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An Analysis of How the Payload and the Speed Affect the Repeatablility of the Microbot Teachmover Robot

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Abstract

With the increasing application of robots to many fields in our life, the accuracy and the repeatability of robots become more and more important. Many applications require robots to have high repeatability and accuracy. There are many factors which can affect the repeatability and the accuracy of a robot.

This study was to examine how the two key factors of payload and speed affect repeatability. The experiment was conducted in the CAM Laboratory of the Industrial Technology Center, University of Northern Iowa, by using Microbot TeachMover. Six different payloads: 2gm, 20gm, 65gm, 130gm, 180gm and 250 gm, and three different speeds: speed(3), speed(5) and speed(?) were exerted under the control of the same program. The robot with certain payload and speed ran 30 cycles, and the spatial positions were measured by three dialindicators which represented three-dimensional coordinates (X,Y,Z). After the data were collected, the relative spatial position deviation was calculated. The first cycle point was used as the original position. The researcher used the mean of the spatial position deviation and the range of spatial position deviation to analyze the affect of payloads and speeds on repeatability. Also linear trend "b" and the coefficient of correlation "r" were used to identify repeatability change during the 30 cycles. Analyzing the collected data led to the conclusion that light payload and medium speed have better repeatability, and both higher speed (7) and lower speed (3) lead to lower repeatability.

AN ANALYSIS OF
HOW PAYLOAD AND SPEED AFFECT THE
REPEATABILITY OF THE MICROBOT TEACHMOVER ROBOT

A Research Paper Presented
to the Graduate Faculty
of the Department of
Industrial Technology
University of Northern Iowa

In Partial Fulfillment of the
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by
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ABSTRACT

With the increasing application of robots to many fields in our life, the accuracy and the repeatability of robots become more and more important. Many applications require robots to have high repeatability and accuracy. There are many factors which can affect the repeatability and the accuracy of a robot.

This study was to examine how the two key factors of payload and speed affect repeatability. The experiment was conducted in the CAM Laboratory of the Industrial Technology Center, University of Northern Iowa, by using Microbot TeachMover. Six different payloads: 2gm, 20gm, 65gm, 130gm, 180gm and 250 gm, and three different speeds: speed(3), speed(5) and speed(7) were exerted under the control of the same program. The robot with certain payload and speed ran 30 cycles, and the spatial positions were measured by three dial-indicators which represented three-dimensional coordinates (X,Y,Z). After the data were collected, the relative spatial position deviation was calculated. The first cycle point was used as the original position. The researcher used the mean of the spatial position deviation and the range of spatial position

deviation to analyze the affect of payloads and speeds on repeatability. Also linear trend "b" and the coefficient of correlation "r" were used to identify repeatability change during the 30 cycles. Analyzing the collected data led to the conclusion that light payload and medium speed have better repeatability, and both higher speed (7) and lower speed (3) lead to lower repeatability.

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CHAPTER I

INTRODUCTION

Since the robot entered our life, it has become more and more important. Industrial robots can be found anywhere producing many products we use and doing many boring jobs that people do not like to do.

Robot applications are continuously widening, and their functions are becoming more and more powerful, but many problems with using robots and with the design and function of robots still exist today. People expect robots to work perfectly. Robots need to meet people's high requirements.

Industrial robots have typically been used as general purpose positioning devices. In such a situation, the robot is programmed to move through a sequence of positions so that a tool or part held by the robot completes a desired task on a workpiece, whose position is already set in relation to that of the robot. The most important requirement for successful accomplishment of its task is the repeatability with which it can return to the taught positions and with which successive workpieces can be presented to it (Taylor, 1985).

Some manufacturing operations, such as welding, deburring, routing and scanning, require the robot to move a tool in a continuous path. Therefore, kinematic measurement of accuracy and repeatability that test the robot's ability to trace accurately a path through its workspace at a rapid pace are far more important for these operations (Tracking system measures continuous path robot motions, 1985).

Most of the tasks need the robot to execute with high accuracy. "Accuracy of robots is required in an increasing number of applications" (Day, 1988, p. 1). Day (1988) said, "It is important for users of robots to understand factors affecting accuracy [and repeatability] and where present technology stands in making accuracy [and repeatability] improvements" (p. 9).

A major goal of robot research and development over many years has been finding techniques for improving the effective accuracy or repeatability of the manipulator, i.e., the precision with which it can place a part or tool at a fixed position relative to a workpiece. Calibration methods and equipment sensing methods are the major approaches for such a problem (Taylor, 1985).

This study will use an experimental method on a Microbot TeachMover Robot to identify some important factors affecting the repeatability of a robot. The effect of payload and speed on repeatability will be determined.

This laboratory research can explore a way for researchers to make a significant study on industrial robots, and provide more information for industrial robot designers to improve the quality of robots. This study can also make up for a shortcoming of specifications on the basic parameters of the Microbot TeachMover Robot -- repeatability.

Purpose of the Research

The purpose of this study was to:

1. Identify key factors that can affect the accuracy and repeatability of the Microbot TeachMover robot.
2. Analyze an important characteristic -- repeatability -- as the dependent variable in a study of the Microbot TeachMover robot.

3. Gain more knowledge about industrial robots from the study of a robot in an educational laboratory.

Research Problem

There are various factors which may affect the repeatability of a given robot. The problem of this research was to determine how the factors of payload and speed affect the repeatability of a Microbot TeachMover Robot (MTMR).

Research Questions

The research questions of this study were:

1. How does the weight of payload affect the repeatability with a certain speed in terms of "$\overline{@D}$" and "R"? "$\overline{@D}$" is the mean of spatial position deviation of the thirty cycles; "R" is the range of spatial position deviation of the thirty cycles. Six different weights of payload were applied.
2. How does the speed with a certain payload affect the repeatability in terms of "$\overline{@D}$" and "R"? Three speeds were tested.
3. How does the spatial position deviation "@D" change during the thirty cycles in regard to the

analysis of "b" and "r"? "b" is the changing rate of "@D"; "r" is the coefficient of correlation.

4. How does @D change when the robot run more than 30 cycles. The payload 65 with speed 5 and 7 was applied under 50 cycles.

Significance of the Research

Robots have a large number of applications. They are generally flexible, reprogrammable and repeatable from cycle to cycle. However, for many new industrial applications in which high repeatability and accuracy are required, the current accuracy and repeatability can not satisfy these high requirements. The robot needs to be more accurate and more repeatable, and the physical location or trajectory reached by the end-effector must be precisely where the robot has been directed (Day, 1988).

The importance of a robot's accuracy and repeatability was recognized in the early years of robotics development, and it has taken some time for the necessary technology in manipulator development, sensor development, and application development to realistically and economically overcome robot inaccuracy and poor repeatability. But we have not quite reached a stage when robots can be produced accurately within desired cost (Day, 1988).

By conducting this research, the factors which can affect the repeatability and accuracy of a robot will be carefully investigated and more valuable data will be collected and analyzed. As a result of this research, the researcher will supply some important information which can be used by robot designers to improve the quality of a robot.

The Microbot TeachMover Robot will be used in the laboratory for this research. The current instruction manual for the Microbot TeachMover Robot lacks information about the accuracy and repeatability in its specification list. This research can remedy this defect and make it better for future educational use.

Delimitations

This study was limited as follows:

1. This research was conducted in the CAM Laboratory at University of Northern Iowa. The Microbot TeachMover robot which was used for this research had been used for about five years. Its accuracy

might not maintain the same level as a new one.

2. The research used the teach pendant to program the robot. Only payload and speed were considered without considering other factors.
3. Three dial-indicators were used to measure the spatial position deviation on X, Y, Z axis separately. Resolution of the Dial-Indicator is .001 inches.
4. Repeatability was studied in regard to the analysis of the relative spatial position deviation. A robot with certain payload and speed was run 30 cycles under the control of the same program.

Assumptions

This study had the following assumptions:

1. All the tests were not affected by environmental conditions.
2. There was no reading error during the measuring process.
3. There was no slippage between payload and gripper, robot and table as well as dial-indicator set-up and table. The table on which all tests were carried out did not shake during the test.

Definitions

The following terms were defined for this study:

1. The Microbot TeachMover Robot -- A small "educational" robot developed to help researchers and students learn about robots, with a low cost machine that fully simulates the large industrial machines (Heath, 1986).
2. The Teach Pendant -- A special command module used to command the robot to memorize points along the path of motion. It can also set timers to synchronize the operation, command the sensing of external inputs, and dispatch output signals to peripheral process equipment (Asfahl, 1985).
3. Payload--Weight of the object handled by the robot.
4. Robotic programming -- A key feature of robots which have capability for being reprogrammed for different tasks. There are many methods of programming. Teach pendant is one of the manual controller methods.
5. Repeatability--The ability to return to the same spot again and again after that point has been specified.
6. Speed--The important characteristic of a robot that

determines how fast the robot performs the programmed operations.

CHAPTER II

LITERATURE REVIEW

Introduction

In the early 1960s, the first industrial robot was built under the cooperation of the George Devol and the Unimation company. Since then, industrial robots have been under serious development. Robots are invading the traditional manufacturing system. Totally automated factories are being built and are changing the landscape of manufacturing. In the last few years, the larger industries of the world have invested heavily in robots and automated manufacturing systems. The entrance of many and many companies into the robot business indicates that robotics will be fully implemented in the factories of the future (Heath, 1985; Hunt, 1990).

A robot is a machine that can easily be directed to do a variety of tasks without human supervision. Typical industrial robots are stationary machines, usually bolted to the floor or in an overhead position that can pick up parts and move them about. The basic concept is to build a machine that is flexible enough to do a variety of jobs automatically, a device that could be easily taught or programmed so that, if the part or process changed, the robot could adapt to its new job without expensive retooling (Health, 1985; Kafrissen, 1984).

Definition

"A robot is a reprogrammable and multifunctional manipulator designed to move materials, parts, tools or specialized devices through various programmable motions in the performance of a variety of tasks" (McDonald, 1986, p. 5). The main applications of industrial robots are:

- Loading and unloading machine tools;
- Handling in manufacturing process, such as die casting;
- Welding;
- Spray painting;
- Assembly;
- Machining, such as deburring and drilling;
- Inspection. (Koren, 1985, p. 175)

Classification and Types of Robots

Since robot configurations vary greatly, some classification of robot geometries is necessary. The industry has settled upon the term "degrees of freedom" to describe the number of ways a robot can move. The form of these movements and the way they are assembled make up the robot configuration. Theoretically, there could be a large number of configurations for a robot. From a practical standpoint, however, almost all robots fall into a few popular configuration categories: articulating configurations, polar configurations, cylindrical configurations and cartesian configurations.

The most distinguishing feature used to describe an industrial robot is its power source. The power source usually determines the range of the robot's performance characteristics and in turn the feasibility of various applications. Basically, there are four principal power sources: hydraulic, pneumatic, electric and mechanical gear and cam. Electric robots are popular for precision jobs because they can be closely controlled and can be taught to follow complicated paths of motion. Electric robots can be divided into groups according to the types of electric motors that drive each of the axes of motion. One type uses stepper motors, which are driven a precise angular displacement for every discrete voltage pulse issued by the control computer interface. The stepper-motor type robot is sometimes of the open-loop type. The other species of electric robot is the dc servo-driven type. These robots invariably incorporate feedback loops from the driven components back to the driver. Thus, the control system continuously monitors the positions of the robot components, compares these positions with the positions desired by the controller, and notes any differences or error conditions.

Another distinguishing feature of the robot is the degree of control possible over the robot motion. This control is affected by the choice of robot drives. Starting from the least sophisticated, we can classify four types of motion control: axis limit, point-to-point, contouring and line tracking. The most complex of contouring motion is line tracking which performs an operation while following alongside a continuously moving path. Line tracking has obvious advantages. The product being processed can be transported on a continuous conveyor instead of an intermittent one.

Although a modern industrial robot looks as though it is a self-contained, intelligent machine, it is, in fact, a sophisticated combination of many engineering disciplines. The clever interfacing of the various parts has achieved the creation of a powerful tool to serve the pursuit of increased productivity and higher quality of manufactured goods (McDonald, 1986; Asfahl,1985).

In order to design robot systems, a company needs a wide variety of skills. When robots were first designed, mechanical engineering skills were the primary requirement. As robots became part of industrial production, manufacturing engineering skills were needed. As servo control and advanced sensors began to be used, the need for electronics engineers to enter the field became important. Further steps required the skills of programmers, computer hardware engineers, language designers, and vision specialists. The next generation of robots will require people skilled in artificial intelligence and such specialized areas as laser technology and ultrasonics (Poole, 1989).

Significance of the Specifications

Generally, industrial robots are built of three basic systems:

1. The mechanical structure consisting of mechanical linkage and joints capable of various movements.
2. The control system, which can be of "non-serve" or "serve" type.
3. The power units, which can be hydraulic, pneumatic, electrical, mechanical or their combinations.

The variability of these systems' functions and the need for programmability make it a challenge to define a unique set of specifications that engineers can comfortably consider adequate for the final design of robots (Rivin, 1988). Stonecipher (1989) said, "The performance functions that can be analyzed in regard to the actuator are its dynamic capabilities, stability, spatial resolution, control accuracy, repeatability, and compliance" (p. 11).

The most obvious specification determined by the use of a manipulator is the physical or fundamental specification, and Andeen (1988) listed them as follow:

* Payload (Maximum)
* Precision
  absolute accuracy, ability to go to any specified point;
  repeatability, ability to repeat a location;
  resolution, the smallest position step;
* Speed
  velocity of the endpoint;

cycle time, includes accelerations and decelerations.
- Reach
- Stiffness. (p. 2)

These specifications are not a set of unrelated numbers, and they may be interrelated. Speed and weight, speed and precision or precision and reach will affect each other. Different payloads in the same speed should not be expected to get the same precision. The designer must recognize that in several performance areas strengthening one specification can decrease performance in another. Resolution, repeatability, and accuracy are the three most important characteristics in evaluating how well an arm can position its end effector (Atkeson, 1986; Andeen, 1988).

Parametric Factors

Robot parameters include kinematic parameters and dynamic parameters. In robotics, the solution of the direct kinematic problem involves the determination of the end effector's position and orientation and their rate of change, as a function of the given positions and speeds of the axes of motion. The position of the end effector, or robot tool, is defined as the TCP (tool center point), which is, for example, the edge of a welding gun or the center of a gripped object.

The kinematic analysis of a mechanical system means the determination of the position, velocity, and acceleration of the various mechanical elements forming the mechanism under consideration. The effect of the associated forces and torques, which take into account the mass and inertia of the mechanical elements, is considered in dynamic analysis (Hollerbach, 1982; N-Nagy, 1987).

In contrast to robot dynamics, one must also consider static conditions. Statics is concerned with forces that act on a body and the conditions required to obtain their equilibrium. Robots require hydraulic, pneumatic, or electric forces to change the position of the free end of the arm. These forces are needed because the robot is a mechanical device that offers resistance to change due to inertia and friction. Once a new position is obtained, the equilibrium has to be reestablished. In this relationship between acting forces and their opposing factors, errors in the response of the robot are produced that must be recognized.

Dynamics also deals with these forces, but it does so with respect to the motion they produce. It establishes the relationship between acceleration (or deceleration) and the forces involved (Holzbock, 1986).

The robot here is nothing but a transducer changing one form of input into some other form of output. The degree to which the output changes in response to changes in input depends on the accuracy of the robot. When the input calls for a certain position, the robot must act to produce this position. The input is the true value and actual result is the inaccuracy or error. There are dynamic and static errors (Holzbock, 1986).

Static Errors

Holzbock (1986) stated:

> Accuracy specifications as given by robot manufacturers practically always refer to the robot arm without end effector and without load being carried. Generally, either one diminishes the specified accuracy. Position accuracy also depends on the deceleration of the motion of the robot arm. For maximum accuracy, the robot has to make final approach to its programmed position very slowly. (p. 3)

But if this high accuracy level is used in program steps where it is not required, cycle time for these steps will be unnecessarily long. This is of particular importance where the motion from one point to another is composed of several steps, for example, when the robot moves around obstacles.

Backlash between two gears that are part of a power transmission produces a dead zone in which no output is produced while the input changes. The increase of the input must first be sufficient to lock the gears together before the output gear begin to follow the input gear. Static friction, also called stiction and break-loose force, is defined as the force required to initiate sliding or rolling motion between two contacting bodies (Holzbock, 1986).

Dynamic Errors

Robot joints are rotational and translational or linear elements that provide elbow, wrist, and other movements. Each degree of freedom of the robot requires its own joint to produce the desired motion. The joints are either directly or remotely driven by actuators that convert electrical, hydraulic, or pneumatic energy into motion.

Mass is a measure of inertia. It is considered a property of matter that resists change of motion. Inertia is the inherent property of bodies to resist any change in their state.

A body in motion may encounter two types of friction: coulomb friction and viscous friction. Static friction resists the onset of motion, not motion once it takes place. Coulomb friction is also called dry friction or sliding friction. It is caused by minute irregularities of one surface engaging those of the surface over which it slides. It is diminished by lubrication. In a dynamic system, oscillation is generally associated with viscous friction and, hence, is proportional to speed. Oscillation is essential to prevent a system from instability that could otherwise produce excessive oscillations of the end effector of a robot (Holzbock, 1986).

Analysis of Repeatability

Repeatability is the function whereby the robot manipulator is able to repeat or reposition itself into a position that was previously trained or commanded. The internal factors that influence the repeatability of the manipulator system are its movement control system and mechanical components of the robot system (Mason, 1985).

Repeatability is different than accuracy. While accuracy deals with actual spatial position attained by the robot, repeatability deals with positional discrepancies from cycle to cycle. When comparing repeatability and accuracy, the factors used to determine repeatability will always be of a greater value than absolute accuracy (Stonecipher, 1989; Day, 1988).

Repeatability is sub-classified by Day (1988) into omnidirectional repeatability and unidirectional repeatability. He said, "Repeatability is a function of many variables such as the number of cycles, location in workspace, temperature, speed/acceleration of path, payload, and so forth" (p. 2). So far, there is no unified method of measuring repeatability. Japan Industrial Standards (JIS) uses a seven-cycle measurement. Large robot users, such as General Motors and Ford, have defined their own test procedures to measure repeatability. Other methods of test and specification, such as the use of measurement cubes and spheres have been proposed (Day, 1988).

Environmental factors can also cause inaccuracies and irrepeatability. For example, temperature variations can cause link length changes in structural components and drive-train components. Temperature and relative humidity can affect characteristics of lubricants used in drive trains (Day, 1988).

Angularity between each pair of adjacent axles also contributes to the inaccuracy of robots. Angularity can come from assembly error of fitting subassemblies together or in the seating of bearings supporting the axles. Day (1988) found, "Just an error of 0.1 degree in angularity could cause a link offset error of 1.745mm when the two adjacent axles were 1000mm apart" (p. 3). Robot accuracy measurement is the first step in understanding what errors are to be corrected.

As Day (1988) suggested, "It is important for users of robots to understand factors affecting [repeatability] and where present technology stands in making [repeatability] improvement" (p. 9).

There are intrinsic limitations in robot manipulators and in robot applications. "It will require joint efforts from users, manipulators, and researchers to achieve the most productive use of [an] accurate robot system" (Day, 1988, p. 9).

CHAPTER III

RESEARCH DESIGN AND METHODOLOGY

Identification of Variables

In this research, there were two independent variables-- payload and speed, and one dependent variable -- repeatability. There were many other variables, such as temperature, humidity, researcher's operating skill, and measurement error, as well as the elastic variation of the robot arm when the payload held by the robot touched the sensor of the dial-indicators, all of which could have impacted the repeatability. But during the research process, the researcher mainly aimed at the relative position deviation caused by different working cycles, and not the absolute accuracy of the position an object needs to reach. The test was set up in an intensive short period of time to eliminate environmental effects on repeatability. Therefore, the variables caused by the system might not be considered. Also, the entire study was conducted on the same robot, so other influences caused by the equipment might be omitted.

Instrumentation

The robot program was made with teach pendant, and stored on a 5 1/4" floppy disc. The same program was used repeatedly with different variables (see Appendix A). Cube-shaped plastic and steel blocks were used to exert different payloads. Three dial-indicators were set together to measure the position deviation on X,Y,Z axis separately. Resolution of the dial-indicators is .001 inches.

The payload was held by the gripper with a pressure about 2.5 lbs and also made more tight by the tape around the payload and gripper. During the first few tests, because the measuring set-up did not match with payload well, the reading might not have been accurate. After the researcher changed the shape of some payloads and adjusted the measuring devices, the experiment began to be in process, and went on smoothly.

The gripper always held a certain payload during the 30 cycles. When the robot finished its one cycle and went back to its home position at which the measuring was carried out, there was a 12 second pause for the researcher to read the data, then the robot automatically went on to the next cycle. The reading was taken as the payload touched the dial-indicators and gave pressure.

The researcher found that after the robot worked for about two to three hours, the heat from the motor made the base part of the robot hot, so when the robot finished one set of 30-cycles, the power of the robot was cut off for about 30-60 minutes to avoid the temperature possibly affecting the results. Before the robot began its first cycle for each pair of payload and speed, all the dial-indicators were set to zero, and the program was set to a new home position, i.e., only the "0" step was changed on a computer. But during the initial setting, human action on equipment might affect the reading of the first cycle, so when the researcher analyzed the data, he considered the position of the first cycle as the "0" position, i.e., the spatial coordinator (X1,Y1,Z1) was considered to be (0,0,0).

Speed/Payload Matrix--Variables Groups

According to the specifications of the MTMR (see appendix B), the payload should range between 0 and 455gm. The maximum number of program steps is 53.

Three maximum non-slip motor speeds correspond to three payloads as shown in Table 1 "Non-slip Motor Speeds vs. Payloads".

TABLE 1: Non-slip Motor Speeds vs. Payloads

Load	Half-steps per second	Equivalent teach control speed No.
0	400	8
226gm	206	5
455gm	99	3

Therefore, the payload and the speed were set for this experimental research as follows:

TABLE 2: Payloads and Speeds

payload	2	20gm	65gm	130gm	180gm	250gm
speeds	3,5,7	3,5,7	3,5,7	3,5,7	3,5,-	3,-,-

Note: For the payload 180gm, speed 7 was not used, in case Motor slip affected results. For the same reason, payload 250gm used speed 3 only.

Data Collection Procedure

The research data of this study were collected during a week of intensive tests. The whole experiment was divided into several groups for analysis. Each group contained one payload with three different speeds. Each pair of payload and speed, such as, 20gm of payload and a speed of 5, was tested during continuous 30 program cycles. Each program cycle gave one reading of position deviation with (@x, @y, @z) coordinates in which @x,@y,@z meant relative axle distance between current position and the original position. Then the relative space distance @D (see Figure 1) was calculated with the following formula:

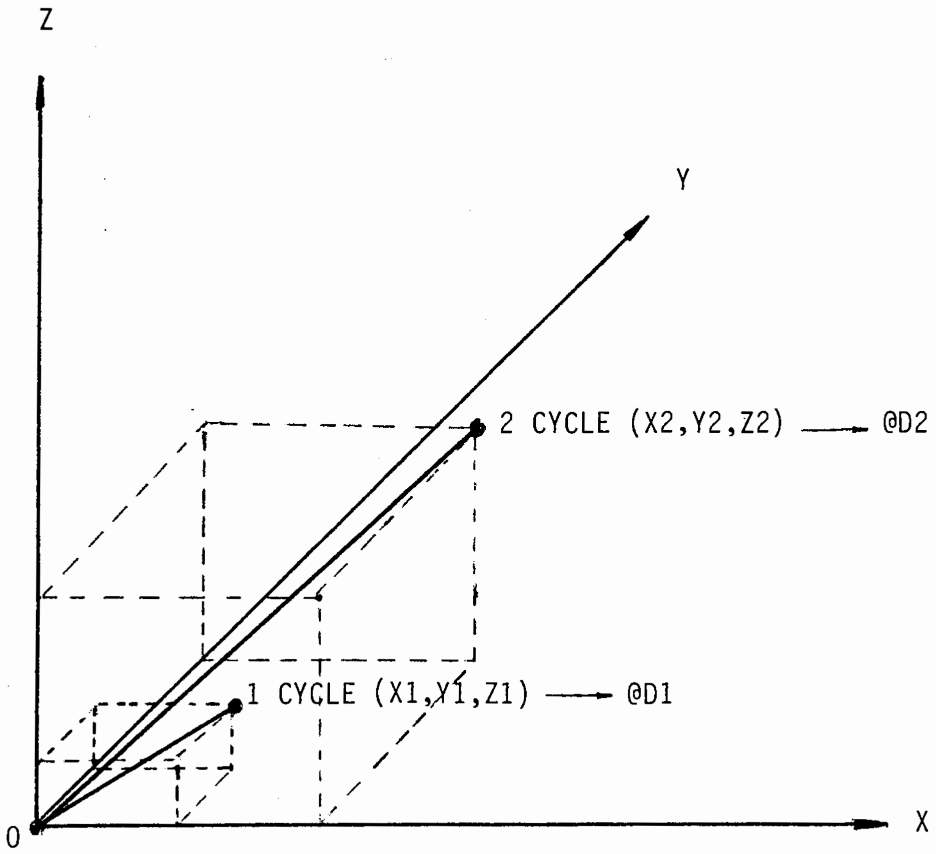
$$@D=\mathrm{SQRT}((@X)\hat{\ }2+(@Y)\hat{\ }2+(@Z)\hat{\ }2) \qquad <1>$$

Data Analysis Procedure

In order to analyze the affect of speeds and payloads on repeatability, the mean of the spatial position deviation "@D" and the range of spatial position "R" in 30 cycles was calculated.

$$\overline{@D}=(@D1+@D2+...+@D30)/30 \qquad <2>$$

$$R=@Dmaximum-@Dminimum \qquad <3>$$



Coordinator: O (X0,Y0,Z0); 1 (X1,Y1,Z1); 2 (X2,Y2,Z2).

@D1=SQRT((X1-X0)^2+(Y1-Y0)^2+(Z1-Z0)^2)

@D2=SQRT((X2-X0)^2+(Y2-Y0)^2+(Z2-Z0)^2)

Figure 1: Calculation Demonstration of "@D"

The researcher also developed a linear trend line with a precise statistical method in order to analyze repeatability change in 30 cycles. The "least squares method" was applied here. This approach results in a straight line that minimizes the sum of the squares of the vertical differences from the line to each of the actual observations. The line is expressed as follows:

$$Y^*=a+bX^* \quad <4>$$

where Y*=completed value of space position deviation"@D".
a=Y*-axis intercept.
b=slope of the regression line (or the rate of change in Y* for given changes in X*).
X*=the number of program cycles.

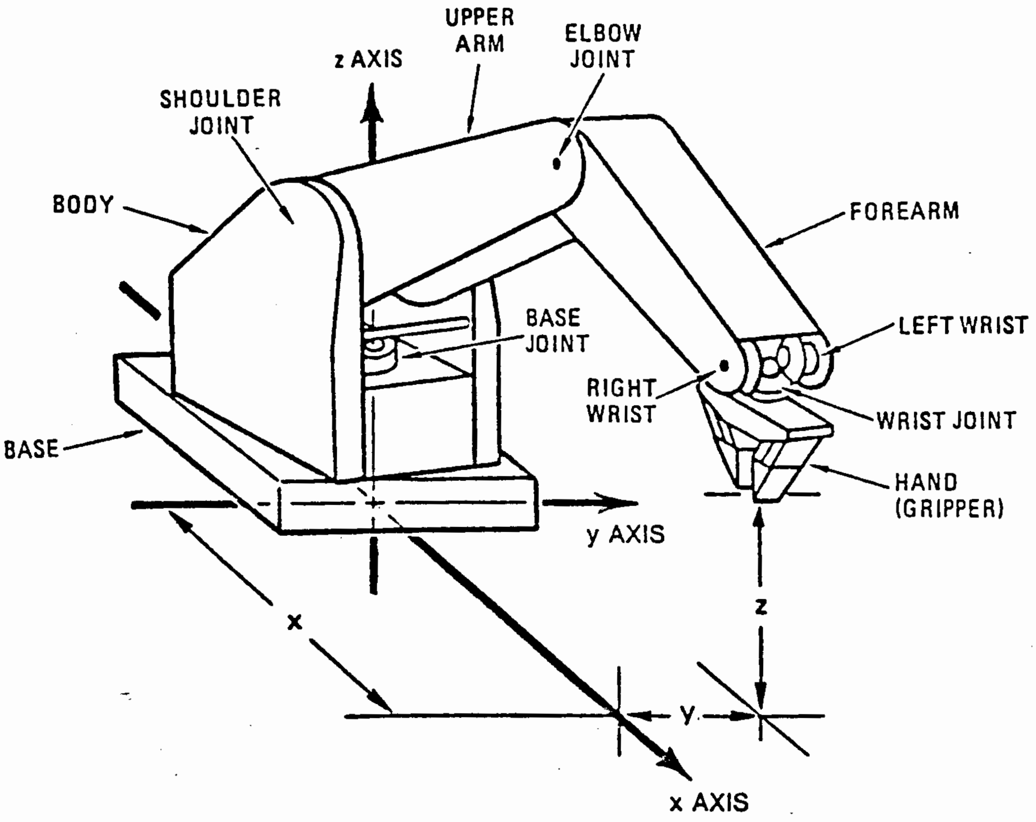
<u>Note</u>: X*, Y* axis in formula <2> have different meaning from X,Y axis in formula <1>. X,Y,Z coordinates are used as a real position of an object robot handling (see Figure 2), but X*,Y* are used for statistical analysis.

The slope "b" is found by the formula:

$$b=(\sum X^*Y^*-n\bar{X}^*\bar{Y}^*)/(\sum X^{*2}-n\bar{X}^2) \quad <5>$$

where b=slope of the regression line.
∑=summation sign.
X*=the number of program cycles.
Y*=computed value of space position deviation "@D".

Figure 2. The Microbot TeachMover Robot



$\bar{X}*$=the average of the value of the X*.
$\bar{Y}*$=the average of the value of the Y*.
n=the number of data points or observations.

"a" was computed as follows:

$$a=\bar{Y}*-b\bar{X}* \quad <6>$$

In addition to linear trend line, the coefficient of correlation "r" was calculated with the following equation:

$$r=(n\sum X*Y*-\sum X*\sum Y*)/\ (n\sum X*^2-(\sum X*)^2)(n\sum Y*^2-(\sum Y*)^2) \quad <7>$$

$$(-1< r <1)$$

A computer program could handle the above calculation "b" and "r'. A microcomputer software package, called AB:POM developed by Howard Weiss, Temple University, was used (see Appendix C). Slope of the regression line "b" and correlation coefficient "r" were used to analyze the distribution of spatial position deviations.

Extended Trend Study of @D

Due to the limitation of time and facility for this research, the researcher used 30 cycles of the program to observe the repeatability and its changing rate. In order to determine if the repeatability pattern changes beyond 30 cycles, the researcher chose two pairs of speed and payload to execute this task; payload 65 with speed 5 and payload 65 with speed 7. Observations were recorded over 50 cycles under the same program used in the 30 cycles procedure. Spatial deviation @D was calculated the same way.

Robot Program Description

The robot program used in this experiment comprised some basic movements: base rotation, shoulder up-and-down, elbow up-and-down, wrist roll rotation and pitch up-and-down. It included the following steps corresponding to the steps in Appendix A.

STEP	DESCRIPTION
0	Home position. The base at 0 degree position, and shoulder and elbow fully extended with object held in gripper.
1	Pause 12 seconds, allow researcher to pick up readings between cycles.
2	Set speeds at 3, 5 or 7.
3	Raise shoulder and elbow away from home position.
4	Lower shoulder and elbow.
5	Rotate base +90 degree.
6	Raise elbow and shoulder to half-position.
7	Rotate base -180 degree.
8	Raise elbow and shoulder, and rise pitch up to limit position.
9	Rotate base +90 degree to 0 position.
10	Lower elbow, shoulder, and pitch.
11	Rotate pitch +90 degree.
12	Rotate pitch -180 degree.

13 Rotate pitch +90 degree.
14 Rotate base +90 degree.
15 Raise elbow and shoulder.
16 Rotate base -180 degree.
17 Lower elbow and shoulder.
18 Rotate pitch +90 degree.
19 Rotate pitch -90 degree.
20 Rotate base back to 0 position.
21 Raise shoulder and elbow, and raise pitch up above home position.
22 Smoothly lower shoulder and elbow to reach home position and touch the dial-indicator.

CHAPTER IV

PRESENTATION AND ANALYSIS OF DATA

Results of Experiment

Following the procedures set in the methodology, the researcher finished testing fifteen pairs of payloads and speeds under thirty cycles and two pairs of payloads and speeds under fifty cycles. All the data are shown on the tables from Table 3 to Table 19, which include payload 65g and speed 5 as well as payload 65g and speed 7 with fifty cycles.

Each table contains the results of only one pair of payload and speed. @X, @Y, @Z were calculated with formulas: @X = X-X1, @Y = Y-Y1 and @Z = Z-Z1, in which (X1, Y1, Z1) is the coordinate of the first cycle's position. Because at the beginning of test, even though the researcher set the three dial-indicators at 0 positions, human action on equipment might affect the reading of the first cycles. Therefore the first cycle's position was considered as "0" position, then the other cycles' deviation @X, @Y, @Z can be looked as the relative distance from the first cycle's position.

As the researcher mentioned before, in this research, relative deviation is more significant than absolute deviation, because the repeatability is only concerned about position change cycle by cycle. Spatial deviation @D were calculated based on @X, @Y and @Z, i.e., @D= SQRT (@X^2+@Y^2+@Z^2). The mean spatial deviation @D and the range of deviation R during the thirty cycles were calculated and the results shown in Table 3 to Table 17. Table 18 and Table 19 would be used for the trend analysis of deviation changes. The unit used for the deviation in these tables are .001 inches. And the symbol "+" (omitted in tables) and "-" can be referenced to the Figure 2. For example, "@Z= -1.5" means the direction of position change is downward on Z axis.

From these tables, it can be seen that both payload and speed had an effect on the position deviation, i.e., the repeatability. Especially the payload from 0 to 130gm could satisfactorily indicate how they affected the repeatability. The heavy payload such as 180g and 250g sometimes made the robot motor slip during the test, which could affect the accuracy of the results.

Table 3

Spatial Deviation for Payload (2) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	1.4	0	6.9	7.0405
3	7.2	0.1	7.5	10.397
4	5.6	0.3	8.8	10.435
5	7.2	0.9	9.7	12.113
6	8.8	0.9	9.8	13.201
7	10.1	1	12.8	16.335
8	11.4	1.1	15.6	19.352
9	12.8	1.2	16.6	20.996
10	13.7	1.2	18.8	23.293
11	14.7	1.5	21.7	26.253
12	15.7	1.9	26.9	31.204
13	13.8	1.9	18.7	23.318
14	15.8	2	29.9	33.876
15	17.8	1.9	31.5	36.231
16	18.7	1.8	32.9	37.885
17	19.5	2	34.7	39.853
18	20.1	1.8	37.5	42.585
19	20.8	1.7	36.7	42.218
20	21.3	1.8	36.8	42.557
21	21.8	2	41.8	47.185
22	22.5	2	42.7	48.306
23	23	1.8	44.7	50.302
24	23.4	2	46.8	52.362
25	23.9	1.7	47.9	53.558
26	24.5	1.5	48.2	54.090
27	24.9	1.1	49.7	55.599
28	25.2	1.1	49.8	55.823
29	25.5	1.1	53.2	59.005
30	26	1.2	52.2	58.329

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=42.08
R=@Dmax-@Dmin=59

Table 4

Spatial Deviation for Payload (2) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycl	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^ 2)
1	0	0	0	0
2	0.8	2.8	2.4	3.7735
3	1.7	5.9	3.5	7.0675
4	2.6	8.9	3.8	10.020
5	3.6	11.6	4.8	13.059
6	4.5	12.6	5.9	14.622
7	5.5	13.9	6.8	16.422
8	5.9	15	6.9	17.533
9	6.9	16	8	19.173
10	7.1	16.8	8.6	20.164
11	7.4	17.8	12	22.706
12	8	18.9	10	22.830
13	8.4	19.8	9.9	23.677
14	8.9	21.8	12	26.428
15	9.4	22.4	12.8	27.458
16	9.6	22.6	14.6	28.567
17	10.4	22.6	16.2	29.687
18	10.5	22.9	15.5	29.578
19	10.9	23.8	17	31.212
20	11.4	24.2	17.2	31.803
21	11.6	24.1	18.8	32.692
22	12	24.7	18.5	33.111
23	12.4	24.3	20	33.826
24	12.7	24.8	20.9	34.830
25	12.9	25.4	22	35.994
26	13.5	25.8	23	37.106
27	13.8	25.7	23	37.147
28	13.9	25.7	24.2	37.938
29	14.2	25.4	24.1	37.783
30	14.7	25.4	25	38.551

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=25.16
R=@Dmax-@Dmin=38.55

Table 5

Spatial Deviation for Payload (2) and Speed (7)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	1	2.9	-0.7	3.1464
3	1.3	6.2	4.2	7.6006
4	1.7	8	-0.2	8.1810
5	1.9	11.6	-1.6	11.862
6	2.1	14.1	-1.7	14.356
7	2.5	15.3	-3.2	15.829
8	2.6	18.3	-3.3	18.776
9	2.8	20.1	-3.9	20.665
10	3.4	22.1	-5.6	23.050
11	3.5	24	-5.6	24.891
12	3.7	27	-5.9	27.883
13	3.8	29.1	-5	29.769
14	4.2	30.5	-5.7	31.311
15	4.3	32.1	-5.7	32.884
16	4.7	33.6	-5.8	34.419
17	5	34.3	-5.8	35.144
18	5.4	34.6	-4.8	35.346
19	5.8	35.1	-4.8	35.898
20	5.8	38.6	-4.8	39.327
21	6.1	39.9	-4	40.561
22	6.5	39.1	-3.9	39.828
23	6.9	39.9	-4.2	40.709
24	7.1	40	-4	40.821
25	7.5	40.6	-3.7	41.452
26	8	41.9	-4	42.844
27	8.3	42.2	-2.3	43.069
28	8.3	43.1	-2.3	43.952
29	8.4	44.2	-2.2	45.044
30	8.8	44.9	-0.9	45.763

Note. $\overline{@D}$=(@D1+@D2+...+@d30)/30=29.15
R=@Dmax-@Dmin=45.76

Table 6

Spatial Deviation for Payload (20) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	3.1	1.5	6	6.9180
3	5.3	3	11.5	13.013
4	5.5	3.9	10.1	12.143
5	7.5	4.3	19.9	21.696
6	10.2	5.6	27.6	29.952
7	12.7	6.2	36.6	39.233
8	18	7.4	56	59.285
9	19.8	8.3	60.3	64.007
10	22.2	9.1	66.1	70.319
11	24.7	9.3	72.7	77.342
12	25	10.1	70.9	75.853
13	26.7	11.2	75.5	80.861
14	28.2	11.3	82.7	88.103
15	29.9	11.6	88.1	93.755
16	30.5	11.5	94.5	99.963
17	32.9	11.2	101.3	107.09
18	34.3	11.1	105.1	111.11
19	35.3	11.7	111.1	117.15
20	36.3	11.1	113.6	119.77
21	38	12	121.3	127.67
22	39.7	11.2	124.5	131.15
23	40.3	11.3	130.3	136.85
24	41.5	12.1	134.6	141.37
25	42.7	12	144	150.67
26	43.6	11.2	144.6	151.44
27	44.4	12.1	147.3	154.32
28	45.5	12.9	150.7	157.94
29	46.4	13	154	161.36
30	47.3	13	157	164.48

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=92.16
R=@Dmax-@Dmin=164.48

Table 7

Spatial Deviation for Payload (20) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	0.6	2.1	0.2	2.1931
3	1.4	9	2.5	9.4451
4	2.2	13.8	3.6	14.430
5	2.9	15.1	4.5	16.020
6	3.7	13.8	4.8	15.072
7	4.9	14.5	2.5	15.508
8	5.4	17.7	4	18.932
9	6.2	18.8	5.4	20.519
10	7.1	24	8.4	26.400
11	7.7	21.9	9	24.897
12	8.6	26.6	11	30.041
13	9.2	24.5	12.5	29.002
14	9.9	25	13.8	30.223
15	9.6	24.2	15.5	30.299
16	11.2	24.9	18.5	32.980
17	11.6	26.5	19.8	35.054
18	11.8	26.9	20.4	35.763
19	12.6	27.1	21.2	36.641
20	13.9	26.9	23.1	38.084
21	13.2	27.7	24.7	39.390
22	13.9	27.9	28.1	41.967
23	14.5	27.9	28.9	42.706
24	14.9	28	32.7	45.555
25	15.4	31.1	33.5	48.235
26	16.8	29.2	35.6	49.012
27	16.4	29.4	35.7	49.069
28	16.8	29	37.1	49.996
29	17.1	28.5	37.7	50.258
30	17.5	29.9	38.5	51.792

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=30.98
R=@Dmax-@Dmin=51.79

Table 8

Spatialeviatiofor Payload (20) and Speed (7)

	Spatialeviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@y^2)
1	0	0	0	0
2	-0.8	3.7	2.4	4.4821
3	-1.8	6.3	-2.2	6.9115
4	-2.9	9.7	-6.9	12.251
5	-2.8	13.9	-6.9	15.768
6	-1.9	18	-10.1	20.727
7	-2.8	22.6	-13.3	26.372
8	-2.5	25.9	-14.7	29.885
9	-1.7	29.6	-15.2	33.318
10	-1.3	33.3	-17	37.410
11	-0.6	36.5	-18	40.701
12	0.3	38.3	-17	41.904
13	0.7	41.6	-17.9	45.293
14	1.7	46.5	-18	49.891
15	2.7	47.5	-17.2	50.590
16	3.9	50.5	-15	52.824
17	4.9	52.1	-15.1	54.464
18	5.2	53.6	-13.4	55.493
19	6.5	54.9	-9.6	56.110
20	6.9	57.4	-8.9	58.494
21	7.5	57.4	-6.7	58.274
22	8.5	58.8	-5.3	59.647
23	9.2	63.4	-5	64.258
24	10	62.6	-3.6	63.495
25	10.8	62.6	-3.6	63.626
26	11.2	63.9	-0.1	64.874
27	11.7	64.5	0.1	65.552
28	12.3	65.6	0.9	66.749
29	12.7	66.6	2.4	67.842
30	13.2	67.5	4.1	68.900

Note. @$\overline{\text{D}}$=(@D1+@D2+...+@D30)/30=44.54
R=@Dmax-@Dmin=68.9

Table 9

Spatial Deviation for Payload (65) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	2.6	-0.1	17.7	17.890
3	4.4	0.8	30.2	30.529
4	7.2	1.8	38.4	39.110
5	9.2	2.4	46.2	47.168
6	11	3.7	53.7	54.939
7	13	3.6	0	13.489
8	14.9	3	69.1	70.751
9	16.8	3.4	77.1	78.982
10	18.6	3.1	78.6	80.830
11	20	2.8	91.3	93.506
12	21.5	2.8	98.3	100.66
13	22.9	2.7	105.9	108.38
14	24.5	2.6	112.7	115.36
15	25.9	1.9	119.9	122.68
16	26.7	2.9	127.4	130.20
17	27.9	2.8	130.6	133.57
18	29.2	3.3	136.3	139.43
19	30.4	3.7	142.7	145.94
20	31.5	2.7	146.3	149.67
21	32.2	2.8	148.9	152.36
22	33.3	3	153.8	157.39
23	34.3	2.7	159.7	163.36
24	34.8	2.8	164.3	167.96
25	35.6	3.2	169.1	172.83
26	36.4	2.9	171.7	175.53
27	37.2	3	175.9	179.81
28	37.8	2.8	179	182.96
29	38.5	2.6	182.2	186.24
30	39.4	2.3	184.2	188.38

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=113.33
R=@Dmax-@Dmin=188.38

Table 10

Spatial Deviation for Payload (65) and Speed (5)

Cycle	Spatial Deviation 9in .001 inches) @x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	1.2	2.2	3.1	3.9862
3	1.4	3.9	7.1	8.2207
4	1.4	5.9	10.8	12.385
5	1.6	8.5	14	16.456
6	1.8	11.5	19.3	22.538
7	1.9	12.1	20.8	24.138
8	2	16.6	24.2	29.414
9	2	18.5	25	31.164
10	2.1	20.1	27.4	34.046
11	2.4	20.5	31.2	37.409
12	2.5	23	35.2	42.122
13	2.7	25.3	37.4	45.234
14	3	27.4	42.7	50.823
15	3	27	42.7	50.609
16	3.2	27.6	44.3	52.292
17	3.6	30.1	48.3	57.025
18	4	30.2	51.3	59.663
19	4.2	31.3	51.2	60.156
20	4.4	35.3	54.3	64.914
21	4.8	31.6	57	65.349
22	5	33.2	60.3	69.016
23	5.4	33	62.1	70.530
24	6	34	64.2	72.894
25	6.1	34	66.3	74.758
26	6.1	36.5	68.3	77.681
27	6.3	34.4	70.4	78.607
28	6.9	33.7	73.6	81.241
29	7	34	75.2	82.825
30	7.2	39	75.5	85.282

Note. $\overline{@D}$=(@D1+@D2+...+@d30)/30=48.72
R=@Dmax-@Dmin=85.28

Table 11

Spatial Deviation for Payload (65) and Speed (7)

Spatial Deviation for Payload (65) and Speed (7)

Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	3.5	2	18.4	18.836
3	4.9	5	27.6	28.474
4	5.8	6.5	33.5	34.614
5	6.4	8.2	37.5	38.915
6	7	9.1	40.7	42.288
7	7.6	10.3	44.4	46.208
8	8.1	10.1	48.4	50.101
9	8.4	11	50.9	52.748
10	11.5	12	63	65.155
11	12.5	15.3	69	71.772
12	13.5	14.1	74.3	76.821
13	14.4	15.3	78.4	81.166
14	15.4	15.9	83.5	86.384
15	16.4	19.6	87.7	91.347
16	17.4	17.1	92.3	95.469
17	18	17.6	94.6	97.892
18	18.3	21.6	98	102.00
19	18.5	19.9	99.3	102.95
20	19	20	101	104.69
21	19.1	20.5	102.6	106.35
22	19.4	21.2	104.4	108.28
23	19.7	21.6	107.2	111.11
24	20	21.6	107.9	111.84
25	20.4	22	108.6	112.66
26	20.8	22	111.5	115.53
27	21.3	23.6	113.6	117.96
28	21.3	23.8	115.7	120.02
29	21.8	23.6	118	122.29
30	21.9	23.6	118.6	122.89

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=81.23
R=@Dmax-@Dmin=122.89

Table 12

spatial Deviation for Payload (130) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	-3.3	7	-4.6	9.0027
3	-2.8	11.5	1.3	11.907
4	-1.9	15.2	9.2	17.868
5	-1.3	18.6	16.2	24.7
6	0.2	20.1	25.3	32.313
7	0.9	22.4	30.2	37.611
8	1.2	24.2	37.1	44.311
9	1.8	25.2	43.1	49.958
10	2.2	26.1	45.5	52.500
11	2.6	25.9	47.3	53.989
12	-1.3	27.1	33	42.721
13	4.8	29	59.1	66.006
14	0.3	29	42.2	51.204
15	4.4	31	59.1	66.881
16	0.2	31.9	43.2	53.701
17	0.2	30.5	43.3	52.963
18	0.1	31.1	43.1	53.149
19	0.1	31.6	43	53.362
20	0.4	31.5	45.3	55.176
21	4.8	32	63.1	70.912
22	4.5	33.2	60.5	69.157
23	4.4	32.5	60	68.378
24	4.4	33.2	60.1	68.801
25	3.8	33.5	60.9	69.609
26	3.8	33.2	59.2	67.980
27	4.5	33	61.1	69.587
28	3.8	33.1	59.7	68.367
29	3.9	33.1	42.9	54.325
30	4.7	33.1	43.1	54.546

Note. @$\overline{D}$=(@D1+@D2+...+@D30)/30=49.67
R=@Dmax-@Dmin=70.91

Table 13

Spatial Deviation for Payload (130) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	5.9	4.3	16.7	18.226
3	8.2	9	24.7	27.537
4	4.5	13.3	26.7	30.166
5	-0.3	16.9	22.8	28.382
6	-2.5	21.5	23	31.583
7	-2.7	26.4	27.4	38.144
8	0.6	30.3	42.1	51.873
9	0.9	33.4	48.1	58.566
10	1.4	33.4	54	63.509
11	1.2	39.6	59.5	71.483
12	1.7	42.4	62.5	75.544
13	1.5	44.6	63.6	77.694
14	0.2	44.6	65.4	79.160
15	0.1	47.6	68.6	83.496
16	-0.1	49.6	70.5	86.199
17	-0.3	51.5	72.5	88.930
18	-0.3	53.4	74.6	91.743
19	-0.5	55	75.1	93.087
20	-0.3	58.4	79	98.242
21	-0.5	57.5	79.7	98.278
22	-0.5	58.5	81.6	100.40
23	-0.4	58.6	82.9	101.52
24	-0.2	59.3	85.3	103.88
25	0	60.5	87.5	106.37
26	-0.2	61.4	87.5	106.89
27	0	61.7	89.6	108.78
28	-0.3	61.7	89.2	108.46
29	-0.2	61.6	91.3	110.13
30	-0.2	62.5	90.6	110.06

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=74.93
R=@Dmax-@Dmin=110.14

Table 14

Spatial Deviation for payload (130) and Speed (7)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	0	4.4	1.8	4.7539
3	5	9.4	18.4	21.258
4	6.6	12	27.3	30.542
5	7.7	15.6	33.6	37.836
6	8.6	17.9	40.2	44.837
7	9.2	20.8	44	49.530
8	9.9	22.9	48.7	54.718
9	10.6	27.5	52.7	60.381
10	11.2	30.2	57.3	65.732
11	12.2	31.9	64.4	72.895
12	13.5	34.6	71.8	80.837
13	14.2	37.4	77.3	87.038
14	15.4	39	84.9	94.689
15	16.8	41.4	93.4	103.53
16	17.9	43.9	99.7	110.39
17	18.8	45.7	105.4	116.40
18	26.8	47.5	134.3	144.95
19	27	50.3	137.2	148.60
20	27.1	50.4	140.9	152.07
21	27.1	52.5	142.9	154.63
22	27.3	53.9	144.2	156.34
23	27.5	55.3	146.7	159.17
24	27.5	54.4	147.6	159.69
25	27.8	55.5	149.8	162.15
26	28.1	55.5	152.8	164.97
27	28.4	57.4	155.3	167.98
28	28.7	57.9	157.1	169.87
29	28.9	59.4	159.3	172.45
30	29.2	60.5	161.5	174.91

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=104.11
R=@Dmax-@Dmin=174.91

Table 15

Spatial Deviation for payload (180) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	1.5	2.9	15.6	15.938
3	2.1	4.3	28.6	28.997
4	2.9	5.4	43.1	43.533
5	3.2	5.4	45.4	45.831
6	3.4	6.1	49.6	50.089
7	3.2	9	49.3	50.216
8	3.2	9.1	49.3	50.234
9	2.8	10.9	47.3	48.620
10	3.1	11.9	48.8	50.325
11	3.4	12.4	50.6	52.208
12	3.6	12.1	52.1	53.607
13	3.8	11.4	54.1	55.418
14	3.8	13.4	52.5	54.316
15	3.5	13.9	49.1	51.149
16	3.5	13.9	45.1	47.323
17	3.5	13.4	48.3	50.246
18	3.4	13.9	45.1	47.315
19	3.4	13.9	45.3	47.506
20	3.4	14.1	46.6	48.805
21	3.5	13.9	45.6	47.799
22	3.3	13.6	46.6	48.656
23	3.4	14.1	45.3	47.565
24	3.3	15	42.2	44.908
25	3.1	13.8	44.1	46.312
26	3.2	14	45.1	47.331
27	3	14.4	41.4	43.935
28	3.1	15	42	44.705
29	2.9	14.6	41.6	44.182
30	3	14.8	38.6	41.448

Note. @$\overline{D}$=(@D1+@D2+...+@D30)/30=44.95
R=@Dmax-@Dmin=55.42

Table 16

Spatial Deviation for Payload (180) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	0.2	5.8	0	5.8034
3	0.2	3.8	3.6	5.2383
4	0.2	1.3	-9.4	9.4915
5	0.4	1.6	1.4	2.1633
6	0.3	1.7	0	1.7262
7	0.4	1.3	1.4	1.9519
8	0.4	6.7	0.6	6.7386
9	0.5	6.9	0.4	6.9296
10	0.5	6.3	-0.5	6.3395
11	0.5	3.7	-0.9	3.8405
12	0.3	3.3	-2.3	4.0336
13	0.3	2.9	-1.4	3.2341
14	0.3	3	-2.3	3.7920
15	0.3	2.2	-1.4	2.6248
16	0.5	2.3	1.5	2.7910
17	0.4	7.3	-2	7.5795
18	0.4	3.7	-0.5	3.7549
19	0.3	3.8	0	3.8118
20	0.3	3.7	-0.5	3.7456
21	0.6	3.6	1.3	3.8742
22	0.6	3.5	0.6	3.6013
23	0.6	7.3	-1.1	7.4067
24	0.4	6.7	-0.6	6.7386
25	0.4	4.8	-0.6	4.8538
26	0.4	4	1.4	4.2567
27	0.3	4.8	1.3	4.9819
28	0.3	4.3	-0.6	4.3520
29	0.3	4.7	-0.5	4.7360
30	0.5	6.4	0.5	6.4389

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=4.56
R=@Dmax-@Dmin=9.49

Table 17

Spatial Deviation for Payload (250) and Speed (3)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	-0.2	1.1	0.5	1.2247
3	-0.7	2.8	7.7	8.2231
4	-1.2	4.7	14	14.816
5	-1.5	4.4	16.7	17.334
6	-1.7	4.9	18.5	19.213
7	-1.7	5.4	21.6	22.329
8	-1.5	5.3	21.5	22.194
9	-1.4	5.8	22.4	23.181
10	-1.1	6	20.6	21.484
11	-0.9	6.4	20.3	21.303
12	-0.9	7	17.4	18.776
13	-0.7	8	14.7	16.750
14	-0.7	8.5	13.1	15.631
15	-0.6	8.9	11.5	14.554
16	-0.6	10.7	12.1	16.163
17	-0.5	9.9	9.7	13.869
18	-0.9	9.9	9.3	13.612
19	-0.8	10.3	8.8	13.570
20	-0.4	10.7	9.9	14.582
21	-0.3	10.9	8.2	13.643
22	-0.2	11.7	7.4	13.845
23	-0.6	12.9	7.6	14.984
24	-0.8	12.7	4.7	13.565
25	11.6	12.9	6.6	18.561
26	11.6	13	5.3	18.211
27	11.6	13.6	3.5	18.214
28	11	13.8	2.5	17.823
29	10.7	13.7	1.6	17.456
30	11	-22	1	24.617

Note. $\overline{@D}$=(@D1+@D2+...+@D30)/30=17.51
R=@Dmax-@Dmin=24.62

Table 18

Spatial Deviation for Payload (65) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	0.5	1.8	3.1	3.6193
3	1	2.2	6.1	6.5612
4	1.8	4.1	7.4	8.6492
5	2.4	4.2	8.2	9.5205
6	2.8	6.6	8	10.742
7	3.5	7.4	8.6	11.873
8	4	11	9.5	15.074
9	4.2	14.2	10	17.868
10	4.7	16.4	11.8	20.743
11	4.8	18.7	12	22.731
12	5.3	21.7	15	26.906
13	5.4	23.1	16.2	28.726
14	5.6	24	18	30.518
15	5.4	26.1	16.2	31.189
16	5.5	23.4	20.8	31.787
17	6	26.2	20.5	33.803
18	6	26.2	21.1	34.170
19	7.4	20.2	24	32.230
20	3.1	42.3	0	42.413
21	3	51.3	1	51.397
22	4.4	33.2	5.9	34.006
23	8	21.7	21.3	31.441
24	8.2	23.7	24.3	34.920
25	8.4	26.3	24.9	37.178
26	8.2	27.8	26.2	39.070
27	7.6	38	20.1	43.655
28	7.6	36.2	22.1	43.088
29	7.7	38.1	23	45.165
30	7.8	35.7	22.5	42.913
31	7.4	35.3	23.4	42.993
32	7.4	36.8	23.5	44.286
33	8	38.3	25.9	46.922
34	8.3	36.2	26.3	45.508
35	8.2	35.6	22.2	42.748

Table 18 (Continued)

Spatial Deviation for Payload (65) and Speed (5)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^2)
36	8.2	34.1	23.1	41.995
37	8.1	38.6	25.1	46.750
38	8.7	36.4	23.6	44.244
39	8.4	37.3	22	44.111
40	8.4	35.1	24.6	43.677
41	8.6	36.5	27	46.208
42	8.6	34.2	25	43.227
43	8.6	35.2	25.5	44.308
44	8.5	33.6	27	43.934
45	8.6	36.6	26.8	46.170
46	8.8	36.2	26.9	45.950
47	8.9	35.4	26.4	45.048
48	9	34.2	25	43.308
49	8.9	34.4	25	43.446
50	9	35.2	25	44.102

Table 19

Spatial Deviation for Payload (65) and Speed (7)

	Spatial Deviation (in .001 inches)			
Cycle	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^2)
1	0	0	0	0
2	0.4	1.4	5.7	5.8830
3	0.6	3	9	9.5057
4	1.8	4.9	8	9.5524
5	2.2	3.1	11.8	12.397
6	2.4	3.6	14.5	15.131
7	2.5	4	13.3	14.111
8	2.9	3.7	13.9	14.673
9	3	4.4	14.7	15.634
10	3.2	4.9	13.6	14.805
11	3.4	9	10.8	14.463
12	3.6	10.7	9.7	14.884
13	3.7	9.9	10.7	15.039
14	4	10.7	10	15.181
15	3.9	11.4	6.8	13.835
16	4.1	11	7.5	13.930
17	4.4	12.3	6.8	14.727
18	4.4	13.3	6.3	15.360
19	4.4	13.9	6.6	16.004
20	4.4	12.7	6.8	15.062
21	4.6	14.7	8.2	17.449
22	4.5	13.4	9.8	17.200
23	4.8	13.4	9.3	17.002
24	4.9	15.7	10.6	19.566
25	4.9	15.9	10.5	19.674
26	5	14.8	10	18.548
27	5.1	15.1	9.8	18.709
28	5.1	17.8	9.7	20.903
29	5.2	17.1	9.7	20.335
30	5.3	18.5	9.6	21.505
31	5.4	17.7	9.6	20.847
32	5.4	17.9	9.8	21.109
33	5.5	18.4	9.3	21.337
34	5.6	19.4	9.7	22.401
35	5.7	18.1	9.7	21.311

Table 19 (Continued)

Spatial Deviation for Payload (65) and Speed (7)

Cycle	@x	@y	@z	+@SQRT(@x^2+@y^2+@z^2)
	Spatial Deviation (in .001 inches)			
36	5.7	17.8	10.4	21.389
37	5.8	17.7	9.1	20.730
38	5.9	18.7	10.7	22.338
39	6	18.9	10.6	22.484
40	6	17.9	10	21.363
41	6.1	16.9	9.9	20.514
42	6.1	18.2	10.8	22.024
43	6.2	17.8	10.9	21.773
44	6.2	17.4	11	21.498
45	6.3	17.9	11	21.933
46	6.4	18.1	10.8	22.027
47	6.4	17.9	12.3	22.641
48	6.4	18	11.9	22.507
49	6.7	17	11.8	21.751
50	6.4	17.9	11.9	22.427

Analysis of Mean Deviation "$\overline{@D}$" and Range of Deviation "R"

The "$\overline{@D}$" and "R" were arranged into two groups. One group of data was organized to show the affect of different speeds on repeatability (see Figure 3 and Figure 4). For the same payload, both high speed (7) and lower speed (3) caused higher spatial position deviation than medium speed (5). This means that the medium speed could have better repeatability than higher speed or lower speed.

Another group was organized to show the effect of different payloads on repeatability (see Figure 5 and Figure 6). It was found that under the same speed, heavier payload caused greater spatial position deviation, i.e., the heavier the payload, the lower the repeatability. Two heavy payloads: 180gm and 250gm gave an opposite result. Because it was very difficult to read the readings from dial-indicators at the beginning of the test, the researcher had to begin recording after few cycles. However, the researcher observed that the first few cycles of high payload had greater deviation, then quickly came to a modest change rate. Both "$\overline{@D}$" and "R" can give the same conclusion.

FIGURE 3. Mean Of Deviation ($\overline{@D}$)

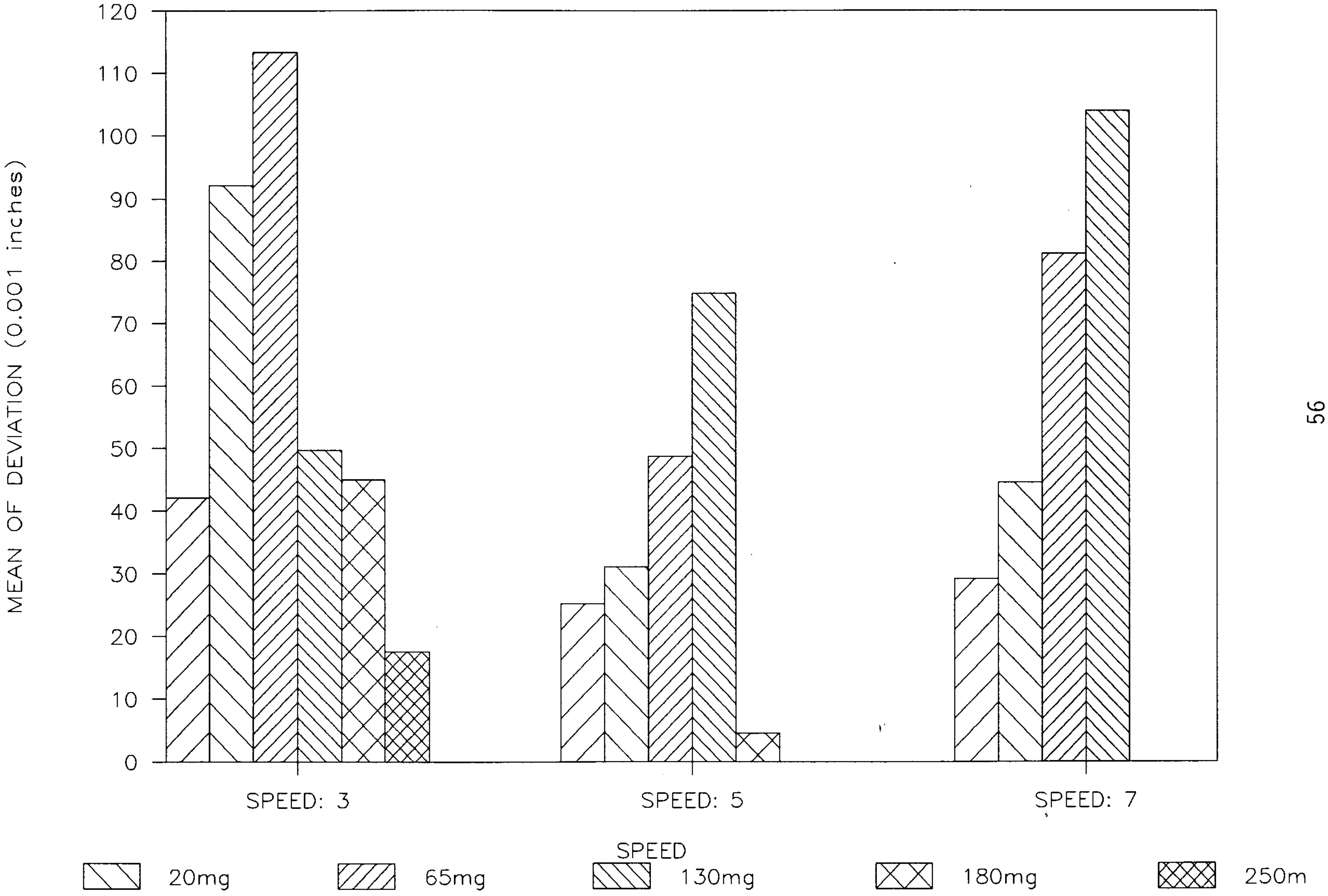


FIGURE 4. Range Of Deviation (R)

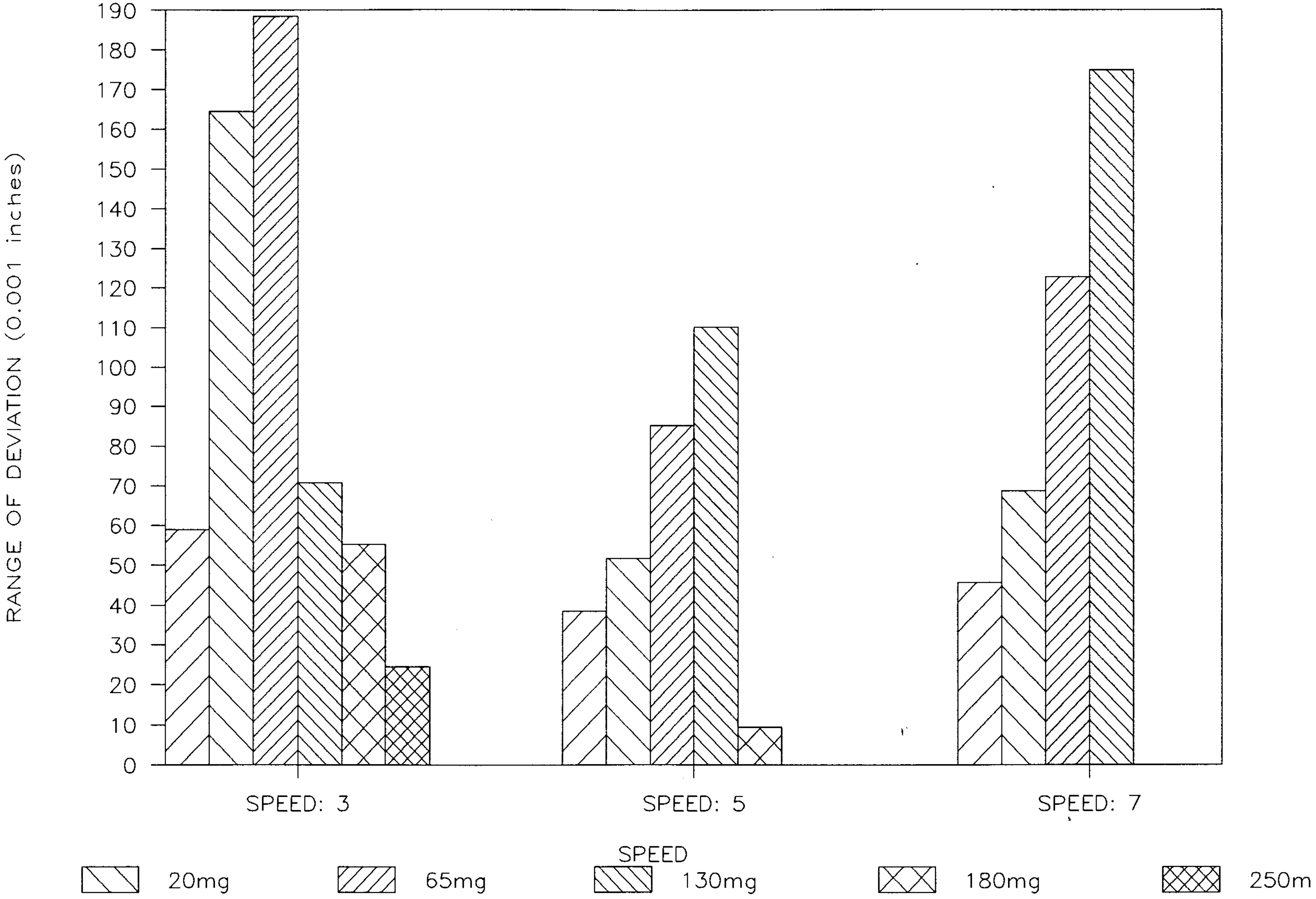


FIGURE 5. Mean Of Deviation ($\overline{@D}$)

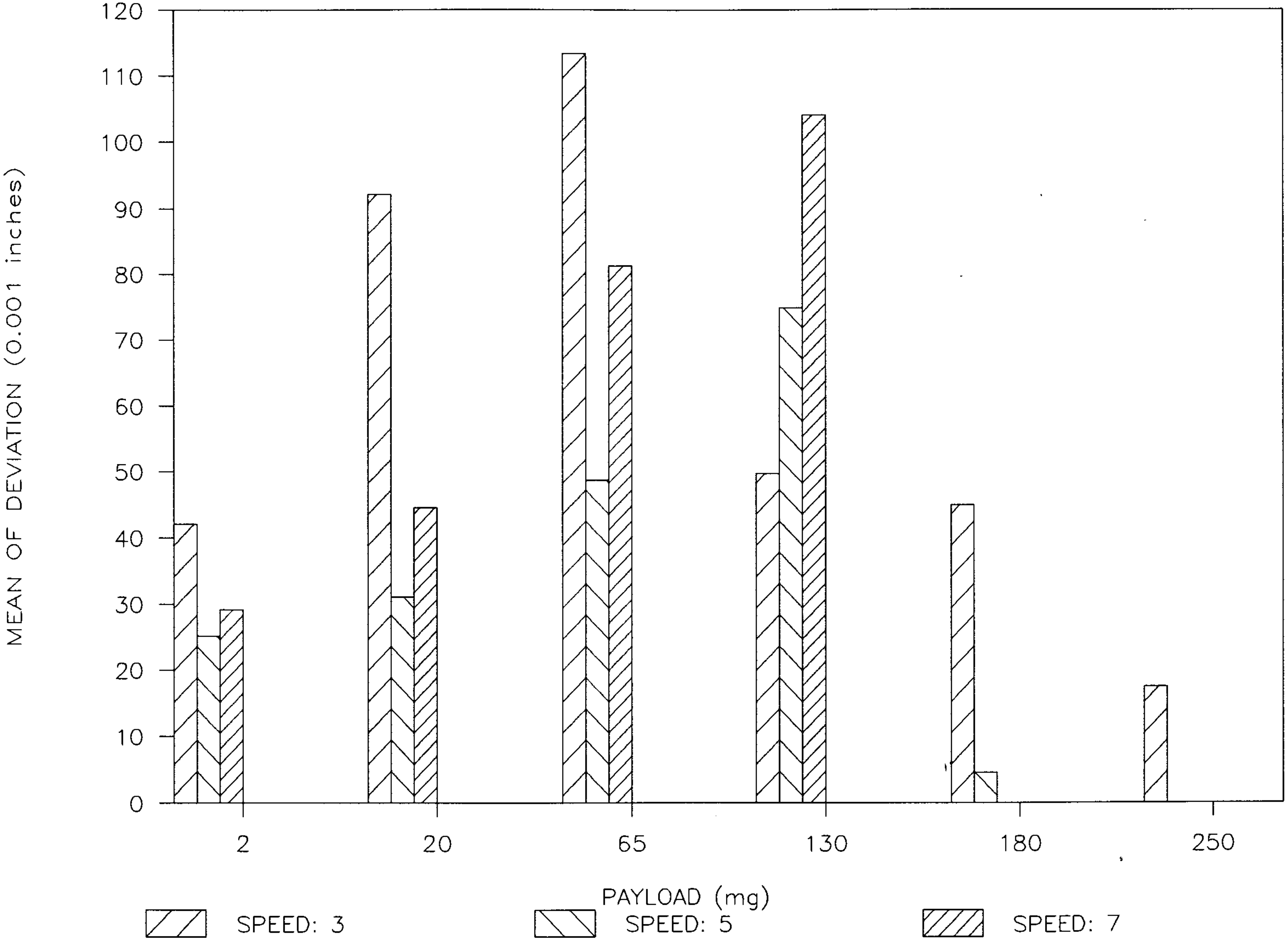
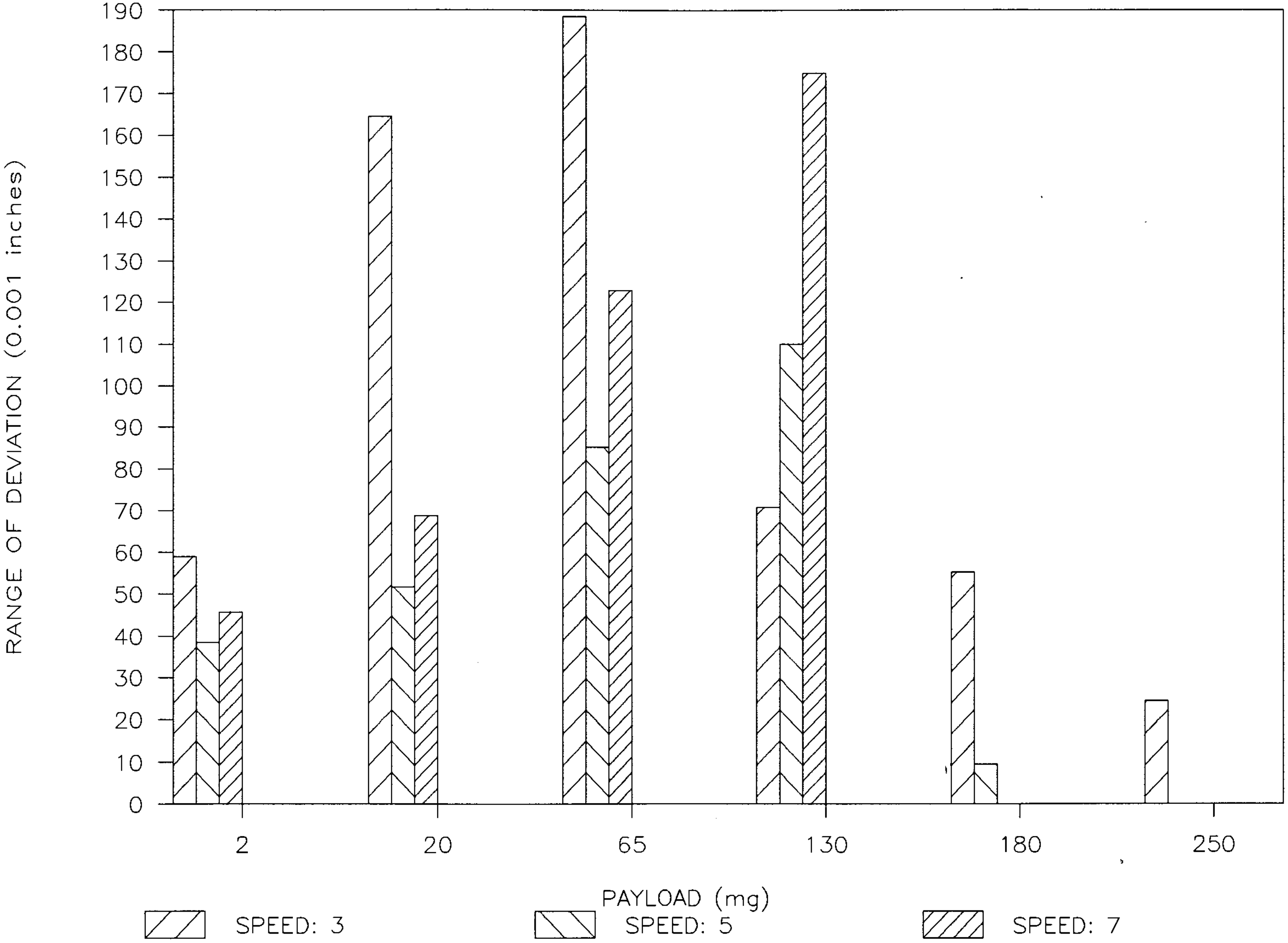


FIGURE 6. Range Of Deviation (R)



Analysis of Change Rate of Deviation "b" and Coefficient of Correlation "r"

The analysis of "b" and "r" can give readers an idea about the spatial position deviation change during the cycle period and how these deviations were distributed. The "b" showed the direction of change, and the "r" showed the correlation of data. Therefore, "b" and "r" represented how the repeatability changed. Table 18 and Table 19 summarized "b" and "r" as shown in Appendix C. It is known that r=1 represents high positive correlation, and r=0 represents no correlation. Payloads of 2-130 gm exhibited higher correlation while the higher payloads of 180gm and 250gm yielded lower correlation results. This means that the repeatability of higher payloads fluctuated. Slope "b" values in table 18 demonstrated that the lower speed (3) had the highest change rate, and medium speed (5) had the lowest change rate. This also indicated that medium speed had good repeatability. Figure 7 to Figure 15 show the whole view of repeatability changes.

TABLE 20:

Summary of the Change Rate of Deviation Slope

SPEEDS	PAYLOAD (GRAMS)					
	2	20	65	130	180	250
3	1.98	5.82	6.41	1.85	0.45	0.2
5	1.20	1.65	2.88	3.52	0.04	--
7	1.50	2.30	3.86	6.36	--	--

Note: Unit = 0.001 inches.

The rows show the payload's effect on the repeatability with a certain speed. The columns show the speed's effect on repeatability with a certain payload.

TABLE 21:

Summary of the Coefficient of Correlation "r"

SPEEDS	PAYLOAD (GRAMS)					
	2	20	65	130	180	250
3	0.99	0.99	0.98	0.82	0.35	0.3
5	0.97	0.98	0.99	0.95	0.16	--
7	0.96	0.96	0.96	0.98	--	--

FIGURE 7. Spatial Deviation For

Speed (3) With Different Payloads

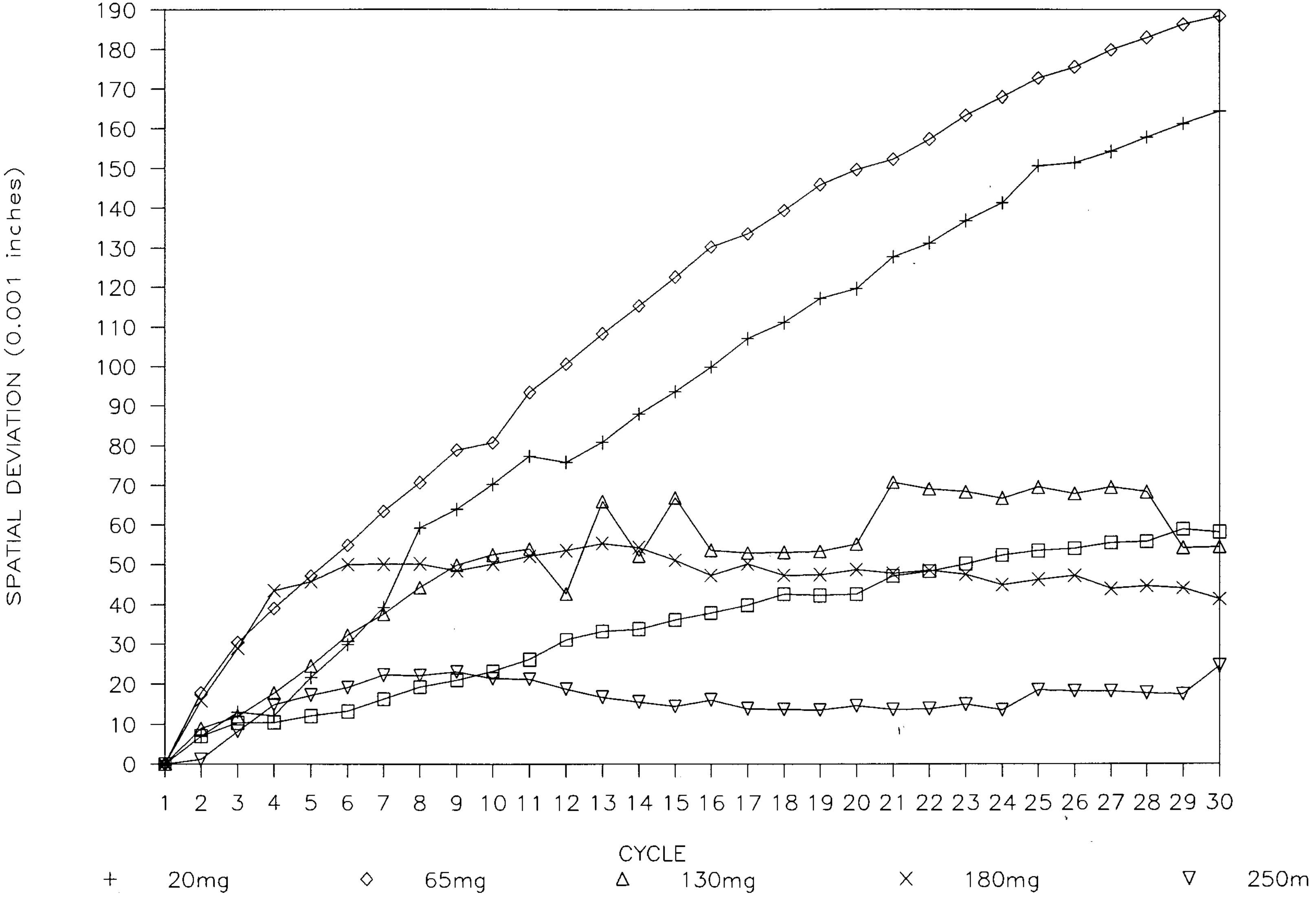


FIGURE 3. Spatial Deviation For

Speed (5) With Different Payloads

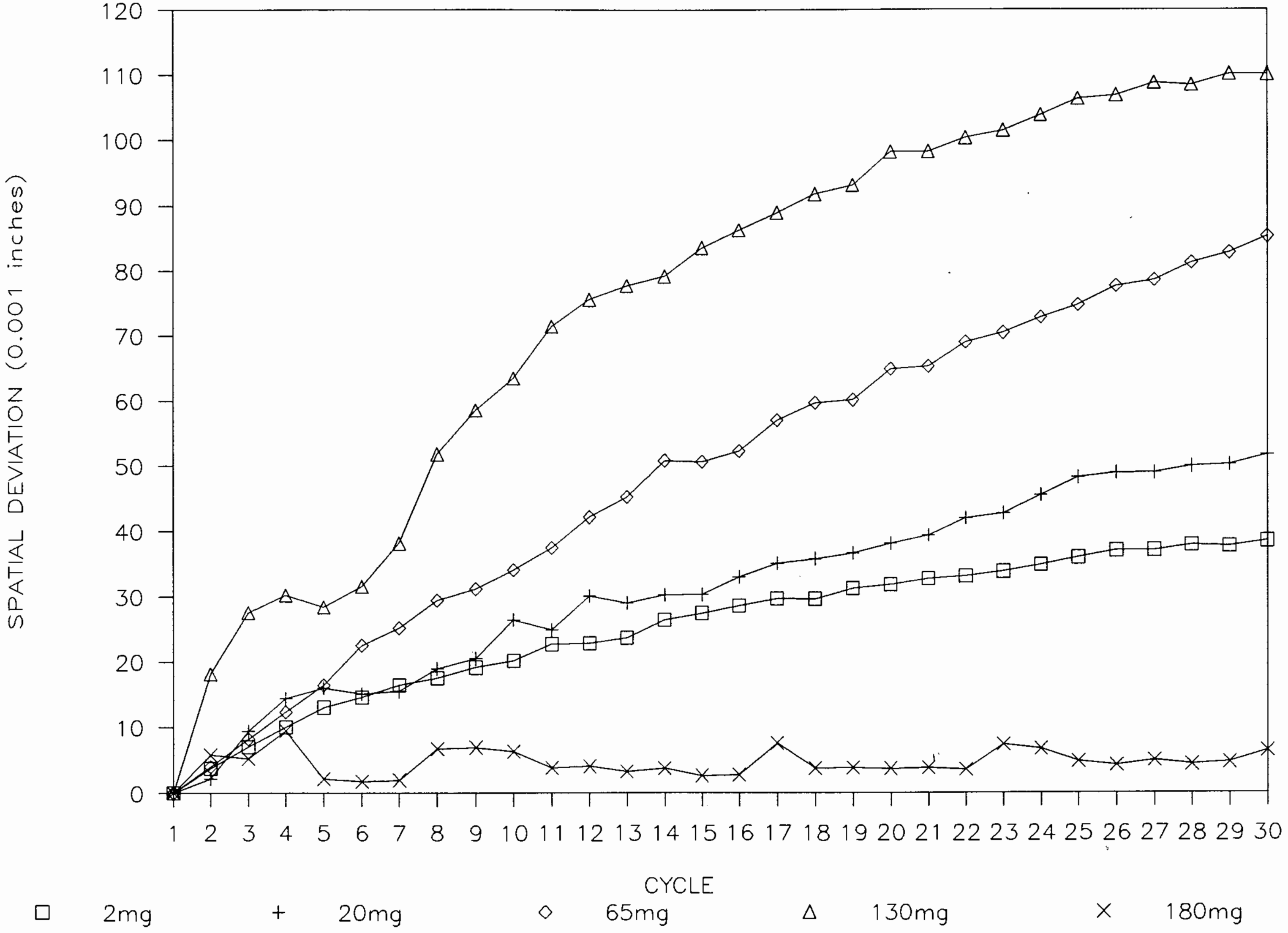
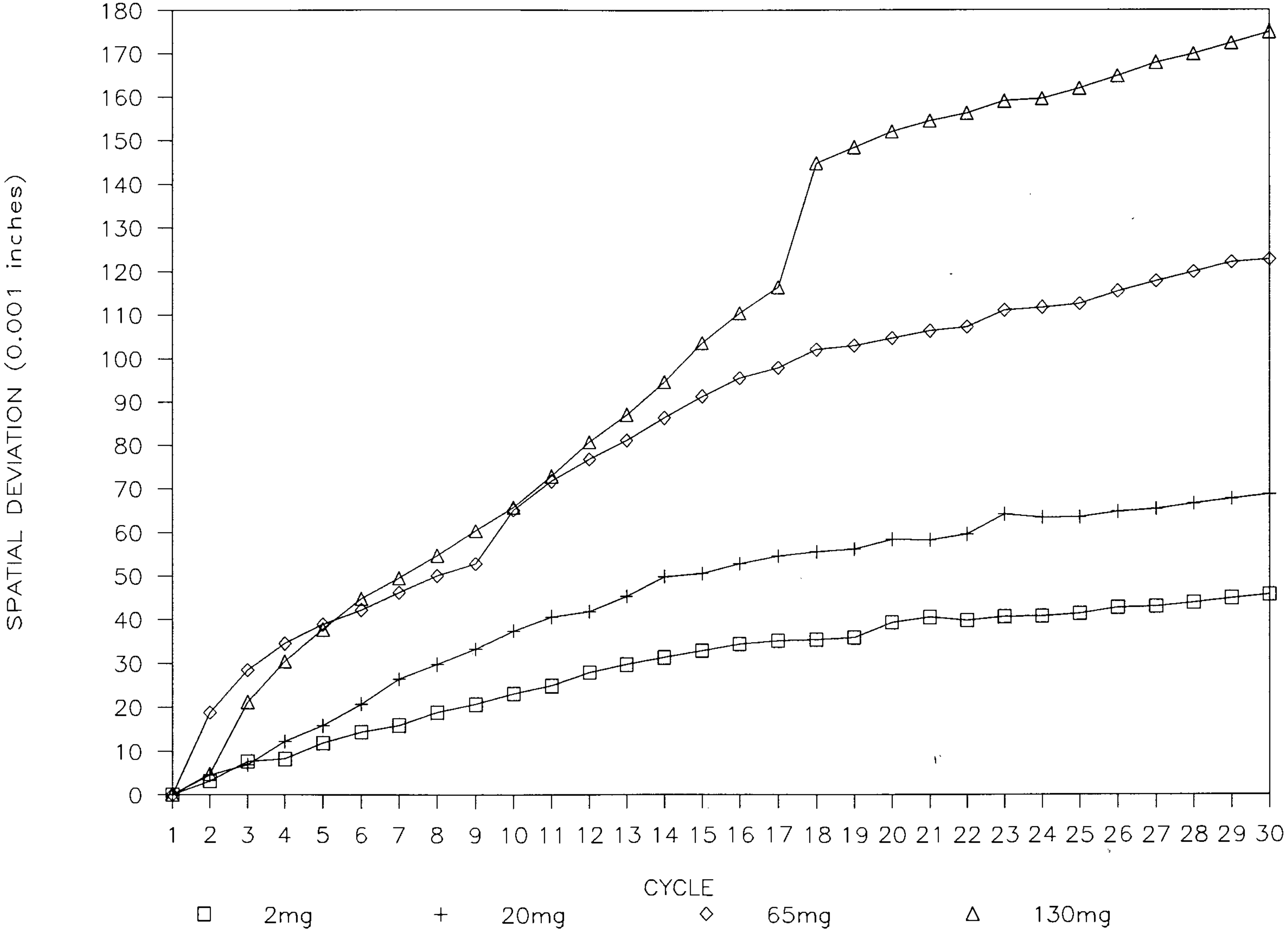


FIGURE 9.



Spatial Deviation For

Speed (7) With Different Payloads

FIGURE 10. Spatial Deviation For Payload (2mg) With Different Speeds

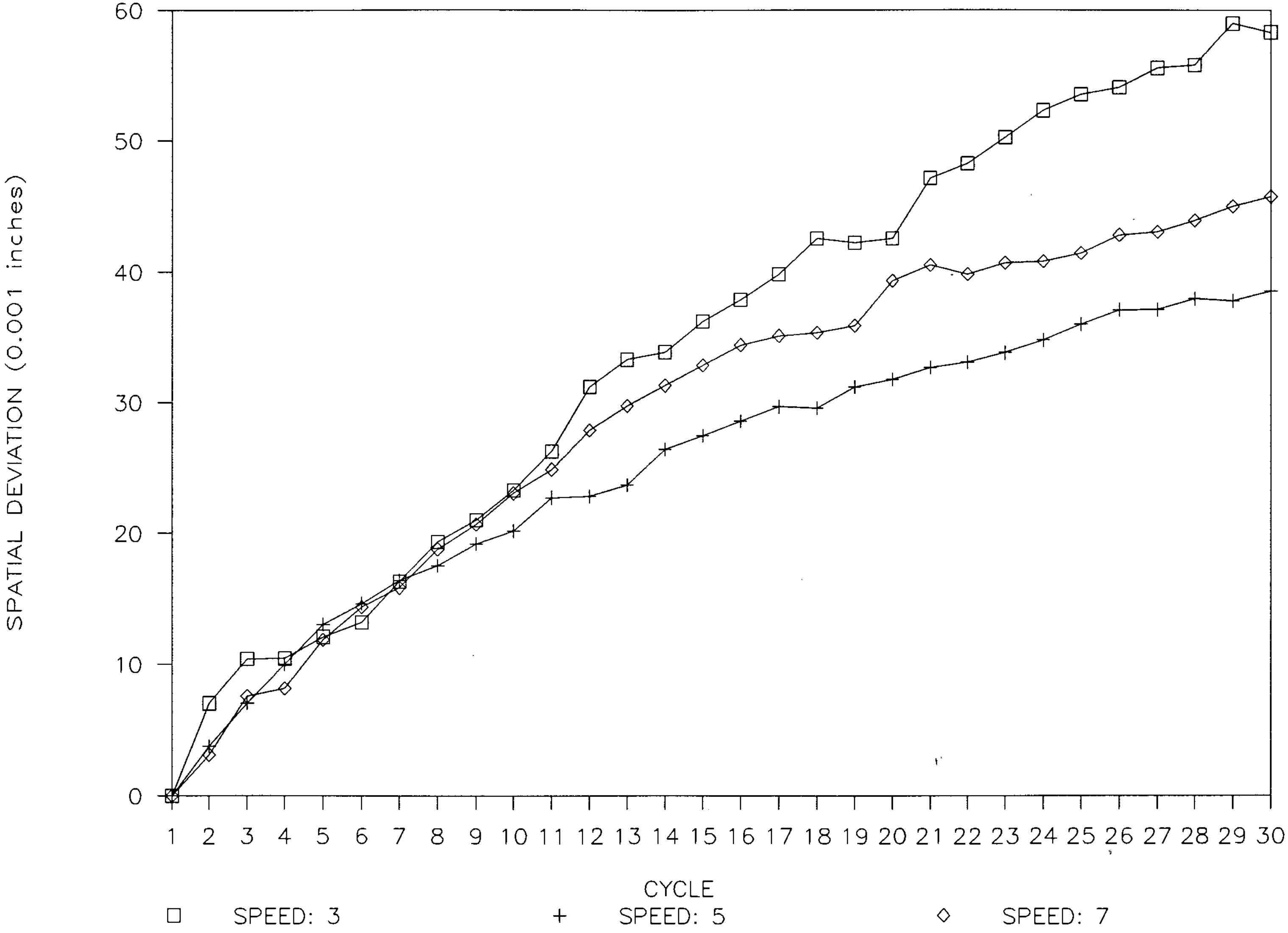


FIGURE 11. Spatial Deviation For

Payload (20mg) With Different Speeds

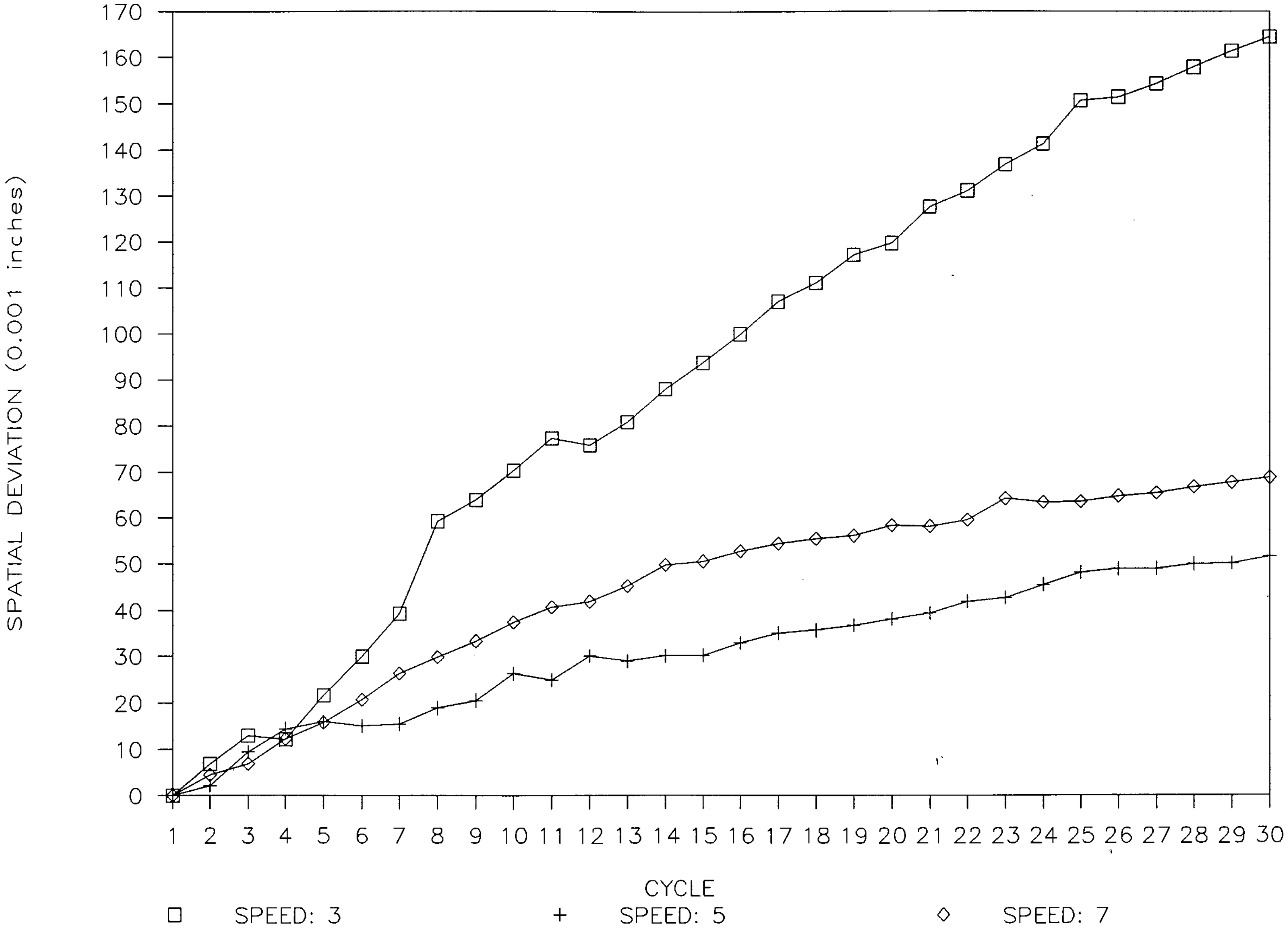


FIGURE 12. Spatial Deviation For

Payload (65mg) With Different Speeds

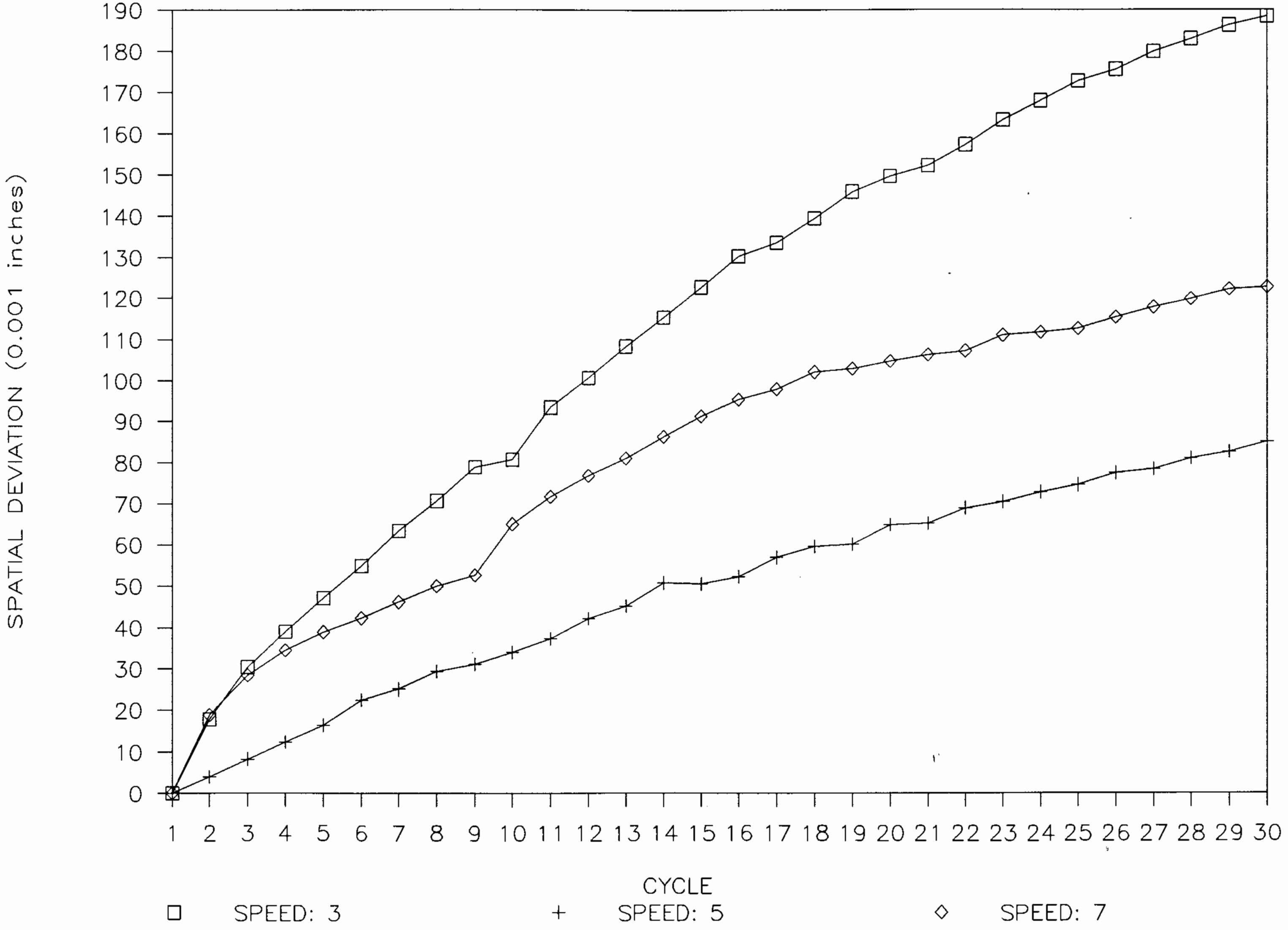


FIGURE 13. Spatial Deviation For

Payload (130mg) With Different Speeds

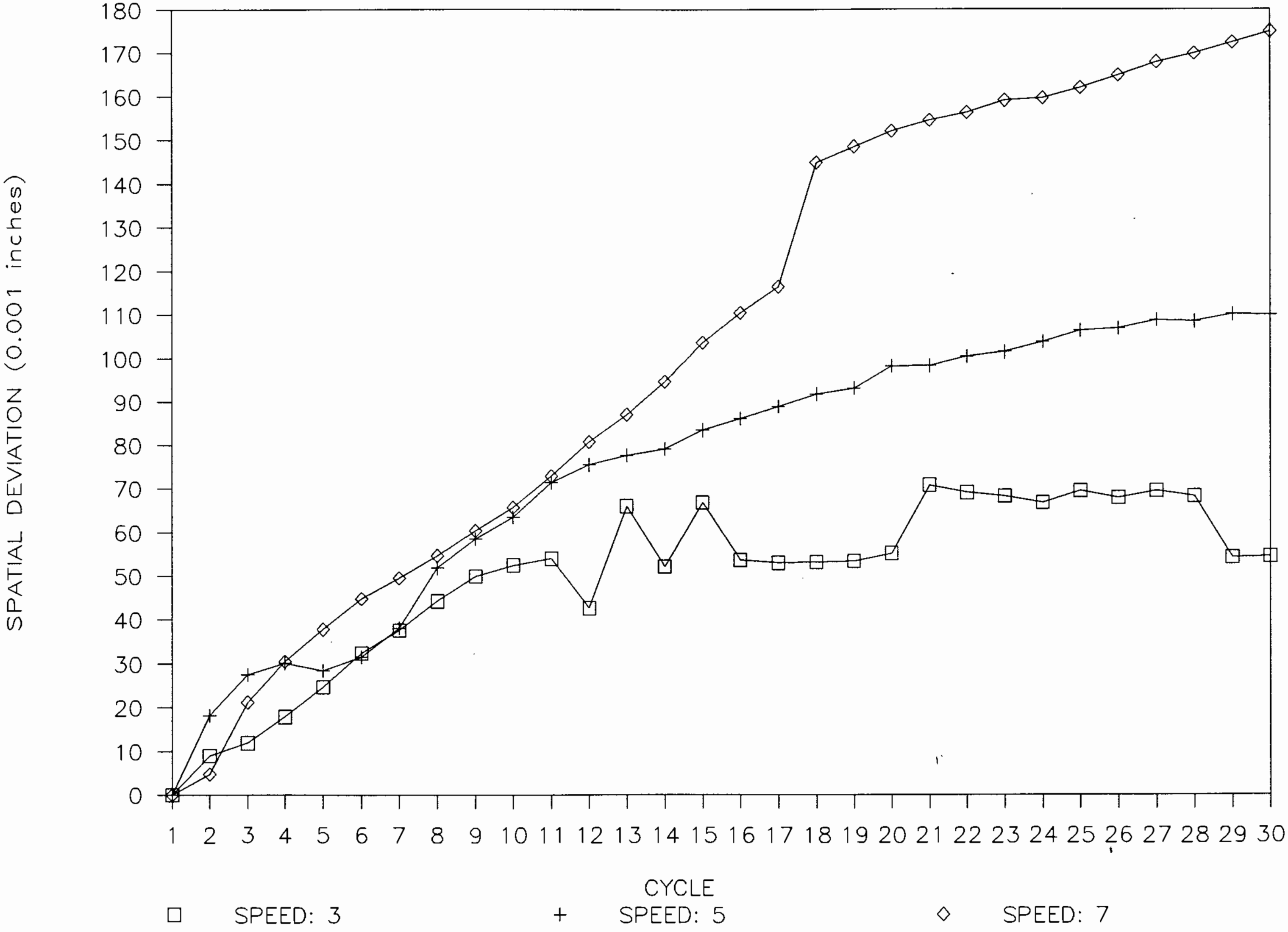


FIGURE 14. Spatial Deviation For Payload (180mg) With Different Speeds

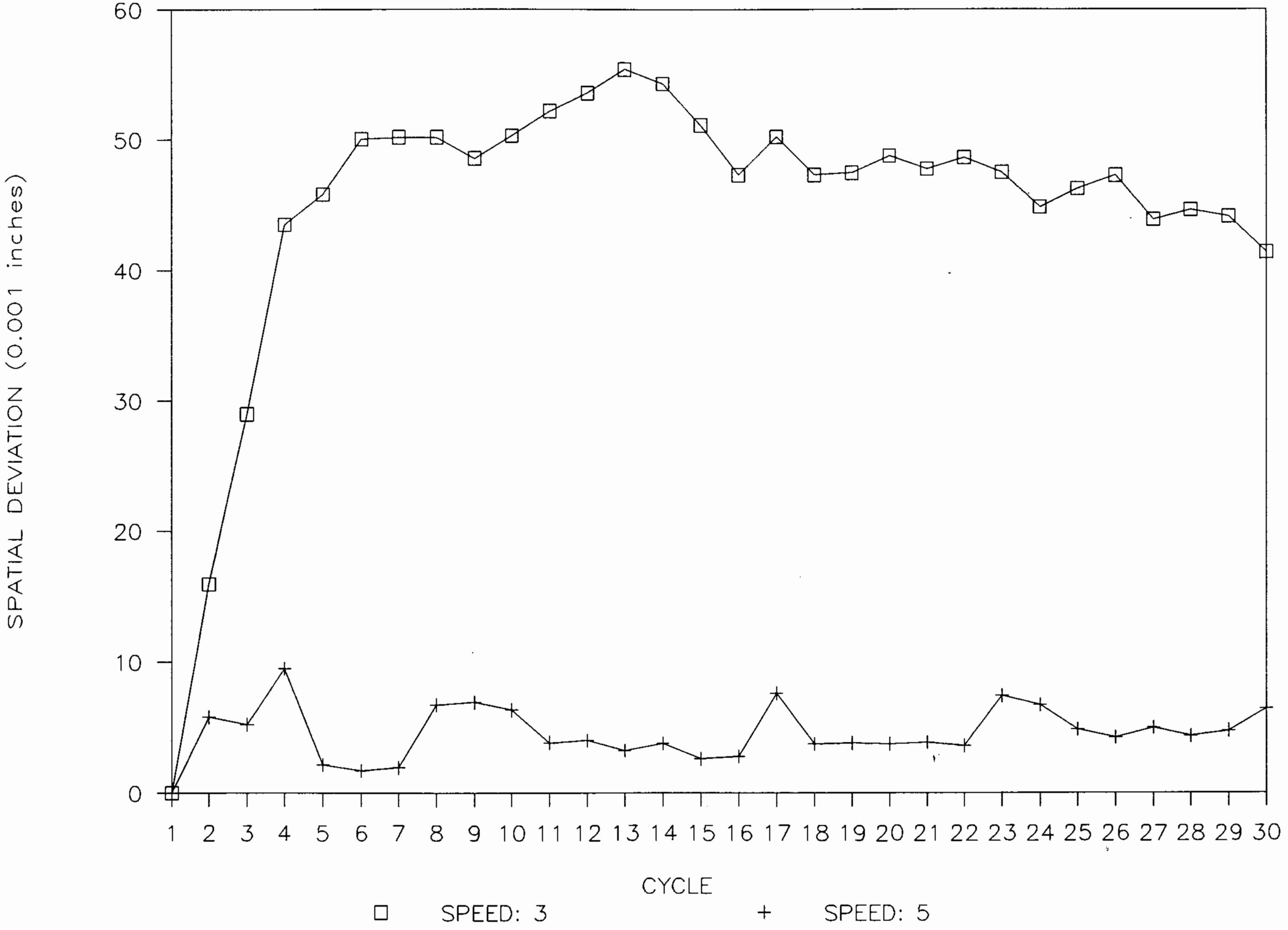
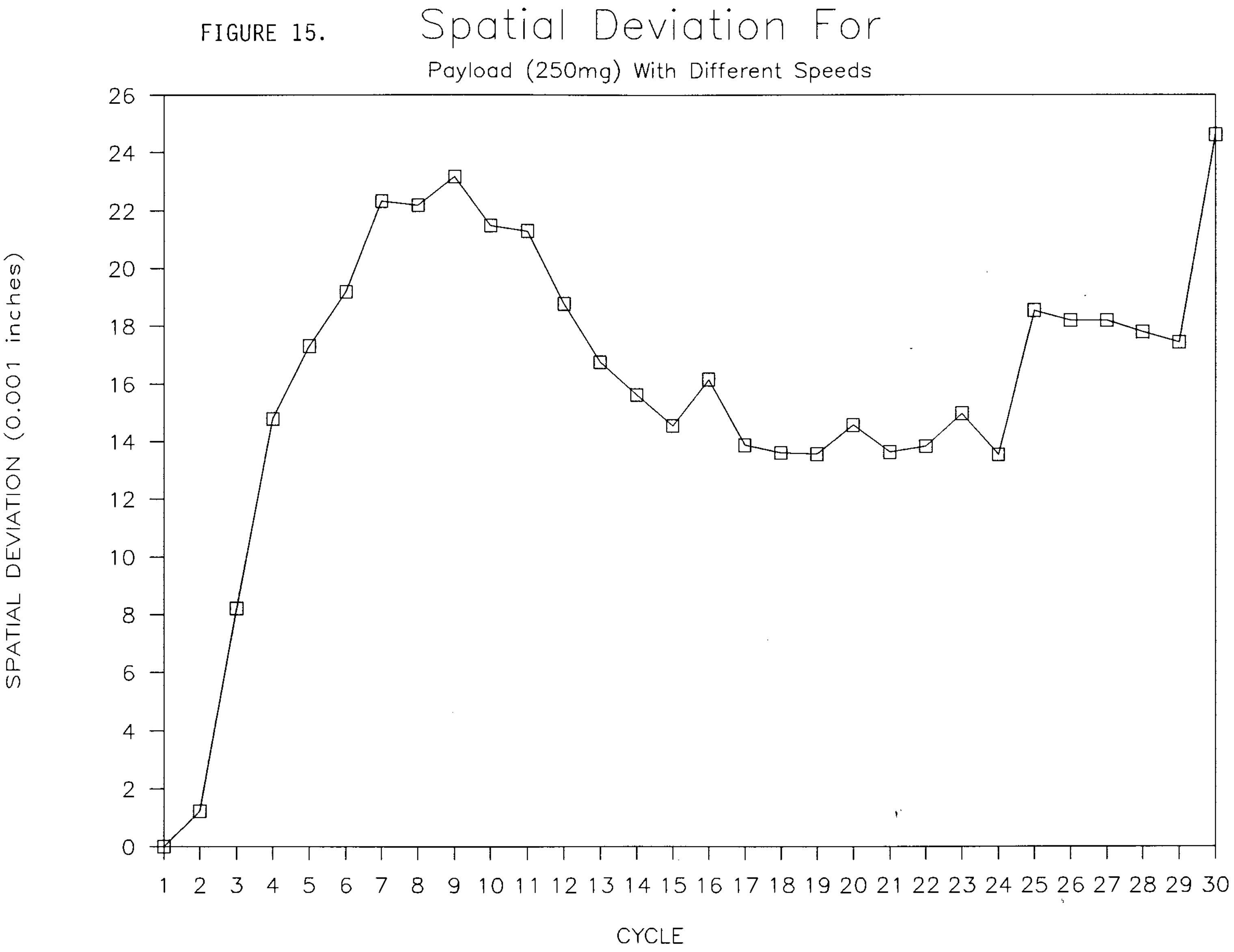


FIGURE 15.


Spatial Deviation For
Payload (250mg) With Different Speeds
SPATIAL DEVIATION (0.001 inches)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
CYCLE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

From Figure 7 to Figure 15, it can be seen that during the thirty cycles, the spatial deviation is always going up. Figure 16 and Figure 17 show the spatial deviation change of payload 65 with speed 5 and speed 7 during 50 cycles.

In Figure 16, the line becomes smoothly flat after 40 cycles. In Figure 17, during the last few cycles, the spatial deviation value have almost no change. These results suggest that the spatial deviation will tend to have low variability as the number of cycles increases. This limitation depends on the configuration or the structure of robots. The driving and the transmission system can especially affect this change of spatial deviation or repeatability. In this study, the researcher used the Microbot. It is equipped with a cable-type transmission system. Under a certain load and speed, this cable is exerted by load, weight or inertial force. Even though its length can be extended, it should have a certain limitation up to which no more significant change occurs.

FIGURE 16. Spatial Deviation For Payload (65mg)

With Speed (5) Under 50 Cycles

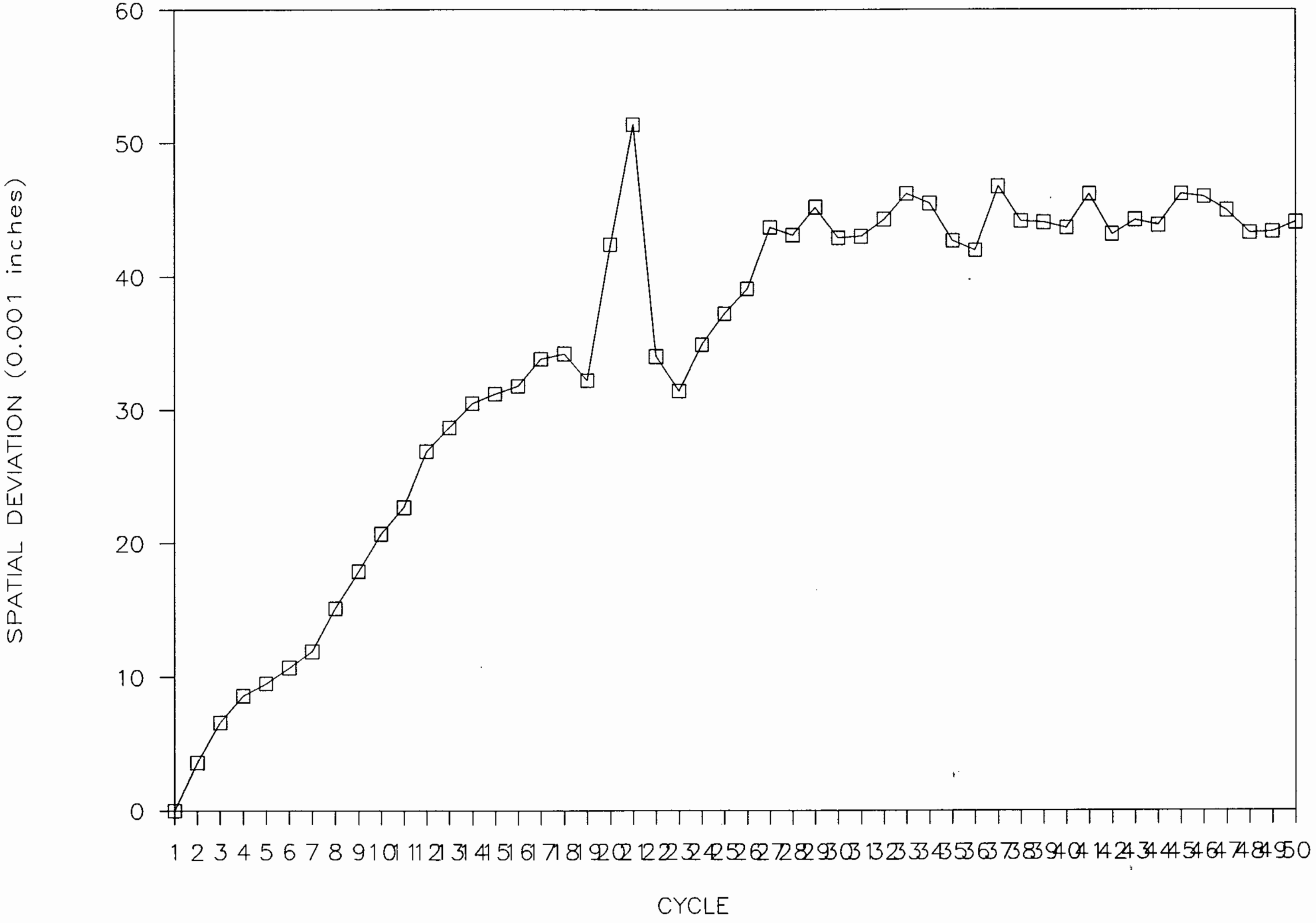
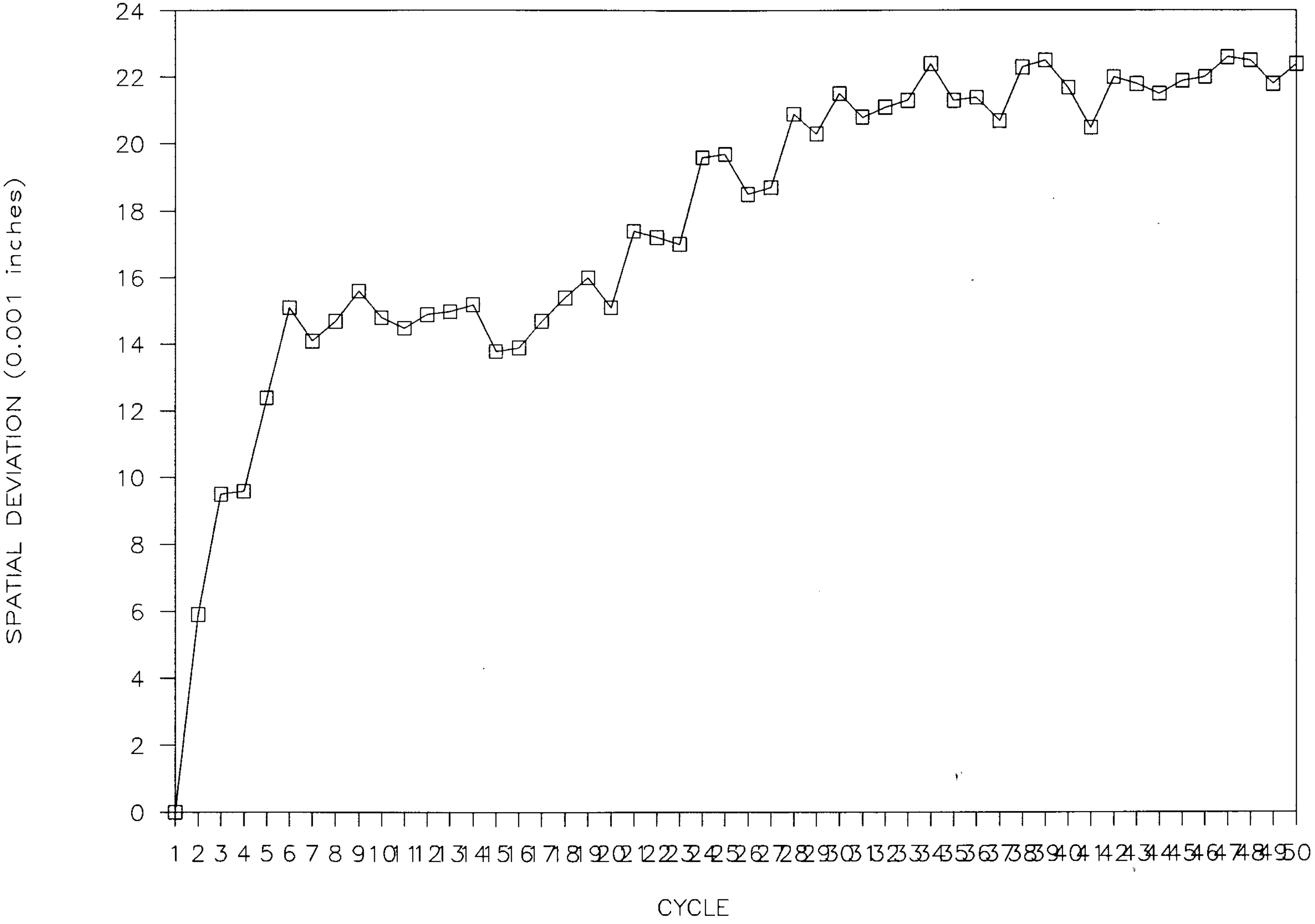


FIGURE 17. Spatial Deviation For Payload (65mg)

With Speed (7) Under 50 Cycles



CHAPTER VI

SUMMARY, CONCLUSION AND RECOMMENDATION

Summary

Industrial robots have typically been used as general purpose positioning devices. In such a situation, the robot is programmed to move through a sequence of positions so that a tool or part held by the robot completes a desired task on a workpiece. The most important requirement for successful accomplishment of its task is the repeatability with which it can return to the taught positions and with which successive workpieces can be presented to it (Taylor, 1985).

The purpose of this research was to identify key factors that can affect the accuracy and repeatability of the Microbot TeachMover robot. There are various factors which may affect the repeatability of a given robot. The problem of this research was to determine how the factors of payload and speed affect the repeatability of a Microbot TeachMover robot. In this study, the repeatability was analyzed in terms of "@D", "R", "r" and "b" ("@D" = spatial deviation; "R" = range of spatial deviation; "r" = coefficient of correlation; and "b" = changing rate of the spatial deviation or slope.

This research was conducted in the CAM Lab of the Industrial Technology Center, University of Northern Iowa. The Microbot TeachMover Robot that was used for this research had been used for about five years, which is a limitation of this study.

The robot program was developed using the standard teach pendent, and stored on a 5 1/4" floppy disc. The same program was used repeatedly with different payloads and different speeds. There were fifteen pairs of payload and speed run under thirty cycles, and two pairs of payload and speed run under fifty cycles. Three dial-indicators were set together to measure the position deviation on X, Y, and Z axis separately. Then the spatial deviation @D was calculated with the formula: @D = SQRT {(@X)^2+(@Y)^2+(@Z)^2}. "R" was calculated with the formula: R = @D(maximum)-@D(minimum).

In order to separately analyze the effect of payload and speed on repeatability, the "$\overline{\text{@D}}$" and "R" were arranged into two groups. One group of data was organized to show the effect of different speeds on repeatability. For the same payload , both high speed and lower speed caused higher spatial deviation than did the medium speed. Another group was organized to show the effect of different payloads on repeatability. It was found that under the same speed, heavier payload caused greater spatial position deviation. The payload 65 with speed 5 and 7 were tested under fifty cycles. These results showed that after certain cycles, the deviation or the repeatability become stable, while they always increase before thirty cycles.

All of the results from this research can add important information about the repeatability of robots. "It will require joint efforts from users, manipulators, and researchers to achieve the most productive use of [an] accurate robot system" (Day, 1988, p. 9).

Discussion and Conclusion

From previous analysis, it was concluded that medium speed and light payload resulted in better repeatability. When the robot held heavier payload and ran at low speed or at high speed, the repeatability became worse. The repeatability (or the spatial deviation in this study) changes cycle by cycle. But up to a certain degree (or certain cycles), there was almost no change in repeatability.

According to the physical configuration, the Microbot used for this study falls into the articulating configuration. It has five degrees of freedom, and five axes provide its basic motions. DC stepper-motors of the open-loop type are used to drive each of the axes of motion.

The mechanical transmissions used in the Microbot can be categorized into cable type transmissions. All motors are connected to a common drive shaft, and then the cables are connected through gears to drive different elements of the robot. Backlash and unstable characteristics are main disadvantages of the cables which contribute much to inaccuracy and poor repeatability.

Dynamic parameters such as force, gravity, and inertia are important in accurate robot controls. Structurally, robots are designed to be more flexible. Being flexible, robots will deflect under the load and under their own weight. There are several components in robots that contribute to flexibility, such as link structures, bearings, and drive train components. They all contribute to robot inaccuracy when payloads change at the robot end effector. The heavier the payload, the more the inaccuracy. The researcher also believes that when speed becomes slower for the same payload, the time the payload is exerted on the robot will be longer, and will create more inaccuracy or irrepeatability. But when speed is high, it will come to another problem. The higher the speed, the larger the inertial force accumulates and the worse its repeatability.

Inertial parameters of robots play a role in trajectory accuracy and velocity accuracy of robots. With inertia and flexibility in a dynamic system, there are resonance or natural liberation. The robot shakes at or near its natural frequencies. When a robot holds a heavy payload, the amplitude of vibration becomes low. This is why heavy payload in this study showed lower "b".

The friction parameters of robots also contribute to the robot's inaccuracy and poor repeatability. Hysteriosis shows up when the drive cycled back and forth, thus contributing errors in omnidirectional repeatability, and accuracy. All friction parameters dissipate energy and contribute to robot inaccuracy.

In order to build a high-quality robot to meet the more rigorous requirements in the modern industrial environment, people should do more patient work on the improvement of robot, and reveal more and more secrets of robots.

Rcommendations

The following recommendations were suggested as a result of this research project:

1. The variable program complexity should be considered when conducting future studies.
2. Researching on the repeatability of industrial robots should be conducted in the manufacturing system.
3. Researchers could use more precise measurement techniques, such as the laser tracking system, to study path repeatability rather than point repeatability.
4. Different types of robots should be studied to compare their repeatability.
5. Research should focus on a specific part of the

robot, such as base rotation, shoulder flex, elbow flex, wrist pitch or wrist roll, to study how this part affects the repeatability of a robot.

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APPENDIX A

The Program of Microbot for this Research

PROGRAM FOR SPEED 3

```
STEP COMMAND OPERANDS

0    MOVE        183,0,0,0,0,0,0
1    PAUSE       12
2    MOVE        183,-51,-361,73,0,0,73
3    MOVE        183,-51,-873,264,0,0,264
4    MOVE     183,-51,-873,578,385,385,578
5    MOVE     183,1763,-873,578,385,385,578
6    MOVE     183,1763,-1183,-240,168,168,-240
7    MOVE     183,-1752,-1183,-240,168,168,-240
8    MOVE     183,-1752,-2009,-1297,-412,-412,-1297
9    MOVE     183,-14,-2009,-1297,-412,-412,-1297
10   MOVE     183,-14,-915,542,405,405,542
11   MOVE     183,-14,-915,542,1151,-341,542
12   MOVE     183,-14,-915,542,68,742,542
13   MOVE     183,-14,-915,542,425,385,542
14   MOVE     183,1743,-915,542,425,385,542
15   MOVE     183,1743,-1605,0,425,385,0
16   MOVE     183,-1707,-1605,0,425,385,0
17   MOVE     183,-1707,-817,674,408,368,674
18   MOVE     183,-18,-817,674,408,368,674
19   MOVE     183,-18,-817,674,731,45,674
20   MOVE     183,-18,-817,674,-38,814,674
21   MOVE     183,-18,-817,674,433,343,674
22   MOVE     183,-18,-699,276,36,-54,276
23   MOVE        183,-52,-366,83,-19,1,83
```

PROGRAM FOR SPEED 5

```
STEP COMMAND OPERANDS

0    MOVE      183,0,0,0,0,0,0
1    PAUSE     12
2    MOVE      221,-51,-361,73,0,0,73
3    MOVE      221,-51,-873,264,0,0,264
4    MOVE   221,-51,-873,578,385,385,578
5    MOVE   221,1763,-873,578,385,385,578
6    MOVE   221,1763,-1183,-240,168,168,-240
7    MOVE   221,-1752,-1183,-240,168,168,-240
8    MOVE   221,-1752,-2009,-1297,-412,-412,-1297
9    MOVE   221,-14,-2009,-1297,-412,-412,-1297
10   MOVE   221,-14,-915,542,405,405,542
11   MOVE   221,-14,-915,542,1151,-341,542
12   MOVE   221,-14,-915,542,68,742,542
13   MOVE   221,-14,-915,542,425,385,542
14   MOVE   221,1743,-915,542,425,385,542
15   MOVE   221,1743,-1605,0,425,385,0
16   MOVE   221,-1707,-1605,0,425,385,0
17   MOVE   221,-1707,-817,674,408,368,674
18   MOVE   221,-18,-817,674,408,368,674
19   MOVE   221,-18,-817,674,731,45,674
20   MOVE   221,-18,-817,674,-38,814,674
21   MOVE   221,-18,-817,674,433,343,674
22   MOVE   221,-18,-699,276,36,-54,276
23   MOVE      221,-52,-366,83,-19,1,83
```

PROGRAM FOR SPEED 7

```
STEP COMMAND OPERANDS

0    MOVE      183,0,0,0,0,0,0
1    PAUSE     12
2    MOVE      236,-51,-361,73,0,0,73
3    MOVE      236,-51,-873,264,0,0,264
4    MOVE   236,-51,-873,578,385,385,578
5    MOVE   236,1763,-873,578,385,385,578
6    MOVE   236,1763,-1183,-240,168,168,-240
7    MOVE   236,-1752,-1183,-240,168,168,-240
8    MOVE   236,-1752,-2009,-1297,-412,-412,-1297
9    MOVE   236,-14,-2009,-1297,-412,-412,-1297
10   MOVE   236,-14,-915,542,405,405,542
11   MOVE   236,-14,-915,542,1151,-341,542
12   MOVE   236,-14,-915,542,68,742,542
13   MOVE   236,-14,-915,542,425,385,542
14   MOVE   236,1743,-915,542,425,385,542
15   MOVE   236,1743,-1605,0,425,385,0
16   MOVE   236,-1707,-1605,0,425,385,0
17   MOVE   236,-1707,-817,674,408,368,674
18   MOVE   236,-18,-817,674,408,368,674
19   MOVE   236,-18,-817,674,731,45,674
20   MOVE   236,-18,-817,674,-38,814,674
21   MOVE   236,-18,-817,674,433,343,674
22   MOVE   236,-18,-699,276,36,-54,276
23   MOVE      236,-52,-366,83,-19,1,83
```

APPENDIX B

Microbot TeachMover Characteristics

Table —— Microbot TeachMover Characteristics

GENERAL

Configuration	5 revolution axes and integral hand
Drive	Electric stepper motors - Open loop control
Controller	6502A microprocessor with 4K bytes of EPROM and 1K bytes of RAM located in the base of the unit
Interface	Dual RS-232C asynchronous serial communications interfaces (baud rate is switch-selectable between 110, 150, 300, 600, 1200, 2400, 4800, and 9600 baud)
Teach Control	14-key 13-function keyboard; 5 output and 7 input bits under computer control
Power requirement	12 to 14 volts, 4.5 amps DC

PERFORMANCE

Resolution	0.011 in (0.25mm) maximum on each axis
Load Capacity	16 oz (455 gm) at full extension
Gripping Force	3 lbs (13 newtons) maximum
Reach	17.5 in (444 mm)
Velocity	0-7 in/sec (0-178 mm/sec) with controlled acceleration

DETAILED PERFORMANCE

Joint	Max Range of Motion	Speed (full Load)	Speed (No load)
Base	±90°	0.37 rad/sec	0.42 rad/sec
Shoulder	+144°, -35°	0.15 rad/sec	0.36 rad/sec
Elbow	+0°, -149°	0.23 rad/sec	0.82 rad/sec
Wrist Roll	±270°	1.31 rad/sec	2.02 rad/sec
Wrist Pitch	±90°	1.31 rad/sec	2.02 rad/sec
Hand	0-3 in	20 mm/sec	

PHYSICAL CHARACTERISTICS

Arm Weight	8 lbs (4kg)
Teach Control Cable Length	3.75 ft.(1150 mm)

Source: Heath, L. (1986). Microbot.

APPENDIX C

The Result of "b" and "r" Calculated with "POM" Software Package

```
File:
PAYLOAD:2 & SPEED:3          PAYLOAD:2 & SPEED:3

Method:Linear Regression/least squares
                 @D    Period   x^2          x * y    Forecast    Error^2
cycle 1        0.00         1        1.00       0.00       5.74      32.97
cycle 2        7.04         2        4.00      14.08    7.72191    .465003
cycle 3       10.40         3        9.00      31.20    9.70221    .486904
cycle 4       10.44         4       16.00      41.76    11.6825    1.54385
cycle 5       12.11         5       25.00      60.55    13.6628    2.41125
cycle 6       13.20         6       36.00      79.20    15.6431    5.96885
cycle 7       16.33         7       49.00     114.31    17.6234    1.67295
cycle 8       19.35         8       64.00     154.80    19.6037    0.06438
cycle 9       21.00         9       81.00     189.00      21.58    .341093
cycle10       23.29        10      100.00     232.90    23.5643    0.07526
cycle11       26.25        11      121.00     288.75    25.5446    .497536
cycle12       31.20        12      144.00     374.40    27.5249      13.51
cycle13       33.32        13      169.00     433.16    29.5052    14.5524
cycle14       33.88        14      196.00     474.32    31.4855    5.73341
cycle15       36.23        15      225.00     543.45    33.4659    7.64052
cycle16       37.88        16      256.00     606.08    35.4462    5.92362
cycle17       39.85        17      289.00     677.45    37.4265    5.87356
cycle18       42.58        18      324.00     766.44    39.4068    10.0695
cycle19       42.22        19      361.00     802.18      41.39    .693788
cycle20       42.56        20      400.00     851.20    43.3674    .651833
cycle21       47.18        21      441.00     990.78    45.3477    3.35744
cycle22       48.31        22      484.00    1062.82    47.3280    .964388
cycle23       50.30        23      529.00    1156.90    49.3083       0.98
cycle24       52.36        24      576.00    1256.64    51.2886    1.14795
cycle25       53.56        25      625.00    1339.00    53.2689    0.08475
cycle26       54.09        26      676.00    1406.34    55.2492       1.34
cycle27       55.60        27      729.00    1501.20    57.2295    2.65522
cycle28       55.82        28      784.00    1562.96      59.21    11.4907
cycle29       59.00        29      841.00    1711.00      61.19    4.79649
cycle30       58.33        30      900.00    1749.90      63.17    23.4294
TOTALS      1033.68    465.00     9455.00    20472.8    65.1507    161.391
AVERAGE      34.456     15.50     315.167    682.426       0.00    5.37971
                                                                     (MSE)

                              Next period forecast=  65.1507
Regression line = : Y =     3.76 +     1.98 * X
Correlation coefficient =    0.9909684Standard error = 2.400828
```

```
File:
PAYLOAD:2 & SPEED:5                PAYLOAD:2 & SPEED:5

Method:Linear Regression/least squares
                @D     Period    x^2          x * y      Forecast     Error^2
cycle 1       0.00          1        1.00        0.00        7.74     59.8715
cycle 2       3.77          2        4.00        7.54     8.93914       26.72
cycle 3       7.07          3        9.00       21.21     10.1406     9.42865
cycle 4      10.02          4       16.00       40.08       11.34        1.75
cycle 5      13.06          5       25.00       65.30     12.5436     .266718
cycle 6      14.62          6       36.00       87.72       13.75     .765582
cycle 7      16.42          7       49.00      114.94     14.9465     2.17122
cycle 8      17.53          8       64.00      140.24     16.1480        1.91
cycle 9      19.17          9       81.00      172.53     17.3494     3.31445
cycle10      20.16         10      100.00      201.60     18.5509     2.58917
cycle11      22.71         11      121.00      249.81     19.7524        8.75
cycle12      22.83         12      144.00      273.96     20.9538        3.52
cycle13      23.68         13      169.00      307.84     22.1553     2.32465
cycle14      26.43         14      196.00      370.02       23.36        9.44
cycle15      27.46         15      225.00      411.90     24.5583     8.42007
cycle16      28.57         16      256.00      457.12     25.7597     7.89759
cycle17      29.69         17      289.00      504.73     26.9612     7.44633
cycle18      29.58         18      324.00      532.44     28.1627        2.01
cycle19      31.21         19      361.00      592.99     29.3641        3.41
cycle20      31.80         20      400.00      636.00     30.5656     1.52370
cycle21      32.69         21      441.00      686.49       31.77        0.85
cycle22      33.11         22      484.00      728.42     32.9686     0.02001
cycle23      33.83         23      529.00      778.09       34.17        0.12
cycle24      34.83         24      576.00      835.92     35.3715     .293222
cycle25      36.00         25      625.00      900.00     36.5730     .328296
cycle26      37.11         26      676.00      964.86     37.7744     .441486
cycle27      37.15         27      729.00     1003.05     38.9759     3.33396
cycle28      37.94         28      784.00     1062.32       40.18        5.01
cycle29      37.78         29      841.00     1095.62     41.3789     12.9518
cycle30      38.55         30      900.00     1156.50     42.5803     16.2435
TOTALS      754.77     465.00     9455.00     14399.2     43.7818     203.111
AVERAGE     25.159      15.50     315.167     479.975        0.00     6.77037
                                                                        (MSE)

                                Next period forecast=  43.7818
Regression line = : Y =    6.54 +  1.20147 * X
Correlation coefficient =   0.9700949Standard error =  2.69332
```

PAYLOAD:2 & SPEED:7

```
File:
PAYLOAD:2 & SPEED:7

Method:Linear Regression/least squares
                 @D  Period(x)  x^2          x * y      Forecast     Error^2
cycle 1        0.00          1       1.00        0.00    7.34823       54.00
cycle 2        3.15          2       4.00        6.30       8.85     32.5071
cycle 3        7.60          3       9.00       22.80    10.3548     7.58878
cycle 4        8.18          4      16.00       32.72      11.86       13.53
cycle 5       11.86          5      25.00       59.30    13.3613     2.25396
cycle 6       14.36          6      36.00       86.16      14.86        0.25
cycle 7       15.83          7      49.00      110.81    16.3679     .289294
cycle 8       18.78          8      64.00      150.24    17.8711     .826042
cycle 9       20.66          9      81.00      185.94    19.3744     1.65275
cycle10       23.05         10     100.00      230.50    20.8777     4.71899
cycle11       24.89         11     121.00      273.79    22.3809     6.29534
cycle12       27.88         12     144.00      334.56    23.8842     15.9663
cycle13       29.77         13     169.00      387.01      25.39       19.21
cycle14       31.31         14     196.00      438.34    26.8908     19.5297
cycle15       32.88         15     225.00      493.20      28.39     20.1239
cycle16       34.42         16     256.00      550.72    29.8973     20.4547
cycle17       35.14         17     289.00      597.38    31.4006     13.9833
cycle18       35.35         18     324.00      636.30    32.9039     5.98364
cycle19       35.90         19     361.00      682.10    34.4071     2.22870
cycle20       39.33         20     400.00      786.60      35.91     11.6937
cycle21       40.56         21     441.00      851.76    37.4137     9.89943
cycle22       39.83         22     484.00      876.26    38.9169     .833691
cycle23       40.71         23     529.00      936.33    40.4202     0.08398
cycle24       40.82         24     576.00      979.68    41.9235     1.21767
cycle25       41.45         25     625.00     1036.25    43.4268     3.90754
cycle26       42.84         26     676.00     1113.84      44.93     4.36820
cycle27       43.07         27     729.00     1162.89    46.4333     11.3118
cycle28       43.95         28     784.00     1230.60    47.9366     15.8927
cycle29       45.04         29     841.00     1306.16    49.4398     19.3586
cycle30       45.76         30     900.00     1372.80    50.9431     26.8647
TOTALS       874.37     465.00    9455.00     16931.3    52.4464      346.82
AVERAGE     29.1457      15.50    315.167     564.378       0.00     11.5607
                                                                      (MSE)

                                  Next period forecast=  52.4464
Regression line = : Y =     5.84 +  1.50327 * X
Correlation coefficient =     0.967512Standard error = 3.519435
```

```
File:
PAYLOAD:20 & SPEED:3                      PAYLOAD:20 & SPEED:3

Method:Linear Regression/least squares
                @D  Period(x)  x^2          x * y      Forecast     Error^2
cycle 1       0.00         1        1.00        0.00    7.83477     61.3836
cycle 2       6.92         2        4.00       13.84    13.6504     45.2985
cycle 3      13.01         3        9.00       39.03      19.47       41.68
cycle 4      12.14         4       16.00       48.56    25.2817     172.705
cycle 5      21.70         5       25.00      108.50    31.0974     88.3104
cycle 6      29.95         6       36.00      179.70      36.91       48.48
cycle 7      39.23         7       49.00      274.61    42.7287     12.2406
cycle 8      59.28         8       64.00      474.24    48.5443     115.255
cycle 9      64.00         9       81.00      576.00    54.3600     92.9305
cycle10      70.32        10      100.00      703.20    60.1756     102.909
cycle11      77.34        11      121.00      850.74    65.9912     128.794
cycle12      75.85        12      144.00      910.20    71.8069     16.3466
cycle13      80.86        13      169.00     1051.18    77.6225     10.4811
cycle14      88.10        14      196.00     1233.40      83.44     21.7324
cycle15      93.76        15      225.00     1406.40    89.2538     20.3055
cycle16      99.96        16      256.00     1599.36      95.07       23.92
cycle17     107.10        17      289.00     1820.70    100.885     38.6245
cycle18     111.11        18      324.00     1999.98     106.70     19.4411
cycle19     117.16        19      361.00     2226.04    112.516     21.5627
cycle20     119.77        20      400.00     2395.40    118.332     2.06759
cycle21     127.68        21      441.00     2681.28    124.148     12.4769
cycle22     131.15        22      484.00     2885.30    129.963     1.40806
cycle23     136.86        23      529.00     3147.78    135.779     1.16851
cycle24     141.37        24      576.00     3392.88    141.595     0.05048
cycle25     150.68        25      625.00     3767.00     147.41     10.6907
cycle26     151.44        26      676.00     3937.44    153.226     3.18967
cycle27     154.32        27      729.00     4166.64    159.042     22.2937
cycle28     157.95        28      784.00     4422.60    164.857     47.7104
cycle29     161.36        29      841.00     4679.44     170.67     86.7303
cycle30     164.48        30      900.00     4934.40    176.489      144.21
TOTALS     2764.85    465.00     9455.00     55925.8    182.304     1414.39
AVERAGE    92.1617     15.50     315.167     1864.19       0.00     47.1465
                                                                      (MSE)

                              Next period forecast=  182.304
Regression line = : Y =  2.01912 +  5.81565 * X
Correlation coefficient =    0.9908249Standard error = 7.107325
```

```
File:
PAYLOAD:20 & SPEED:5              PAYLOAD:20 & SPEED:5

Method:Linear Regression/least squares
                @D  Period(x)  x^2           x * y      Forecast     Error^2
cycle 1        0.00         1        1.00        0.00   6.98734      48.8230
cycle 2        2.19         2        4.00        4.38   8.64217      41.6305
cycle 3        9.44         3        9.00       28.32    10.297      .734443
cycle 4       14.43         4       16.00       57.72   11.9518      6.14136
cycle 5       16.02         5       25.00       80.10   13.6067         5.82
cycle 6       15.07         6       36.00       90.42   15.2615      0.03666
cycle 7       15.51         7       49.00      108.57   16.9163         1.98
cycle 8       18.93         8       64.00      151.44   18.5711      .128787
cycle 9       20.52         9       81.00      184.68   20.2260         0.09
cycle10       26.40        10      100.00      264.00   21.8808      20.4233
cycle11       24.90        11      121.00      273.90   23.5356      1.86155
cycle12       30.04        12      144.00      360.48   25.1904      23.5183
cycle13       29.00        13      169.00      377.00   26.8453      4.64289
cycle14       30.22        14      196.00      423.08     28.50      2.95808
cycle15       30.30        15      225.00      454.50   30.1549      0.02105
cycle16       32.98        16      256.00      527.68   31.8097      1.36949
cycle17       35.05        17      289.00      595.85   33.4646      2.51358
cycle18       35.76        18      324.00      643.68   35.1194      .410366
cycle19       36.64        19      361.00      696.16   36.7742         0.02
cycle20       38.08        20      400.00      761.60     38.43      .121838
cycle21       39.39        21      441.00      827.19   40.0839      .481472
cycle22       41.97        22      484.00      923.34   41.7387      0.05350
cycle23       42.71        23      529.00      982.33   43.3935      .467222
cycle24       45.55        24      576.00     1093.20   45.0484      .251639
cycle25       48.24        25      625.00     1206.00     46.70         2.36
cycle26       49.01        26      676.00     1274.26     48.36      .425085
cycle27       49.07        27      729.00     1324.89   50.0128      .888948
cycle28       50.00        28      784.00     1400.00   51.6677      2.78111
cycle29       50.26        29      841.00     1457.54     53.32      9.37888
cycle30       51.79        30      900.00     1553.70   54.9773        10.16
TOTALS       929.47    465.00     9455.00     18126.0   56.6321       190.49
AVERAGE     30.9823     15.50     315.167      604.20      0.00      6.34968
                                                                       (MSE)

                                Next period forecast=  56.6321
Regression line = : Y =  5.33252 +  1.65483 * X
Correlation coefficient =    0.9848743Standard error = 2.608299
```

```
File:
[illegible]AYLOAD:20 & SPEED:7          PAYLOAD:20 & SPEED:7

Method:Linear Regression/least squares
                 @D  Period(x)  x^2          x * y      Forecast     Error^2
cycle 1        0.00          1        1.00        0.00      11.24     126.294
cycle 2        4.48          2        4.00        8.96    13.5344     81.9825
cycle 3        6.91          3        9.00       20.73    15.8308     79.5804
cycle 4       12.25          4       16.00       49.00    18.1271     34.5408
cycle 5       15.77          5       25.00       78.85    20.4235     21.6551
cycle 6       20.72          6       36.00      124.32    22.7199        4.00
cycle 7       26.37          7       49.00      184.59    25.0162     1.83267
cycle 8       29.88          8       64.00      239.04    27.3126     6.59152
cycle 9       33.32          9       81.00      299.88    29.6090     13.7718
cycle10       37.41         10      100.00      374.10    31.9053     30.3014
cycle11       40.70         11      121.00      447.70      34.20       42.23
cycle12       41.90         12      144.00      502.80      36.50     29.1809
cycle13       45.29         13      169.00      588.77    38.7944       42.19
cycle14       49.89         14      196.00      698.46      41.09       77.43
cycle15       50.59         15      225.00      758.85    43.3872      51.881
cycle16       52.82         16      256.00      845.12    45.6835     50.9294
cycle17       54.46         17      289.00      925.82    47.9799     41.9919
cycle18       55.49         18      324.00      998.82    50.2762     27.1833
cycle19       56.11         19      361.00     1066.09    52.5726     12.5131
cycle20       58.49         20      400.00     1169.80    54.8690     13.1119
cycle21       58.27         21      441.00     1223.67    57.1653     1.22027
cycle22       59.64         22      484.00     1312.08    59.4617     0.03179
cycle23       64.26         23      529.00     1477.98      61.76     6.25967
cycle24       63.50         24      576.00     1524.00    64.0544        0.31
cycle25       63.63         25      625.00     1590.75    66.3508     7.40274
cycle26       64.87         26      676.00     1686.62    68.6472     14.2669
cycle27       65.55         27      729.00     1769.85    70.9435     29.0901
cycle28       66.75         28      784.00     1869.00      73.24       42.12
cycle29       67.84         29      841.00     1967.36    75.5363     59.2324
cycle30       68.90         30      900.00     2067.00    77.8326     79.7916
TOTALS      1336.06     465.00     9455.00     25870.0    80.1290     1028.91
AVERAGE     44.5353      15.50     315.167     862.334       0.00     34.2970
                                                                       (MSE)

                                Next period forecast=  80.1290
Regression line = : Y =     8.94 +   2.29636 * X
Correlation coefficient =     0.9592287Standard error =   6.06191
```

```
File:
PAYLOAD:65 & SPEED:3              PAYLOAD:65 & SPEED:3

Method:Linear Regression/least squares
                @D  Period(x)  x^2          x * y    Forecast    Error^2
cycle 1       0.00          1       1.00       0.00   20.2583     410.40
cycle 2      17.89          2       4.00      35.78   26.6773    77.2168
cycle 3      30.53          3       9.00      91.59   33.0963    6.58577
cycle 4      39.11          4      16.00     156.44   39.5152    .164219
cycle 5      47.17          5      25.00     235.85   45.9342    1.52719
cycle 6      54.94          6      36.00     329.64   52.3532    6.69169
cycle 7      13.49          7      49.00      94.43   58.7721    2050.47
cycle 8      70.75          8      64.00     566.00   65.1911    30.9014
cycle 9      78.98          9      81.00     710.82     71.61      54.32
cycle10      80.83         10     100.00     808.30     78.03    7.84544
cycle11      93.51         11     121.00    1028.61     84.45      82.12
cycle12     100.66         12     144.00    1207.92   90.8670    95.9037
cycle13     108.38         13     169.00    1408.94   97.2859    123.078
cycle14     115.36         14     196.00    1615.04    103.70    135.842
cycle15     122.68         15     225.00    1840.20    110.12    157.657
cycle16     130.20         16     256.00    2083.20   116.543    186.519
cycle17     133.58         17     289.00    2270.86   122.962    112.747
cycle18     139.43         18     324.00    2509.74    129.38    100.987
cycle19     145.95         19     361.00    2773.05   135.800    103.028
cycle20     149.68         20     400.00    2993.60   142.219    55.6713
cycle21     152.37         21     441.00    3199.77   148.638    13.9304
cycle22     157.39         22     484.00    3462.58   155.057       5.44
cycle23     163.36         23     529.00    3757.28   161.476    3.55108
cycle24     167.97         24     576.00    4031.28   167.895    0.00570
cycle25     172.84         25     625.00    4321.00   174.314    2.17123
cycle26     175.54         26     676.00    4564.04   180.732      26.96
cycle27     179.82         27     729.00    4855.14   187.151    53.7497
cycle28     182.97         28     784.00    5123.16    193.57    112.369
cycle29     186.24         29     841.00    5400.96   199.989     189.04
cycle30     188.38         30     900.00    5651.40   206.408     325.02
TOTALS     3400.00     465.00    9455.00    67126.6   212.827    4531.92
AVERAGE    113.333      15.50    315.167    2237.55      0.00    151.064
                                                                   (MSE)

                                Next period forecast=  212.827
Regression line = : Y =  13.8394 +  6.41896 * X
Correlation coefficient =    0.9763941Standard error =  12.7222
```

```
File:
PAYLOAD:65 & SPEED:5                PAYLOAD:65 & SPEED:5

Method:Linear Regression/least squares
               @D  Period(x)  x^2         x * y     Forecast     Error^2
cycle 1      0.00          1       1.00       0.00       6.92     47.8989
cycle 2      3.99          2       4.00       7.98       9.80     33.8015
cycle 3      8.21          3       9.00      24.63    12.6869     20.0426
cycle 4     12.38          4      16.00      49.52      15.57     10.1754
cycle 5     16.46          5      25.00      82.30      18.45        3.97
cycle 6     22.54          6      36.00     135.24    21.3359        1.45
cycle 7     25.14          7      49.00     175.98    24.2189     .848465
cycle 8     29.41          8      64.00     235.28    27.1019     5.32745
cycle 9     31.16          9      81.00     280.44    29.9849     1.38093
cycle10     34.05         10     100.00     340.50    32.8679     1.39745
cycle11     37.41         11     121.00     411.51    35.7509     2.75275
cycle12     42.12         12     144.00     505.44    38.6339     12.1532
cycle13     45.23         13     169.00     587.99    41.5168     13.7875
cycle14     50.82         14     196.00     711.48    44.3998     41.2184
cycle15     50.61         15     225.00     759.15    47.2828       11.07
cycle16     52.29         16     256.00     836.64    50.1658     4.51207
cycle17     57.02         17     289.00     969.34    53.0488     15.7702
cycle18     59.66         18     324.00    1073.88    55.9318     13.8993
cycle19     60.16         19     361.00    1143.04    58.8148      1.8095
cycle20     64.91         20     400.00    1298.20    61.6978     10.3181
cycle21     65.35         21     441.00    1372.35    64.5808        0.59
cycle22     69.02         22     484.00    1518.44    67.4638        2.42
cycle23     70.53         23     529.00    1622.19    70.3468     0.03356
cycle24     72.89         24     576.00    1749.36    73.2298     .115463
cycle25     74.76         25     625.00    1869.00      76.11     1.83004
cycle26     77.68         26     676.00    2019.68      79.00        1.73
cycle27     78.61         27     729.00    2122.47    81.8788     10.6849
cycle28     81.24         28     784.00    2274.72    84.7618     12.4029
cycle29     82.80         29     841.00    2401.20    87.6448     23.4718
cycle30     85.28         30     900.00    2558.40    90.5278     27.5391
TOTALS    1461.73     465.00    9455.00    29136.3    93.4108     334.408
AVERAGE   48.7243      15.50    315.167    971.212       0.00     11.1469
                                                                    (MSE)

                                Next period forecast=  93.4108
Regression line = : Y =  4.03791 +   2.88300 * X
Correlation coefficient =    0.9911672Standard error = 3.455884
```

```
File:
PAYLOAD:65 & SPEED:7              PAYLOAD:65 & SPEED:7

Method:Linear Regression/least squares
                 @D  Period(x)  x^2          x * y      Forecast     Error^2
cycle 1        0.00          1        1.00        0.00   25.3003     640.104
cycle 2       18.84          2        4.00       37.68   29.1574     106.448
cycle 3       28.47          3        9.00       85.41   33.0144     20.6519
cycle 4       34.61          4       16.00      138.44   36.8715     5.11447
cycle 5       38.92          5       25.00      194.60   40.7286     3.27107
cycle 6       42.29          6       36.00      253.74     44.59        5.27
cycle 7       46.21          7       49.00      323.47   48.4428     4.98529
cycle 8       50.10          8       64.00      400.80   52.2999        4.84
cycle 9       52.75          9       81.00      474.75   56.1569     11.6073
cycle10       65.16         10      100.00      651.60     60.01       26.48
cycle11       71.77         11      121.00      789.47   63.8711     62.3923
cycle12       76.82         12      144.00      921.84   67.7282     82.6608
cycle13       81.17         13      169.00     1055.21     71.59     91.8667
cycle14       86.38         14      196.00     1209.32   75.4424     119.632
cycle15       91.35         15      225.00     1370.25   79.2995     145.216
cycle16       95.47         16      256.00     1527.52   83.1565     151.621
cycle17       97.89         17      289.00     1664.13   87.0136     118.295
cycle18      102.01         18      324.00     1836.18   90.8707     124.084
cycle19      102.95         19      361.00     1956.05     94.73     67.6047
cycle20      104.70         20      400.00     2094.00   98.5849       37.39
cycle21      106.36         21      441.00     2233.56   102.442       15.35
cycle22      108.28         22      484.00     2382.16   106.299     3.92416
cycle23      111.11         23      529.00     2555.53   110.156     .909859
cycle24      111.84         24      576.00     2684.16   114.013     4.72288
cycle25      112.67         25      625.00     2816.75    117.87     27.0431
cycle26      115.54         26      676.00     3004.04   121.727     38.2837
cycle27      117.96         27      729.00     3184.92   125.584     58.1326
cycle28      120.03         28      784.00     3360.84   129.442     88.5775
cycle29      122.30         29      841.00     3546.70   133.299      120.97
cycle30      122.89         30      900.00     3686.70   137.156     203.511
TOTALS      2436.84     465.00     9455.00     46439.8   141.013     2390.97
AVERAGE      81.228      15.50     315.167     1547.99      0.00     79.6988
                                                                       (MSE)

                              Next period forecast=  141.013
Regression line = : Y =  21.4432 +  3.85708 * X
Correlation coefficient =    0.9660556Standard error = 9.240759
```

PAYLOAD:130 & SPEED:3

```
File:
PAYLOAD:130 & SPEED:3

Method:Linear Regression/least squares
               @D  Period(x)  x^2          x * y     Forecast    Error^2
cycle 1      0.00         1       1.00         0.00   22.7515   517.629
cycle 2      9.00         2       4.00        18.00   24.6077   243.599
cycle 3     11.91         3       9.00        35.73   26.4639    211.81
cycle 4     17.87         4      16.00        71.48     28.32   109.204
cycle 5     24.70         5      25.00       123.50   30.1763   29.9894
cycle 6     32.31         6      36.00       193.86   32.0325   0.07703
cycle 7     37.61         7      49.00       263.27   33.8887   13.8484
cycle 8     44.31         8      64.00       354.48   35.7449   73.3618
cycle 9     49.96         9      81.00       449.64     37.60   152.744
cycle10     52.50        10     100.00       525.00   39.4572   170.113
cycle11     53.99        11     121.00       593.89   41.3134   160.695
cycle12     42.72        12     144.00       512.64   43.1696   .202175
cycle13     66.01        13     169.00       858.13   45.0258   440.335
cycle14     52.20        14     196.00       730.80     46.88   28.2808
cycle15     66.88        15     225.00      1003.20   48.7382   329.124
cycle16     53.70        16     256.00       859.20   50.5944   9.64458
cycle17     52.96        17     289.00       900.32   52.4506   .259457
cycle18     53.15        18     324.00       956.70   54.3068   1.33825
cycle19     53.36        19     361.00      1013.84     56.16   7.85695
cycle20     55.18        20     400.00      1103.60   58.0192   8.06118
cycle21     70.91        21     441.00      1489.11   59.8754   121.762
cycle22     69.16        22     484.00      1521.52   61.7316   55.1809
cycle23     68.38        23     529.00      1572.74   63.5878     22.97
cycle24     66.80        24     576.00      1603.20     65.44   1.83872
cycle25     69.61        25     625.00      1740.25   67.3002   5.33514
cycle26     67.98        26     676.00      1767.48   69.1564   1.38392
cycle27     69.59        27     729.00      1878.93   71.0126   2.02381
cycle28     68.37        28     784.00      1914.36   72.8688   20.2392
cycle29     54.32        29     841.00      1575.28    74.725   416.364
cycle30     54.55        30     900.00      1636.50     76.58   485.373
TOTALS    1489.99    465.00    9455.00      27266.6     78.44   3640.65
AVERAGE   49.6663     15.50    315.167      908.888      0.00   121.355
                                                                  (MSE)

                              Next period forecast=     78.44
Regression line = : Y =  20.8953 +  1.85620 * X
Correlation coefficient =    0.8247457Standard error = 11.40276
```

PAYLOAD:130 & SPEED:5

```
File:
AYLOAD:130 & SPEED:5

Method:Linear Regression/least squares
                @D  Period(x)  x^2          x * y      Forecast     Error^2
cycle 1       0.00         1       1.00        0.00    23.8771      570.12
cycle 2      18.23         2       4.00       36.46    27.3993     84.0768
cycle 3      27.54         3       9.00       82.62    30.9216     11.4350
cycle 4      30.17         4      16.00      120.68      34.44     18.2653
cycle 5      28.38         5      25.00      141.90      37.97     91.8915
cycle 6      31.58         6      36.00      189.48    41.4882     98.1730
cycle 7      38.14         7      49.00      266.98    45.0104       47.20
cycle 8      51.87         8      64.00      414.96    48.5327     11.1378
cycle 9      58.57         9      81.00      527.13      52.05     42.4466
cycle10      63.51        10     100.00      635.10    55.5771     62.9307
cycle11      71.48        11     121.00      786.28    59.0993     153.281
cycle12      75.54        12     144.00      906.48    62.6216     166.886
cycle13      77.69        13     169.00     1009.97    66.1438     133.315
cycle14      79.16        14     196.00     1108.24     69.666     90.1361
cycle15      83.50        15     225.00     1252.50    73.1882     106.333
cycle16      86.20        16     256.00     1379.20    76.7104     90.0517
cycle17      88.93        17     289.00     1511.81    80.2327     75.6436
cycle18      91.74        18     324.00     1651.32    83.7549       63.76
cycle19      93.09        19     361.00     1768.71    87.2771     33.7897
cycle20      98.24        20     400.00     1964.80    90.7993     55.3635
cycle21      98.28        21     441.00     2063.88    94.3215     15.6693
cycle22     100.40        22     484.00     2208.80    97.8438        6.53
cycle23     101.52        23     529.00     2334.96    101.366        0.02
cycle24     103.89        24     576.00     2493.36    104.888     .996433
cycle25     106.38        25     625.00     2659.50     108.41     4.12269
cycle26     106.89        26     676.00     2779.14    111.933     25.4285
cycle27     108.79        27     729.00     2937.33     115.45     44.4206
cycle28     108.46        28     784.00     3036.88    118.977     110.609
cycle29     110.14        29     841.00     3194.06    122.499     152.753
cycle30     110.17        30     900.00     3305.10    126.022     251.272
TOTALS     2248.48    465.00    9455.00     42767.6    129.544     2618.07
AVERAGE    74.9493     15.50    315.167     1425.59       0.00     87.2689
                                                                     (MSE)

                                Next period forecast=  129.544
Regression line = : Y =  20.3549 +  3.52222 * X
Correlation coefficient =    0.9561192Standard error = 9.669665
```

```
File:
PAYLOAD:130 & SPEED:7              PAYLOAD:130 & SPEED:7

Method:Linear Regression/least squares
          Demand(y) Period(x)  x^2          x * y     Forecast    Error^2
cycle 1       0.00         1        1.00        0.00   11.8843    141.237
cycle 2       4.75         2        4.00        9.50   18.2446    182.103
cycle 3      21.26         3        9.00       63.78     24.60    11.1876
cycle 4      30.54         4       16.00      122.16     30.97       0.18
cycle 5      37.84         5       25.00      189.20   37.3252    .264973
cycle 6      44.84         6       36.00      269.04   43.6855    1.33293
cycle 7      49.53         7       49.00      346.71   50.0457    .265952
cycle 8      54.72         8       64.00      437.76   56.4059    2.84237
cycle 9      60.38         9       81.00      543.42   62.7662    5.69377
cycle10      65.73        10      100.00      657.30     69.13    11.5354
cycle11      72.90        11      121.00      801.90   75.4866    6.69059
cycle12      80.84        12      144.00      970.08   81.8468       1.01
cycle13      87.04        13      169.00     1131.52     88.21    1.36207
cycle14      94.69        14      196.00     1325.66   94.5673       0.02
cycle15     103.54        15      225.00     1553.10   100.928    6.82497
cycle16     110.40        16      256.00     1766.40   107.288    9.68601
cycle17     116.41        17      289.00     1978.97   113.648    7.62869
cycle18     144.95        18      324.00     2609.10   120.008    622.092
cycle19     148.60        19      361.00     2823.40   126.368     494.24
cycle20     152.08        20      400.00     3041.60   132.729    374.474
cycle21     154.63        21      441.00     3247.23    139.09    241.526
cycle22     156.35        22      484.00     3439.70   145.449    118.829
cycle23     159.17        23      529.00     3660.91   151.809    54.1788
cycle24     159.69        24      576.00     3832.56   158.170       2.31
cycle25     162.15        25      625.00     4053.75   164.530    5.66362
cycle26     164.98        26      676.00     4289.48    170.89    34.9289
cycle27     167.99        27      729.00     4535.73    177.25    85.7529
cycle28     169.87        28      784.00     4756.36    183.61    188.802
cycle29     172.45        29      841.00     5001.05    189.97    306.977
cycle30     174.91        30      900.00     5247.30   196.331    458.858
TOTALS     3123.23    465.00     9455.00     62704.7   202.691    3378.50
AVERAGE    104.108     15.50     315.167     2090.16      0.00    112.617
                                                                    (MSE)

                                 Next period forecast=  202.691
Regression line = : Y =     5.52 +      6.36 * X
Correlation coefficient =    0.9819223Standard error = 10.98457
```

```
File:
PAYLOAD:180 & SPEED:3
```

PAYLOAD:180 & SPEED:3

```
Method:Linear Regression/least squares
                @D      Period    x^2           x * y      Forecast     Error^2
cycle 1         0.00         1        1.00         0.00     38.3746     1472.61
cycle 2        15.94         2        4.00        31.88     38.8281     523.866
cycle 3        29.00         3        9.00        87.00     39.2817     105.712
cycle 4        43.53         4       16.00       174.12     39.7352     14.4004
cycle 5        45.83         5       25.00       229.15     40.1888     31.8237
cycle 6        50.09         6       36.00       300.54     40.6423       89.26
cycle 7        50.22         7       49.00       351.54     41.0958     83.2502
cycle 8        50.23         8       64.00       401.84       41.55     75.3529
cycle 9        48.62         9       81.00       437.58     42.0029     43.7855
cycle10        50.32        10      100.00       503.20       42.46       61.83
cycle11        52.21        11      121.00       574.31       42.91     86.4893
cycle12        53.61        12      144.00       643.32     43.3636     104.989
cycle13        55.42        13      169.00       720.46     43.8171     134.627
cycle14        54.32        14      196.00       760.48     44.2707      100.99
cycle15        51.15        15      225.00       767.25     44.7242     41.2906
cycle16        47.32        16      256.00       757.12     45.1778     4.58914
cycle17        50.25        17      289.00       854.25     45.6313     21.3322
cycle18        47.32        18      324.00       851.76     46.0849     1.52556
cycle19        47.51        19      361.00       902.69     46.5384     .943976
cycle20        48.80        20      400.00       976.00     46.9920     3.26901
cycle21        47.80        21      441.00      1003.80     47.4455     .125665
cycle22        48.66        22      484.00      1070.52       47.90     .579036
cycle23        47.56        23      529.00      1093.88     48.3526     .628213
cycle24        44.91        24      576.00      1077.84     48.8061     15.1800
cycle25        46.31        25      625.00      1157.75     49.2597        8.70
cycle26        47.33        26      676.00      1230.58     49.7132     5.67983
cycle27        43.94        27      729.00      1186.38       50.17     38.7729
cycle28        44.70        28      784.00      1251.60     50.6203     35.0504
cycle29        44.18        29      841.00      1281.22     51.0739     47.5256
cycle30        41.45        30      900.00      1243.50     51.5274     101.555
TOTALS       1348.53    465.00     9455.00      21921.6     51.9810     3255.73
AVERAGE       44.951     15.50     315.167      730.719        0.00     108.524
                                                                        (MSE)

                                  Next period forecast=  51.9810
Regression line = : Y =    37.92 +   .453547 * X
Correlation coefficient =    0.3526257Standard error = 10.78314
```

```
File:
PAYLOAD:180 & SPEED:5          PAYLOAD:180 & SPEED:5

Method:Linear Regression/least squares
                 @D    Period   x^2         x * y     Forecast    Error^2
cycle 1        0.00       1       1.00        0.00    4.01796    16.1440
cycle 2        5.80       2       4.00       11.60    4.05539       3.04
cycle 3        5.24       3       9.00       15.72    4.09281    1.31604
cycle 4        9.49       4      16.00       37.96    4.13024     28.727
cycle 5        2.16       5      25.00       10.80    4.16767    4.03074
cycle 6        1.73       6      36.00       10.38       4.21    6.12611
cycle 7        1.95       7      49.00       13.65    4.24253    5.25568
cycle 8        6.74       8      64.00       53.92    4.27995    6.05182
cycle 9        6.93       9      81.00       62.37    4.31738    6.82577
cycle10        6.34      10     100.00       63.40    4.35481    3.94097
cycle11        3.84      11     121.00       42.24    4.39224    .304969
cycle12        4.03      12     144.00       48.36    4.42967    .159734
cycle13        3.23      13     169.00       41.99    4.46710       1.53
cycle14        3.79      14     196.00       53.06    4.50452    .510545
cycle15        2.64      15     225.00       39.60    4.54195    3.61742
cycle16        2.79      16     256.00       44.64    4.57938    3.20188
cycle17        7.58      17     289.00      128.86       4.62       8.78
cycle18        3.75      18     324.00       67.50    4.65424    .817645
cycle19        3.81      19     361.00       72.39    4.69167    .777334
cycle20        3.74      20     400.00       74.80    4.72909    .978306
cycle21        3.87      21     441.00       81.27    4.76652    .803752
cycle22        3.60      22     484.00       79.20    4.80395    1.44950
cycle23        7.41      23     529.00      170.43    4.84138    6.59782
cycle24        6.74      24     576.00      161.76       4.88    3.46404
cycle25        4.85      25     625.00      121.25    4.91623    0.00439
cycle26        4.26      26     676.00      110.76    4.95366       0.48
cycle27        4.98      27     729.00      134.46    4.99109       0.00
cycle28        4.35      28     784.00      121.80       5.03    .460388
cycle29        4.74      29     841.00      137.46    5.06595       0.11
cycle30        6.44      30     900.00      193.20    5.10338    1.78657
TOTALS       136.82  465.00    9455.00     2204.83       5.14    117.295
AVERAGE     4.56067   15.50    315.167     73.4943       0.00    3.90982
                                                                   (MSE)

                             Next period forecast=      5.14
Regression line = : Y =  3.98053 +  .037428 * X
Correlation coefficient =    0.1616808Standard error = 2.046727
```

```
File:
PAYLOAD:250 & SPEED:3         PAYLOAD:250 & SPEED:3

Method:Linear Regression/least squares
                @D    Period   x^2       x * y      Forecast    Error^2
cycle 1       0.00         1       1.00       0.00      13.10    171.584
cycle 2       1.22         2       4.00       2.44    13.2983    145.885
cycle 3       8.22         3       9.00      24.66    13.4976      27.85
cycle 4      14.80         4      16.00      59.20    13.6969    1.21693
cycle 5      17.33         5      25.00      86.65    13.8961      11.79
cycle 6      19.21         6      36.00     115.26    14.0954    26.1588
cycle 7      22.33         7      49.00     156.31    14.2947    64.5658
cycle 8      22.19         8      64.00     177.52      14.49    59.2283
cycle 9      23.18         9      81.00     208.62      14.69      72.02
cycle10      21.48        10     100.00     214.80    14.8926      43.39
cycle11      21.30        11     121.00     234.30    15.0919    38.5409
cycle12      18.78        12     144.00     225.36    15.2912      12.17
cycle13      16.75        13     169.00     217.75    15.4904    1.58648
cycle14      15.63        14     196.00     218.82    15.6897    0.00357
cycle15      14.55        15     225.00     218.25      15.89       1.79
cycle16      16.16        16     256.00     258.56    16.0883    .005139
cycle17      13.87        17     289.00     235.79    16.2876       5.84
cycle18      13.61        18     324.00     244.98      16.49    8.27648
cycle19      13.57        19     361.00     257.83    16.6862    9.71054
cycle20      14.58        20     400.00     291.60    16.8855    5.31515
cycle21      13.64        21     441.00     286.44    17.0848    11.8663
cycle22      13.84        22     484.00     304.48      17.28    11.8614
cycle23      14.98        23     529.00     344.54    17.4833    6.26664
cycle24      13.56        24     576.00     325.44    17.6826    16.9960
cycle25      18.56        25     625.00     464.00    17.8819    .459815
cycle26      18.21        26     676.00     473.46      18.08    0.01659
cycle27      18.21        27     729.00     491.67    18.2805       0.00
cycle28      17.82        28     784.00     498.96    18.4798    .435293
cycle29      17.46        29     841.00     506.34      18.68    1.48610
cycle30      24.62        30     900.00     738.60    18.8783    32.9666
TOTALS      479.66    465.00    9455.00    7882.63    19.0776    789.308
AVERAGE    15.9887     15.50    315.167    262.754       0.00    26.3103
                                                                   (MSE)

                              Next period forecast=  19.0776
Regression line = : Y =  12.8997 +   .199288 * X
Correlation coefficient =    0.3187449Standard error = 5.309386
```