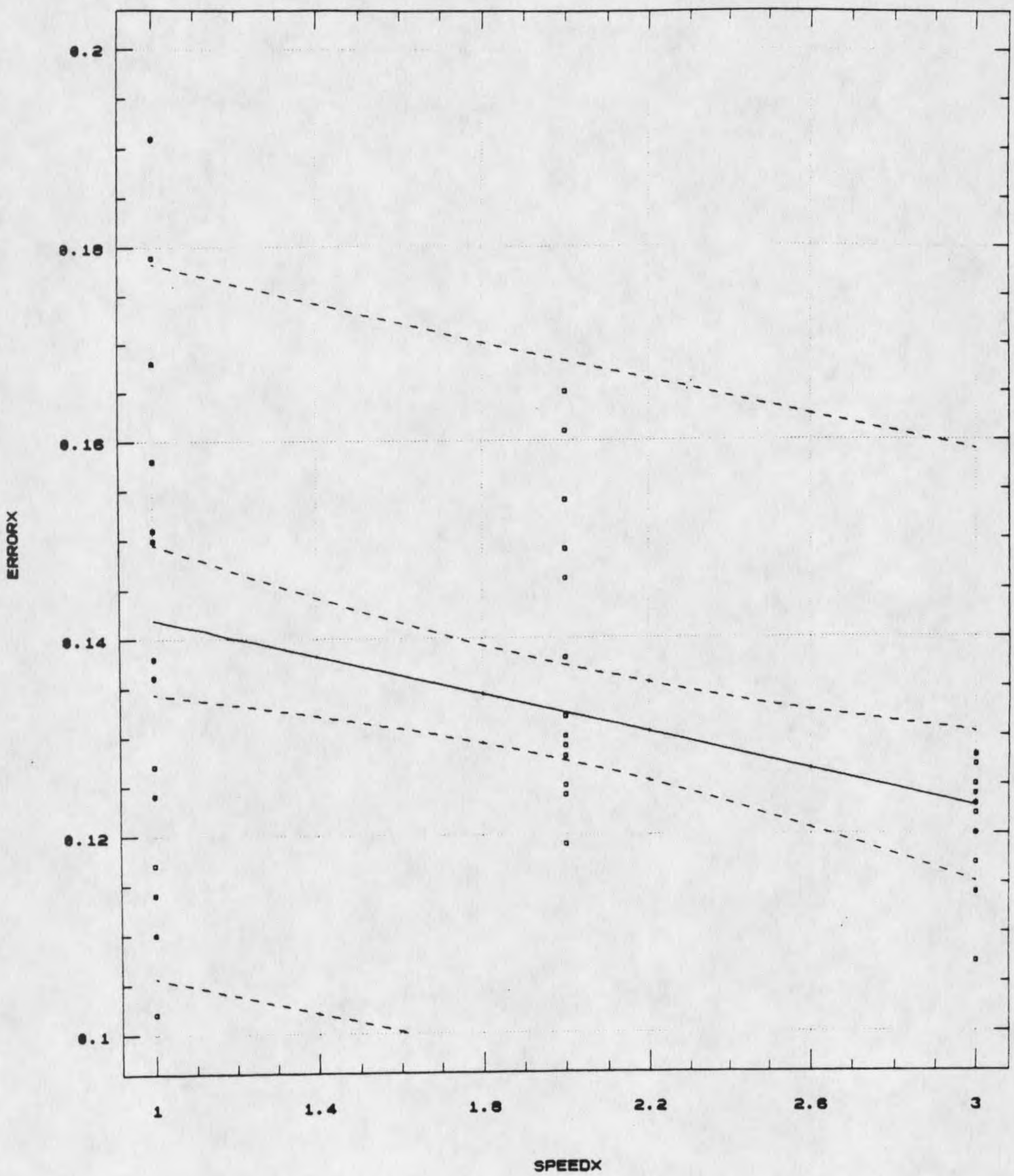

Figure 5. Regression of ERRORX on SPEEDX

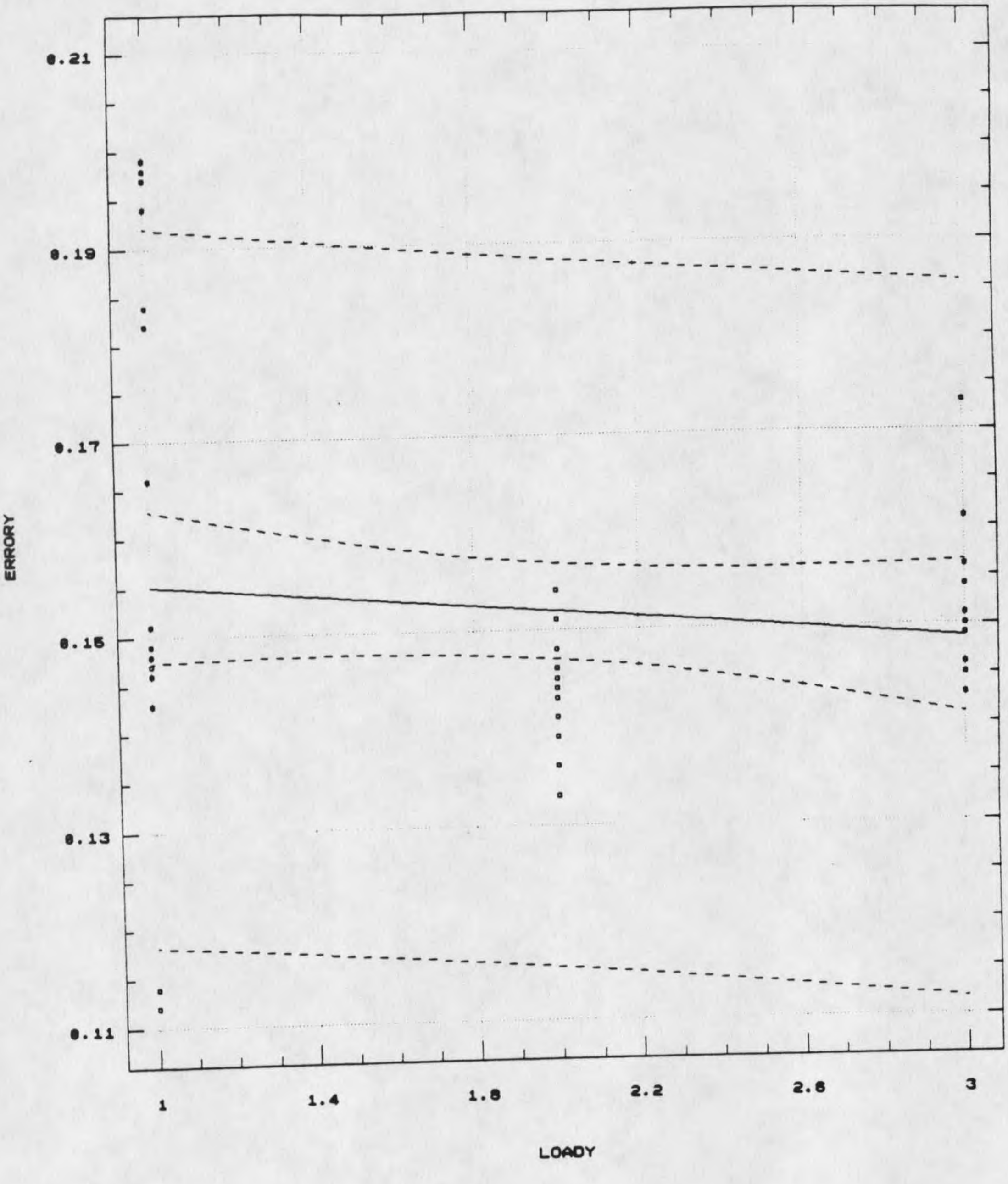

Figure 6. Regression of ERRORY on LOADY

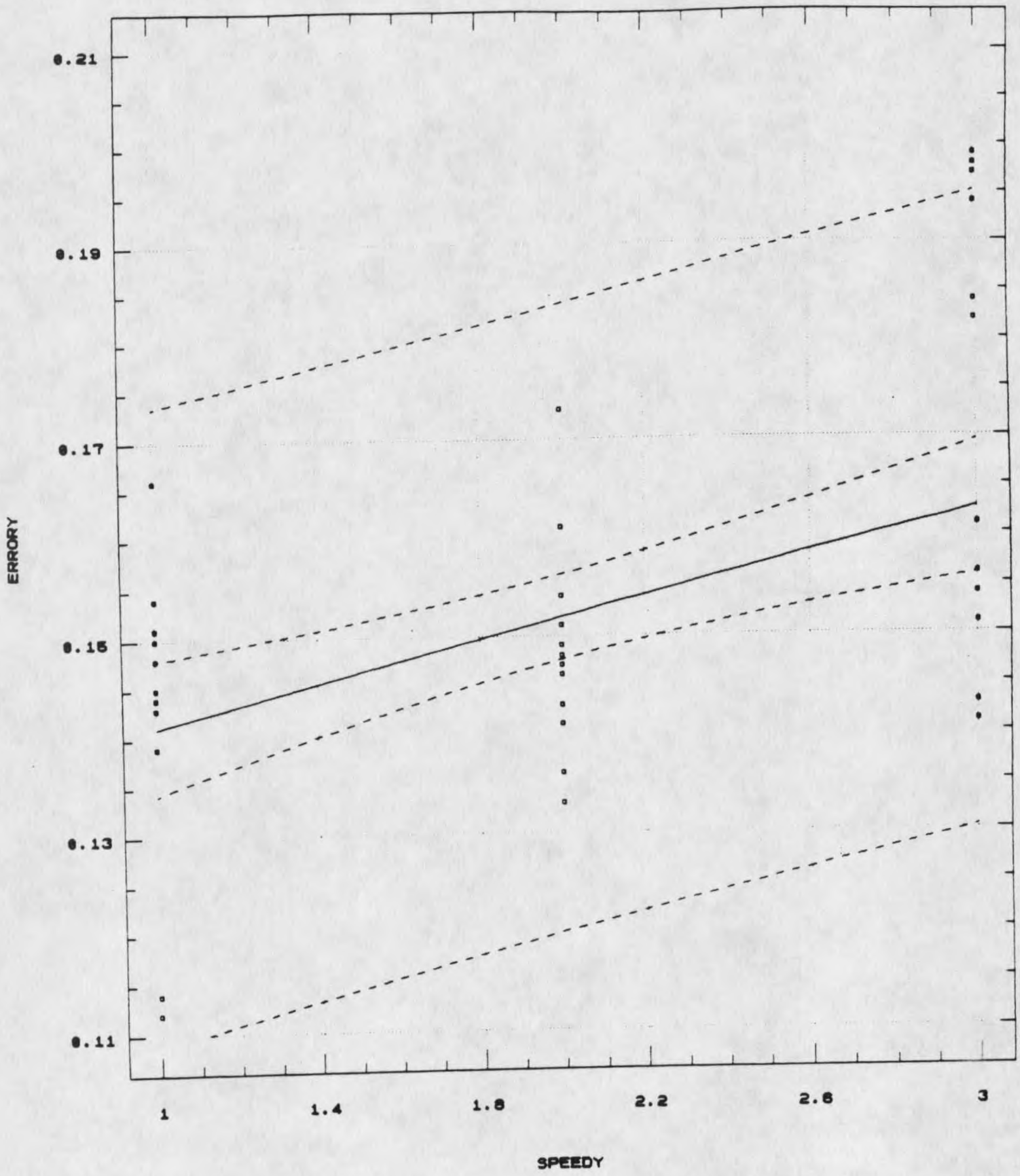

Figure 7. Regression of ERRORY on SPEEDY

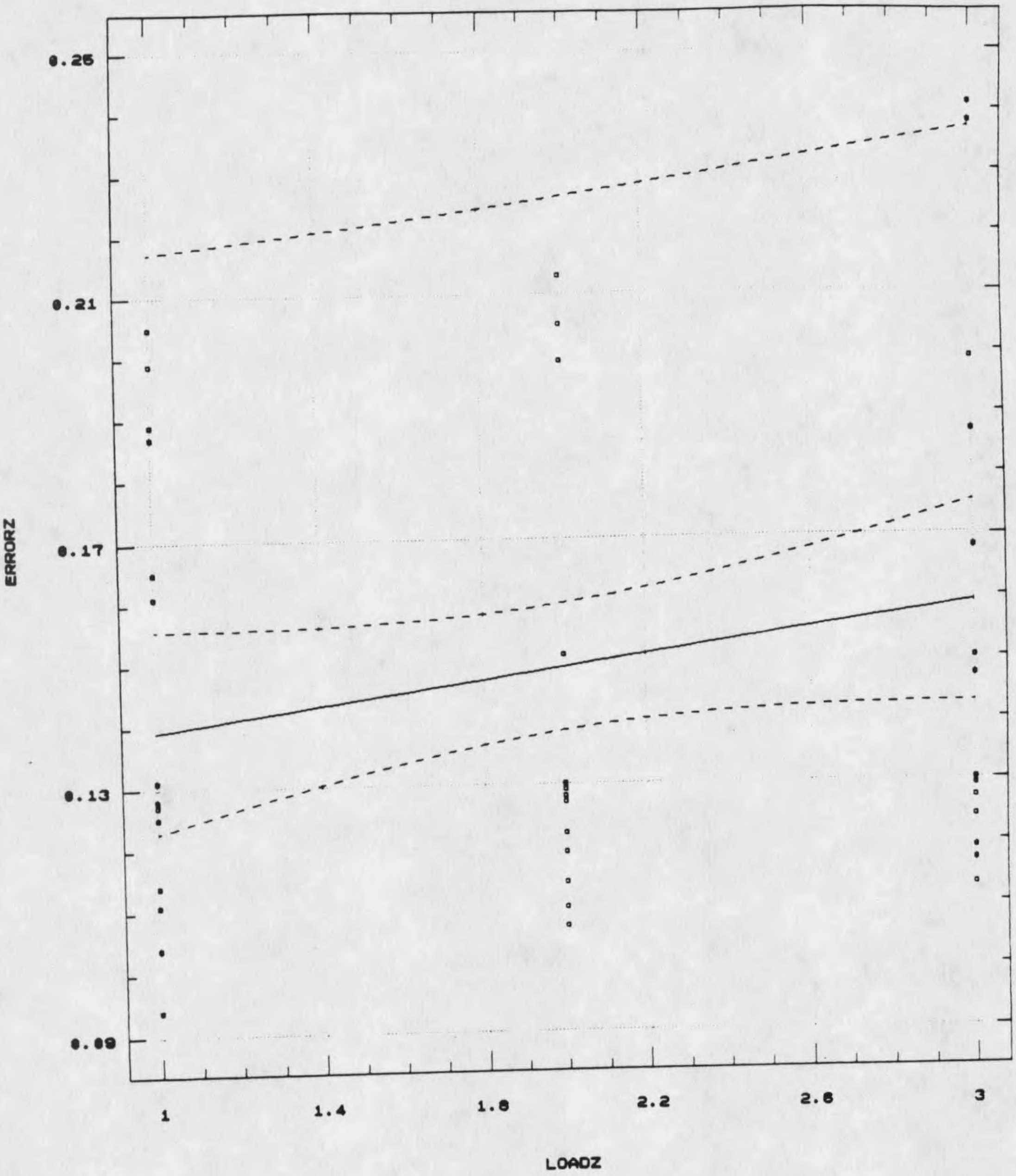

Figure 8. Regression of ERRORZ on LOADZ

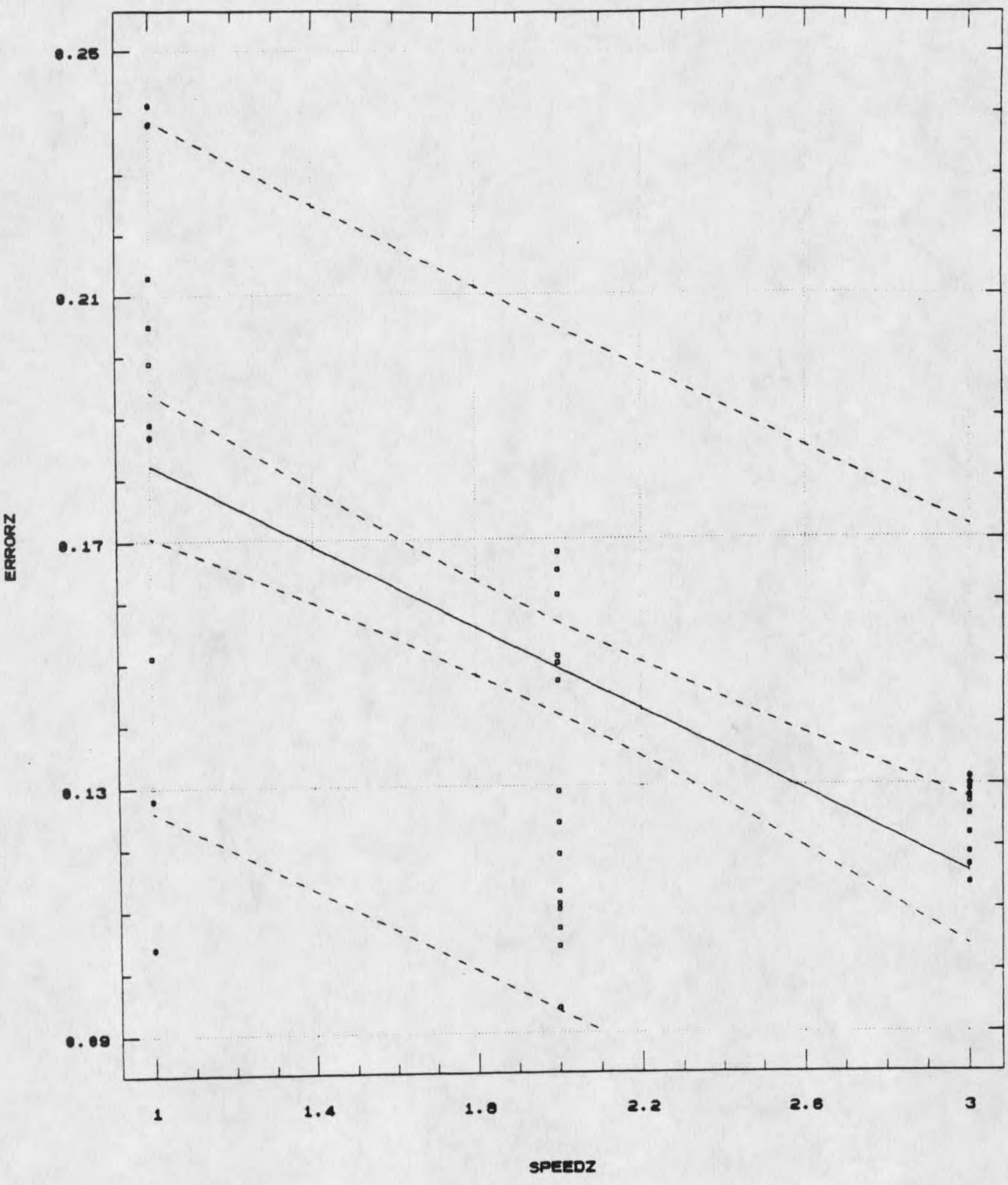

Figure 9. Regression of ERRORZ on SPEEDZ

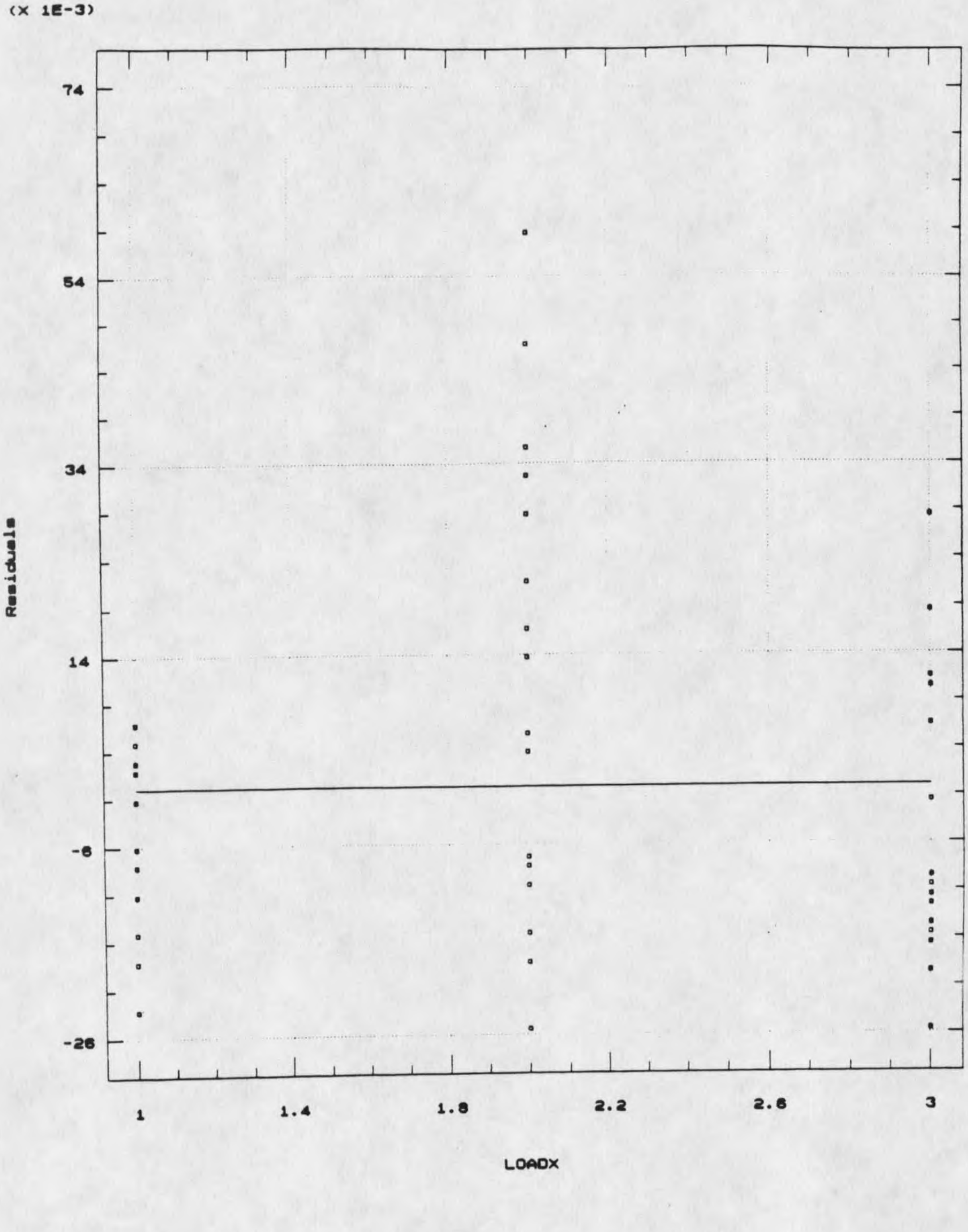

Figure 10. Residuals of ERRORX on LOADX

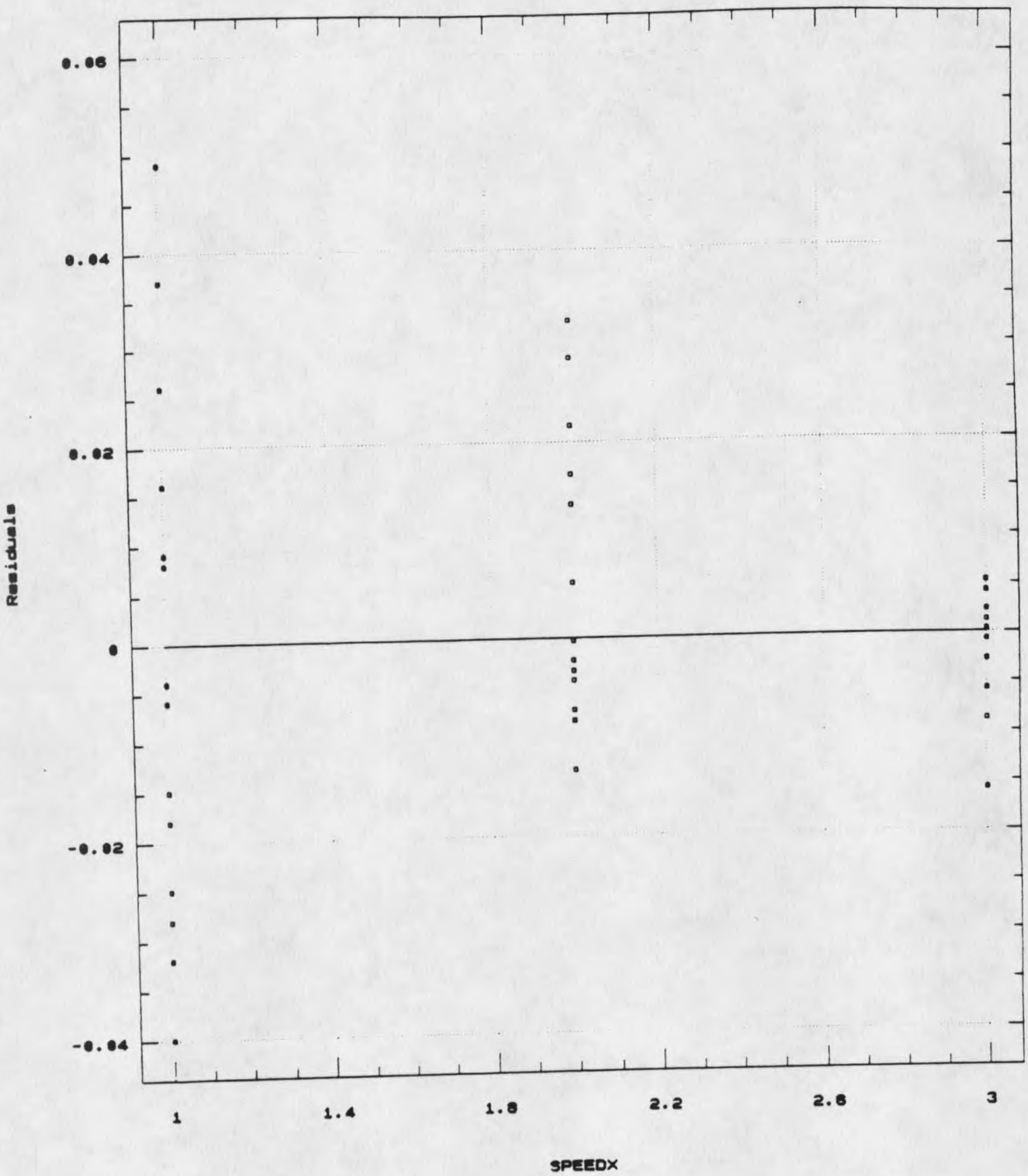

Figure 11. Residuals of ERRORX on SPEEDX

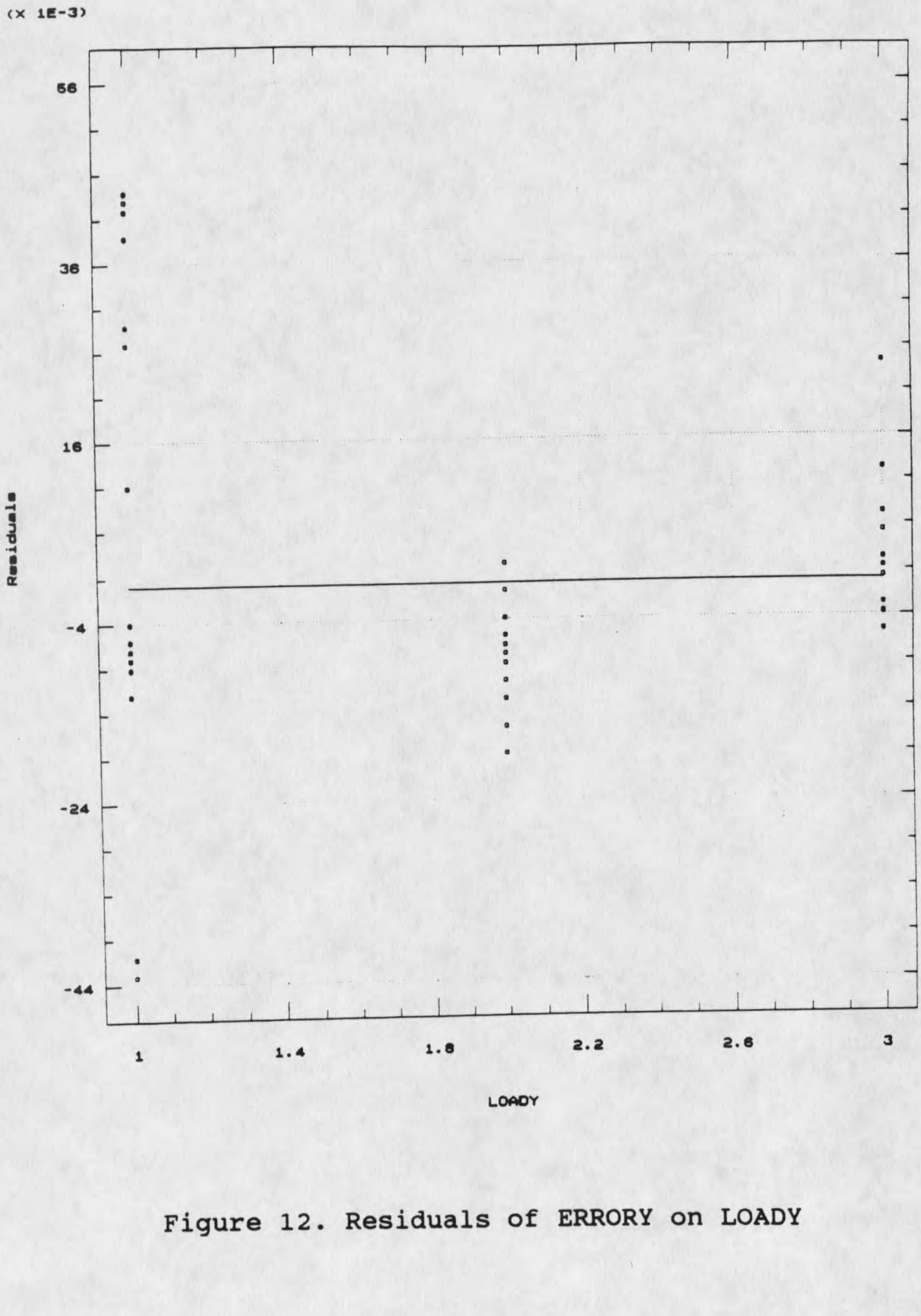

Figure 12. Residuals of ERRORY on LOADY

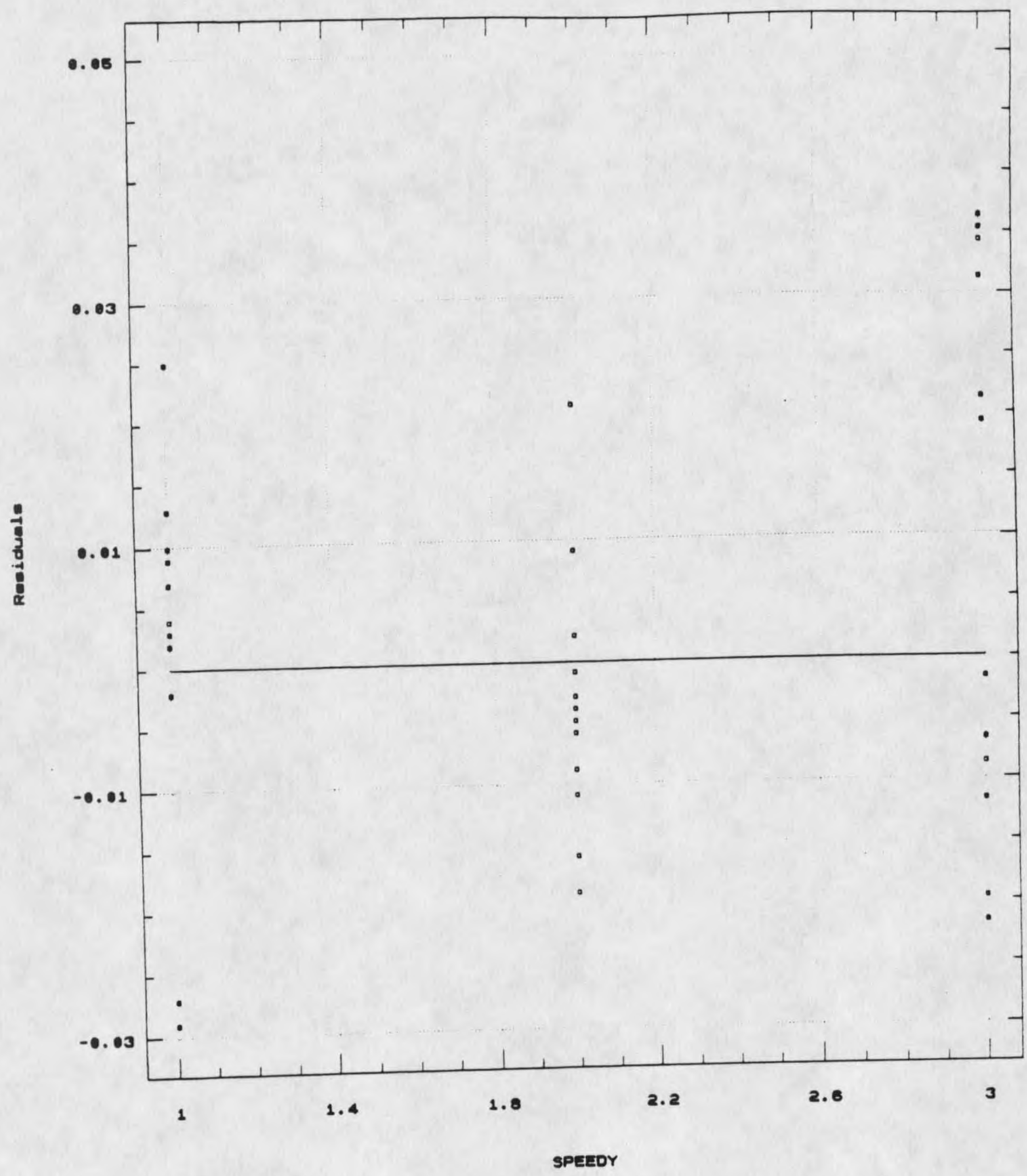

Figure 13. Residuals of ERRORY on SPEEDY

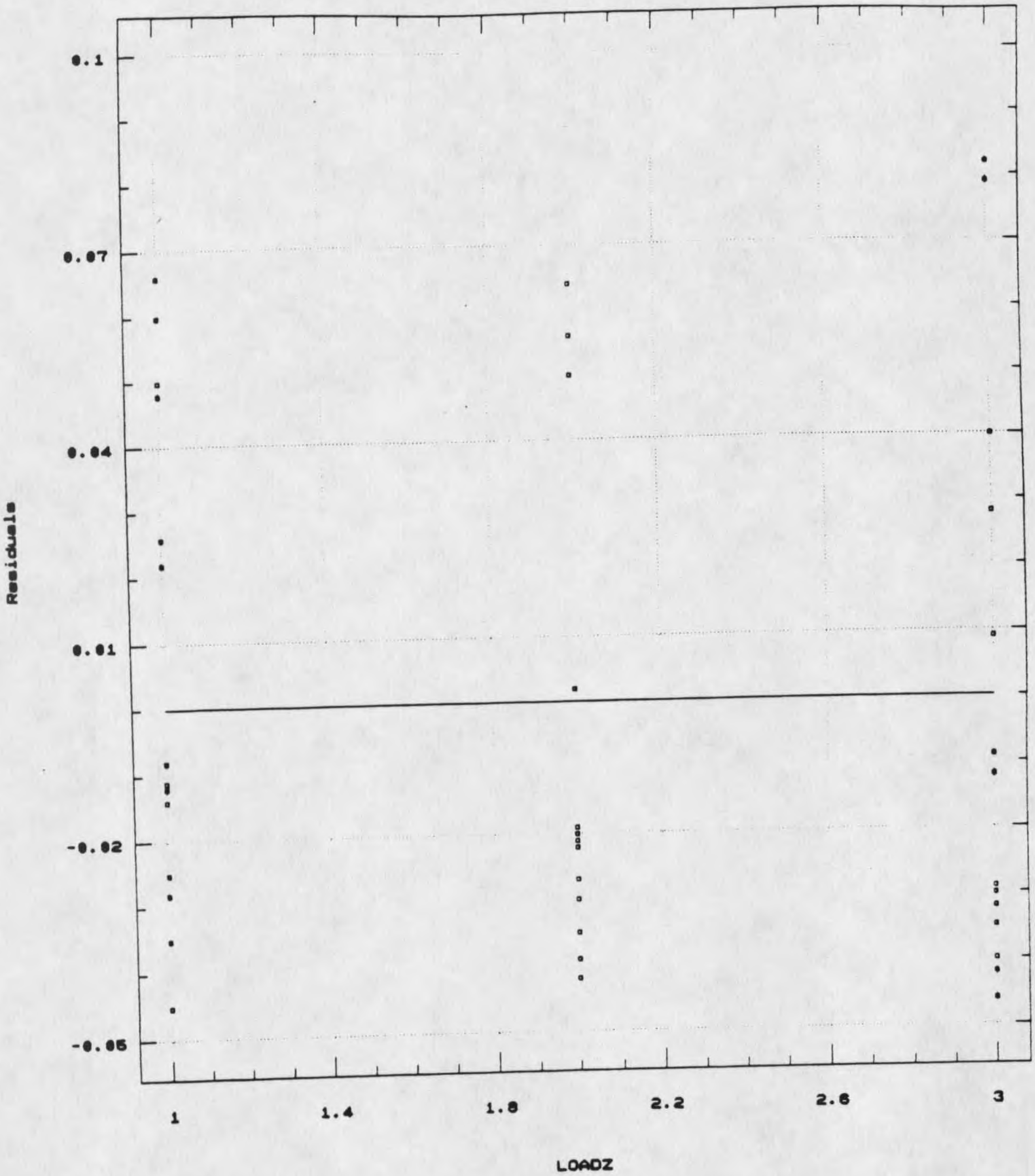

Figure 14. Residuals of ERRORZ on LOADZ

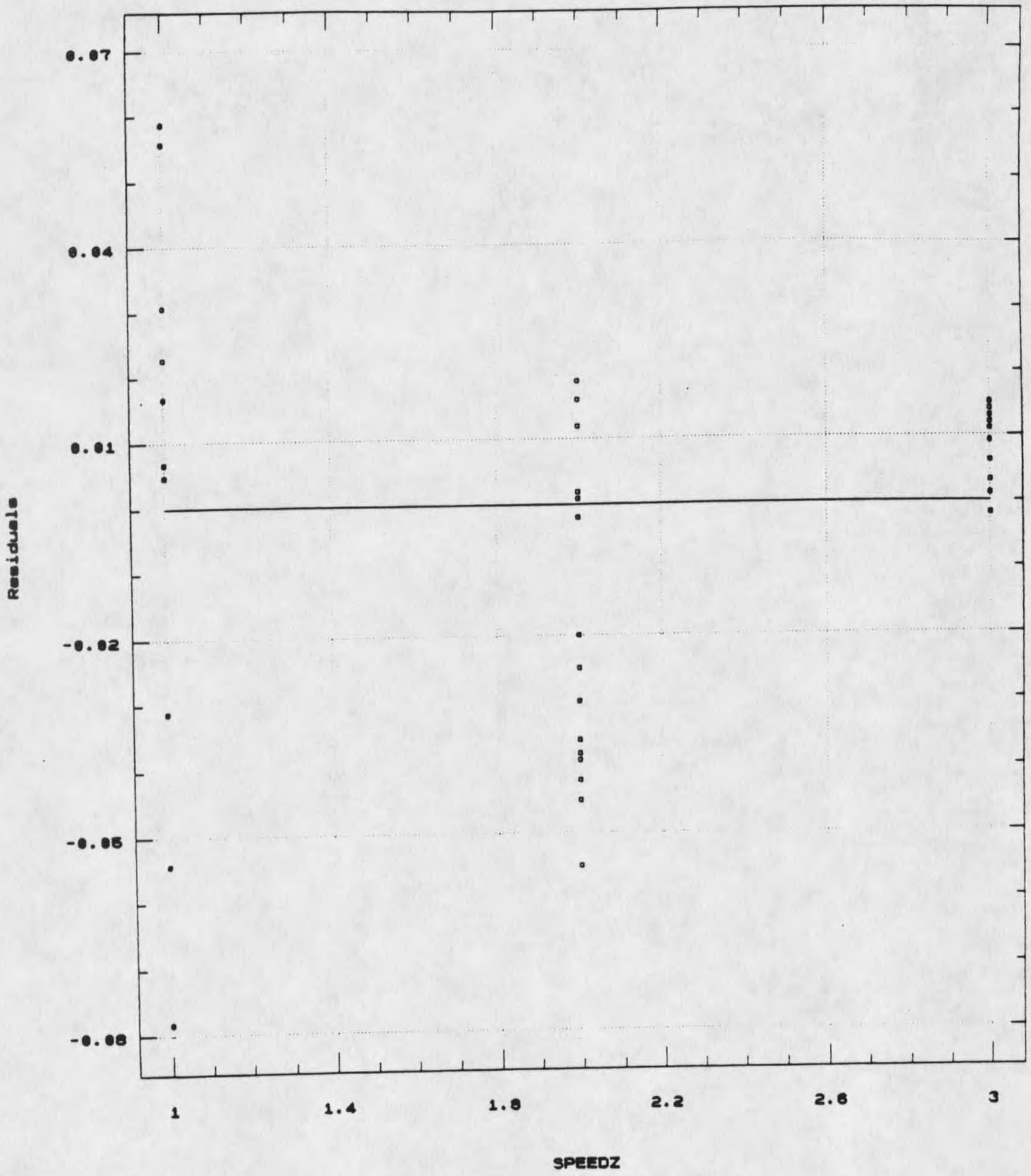

Figure 15. Residuals of ERRORZ on SPEEDZ

The Teachmover uses plastic gears for transmittal of torque from a stepper motor to the joints. It was observed that slippage occurred between the gears at low and high speeds. The slippage appears to be have a more predominant affect on the X and Z axes at low speeds and the Y axis at higher speeds, which indicates uneven behavior between gears. Slippage also increased with the load on the robot. The robot performed with minimum error at mid-range speeds (99 to 300 half-steps per second) and low loads. The slippage of gears under high loads and extreme speeds was probably the cause of error, which of course, is cumulative and not subject to algebraic fluctuation.

The number of cycles apparently did not affect the error. This indicated that the error was not cumulative and that errors were algebraic, random in both the positive and negative directions (with respect to the programmed home).

CONCLUSIONS

The following conclusions were drawn from this experiment (at Level of Significance = 5%):

1. Null hypothesis (a) was rejected. Load had a significant effect on error on X, Y and Z axes.
2. Null hypothesis (b) was also rejected. Speed of execution on a robot has a significant effect on error on all three cartesian axes.
3. Null hypothesis (c) was accepted. Number of cycles had no effect on error.
4. Null hypothesis (d) was rejected. Load and speed interaction had a significant effect on error on the X and Y axes.
5. Null hypothesis (e) was rejected. The load and cycles interactions had a significant effect on error on the Z axis.
6. Null hypothesis (f) was rejected. The speed and cycles interaction was significant on the X axis.
7. Null hypotheses (g) and (h) were accepted. The 3-level interactions between load, speed, and cycles had no effect on error. The replications were not an effect.

Concluding Remarks

This project has demonstrated a procedure which can be used to analyze similar problems. A body of knowledge has been formed which is intended for the use of researchers in testing and calibration of other types of equipment. The project illustrates the application of statistical procedures to the type of data commonly gathered in automation laboratories. The techniques applied here can be extremely useful in reducing the dimensions of experimental design problems.

Recommendations for improvements include: more sophisticated procedures for feedback by using better sensors and measuring equipment for the measurement of error. Further analysis of the effect of the load and the speed on error can be performed by increasing the number of levels from three to possibly five.

This project analyzed deviations of the Teachmover robot from programmed points with respect to only three degrees of freedom (base, shoulder and elbow joints). A possible extension would be to analyze the deviations by including the other two joints related to the wrist. A similar methodology may be adopted for this extension with minor modifications in the attachments to the robot.

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LITERATURE CITED

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APPENDICES

APPENDIX A

Circuit Diagram for External Hardware

(Cross Reference. p 18)

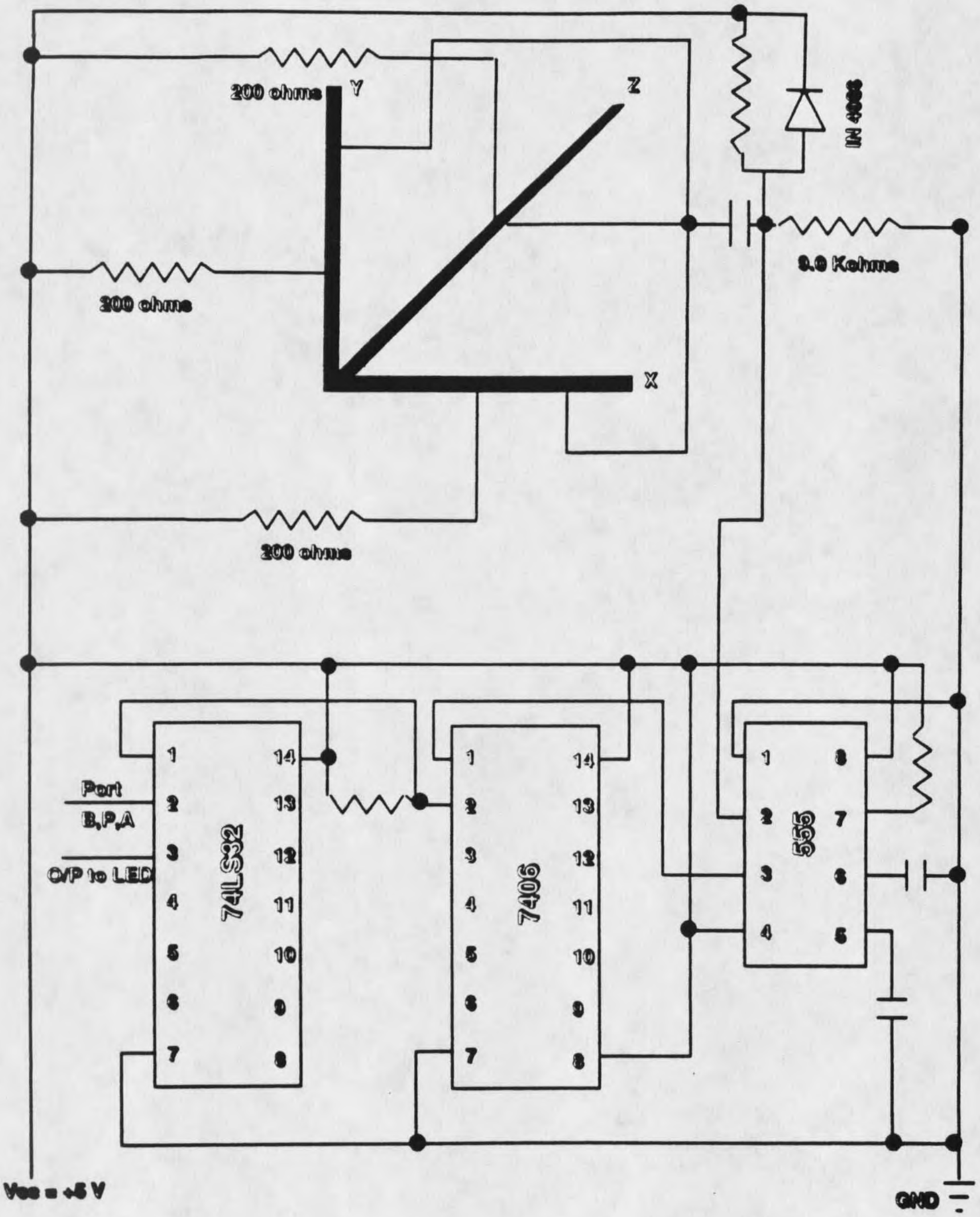

Figure 16. Circuit Diagram for External Hardware

APPENDIX B

Software Listing

(Cross Reference. p 19)

Figure 17. Software Listing

```
10 REM ***03-14-90**Anand Adkoli***Industrial Engineering, MSU***
20 REM 'This program was written as part of the project conducted on
30 REM  the Teachmover Robot. It is designed to execute the homing
40 REM  routine designed and built by me.'
50 REM 'Please ensure that the hardware is configured before you
60  REM execute this program'
70 REM 'Suggestions for modifications will be appreciated'
100  CLS
110   PRINT "RUN THE ROBOT OR HOME? "  'RUN ROBOT ROUTINE OR HOME
120   PRINT "0 - HOME"
130   PRINT "1 - RUN THE ROBOT"
140   PRINT "2 - EXIT"
150   INPUT "INPUT COMMAND";Y
160   IF Y = 0 THEN GOSUB 190
170   IF Y = 1 THEN GOSUB 520
180   IF Y = 2 THEN END
190 OPEN "COM1:9600,N,8,1,RS,DS,CS" AS #1 'START OF HOME SUBROUTINE
200 OUT &H303,&H91 ' SET CONTROL WORD FOR PIA
210 OUT &H301,0 ' OUTPUT ZERO FROM PIA
220 PRINT #1, "@STEP",(0),0,200,85,0,0,0 ' MOVE TOWARDS Z PLATE
230 A%=INP(&H300):PRINT "A%="A% ' MONITOR INPUT SIGNAL FROM PLATE
240 IF A%<>1 GOTO 250 ELSE 230
250 OUT &H301,255 ' CHANGE PIA SIGNAL TO 1
260 GOSUB 480
270 PRINT #1,"@STEP",(0),0,-60,-20,0,0,0
280 GOSUB 480
290 PRINT #1,"@STEP",(0),-125,40,-20,0,0,0
300 OUT &H301,0 'REPEAT FOR Y PLATE
310 B%=INP(&H300):PRINT "B%="B%
320 IF B%<>1 GOTO 330 ELSE 310
330 OUT &H301,255
340 GOSUB 480
350 PRINT #1,"@STEP",(0),100,0,0,0,0,0
360 GOSUB 480
370 PRINT #1,"@STEP",(0),0,100,-80,0,0,0
380 OUT &H301,0 ' REPEAT FOR Y PLATE
390 C%=INP(&H300):PRINT "C%="C%
400 IF C%<>1 GOTO 410 ELSE 390
410 OUT &H301,255
420 GOSUB 480
430 PRINT #1,"@STEP",(0),-55,-9,6,0,0,0
440 GOSUB 480
450 CLOSE #1
460 CLS
470 RETURN 110
480 TIME$="0:0:00"
490 T$=RIGHT$(TIME$,2)
500 IF T$="05" GOTO 510 ELSE 490
```

Figure 17. Software Listing (continued)

```
510 RETURN
515 REM THIS PORTION IS USED TO EXECUTE A TYPE OF ROUTINE
520 DEFINT A-Z
530 OPEN "COM1:9600,N,8,1,RS,DS,CS" AS #1
540 INPUT "INPUT SPEED";SPD
550 CLS
560 DIM A1(50),A2(50),A3(50),A4(50),A5(50),A6(50)
570 LOCATE 15,15:PRINT "RUN MODE"
580 INPUT "please input file name";FILE$
590 INPUT "INPUT NO. OF CYCLES";Y
600 INPUT "INPUT THE NO. OF STEPS";N
610 FOR Z = 1 TO Y
620 OPEN "I",2,FILE$
630 CLS
640 FOR J = 1 TO N:PRINT "STEP #";J;
650 INPUT#2, A1(J),A2(J),A3(J),A4(J),A5(J),A6(J)
660 PRINT #1,"@STEP",SPD,A1(J),A2(J),A3(J),A4(J),A5(J),A6(J):INPUT #1,I
670 NEXT J
680 CLOSE #2
690 NEXT Z
700 CLS
710 RETURN 110
```

APPENDIX C

Sampling Scheme for One-way ANOVA

(Cross Reference. p 23)

Table 13. Sampling Schema for One-Way ANOVA

	Treatments (j)							
OBS. (i)	S1	S2	S3	S4	S5	S6	S7	S8
1	16	3	7	1	5	9	6	10
2	4	8	2	14	12	11	13	15

APPENDIX D

One-way ANOVA for SEQUENCE

(Cross Reference. p 23)

Table 14. One-Way Analysis of Variance

Data: seqx

Level codes: seqcod

Labels:

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0068660	7	.0009809	.224	.9681
Within groups	.0349990	8	.0043749		
Total (corrected)	.0418650	15			

0 missing value(s) have been excluded.

Table 14. One-Way Analysis of Variance (continued)

Data: seqy

Level codes: seqcod

Labels:

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0043254	7	6.17920E-004	1.291	.3615
Within groups	.0038295	8	4.78688E-004		
Total (corrected)	.0081549	15			

0 missing value(s) have been excluded.

Table 14. One-Way Analysis of Variance (continued)

Data: seqz

Level codes: seqcod

Labels:

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0090200	7	.0012886	.685	.6843
Within groups	.0150460	8	.0018807		
Total (corrected)	.0240660	15			

0 missing value(s) have been excluded.

APPENDIX E

Sampling Scheme for 4-Factor Experiment

(Cross Reference. p 24)

Table 15. Random Numbers Sorted in Ascending Order

RANDOM NUMBER	OBSERVATION TYPE	RANDOM NUMBER	OBSERVATION TYPE
2	1322	185	2133
4	3122	188	2123
7	1211	189	3313
9	2000	193	1123
13	3132	193	1321
25	1111	194	1311
33	2112	199	1323
34	2223	207	2311
48	1133	207	3112
49	1331	211	2132
52	2313	211	2112
55	1000	218	3233
55	1000	219	3113
58	3322	220	3321
58	3331	228	1232
59	1113	228	2233
59	3322	229	3211
61	3113	231	2331
62	2321	231	1311
65	3333	231	1213
66	1233	232	3331
66	3312	234	1323
66	3333	236	3323
69	2323	241	1332
70	1222	241	3323
72	2000	241	1323
73	1123	244	3111
74	1212	251	3223
77	3233	253	3123
79	3133	262	1211
80	2222	265	3211
81	3321	265	3332
86	3311	266	2232
87	3223	267	1323
88	1231	274	3113
90	1111	277	2312
99	2121	278	1312
100	3312	284	1332
102	1111	285	1223
103	2221	285	2332
104	1321	288	2213
107	2122	288	2231
107	1133	290	3233

Table 15. Random Numbers Sorted in Ascending Order (continued)

RANDOM NUMBER	OBSERVATION TYPE	RANDOM NUMBER	OBSERVATION TYPE
108	3232	292	3213
108	2111	300	3121
109	2211	301	3121
109	1333	302	3232
111	1111	302	1332
114	2333	302	3332
114	1211	303	1123
117	3132	310	1233
117	3113	314	2323
119	1221	314	1223
121	1111	319	1232
123	1313	320	1222
124	1112	320	3131
124	3211	321	2332
125	1113	323	1211
128	3321	328	3312
129	3123	328	3311
129	1112	329	3233
129	2212	334	1323
133	2233	334	3311
137	3331	335	2332
138	2133	336	3331
142	3111	342	3322
143	2113	342	1112
146	2223	343	2123
147	3321	345	2212
153	2322	346	1233
155	1311	350	2323
156	1331	351	2322
162	1313	352	1311
167	2222	353	2132
167	3233	357	2113
170	3231	362	1332
173	1322	363	1131
176	2123	365	2131
178	1122	379	3323
182	1332	380	2212
184	1123	381	1231

APPENDIX F

Discriminant Analysis Results

(Cross Reference. p 25)

Table 16. Discriminant Analysis for CODEX

Discriminant Function	Eigenvalue	Relative Percentage	Canonical Correlation
1	7.7896799	100.00	.94140

Functions Derived	Wilks Lambda	Chi-Square	DF	Sig.Level
0	.1137698	345.59895	2	.00000

Table 17. Discriminant Analysis for CODEY

Discriminant Function	Eigenvalue	Relative Percentage	Canonical Correlation
1	5.7995483	100.00	.92354

Functions Derived	Wilks Lambda	Chi-Square	DF	Sig.Level
0	.1470686	304.78013	2	.00000

Table 18. Discriminant Analysis for CODEZ

Discriminant Function	Eigenvalue	Relative Percentage	Canonical Correlation
1	4.0985747	100.00	.89659

Functions Derived	Wilks Lambda	Chi-Square	DF	Sig.Level
0	.1961332	259.00480	2	.00000

APPENDIX G

ANOVA Results for 4-Factor Experiment

(Cross Reference. p 26)

Table 19. Analysis of Variance for ERRORX

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		.0385130	9	.0042792	7.597	.0000
LOADX		.0231806	2	.0115903	20.575	.0000
SPEEDX		.0115160	2	.0057580	10.222	.0001
CYCLEX		.0009422	2	.0004711	.836	.4358
ROUTINEX		.0021352	2	.0010676	1.895	.1548
REPX		.0007390	1	.0007390	1.312	.2543
2-FACTOR INTERACTIONS		.0399320	32	.0012479	2.215	.0011
LOADX	SPEEDX	.0162694	4	.0040673	7.220	.0000
LOADX	CYCLEX	.0007070	4	.0001768	.314	.8683
SPEEDX	CYCLEX	.0011284	4	.0002821	.501	.7352
LOADX	ROUTINEX	.0105525	4	.0026381	4.683	.0015
SPEEDX	ROUTINEX	.0005943	4	.0001486	.264	.9007
CYCLEX	ROUTINEX	.0001289	4	.0000322	.057	.9938
LOADX	REPX	.0006750	2	.0003375	.599	.5509

0 missing values have been excluded.

Table 20. Analysis of Variance for ERRORY

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		.0414654	9	.0046073	4.963	.0000
LOADY		.0057487	2	.0028743	3.097	.0488
SPEEDY		.0261428	2	.0130714	14.082	.0000
CYCLEY		.0075106	2	.0037553	4.046	.0199
ROUTINEY		.0003490	2	.0001745	.188	.8288
REPY		.0017144	1	.0017144	1.847	.1767
2-FACTOR INTERACTIONS		.0403898	32	.0012622	1.360	.1202
LOADY	SPEEDY	.0064226	4	.0016057	1.730	.1478
LOADY	CYCLEY	.0040892	4	.0010223	1.101	.3592
SPEEDY	CYCLEY	.0052488	4	.0013122	1.414	.2336
LOADY	ROUTINEY	.0012948	4	.0003237	.349	.8445
SPEEDY	ROUTINEY	.0020288	4	.0005072	.546	.7020
CYCLEY	ROUTINEY	.0020821	4	.0005205	.561	.6916
LOADY	REPY	.0008545	2	.0004273	.460	.6322

0 missing values have been excluded.

Table 21. Analysis of Variance for ERRORZ

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		.0358985	9	.0039887	4.990	.0000
LOADZ		.0114388	2	.0057194	7.155	.0012
SPEEDZ		.0072643	2	.0036322	4.544	.0125
CYCLEZ		.0168703	2	.0084351	10.553	.0001
ROUTINEZ		.0000236	2	.0000118	.015	.9854
REPZ		.0003015	1	.0003015	.377	.5468
2-FACTOR INTERACTIONS		.0881485	32	.0027546	3.446	.0000
LOADZ	SPEEDZ	.0225066	4	.0056267	7.039	.0000
LOADZ	CYCLEZ	.0066169	4	.0016542	2.070	.0890
SPEEDZ	CYCLEZ	.0012656	4	.0003164	.396	.8113
LOADZ	ROUTINEZ	.0008243	4	.0002061	.258	.9044
SPEEDZ	ROUTINEZ	.0006539	4	.0001635	.205	.9355
CYCLEZ	ROUTINEZ	.0006968	4	.0001742	.218	.9280
LOADZ	REPZ	.0019728	2	.0009864	1.234	.2948

0 missing values have been excluded.

APPENDIX H

Sampling Scheme for 3-Factor Experiment

(Cross Reference. p 27)

Table 22. Sampling Schema for ANOVA

69	367	621	349
84	147	652	159
100	369	657	168
103	258	675	258
111	269	685	169
163	158	708	259
171	257	723	249
186	248	728	357
195	259	729	157
204	148	748	359
213	169	759	368
233	267	765	149
271	249	767	168
295	358	797	368
301	147	825	369
301	268	856	358
334	157	857	269
391	347	869	348
426	247	873	159
505	367	884	348
511	248	889	257
513	268	904	347
559	349	917	167
567	148	926	167
569	357	926	247
615	149	927	267
617	158	993	359

NOTE:
First digit represents load, second speed, and third the number of cycles.

APPENDIX I

Sample Data Sheet

(Cross Reference. p 31)

REP 1 SPEED 1

# CYCLES	2	4	6
LOAD 1			
LOAD 2			
LOAD 3			

REP 1 SPEED 2

# CYCLES	2	4	6
LOAD 1			
LOAD 2			
LOAD 3			

REP 1 SPEED 3

# CYCLES	2	4	6
LOAD 1			
LOAD 2			
LOAD 3			

Figure 18. SAMPLE DATA SHEET

APPENDIX J

ANOVA Results for 3-Factor Experiment

(Cross Reference. p 32)

Table 23. Analysis of Variance for ERRORX

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		.0100728	7	.0014390	15.973	.0000
LOADX		.0053200	2	.0026600	29.528	.0000
SPEEDX		.0042018	2	.0021009	23.321	.0000
CYCLEX		.0002234	2	.0001117	1.240	.3049
REPX		.0003276	1	.0003276	3.636	.0668
2-FACTOR INTERACTIONS		.0070091	18	3.89395E-004	4.322	.0003
LOADX	SPEEDX	.0039663	4	9.91574E-004	11.007	.0000
LOADX	CYCLEX	.0001914	4	4.78519E-005	.531	.7138
SPEEDX	CYCLEX	.0011540	4	2.88491E-004	3.202	.0276
LOADX	REPX	.0006551	2	3.27574E-004	3.636	.0395
SPEEDX	REPX	.0010296	2	5.14796E-004	5.714	.0083
CYCLEX	REPX	.0000127	2	6.35185E-006	.071	.9321
RESIDUAL		.0025224	28	9.00860E-005		

0 missing values have been excluded.

Table 24. Analysis of Variance for ERRORY

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		.0061940	7	.0008849	18.503	.0000
LOADY		.0013574	2	.0006787	14.192	.0001
SPEEDY		.0045554	2	.0022777	47.628	.0000
CYCLEY		.0001243	2	.0000622	1.300	.2885
REPY		.0001567	1	.0001567	3.278	.0810
2-FACTOR INTERACTIONS		.0096623	18	.0005368	11.225	.0000
LOADY	SPEEDY	.0068038	4	.0017009	35.568	.0000
LOADY	CYCLEY	.0004076	4	.0001019	2.131	.1034
SPEEDY	CYCLEY	.0002129	4	.0000532	1.113	.3701
LOADY	REPY	.0009300	2	.0004650	9.724	.0006
SPEEDY	REPY	.0012269	2	.0006135	12.828	.0001
CYCLEY	REPY	.0000811	2	.0000406	.848	.4388
RESIDUAL		.0013390	28	4.78228E-005		

0 missing values have been excluded.

Table 25. Analysis of Variance for ERRORZ

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0549011	7	.0078430	21.131	.0000
LOADZ	.0035891	2	.0017946	4.835	.0157
SPEEDZ	.0484099	2	.0242050	65.216	.0000
CYCLEZ	.0001571	2	.0000786	.212	.8105
REPZ	.0007449	1	.0007449	2.006	.1085
2-FACTOR INTERACTIONS	.0135151	18	.0007508	2.023	.0457
LOADZ SPEEDZ	.0031770	4	.0007942	2.140	.1022
LOADZ CYCLEZ	.0055407	4	.0013852	3.732	.0148
SPEEDZ CYCLEZ	.0008183	4	.0002046	.551	.6997
LOADZ REPZ	.0002271	2	.0001136	.306	.7388
SPEEDZ REPZ	.0033584	2	.0016792	4.524	.0198
CYCLEZ REPZ	.0003936	2	.0001968	.530	.5943
RESIDUAL	.0103923	28	3.71153E-004		

0 missing values have been excluded.

APPENDIX K

Correlation Matrix for Main Effects

(Cross Reference. p 34)

Table 26. Sample Correlations

	ERRORX	LOADX	CYCLEX	SPEEDX	REPX
ERRORX	1.0000	.3083	-.1059	-.4107	.1293
	(54)	(54)	(54)	(54)	(54)
	.0000	.0233	.4458	.0020	.3516
LOADX	.3083	1.0000	.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.0233	.0000	1.0000	1.0000	1.0000
CYCLEX	-.1059	.0000	1.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.4458	1.0000	.0000	1.0000	1.0000
SPEEDX	-.4107	.0000	.0000	1.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.0020	1.0000	1.0000	.0000	1.0000

Coefficient (sample size) significance level

Table 26. Sample Correlations (continued)

	ERRORY	LOADY	CYCLEY	SPEEDY	REPY
ERRORY	1.0000	-.1462	.0801	.4944	.0955
	(54)	(54)	(54)	(54)	(54)
	.0000	.2916	.5649	.0001	.4922
LOADY	-.1462	1.0000	.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.2916	.0000	1.0000	1.0000	1.0000
CYCLEY	.0801	.0000	1.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.5649	1.0000	.0000	1.0000	1.0000
SPEEDY	.4944	.0000	.0000	1.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.0001	1.0000	1.0000	.0000	1.0000

Coefficient (sample size) significance level

Table 26. Sample Correlations (continued)

	ERRORZ	LOADZ	CYCLEZ	SPEEDZ	REPZ
ERRORZ	1.0000	.2125	-.0083	-.7101	.1866
	(54)	(54)	(54)	(54)	(54)
	.0000	.1228	.9524	.0000	.1766
LOADZ	.2125	1.0000	.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.1228	.0000	1.0000	1.0000	1.0000
CYCLEZ	-.0083	.0000	1.0000	.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.9524	1.0000	.0000	1.0000	1.0000
SPEEDZ	-.7101	.0000	.0000	1.0000	.0000
	(54)	(54)	(54)	(54)	(54)
	.0000	1.0000	1.0000	.0000	1.0000

Coefficient (sample size) significance level

APPENDIX L

Regression Analysis Results

(Cross Reference. p 35)

Table 27. Regression Analysis - Linear model: Y = a+bX

Dependent variable: ERRORX — Independent variable: LOADX

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.117963	6.65026E-3	17.7381	.00000
Slope	7.19444E-3	3.07847E-3	2.33702	.02332

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.0018634	1	.0018634	5.461644	.02332
Error	.017741	52	.000341		
Total (Corr.)	.019604	53			

Correlation Coefficient = 0.308299
Stnd. Error of Est. = 0.0184708

Table 27. Regression Analysis - Linear model: Y = a+bX (continued)

Dependent variable: ERRORX — Independent variable: SPEEDX

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.151519	6.37409E-3	23.771	.00000
Slope	-9.58333E-3	2.95063E-3	-3.24789	.00204

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.003306	1	.003306	10.54880	.00204
Error	.016298	52	.000313		
Total (Corr.)	.019604	53			

Correlation Coefficient = -0.410669
Stnd. Error of Est. = 0.0177038

Table 27. Regression Analysis - Linear model: Y = a+bX (continued)

Dependent variable: ERRORY — Independent variable: LOADY

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.158278	6.47689E-3	24.4373	.00000
Slope	-3.19444E-3	2.99822E-3	-1.06545	.29160

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.0003674	1	.0003674	1.135180	.29160
Error	.016828	52	.000324		
Total (Corr.)	.017195	53			

Correlation Coefficient = -0.146164
Stnd. Error of Est. = 0.0179893

Table 27. Regression Analysis - Linear model: Y = a+bX (continued)

Dependent variable: ERRORY | Independent variable: SPEEDY

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.130278	5.69099E-3	22.8919	.00000
Slope	0.0108056	2.63442E-3	4.10169	.00014

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.004203	1	.004203	16.82383	.00014
Error	.012992	52	.000250		
Total (Corr.)	.017195	53			

Correlation Coefficient = 0.494417
Stnd. Error of Est. = 0.0158065

Table 27. Regression Analysis - Linear model: Y' = a+bX (continued)

Dependent variable: ERRORZ — Independent variable: LOADZ

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.129204	0.0136962	9.43356	.00000
Slope	9.94444E-3	6.3401E-3	1.5685	.12283

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.0035601	1	.0035601	2.460195	.12283
Error	.075248	52	.001447		
Total (Corr.)	.078809	53			

Correlation Coefficient = 0.212542
Stnd. Error of Est. = 0.0380406

Table 27. Regression Analysis - Linear model: Y = a+bX (continued)

Dependent variable: ERRORZ — Independent variable: SPEEDZ

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	0.215537	9.86958E-3	21.8385	.00000
Slope	-0.0332222	4.56873E-3	-7.27166	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.039734	1	.039734	52.87701	.00000
Error	.039075	52	.000751		
Total (Corr.)	.078809	53			

Correlation Coefficient = -0.710057
Stnd. Error of Est. = 0.0274124