AUTOMATED EXCAVATOR STUDY

by

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PURDUE UNIVERSITY
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Engineering and Management
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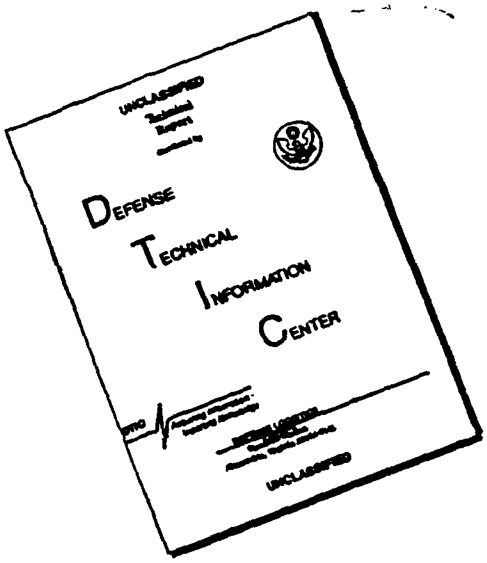

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AUTOMATED EXCAVATOR STUDY

A Special Research Problem
Presented To

The Faculty of the Construction
Engineering and Management Program
Purdue University

by

James G. Cruz

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Civil Engineering

Approved:

M. J. Skibniewski, Ph.D.	7-23-90 Date
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ABSTRACT

With the projection of an upcoming shortage of skilled labor, contractors must begin now to research and develop new and innovative methods of completing construction processes with the use of a smaller and possibly less skilled work force. One area of research which can help in meeting contractors' future needs is construction automation.

One construction process which lends itself to automation is the excavation process. With an automated excavator system, contractors will have the capability of performing site excavations without the need for highly skilled equipment operators. Keywords: Computers; [illegible] Programming manuals; Excavation; Computerized Simulation [illegible]
Every technological advancement requires many hours of experimentation and research into the development of an optimum design. This study focuses on the preliminary phases of the development of an automated excavator with the use of the Mitsubishi MoveMasterEX Industrial Micro-Robot System (Model RV-M1). The micro-robot, the central element in the CEM Robotics laboratory, is programmed to emulate the excavation of a user-defined building foundation footing.

Included in this study is a demonstration of the use of CYCLONE simulation in the modeling of the automated excavator to a) provide a simple diagrammatic representation of the automated excavation process, and b) to provide a framework for forecasting field productivity.

Final products of this study include an Automated Excavator Program Manual and a CEM Robotics Laboratory User's Manual, both of which can be used to assist future CEM Robotics Laboratory research.

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CHAPTER I

BACKGROUND

Introduction

Forecasts given for the size and the skill level of the construction work force by the year 2000 are not very optimistic. The work force is predicted to be smaller and less skilled. This is attributed by various sources to the aging of the construction workers, decline in traditional working skills, and a tendency of youth to move to more challenging and more convenient tasks (Warszawski 1990). Consequently, many construction tasks, especially those associated with tedious, physically demanding, or hazardous work, will be done by workers unskilled for any other jobs.

In order for contractors to meet the construction demands of the next century, they must begin to support research and development of alternative construction processes which are less labor intensive and which can be completed by lower skill levels. One such research area in which contractors may find the answer to this problem is construction automation.

CEM Robotics Laboratory

In 1988, the National Science Foundation awarded the Construction Engineering and Management Division of Purdue University a grant to establish a robotics laboratory which would provide a "hands on" environment in which researchers can study the adaptability of high technology to today's construction processes.

The key element in the CEM Robotics Laboratory is the Mitsubishi MoveMasterEX Industrial Micro-Robot System (Model RV-M1), a stationary robot arm with five degrees of freedom.

Simulation

Simulation is a very useful and powerful tool which can be used to describe and analyze a construction process. It is nothing more than a model of a work process, broken down into detailed activities, which can be manipulated with the use a computer to gain insight on field productivity and process sensitivity. The basic modeling shapes used in the development of a process model are (Halpin 1976):

1. The active state square node model of a work task.
2. The idle state circle model of a resource entity.
3. The directional flow arc model of a resource entity as it moves between idle and active states.

With the use of these basic modeling shapes, an automated construction process can be easily modeled. This model can in turn be used to describe the flow of the automated process as well as to forecast field productivity.

CHAPTER II

STUDY DESCRIPTION

Objectives of the Study

Construction automation research may soon become a major emphasis for research institutions as contractors begin to realize that supporting the development of automated construction processes is necessary if they are to remain competitive in the construction market.

The Construction Engineering and Management Division of Purdue University is developing the framework to support this future automated construction research by purchasing an entry level micro-robot system which can be used by both undergraduate and graduate student researchers.

The main objective of this study is to develop an automated excavation program which, when executed, demonstrates the capabilities as well as the limitations of this Mitsubishi MoveMasterEX Industrial Micro-Robot System (Model RV-M1). Included in this study is a demonstration of the use of simulation modeling and output analysis in the description and the analysis of the automated excavation process.

Products of this study include the CEM Robotics Laboratory User's Manual and the Automated Excavator Program Manual. Both of these manuals will serve as user-friendly resources for future CEM Robotics Laboratory research.

CHAPTER III

ROBOT SYSTEM DESCRIPTION

Robot System Description

The RV-M1 micro-robot system consists of several major components as described below:

a. robot arm - composed of six parts: base, shoulder, upper arm, elbow, fore arm, wrist and hand-gripper. Together they allow for five degrees of freedom as shown in Fig. 3.1:

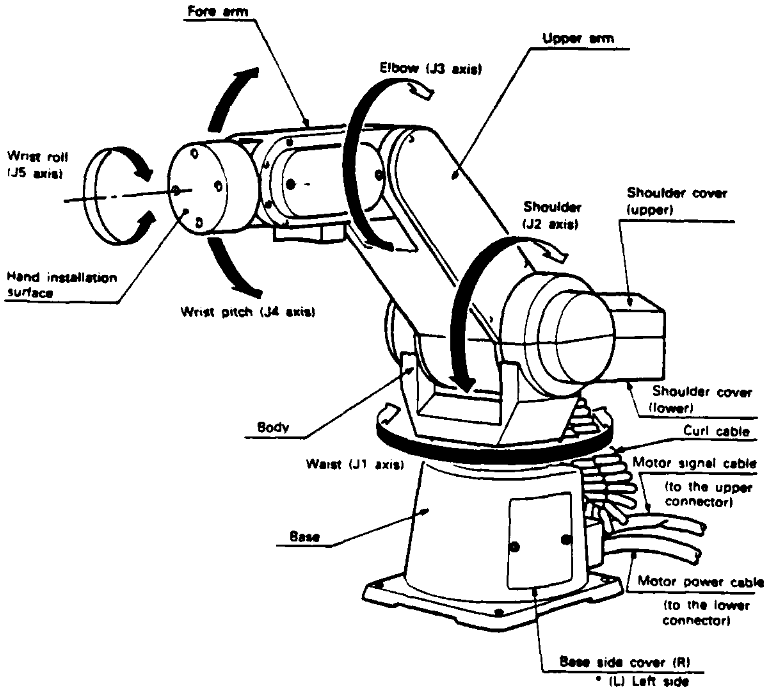


FIG. 3.1. - Five degrees of freedom

base (waist):	300 degrees
shoulder:	130 degrees
elbow:	110 degrees
wrist pitch:	180 degrees
wrist roll:	360 degrees

b. drive unit - accepts movement commands from either the teaching box or the personal computer. It controls the robot arm components to perform the movement commands. It also controls the robot speed and stores up to 629 robot positions in its RAM.

c. teaching box - hand-held control box which contains an LED digital display, numeric keypad, ON/OFF switch and emergency stop button. When ON, the teaching box has control of the robot and when OFF, the computer has control.

d. personal computer - although not an original component of the system, it runs the QuickBASIC programs which direct commands to the drive unit.

The drive unit is electrically wired through a main circuit breaker. The main circuit breaker is then routed to the main power strip, where it is plugged-in only during actual operation. The personal computer also gets its power from the main power strip, but unlike the main circuit breaker, it is plugged-in at all times. Fig. 3.2 shows the main components of the robot system. Fig. 3.3 is a plan view of the system as presently configured in the CEM Robotics Laboratory.

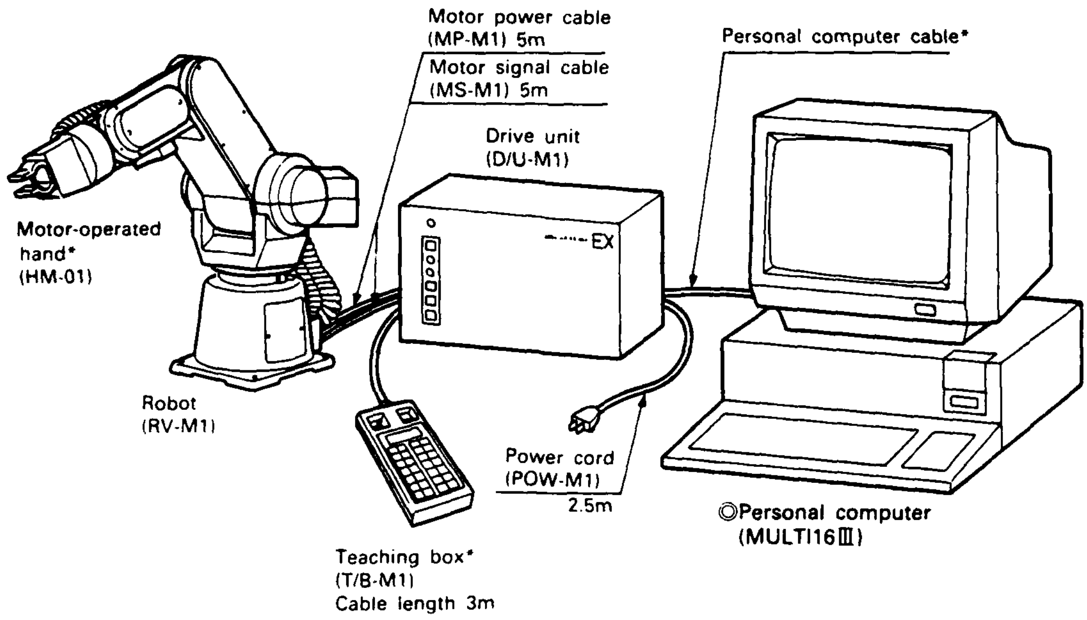


FIG. 3.2. - Robot system main components

Robot Operating Systems

Two operating systems are available for controlling the robot arm:

a. articulated system

In the articulated system, the movements of the robot arm are defined in terms of individual joint movements and pre-set positions within its operating envelope. The positions are stored in the drive unit RAM in the form of position numbers between 001 and 629. Fig. 3.4 shows the robot axis operations in the articulated system. These positions can be entered into the

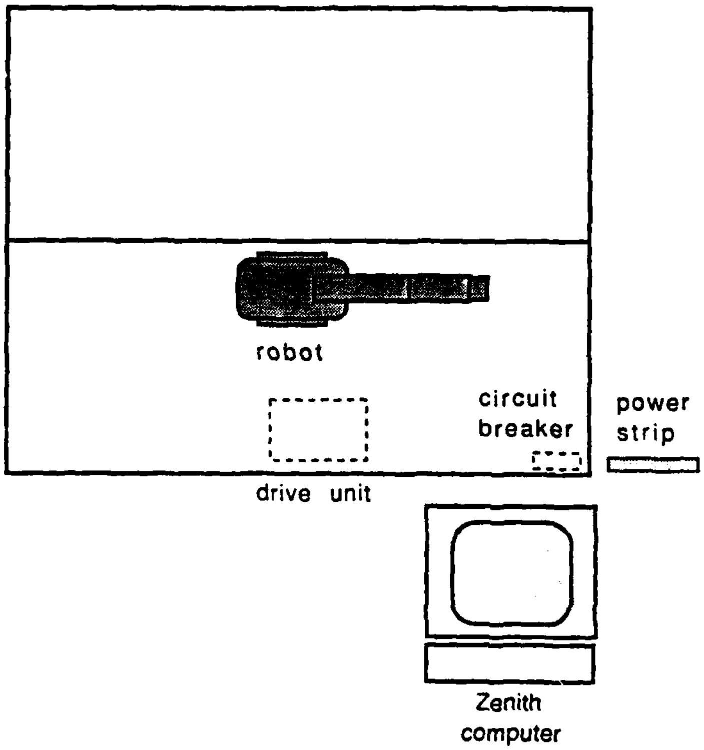


FIG. 3.3. - Original system configuration

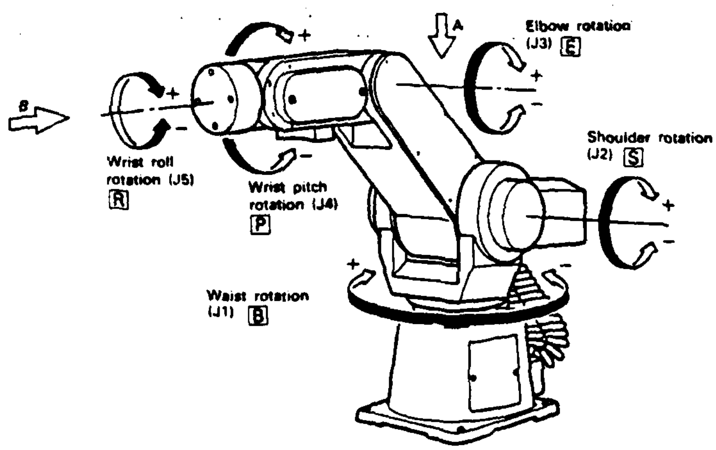


FIG. 3.4. - Operations in the articulated system

drive unit RAM by using either the teaching box or the computer.

b. cartesian coordinate system

In the cartesian coordinate system, the robot's movements are determined by cartesian coordinates points within the operating envelope. Two main reference points in this operating system are the "origin" and the "tool center point". The cartesian coordinate origin, the point from which all cartesian coordinates are referenced, is located at the center of the bottom of the robot base. The tool center point is defined as the end of the tool which is presently attached to the wrist surface as measured from the wrist surface. This is defined by the "TL XXX" or tool length command, in which XXX is the distance in millimeters in which the tool extends from the wrist surface. Fig. 3.5 shows the axis operations in the cartesian coordinate system.

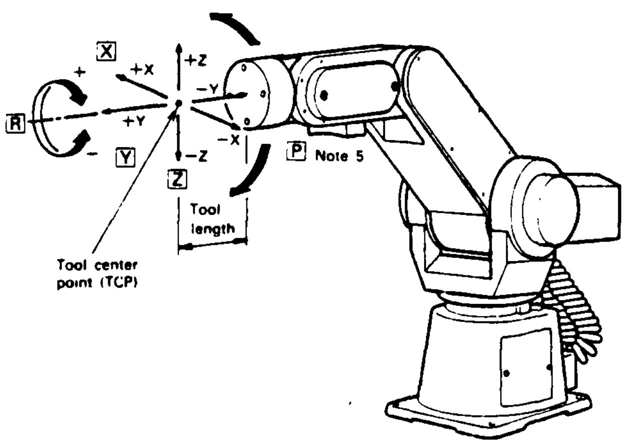


FIG. 3.5. - Operations in the cartesian coordinate system

Robot Control Modes

The robot can be controlled in two modes:

a. teaching box mode

When the teaching box switch is in the ON position, the robot movements can be controlled by depressing buttons on the teaching box keypad. Appendix A is a complete listing of keypad functions. When the teaching box is initially turned ON, the teaching box is set in the **PTP** or "point to point" control mode. This means that the individual robot joints can be operated independently by depressing the corresponding joint keys. If axis movements in the cartesian coordinate system are desired, depress the **XYZ** and **ENT** key. Movements in this control mode are initiated by depressing the axis keys on the teaching box.

b. computer control mode

When in the computer control mode, commands to the drive unit are formatted in the form of QuickBASIC LPRINT statements. When writing programs for execution, PRINT statements should be used to communicate information to the user via computer screen presentations and LPRINT commands should be used with robot commands. A complete listing of robot command and their descriptions is available in appendix B.

Examples of LPRINT command statements are the following:

Command	Meaning
LPRINT "NT"	Nest the robot arm
LPRINT "RS"	Reset computer/clear error signal
LPRINT "TL 105"	Tool length is 105 millimeters

```
LPRINT "SP 5"                  Set robot arm speed to 5
```

CHAPTER IV

EXCAVATION EMULATION

Excavator Bucket Design

The only modification to the robot arm which is required to execute the excavation program is the replacement of the motor-operated hand-gripper with a stainless steel excavator bucket. The dimensions of the fabricated bucket were developed to scale. Instead of attaching the excavator bucket directly to the robot wrist surface, an extension bracket of approximately 30 millimeters is designed in order to provide separation distance between the wrist joint and the excavation soil. This extension will prevent the entry of soil into the wrist joint area. If no extension is provided, the wrist joint could eventually fail due to excessive wear and tear as a result of sand being trapped between the wrist and fore arm surfaces.

The following procedure should be followed when removing the motor-operated hand-gripper and attaching the excavator bucket:

1. UNPLUG THE MOTOR-OPERATED HAND-GRIPPER FROM THE ROBOT FORE ARM. UNSCREW THE HAND FROM THE WRIST SURFACE (TWO SCREWS).
2. FASTEN THE EXCAVATOR BUCKET EXTENSION BRACKET ONTO THE WRIST SURFACE WITH THE TWO MOTOR-OPERATED HAND-GRIPPER SCREWS.
3. FASTEN THE EXCAVATOR BUCKET TO THE BRACKET WITH THE FOUR BUCKET SCREWS.

Construction Site Simulation

In order to provide realism to the automated excavation process, two sandboxes were fabricated and positioned in the workcell to represent an excavation and a spoils site for the automated excavator. Fig. 4.1 is a plan view of the modified workcell.

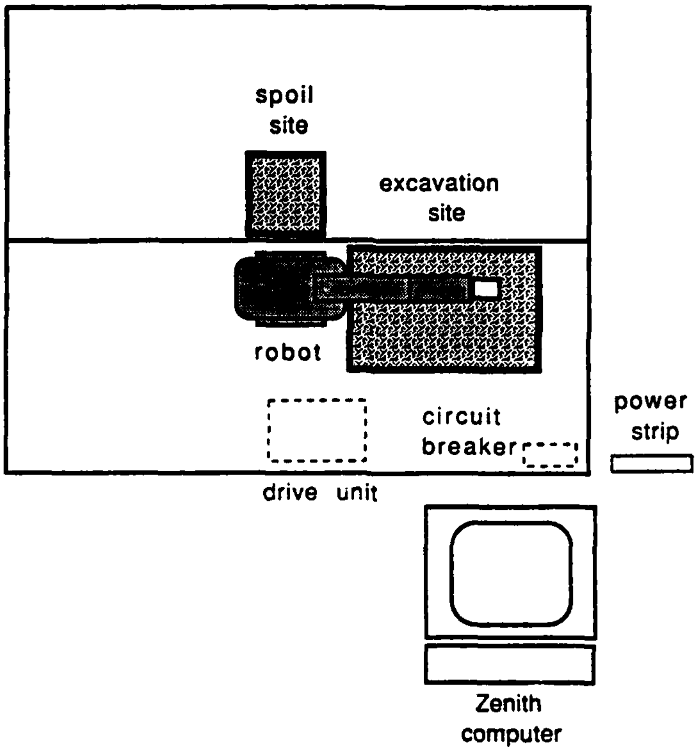


FIG. 4.1. - Modified workcell configuration

When re-configuring the workcell to execute the automated excavation program, perform the following steps:

1. ATTACH THE STAINLESS STEEL EXCAVATOR BUCKET AS DESCRIBED ABOVE.

2. POSITION THE EXCAVATION AND SPOIL SITE SANDBOXES ALONGSIDE THE ROBOT BASE AS SHOWN IN FIG. 4.1.
3. VERIFY THAT ALL OBSTRUCTIONS ARE REMOVED FROM THE ROBOT'S OPERATING ENVELOPE.

QuickBASIC Programming

Whether operating the robot in either the articulated or the cartesian coordinate system, QuickBASIC programming language is used to sequence the movement commands and to send them from the personal computer to the robot drive unit.

When developing a QuickBASIC program, several fundamental commands must always be included at the beginning of the program to ensure that the robot is operated safely. They are the following:

1. The introductory computer screen presentation must include the nesting of the robot to verify that the robot is under computer control.
   (**LPRINT "NT"**)
2. A tool length must be defined prior to any movement commands. If no tool length is defined, serious damage to the robot may occur as it maneuvers through the work envelope without compensation for its tool extension.
   (**LPRINT "TL XXX"**); XXX - millimeters
3. The speed of the robot's movements must be defined prior to any robot movements.
   (**LPRINT "SP X"**); X - 0 to 9.

Automated Excavator Program Description

The automated excavator program prompts the user, through computer screen presentations, for foundation dimensions. With the inputted information, it calculates the number of excavation passes that are required for the completion of each foundation side. Once the user initiates the excavation process, the computer keeps the user informed, once again through computer screen presentations, as to the status of the excavation in terms of side in progress and length (in millimeters) being excavated. After the robot completes a full cycle, it nests its bucket and informs the user that the excavator is simulating re-positioning itself along the foundation perimeter.

When a foundation side is completed, the bucket is again nested and the user is informed that the excavator is simulating re-positioning itself along the next foundation side and aligning itself for the next sequence of passes. At the completion of the final foundation side, the user is informed that the footings are completed and that nesting of the robot arm is requested.

The coordinates of the robot arm movements allow for the excavation to a depth of 50 millimeters and a length of 190 millimeters per full cycle. A full cycle is composed of two 95 millimeter passes, with each full pass ending in the nesting of the bucket.

In those cases in which the foundation dimensions are not multiples of 190 millimeters, the program calculates the number and the length of each side's passes and also informs the user that the excavator is adjusting its position to complete these lengths. For example, for a foundation with dimensions of 500 millimeters by 600 millimeters, the following excavation sequence will be executed:

<u>500 mm sides</u>

190 mm (adjust position)

190 mm (adjust position)

95 mm (adjust position)

25 mm (relocate to next side)

<u>600 mm sides</u>

190 mm (adjust position)

190 mm (adjust position)

190 mm (adjust position)

30 mm (relocate to next side)

The automated excavator program consists of one main routine, with seven subroutines contained within. The program is written as follows:

a. seven subroutines are initialized.

b. all variables are initialized.

c. SUBROUTINE INTRODUCTION - introductory screens (standardized formats) are presented describing the excavation program. Foundation dimensions are requested from user. User intiates nesting to verify computer control. Robot speed is defined. Length of bucket is defined for use in cartesian coordinate reference.

d. SUBROUTINE XYDIMCALC - exact number of excavation passes are calculated based on user inputs.

e. SUBROUTINE SIDEINTRO - informs user of the length being excavated and the side in progress.

f. SUBROUTINES EXCAVATE1 AND EXCAVATE2 - define the "MP" or move position commands which make up the 190 millimeter excavation cycle. Fig. 4.2 is a profile view of the two excavation passes which are represented in EXCAVATE1 and EXCAVATE2.

g. SUBROUTINE MOVESKIBBY - informs user that an excavation pass has been completed and that SKIBBY is re-positioning along the foundation perimeter.

h. SUBROUTINE TURNCORNER - informs user that a side has been completely excavated and that the excavator is simulating relocating to the next side.

i. SUBROUTINE FINALSCREEN - informs user that the excavation has been executed successfully. Nesting of the robot is executed.

All complete set of screen presentations and a copy of the QuickBASIC program are provided in the Automated Excavator Program Manual (appendix C). These presentations will serve as a standard format for future robotics programs.

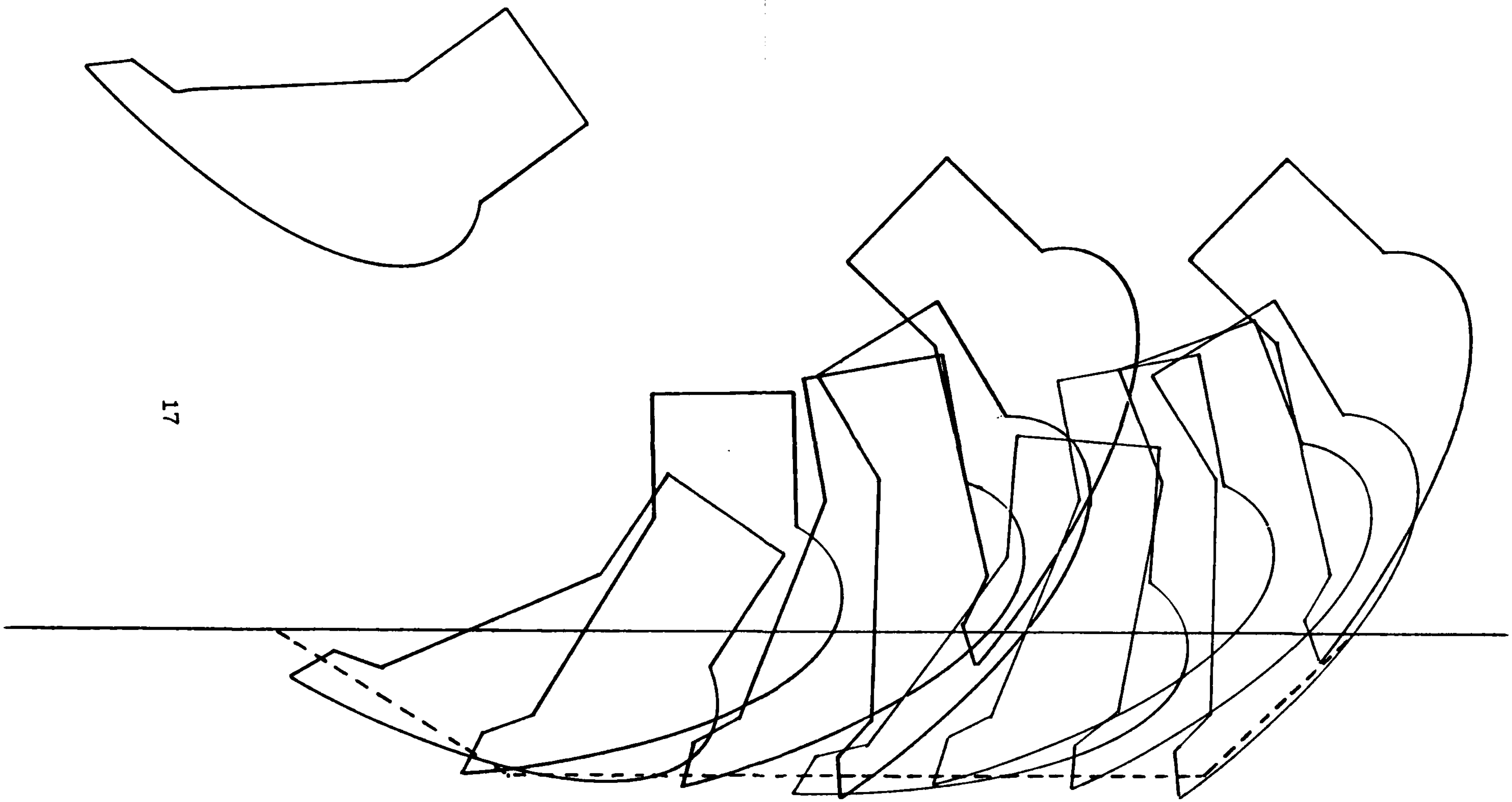


FIG. 4.2. - Profile view of full cycle excavation passes

CHAPTER V
SIMULATION

Simulation is used in this study to describe the automated excavation process diagrammatically with the application of CYCLONE modeling techniques and to demonstrate the use of simulation in forecasting field productivity and determining excavation process sensitivity.

Two CYCLONE models were developed to assist in the demonstration of the use of simulation in representing automated processes. The original model contains only actual activities as they were observed during the execution of the automated excavation program.

A modified CYCLONE model was developed which incorporated two additional activities: 1) rock/dense soil excavation (activity 330), and 2) excavator breakdown (activity 300). This modified model was used to demonstrate stochastic output analysis.

In both CYCLONE models, the automated excavator performs the excavation of a 380 millimeter by 380 millimeter foundation footing.

Original CYCLONE Model

The original CYCLONE model representing the automated excavation process is shown in Fig. 5.1. Fig. 5.2 is a copy of the corresponding network input file.

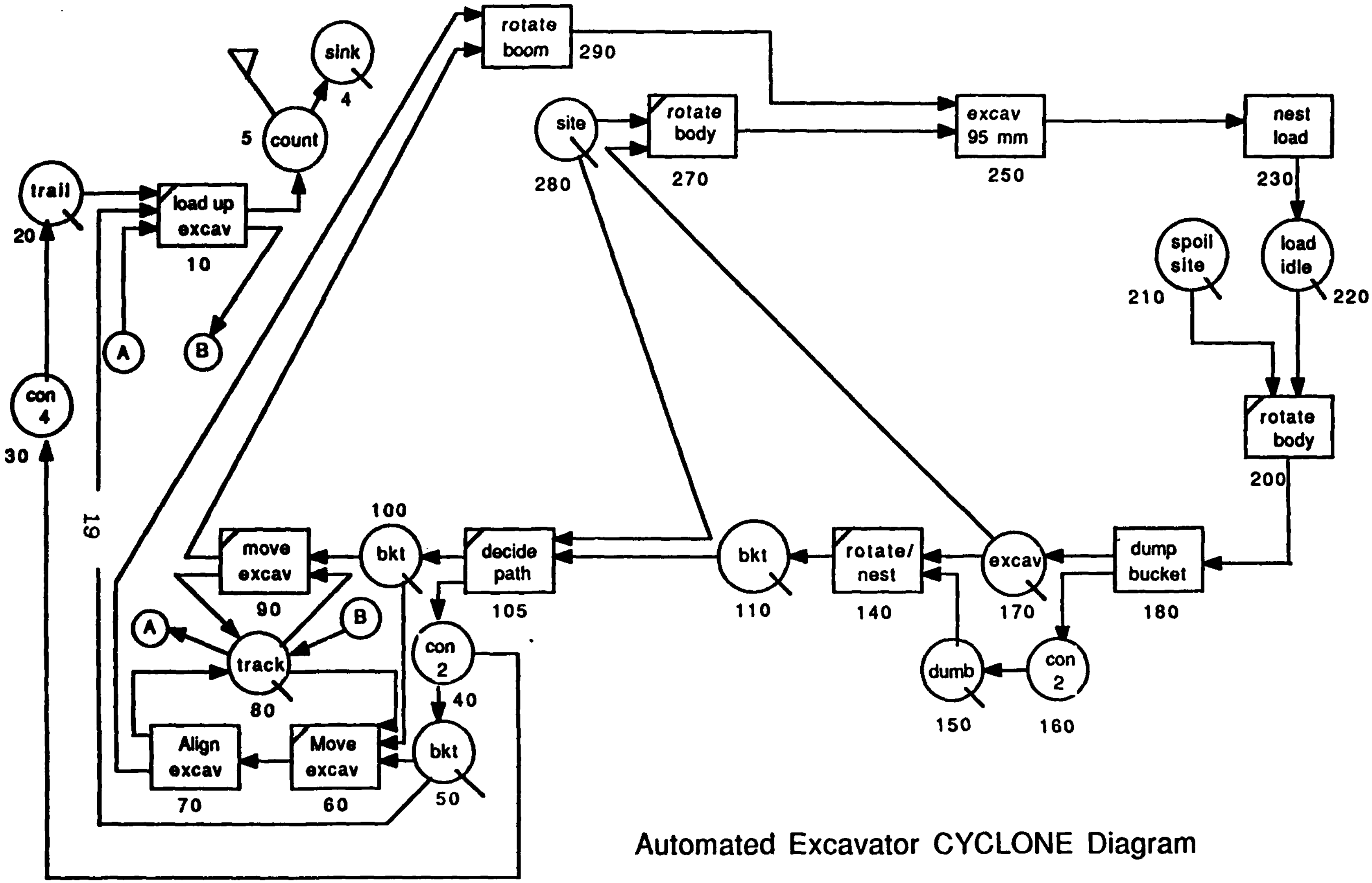


FIG. 5.1. - Original CYCLONE diagram

PROCESS: EXCAV

```
------------------------------------------------------------------------
                         ***  NETWORK FILE  ***
------------------------------------------------------------------------
LINE   1 :  NAME 'FOUNDATION FOOTINGS EXCAVATOR' LENGTH 20000 CYCLE 1
LINE   2 :  NETWORK INPUT
LINE   3 :  4 QUE 'SINK'
LINE   4 :  5 FUN COU QUA 1 FOL 4
LINE   5 :  10 COM 'LOAD UP EXCAVATOR' SET 1 PRE 20 50 80 FOL 5 80
LINE   6 :  20 QUE 'TRAILER AVAIL'
LINE   7 :  30 FUN CON 4 'EXCAVATION COMPLETED' FOL 20
LINE   8 :  40 FUN CON 2 'SIDE COMPLETED' FOL 30 50
LINE   9 :  50 QUE 'BUCKET IDLE'
LINE  10 :  60 COM 'MOVE EXCAVATOR' SET 2 PRE 50 80 100 FOL 70
LINE  11 :  70 NOR 'ALIGN EXCAVATOR' SET 3 FOL 80 290
LINE  12 :  80 QUE 'TRACK AVAIL'
LINE  13 :  90 COM 'MOVE EXCAVATOR' SET 4 PRE 80 100 FOL 80 290
LINE  14 :  100 QUE 'BUCKET IDLE'
LINE  15 :  105 COM 'DECIDE PATH' SET 16 PRE 110 280 FOL 40 100
LINE  16 :  110 QUE 'BUCKET IDLE'
LINE  17 :  140 COM 'ROTATE BODY/NEST BUCKET' SET 6 PRE 150 170 FOL 110
LINE  18 :  150 QUE 'DUMMY'
LINE  19 :  160 FUN CON 2 'MOVE EXCAVATOR' FOL 150
LINE  20 :  170 QUE 'EXCAVATOR AVAIL'
LINE  21 :  180 NOR 'DUMP BUCKET' SET 7 FOL 160 170
LINE  22 :  200 COM 'ROTATE BODY' SET 9 PRE 210 220 FOL 180
LINE  23 :  210 QUE 'SPOIL SITE AVAIL'
LINE  24 :  220 QUE 'LOAD IDLE'
LINE  25 :  230 NOR 'NEST LOAD' SET 10 FOL 220
LINE  26 :  250 NOR 'EXCAV 95 MM' SET 12 FOL 230
LINE  27 :  270 COM 'ROTATE BODY' SET 14 PRE 170 280 FOL 250
LINE  28 :  280 QUE 'SITE AVAIL'
LINE  29 :  290 NOR 'ROTATE BOOM' SET 15 FOL 250
LINE  30 :  DURATION INPUT
LINE  31 :  SET 1 30
LINE  32 :  SET 2 60
LINE  33 :  SET 3 15
LINE  34 :  SET 4 20
LINE  35 :  SET 6 3
LINE  36 :  SET 7 3
LINE  37 :  SET 9 3
LINE  38 :  SET 10 3
LINE  39 :  SET 12 12
LINE  40 :  SET 14 3
LINE  41 :  SET 15 5
LINE  42 :  SET 16 0
LINE  43 :  RESOURCE INPUT
LINE  44 :  17 'SITES' AT 280
LINE  45 :  1 'TRACK' AT 80
LINE  46 :  16 'SPOIL SITES' AT 210
LINE  47 :  1 'EXCAVATOR' AT 170
LINE  48 :  ENDDATA
```

FIG. 5.2. - Original network input file

The excavation process begins at activity 270 where the excavator rotates to align itself with the foundation line. At activity 250, the excavator begins the foundation excavation by completing a 95 millimeter pass. It completes the pass by nesting the loaded excavator bucket under the boom and rotating its body 110 degrees in order to deposit the excavated soil into the spoil site sandbox. The excavator then rotates back to the foundation line and executes another 95 millimeter pass and rotates again to the spoil site sandbox. Upon completion of this pass, the consolidation function (activity 160) releases a unit to a dummy queue (activity 150), which forces the excavator to nest and simulate re-positioning itself (activity 90) along this same side in preparation for the next 190 millimeter excavation cycle. After re-positioning, the excavator repeats the 190 millimeter cycle to complete the 380 millimeter which has been defined as the length of the foundation sides.

After the first side is completed, the consolidation function (activity 40) releases a unit to the bucket queue (activity 50) in order to force the excavator to stop excavating and to simulate re-positioning itself along the next foundation side (activities 60 and 70).

The procedures of the first side are now repeated for the remaining three sides until the foundation footings are completed. Upon completion of the excavation, the excavator simulates being loaded onto a trailer (activity 10).

Because of the deterministic nature of the robot, only activity duration data from one program run was required. Table 5.1 is a listing of the deterministic activity durations. Deterministic activity durations for the following activities were not observed, but instead approximated due to the stationary configuration of the robot:

<u>Activity</u>

90 Move excavator (along foundation line)

60 Move excavator (to next side)

70 Align excavator

10 Load up excavator

The simulation end-time associated with this deterministic model is given in Table 5.2.

Activity		duration (sec)
290	Rotate boom	5
270	Rotate body	3
250	Excavate 95 mm	12
230	Nest load	3
200	Rotate body	3
180	Dump bucket	3
140	Rotate/nest	3
105	Decide path (decision node)	0
90	Move excavator (along foundation line)	20
60	Move excavator (to next side)	60
70	Align excavator	15
10	Load up excavator	30

TABLE 5.1. - Automated excavator deterministic activity durations

Simulation end-time:	757.00 sec (12.6 minutes)

TABLE 5.2. - Simulation run end-time

Modified CYCLONE Model

In an attempt to introduce uncertainty and variability into an otherwise very deterministic simulation model, two stochastic activities were incorporated into the original CYCLONE diagram previously described. A modified CYCLONE diagram representing the incorporation of these two additional activities is shown in Fig. 5.3. Fig. 5.4 is a copy of the corresponding network input file.

The first activity chosen for incorporation into the original CYCLONE diagram was a rock/dense soil excavation activity (activity 330) which was inserted into the diagram prior to the actual excavation activity (activity 250). In actual excavation processes, the excavation duration times are functions of the site soil characteristics. To provide for the probability of non-uniform soil conditions, probabilitic arcs of 20% and 80% were chosen for rock/dense soil excavation and unobstructed excavation, respectively. The probabilistic arc percentages were chosen to reflect an excavation site with 20% probability of hitting rock and/or dense soil. In real world excavation projects, these probabilistic values can be determined from a review of soil boring logs.

The second activity included in the modified diagram was an excavator repair activity (activity 300). It, like activity 330, has probabilistic arcs associated with its activation. Data which could be used to approximate the actual probability percentages of an excavator breakdown can be found in equipment

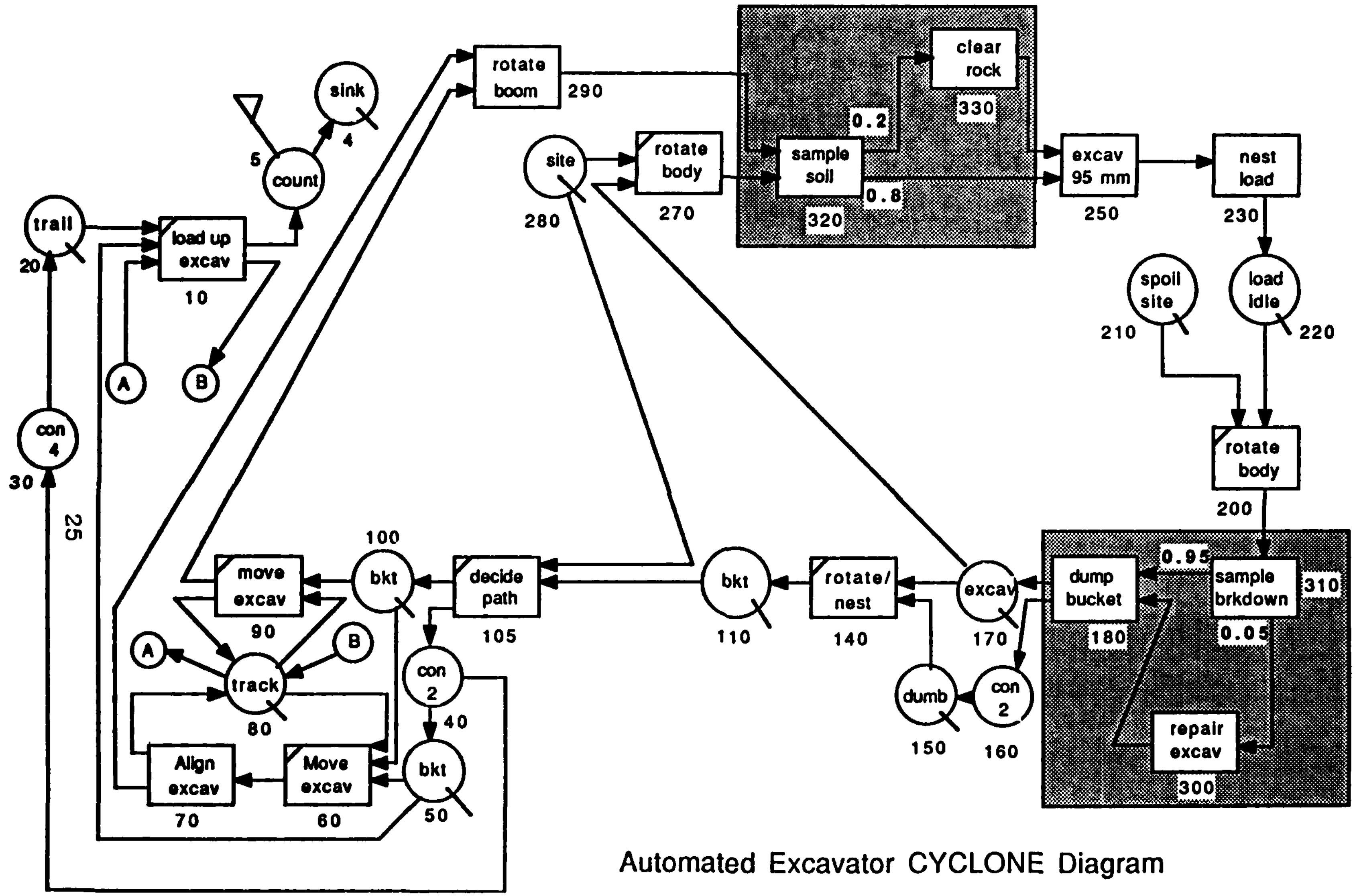


FIG. 5.3. - Modified CYCLONE diagram

PROCESS: EXCAV2 FIG. 5.4. - Modified network input file

```
------------------------------------------------------------------------
                                    ***  NETWORK FILE  ***
------------------------------------------------------------------------
LINE   1 :  NAME 'FOUNDATION FOOTINGS EXCAVATOR' LENGTH 20000 CYCLE 1
LINE   2 :  NETWORK INPUT
LINE   3 :  4 QUE 'SINK'
LINE   4 :  5 FUN COU QUA 1 FOL 4
LINE   5 :  10 COM 'LOAD UP EXCAVATOR' SET 1 PRE 20 50 80 FOL 5 80
LINE   6 :  20 QUE 'TRAILER AVAIL'
LINE   7 :  30 FUN CON 4 'EXCAVATION COMPLETED' FOL 20
LINE   8 :  40 FUN CON 2 'SIDE COMPLETED' FOL 30 50
LINE   9 :  50 QUE 'BUCKET IDLE'
LINE  10 :  60 COM 'MOVE EXCAVATOR' SET 2 PRE 50 80 100 FOL 70
LINE  11 :  70 NOR 'ALIGN EXCAVATOR' SET 3 FOL 80 290
LINE  12 :  80 QUE 'TRACK AVAIL'
LINE  13 :  90 COM 'MOVE EXCAVATOR' SET 4 PRE 80 100 FOL 80 290
LINE  14 :  100 QUE 'BUCKET IDLE'
LINE  15 :  105 COM 'DECIDE PATH' SET 16 PRE 110 280 FOL 40 100
LINE  16 :  110 QUE 'BUCKET IDLE'
LINE  17 :  140 COM 'ROTATE BODY/NEST BUCKET' SET 6 PRE 150 170 FOL 110
LINE  18 :  150 QUE 'DUMMY'
LINE  19 :  160 FUN CON 2 'MOVE EXCAVATOR' FOL 150
LINE  20 :  170 QUE 'EXCAVATOR AVAIL'
LINE  21 :  180 NOR 'DUMP BUCKET' SET 7 FOL 160 170
LINE  22 :  200 COM 'ROTATE BODY' SET 9 PRE 210 220 FOL 310
LINE  23 :  210 QUE 'SPOIL SITE AVAIL'
LINE  24 :  220 QUE 'LOAD IDLE'
LINE  25 :  230 NOR 'NEST LOAD' SET 10 FOL 220
LINE  26 :  250 NOR 'EXCAV 95 MM' SET 12 FOL 230
LINE  27 :  270 COM 'ROTATE BODY' SET 14 PRE 170 280 FOL 320
LINE  28 :  280 QUE 'SITE AVAIL'
LINE  29 :  290 NOR 'ROTATE BOOM' SET 15 FOL 320
LINE  30 :  300 NOR 'REPAIR EXCAV' SET 17 FOL 180
LINE  31 :  310 NOR 'SAMPLE BREAKDOWN' SET 18 FOL 180 300 PRO 0.95 0.05
LINE  32 :  320 NOR 'SAMPLE SOIL' SET 19 FOL 250 330 PRO 0.8 0.2
LINE  33 :  330 NOR 'CLEAR ROCK' SET 20 FOL 250
LINE  34 :  DURATION INPUT
LINE  35 :  SET 1 30
LINE  36 :  SET 2 60
LINE  37 :  SET 3 15
LINE  38 :  SET 4 20
LINE  39 :  SET 6 3
LINE  40 :  SET 7 3
LINE  41 :  SET 9 3
LINE  42 :  SET 10 3
LINE  43 :  SET 12 12
LINE  44 :  SET 14 3
LINE  45 :  SET 15 5
LINE  46 :  SET 16 0
LINE  47 :  SET 17 BETA 285.0 3780.0 0.4438808 0.750775 SEED 3345
LINE  48 :  SET 18 0
LINE  49 :  SET 19 0
LINE  50 :  SET 20 BETA 60.0 300.0 1.438 4.313 SEED 43892
LINE  51 :  RESOURCE INPUT
LINE  52 :  17 'SITES' AT 280
LINE  53 :  1 'TRACK' AT 80
LINE  54 :  16 'SPOIL SITES' AT 210
LINE  55 :  1 'EXCAVATOR' AT 170
LINE  56 :  ENDDATA
```

operating/maintenance records. For the purpose of this demonstration, 95% and 5% were used for non-breakdown cycles and breakdown cycles, respectively.

A series of 25 runs was performed on this modified CYCLONE model to determine a range of excavation durations with a 95% confidence level. Table 5.3 lists the results of this sensitivity analysis.

Mean:	2453 sec (40.9 minutes)
Standard deviation:	1545 sec (25.8 minutes)
95% confidence interval:	1816 sec - 3092 sec
	(30.2 - 51.5 minutes)

Table 5.3. - Sensitivity analysis results

The confidence interval obtained from this modified excavation process indicates the wide variability of excavation durations which can be expected should this exact same model be used to forecast an excavation process.

Simulation is a powerful process analysis tool which is easily learned and applied. The application of simulation techniques to this automated excavator program should serve as an example to future robotics researchers of the use of simulation in the enhancement of a research project.

CHAPTER VI

CEM ROBOTICS LABORATORY MANUALS

CEM Robotics Laboratory User's Manual

Several references are available which provide general information on the operation of the RV-M1 robot, but neither is tailored to the specific system configuration which exists in the CEM Robotics Laboratory. As a result, one of the objectives of this study is to develop a CEM Robotics Laboratory User's Manual which addresses the peculiarities and unique features which a researcher will most likely encounter during the course of his/her robotics research.

The references used in the development of the user's manual are:

a. Mitsubishi MoveMasterEX Industrial Micro-robot System (Model RV-M1) Instruction Manual

b. The RM-501 Robot Workbook

c. Purdue University Surface Finishing Robotics Laboratory User's Manual.

About 25 percent of the material incorporated into the user's manual is based on procedures which were developed as a result many hours of proven system operation.

The user's manual is designed to be user-friendly and is intended to complement, **not replace**, the RV-M1 instruction manual. The CEM Robotics Laboratory User's Manual is provided in appendix C.

Automated Excavator Program Manual

One of the standard products of any CEM robotics research should be a program manual which can be used by other researchers to safely execute the robotics program without personnel injury or equipment damage.

During the development of the automated excavator program, a modified workcell configuration and several unique system procedures were developed in order to properly execute a user-defined foundation footings excavation process. These procedures as well as a complete description of required workcell modifications are addressed in the program manual. The Automated Excavator Program Manual is provided in appendix D.

CHAPTER VII

RECOMMENDATIONS AND CONCLUSIONS

Recommendations for Future Work

The RV-M1 micro-robot is a very reliable and flexible research tool which has significant potential for constructive use in the near future. Several system modifications are recommended to increase its flexibility and at the same time its appeal to potential undergraduate and graduate student researchers. They include:

1. mounting the robot arm onto a sliding platform so that a sixth degree of freedom can be provided. Included with this modification would be a motor which would provide sliding platform motion and would be controllable by a computer program. A plan view of this recommended configuration is shown in Fig. 7.1.
2. mount a force/torque sensor between the wrist surface and the excavator bucket to allow for the measurement of forces and torques experienced during an emulated excavation process. This feature would allow for the development of a more sophisticated automated excavator program which would be able to react to rock/dense soil conditions by stopping the excavation process before serious excavator damage occurred.
3. configure the laboratory into a self-sufficient research facility by installing demountable partitions to enclose

the work area, installing a telephone and printer.

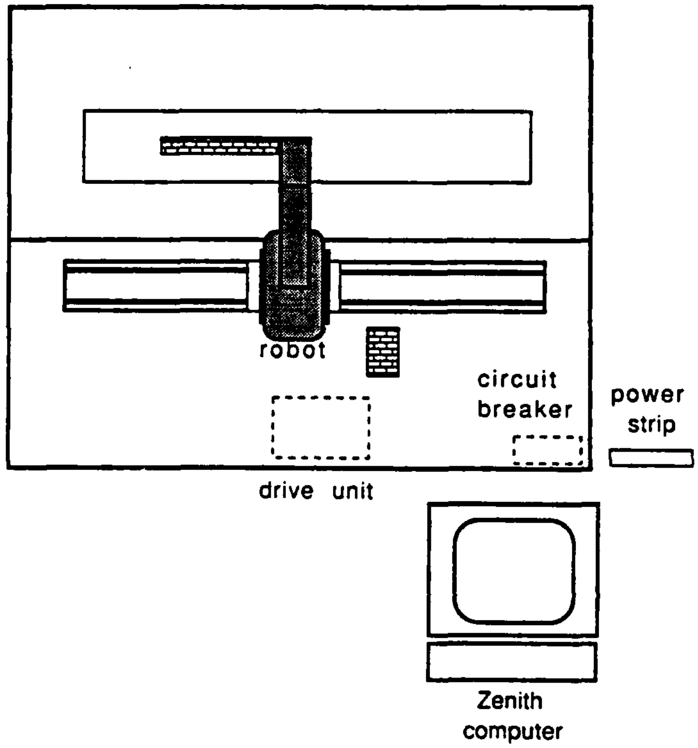


FIG. 7.1. - Recommended system configuration

Several construction processes lend themselves to automation research at the micro-robot scale. They include:

1. modular building construction
2. bricklaying/masonry
3. pipeline excavation/pipelaying
4. structural steel fireproofing application
5. Field painting

Conclusions

An automated excavation program was developed and successfully demonstrated during this study period.

One measure of this study's success was the fact that the only major cost incurred during the development of this automated excavation program was the fabrication of the stainless steel excavator bucket assembly. All other workcell modifications, such as the addition of the excavation and spoil site sandboxes, were fabricated from locally available surplus.

Simulation proved to be an inexpensive, yet very powerful tool in the diagrammatical description of the automated excavation process, but more importantly as a valid predictor and forecaster of resource and excavation time requirements.

The final products of this study, the CEM Robotics Laboratory User's Manual and the Automated Excavator Program Manual, are expected to provide future robotics researchers with the preliminary structure for their research efforts. With the help of these manuals, future researchers will develop and expand the CEM Robotics Laboratory into a competitive robotics research facility.

With the projection of a smaller and less skilled construction industry work force, we must begin now to develop Purdue University's niche in the construction automation research field.

REFERENCES

REFERENCES

AbouRizk, S.M. (1990), "BetaFit User's Guide, Construction Engineering and Management Division, Purdue University, West Lafayette, Indiana

AbouRizk, S.M., Wilson, J.R., Halpin, D.W. (1990), "Graphical Interactive Fitting of Beta Distributions", Construction Engineering and Management Division, Purdue University, West Lafayette, Indiana

Alekseeva, T.V., Artem'ev, K.A., Bromberg, A.A., Voitsekhouskii, R.I., and Ul'yanov, N.A. (1985), Machines for Earthmoving Work, Amerind Publishing Co., Pvt., New Delhi, India

ARC (1988), Purdue University Surface Finishing Robotics Laboratory User's Manual, ARC Inc., Indianapolis, Indiana

Bernold, L.E., Altobelli, F.R., Taylor, H.F. (1989), "Computer Controlled Brick Masonry", Department of Civil Engineering, University of Maryland, College Park, Maryland

Caterpillar (1988), Caterpillar Performance Handbook (19th ed), Caterpillar Inc., Peoria, Illinois

Cruz, J.G. (1990), "Automated Excavator Simulation Study", unpublished report for the Construction Engineering and Management Division, Purdue University, West Lafayette, Indiana

Fujii, T., Hergert, D. (1988), The RM-501 Robot Workbook, Rixan Associates, Dayton, Ohio

Halpin, D.W., Woodhead, R.W. (1976), Design of Construction and Process Operations, John Wiley and Sons, New York, New York

Mitsubishi (1988), Industrial Micro-Robot System (Model RV-M1) Instruction Manual, Mitsubishi Electric Corporation, Tokyo, Japan

Nicholas Jr., H.L. (1961), Moving the Earth, D. Van Nostrand Company, Inc., Princeton, New Jersey

Scott, P.B. (1984), The Robotics Revolution, the Complete Guide, Basil Blackwell Inc., New York, New York

Warszawski, A. (1990), Industrialization and Robotics in Building: A Managerial Approach, Harper and Row, New York, New York

Zelenin, A.N., Balovnev, V.I., and Kerov, I.P., (1986), Machines for Moving the Earth, Amerind Publishing Co., Pvt. Ltd., New Delhi, India

APPENDICES

APPENDIX A

Teaching Box Keypad Functions

2.2 Teaching Box

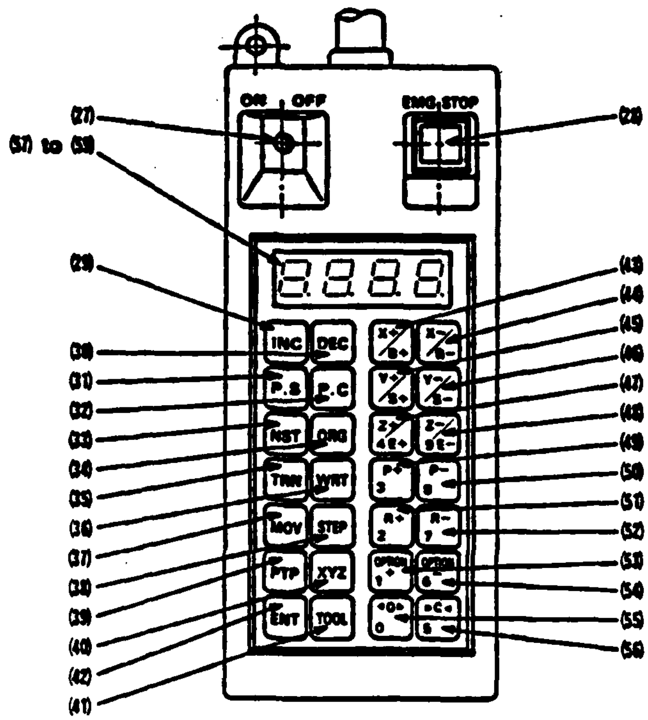


Fig. 2.2.4 Teaching Box

2.2.1 Functions of the switches

(27) ON/OFF (Power switch)
Selects whether to enable or disable keys on the teaching box. When the robot is to be operated using the teaching box, turn this switch ON. During program run or when controlling the robot by means of commands sent from a personal computer, turn the switch OFF. An erroneous key entry can also be cleared by turning the switch OFF.

(28) EMG. STOP (Emergency stop switch)
Pushbutton switch used for emergency stop of the robot (signal is internally latched when this switch is pressed). When the switch is pressed, the robot is immediately brought to a stop and the error indicator LED blinks (error mode I). LED4 inside the drive unit side door also comes on.

2.2.2 Functions of each key

(29) [INC] (+ [ENT])
Moves the robot to a predefined position with a position number greater than the current one. To move the robot through a certain sequence, repeat the keying-in sequence. (See command "IP.")

(30) [DEC] (+ [ENT])
Moves the robot to a predefined position with a position number smaller than the current one. To move the robot through a certain sequence, repeat the keying-in sequence. (See command "DP.")

(31) [P. S] (+ [Number] + [ENT])
Defines the coordinates of the current position of the robot into a position with the number specified. If a single number is assigned to two different positions, the one defined last takes precedence. (See command "HE.")

(32) [P. C] (+ [Number] + [ENT])
Deletes the contents of a position with the number specified. (See command "PC.")

(33) [NST] (+ [ENT])
Returns the robot to origin. (See command "NT.")

(34) [ORG] (+ [ENT])
Moves the robot to the reference position in the cartesian coordinate system. (See command "OG.")

(35) [TRN] (+ [ENT])
Transfers the contents of the user EPROM (program and position data) installed in SOC2 of the drive unit side panel to the drive unit RAM. (See command "TR.")

(36) [WRT] (+ [ENT])
Writes the program and position data written in the drive unit RAM into the user EPROM installed in SOC2 of the drive unit side panel. (See command "CR.")

(37) [MOV] (+ [Number] + [ENT])
Moves the end of the hand to a specified position. (See command "MO.") The moving speed is equivalent to SP4.

(38) [STEP] (+ [Number] + [ENT])
Executes the program step by step starting with the line number specified. To cause the program to be executed sequentially from one step to another, repeat the keying-in sequence. Note that, at this time, no number entry is necessary. Error mode II is caused if an error occurs while the steps are being executed.

(39) [PTP]
Selects the articulated jog operation. When this key is pressed, operation of any jog key thereafter effects a motion in each joint. In the initial condition when the teaching box is turned ON, this PTP state is set.

(40) [XYZ]
Selects the cartesian jog operation. When this key is pressed, operation of any jog key thereafter effects an axis motion in the cartesian coordinate system.

(41) TOOL

Selects the tool jog operation. When this key is pressed, operation of any jog key thereafter effects an axis motion in the tool coordinate system (advance/retract motion in the hand direction).

(42) ENT

Completes each key entry from (29) through (38) to effect corresponding operation.

(43) X+/B+

Moves the end of the hand in positive X-axis (to the left looking toward the front of robot) in the cartesian jog operation and sweeps the waist in the positive direction (clockwise as viewed from the top of robot) in the articulated jog operation.

(44) X−/B−

Moves the end of the hand in negative X-axis (to the right looking toward the front of robot) in the cartesian jog and sweeps the waist in the negative direction (counterclockwise as viewed from the top of robot) in the articulated jog.

(45) Y+/S+

Moves the end of the hand in positive Y-axis (to the front of the robot) in the cartesian jog and swivels the shoulder in the positive direction (upward) in the articulated jog.

(46) Y−/S−

Moves the end of the hand in negative Y-axis (to the rear of the robot) in the cartesian jog and swivels the shoulder in the negative direction (downward) in the articulated jog.

(47) Z+/E+ 4

Moves the end of the hand in positive Z-axis (straight upward) in the cartesian jog, turns the elbow in the positive direction (upward) in the articulated jog, and advances the hand in the tool jog. It serves also as the numeric key "4."

(48) Z−/E− 9

Moves the end of the hand in negative Z-axis (straight downward) in the cartesian jog, turns the elbow in the negative direction (downward) in the articulated jog, and retracts the hand in the tool jog. It serves also as the numeric key "9."

(49) P+ 3

Turns the end of the hand, while maintaining its current position determined by the "TL" command, in the positive direction (upward) in the cartesian jog and bends the wrist (wrist pitch) in the positive direction (upward) in the articulated jog. It also serves as the numeric key "3.".

(50) [P− 8]
Turns the end of the hand, while maintaining its current position determined by the "TL" command, in the negative direction (downward) in the cartesian jog and bends the wrist (wrist pitch) in the negative direction (downward) in the articulated jog. It also serves as the numeric key "8.".

(51) [R+ 2]
Twists the wrist (wrist roll) in the positive direction (clockwise looking toward the hand mounting surface). It also serves as the numeric key "2."

(52) [R− 7]
Twists the wrist (wrist roll) in the negative direction (counterclockwise looking toward the hand mounding surface). It also serves as the numeric key "7."

(53) [OPTION+ 1]
Moves the optional axis in the positive direction. It also serves as the numeric key "1."

(54) [OPTION− 6]
Moves the optional axis in the negative direction. It also serves as the numeric key "6."

(55) [◀O▶ 0]
Opens the hand gripper. It also serves as the numeric key "0."

(56) [▶C◀ 5]
Closes the hand gripper. It also serves as the numeric key "5."

2.2.3 Functions of the indicator LED

The 4-digit LED shows the following information.

(57) Position number
Shows the position number in 3 digits when [INC], [DEC], [P. S], [P. C], or [MOV] key is being used.

(58) Program line number
Shows the program line number in 4 digits when [STEP] key is being used or when program is running.

(59) Teaching box status indicator (the first digit from the left)
"⊔" means processing invoked by depression of ENT key is either in progress or at an end.
"⊏" means processing invoked by depression of ENT key cannot be carried out.

APPENDIX B

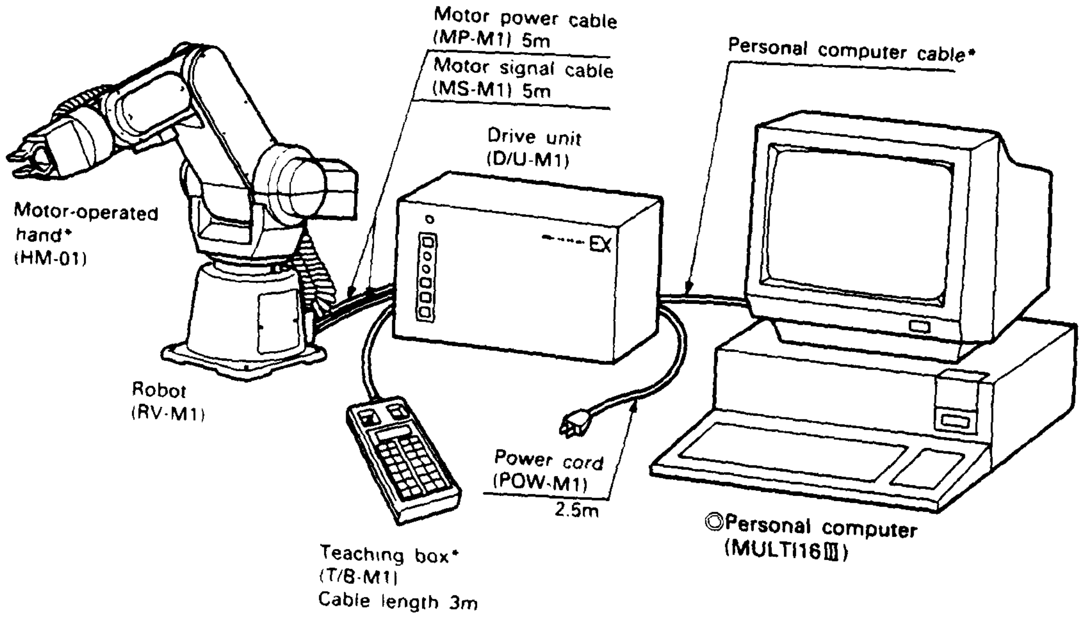
Robot Command Descriptions

CONTENTS (DESCRIPTION OF THE COMMANDS)

APPENDIX C

CEM Robotics Laboratory User's Manual

CEM Robotics Laboratory User's Manual



Division of Construction Engineering and Management
School of Civil Engineering
Purdue University

TABLE OF CONTENTS

INTRODUCTION

In 1988, the Construction Engineering and Management Division of Purdue University received a grant from the National Science Foundation to establish a robotics laboratory which would provide a "hands on" environment in which research personnel could work. The overall goal of this research is to study the adaptability of high technology to today's construction processes.

This user's manual was written to be a user-friendly laboratory manual for the Mitsubishi MoveMasterEX (Model RV-M1) micro-robot. The purpose of this manual is to complement, **not replace**, the MoveMasterEX Industrial Micro-Robot System (Model RV-M1) Instruction Manual which was supplied with the robot. Please review the instruction manual prior to operating the robot.

The robot has been affectionately named "SKIBBY", in recognition of Professor M. J. Skibniewski's dedicated efforts towards the promotion and advancement of construction automation research.

SAFETY PRECAUTIONS

Both equipment and personnel safety are the most important concerns whenever SKIBBY is being operated. Please review these safety precautions and ensure that they are strictly observed at all times.

Robot Safety

Always observe the following precautions when working with the robot:

1. DO NOT TOUCH ANY MOVING PART OF THE ROBOT WHILE IT IS RUNNING.
2. TURN OFF THE POWER BEFORE YOU WORK WITHIN THE ROBOT WORK ENVELOPE.
3. DO NOT ALLOW WATER, SOLVENTS, OR METAL SHAVINGS TO ENTER THE ROBOT ARM OR DRIVE UNIT.
4. DO NOT STORE THE ROBOT IN A POSITION OUTSIDE THE SPACE SHOWN IN FIG. 1 FOR LONGER THAN 10 MINUTES, AS DAMAGE TO THE MOTORS MAY RESULT.
5. PROTECT THE ROBOT FROM UNAUTHORIZED USE.

Electrical Safety

All components of the workcell are connected through a ground-fault circuit breaker. The breaker will trip if the circuit is ever shorted to ground. The chassis of all components are connected to a safety ground. Nevertheless, the following

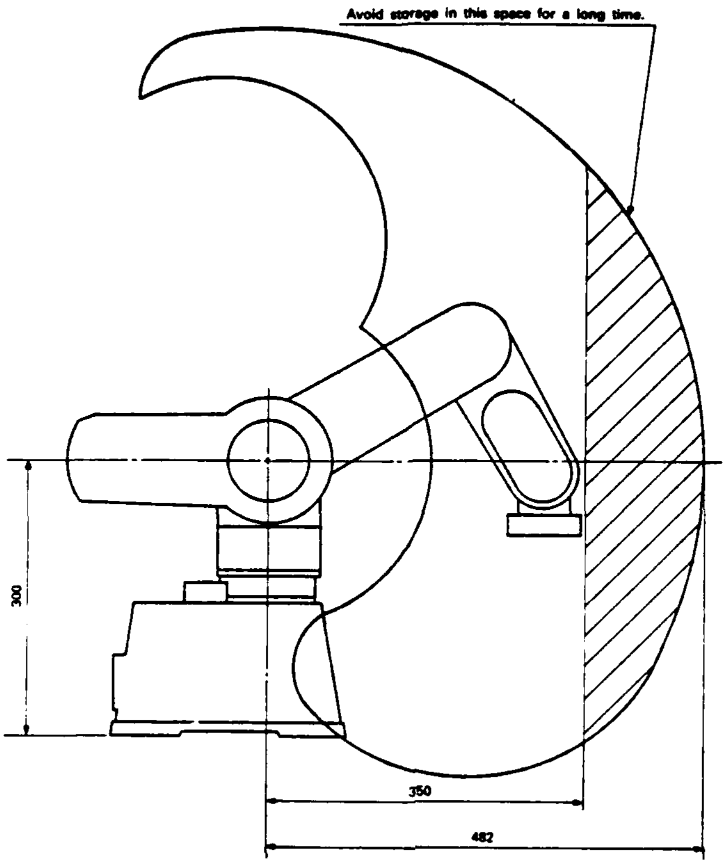


FIG. 1. - Robot storage position space

precautions must be followed:

1. DO NOT ALLOW WATER, SOLVENTS, OR METAL SHAVINGS TO ENTER ANY ELECTRICAL COMPONENT.
2. PLUG THE WORKCELL AND AIR COMPRESSOR INTO GROUNDED OUTLETS ONLY. THE COMPRESSOR REQUIRES A SEPARATE 15 AMP CIRCUIT.
3. TURN OFF THE MAIN POWER SWITCH AND UNPLUG THE WORKCELL AND COMPRESSOR FROM THE POWER STRIP WHEN NOT IN USE.
4. DO NOT REMOVE THE COVERS FROM ANY OF THE ELECTRICAL BOXES. THERE IS EXPOSED LIVE POWER INSIDE, AND YOU RISK

SERIOUS ELECTRICAL SHOCK. **THERE ARE NO USER SERVICEABLE PARTS INSIDE.**

Personnel Safety

The following rules for general personnel safety must always be followed:

1. ALL PERSONNEL, INCLUDING THE OPERATOR, MUST STAY OUTSIDE THE ROBOT WORK ENVELOPE THROUGHOUT THE EXECUTION OF THE ROBOT'S MOVEMENTS.
2. ALWAYS BE AWARE OF THE LOCATION OF THE EMERGENCY STOP BUTTON IN THE EVENT THAT ITS USE IS WARRANTED.
3. IF THE COMPRESSED AIR VALVES ARE BEING USED, ENSURE THAT ALL PERSONNEL ARE WEARING SAFETY GLASSES.

WORKCELL DESCRIPTION

Table Top Equipment

The following items are located on top of the work table:

- RV-M1 robot arm (SKIBBY)
- teaching box
- emergency stop switch

Robot arm - The robot arm has five degrees of freedom as shown in Fig. 2. Its operational space (without a tool) is shown in Fig. 3. The tool most widely used is the motor-operated hand gripper, which is attached to the wrist plate surface.

Teaching box - The teaching box can be placed anywhere behind the robot arm where it is convenient for the operator. The teaching box is used for nesting the robot, manually moving the arm, and initiating emergency stops, if necessary. The teaching box has an ON/OFF and an emergency stop button. When ON, the teaching box controls the robot. When OFF, the personal computer has control. The emergency stop button on the teaching box will stop the motion of the **robot arm only** and will not close any open compressed air valves. The teaching box is shown in Fig. 4.

Emergency stop switch - The emergency stop switch should be placed in a position which is easily accessible to the operator. When depressed, the switch will deenergize a relay in the drive unit, securing all operating equipment.

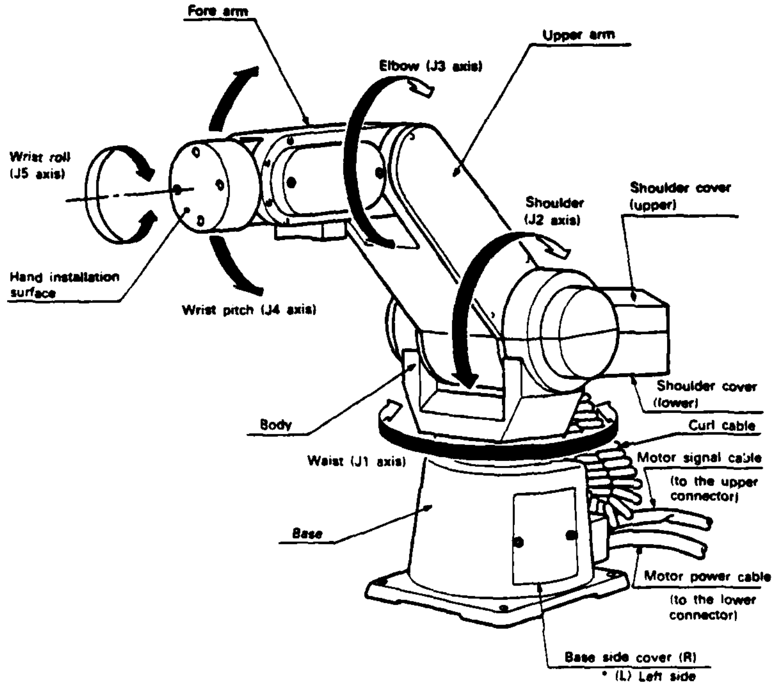


FIG. 2. - Five degrees of freedom

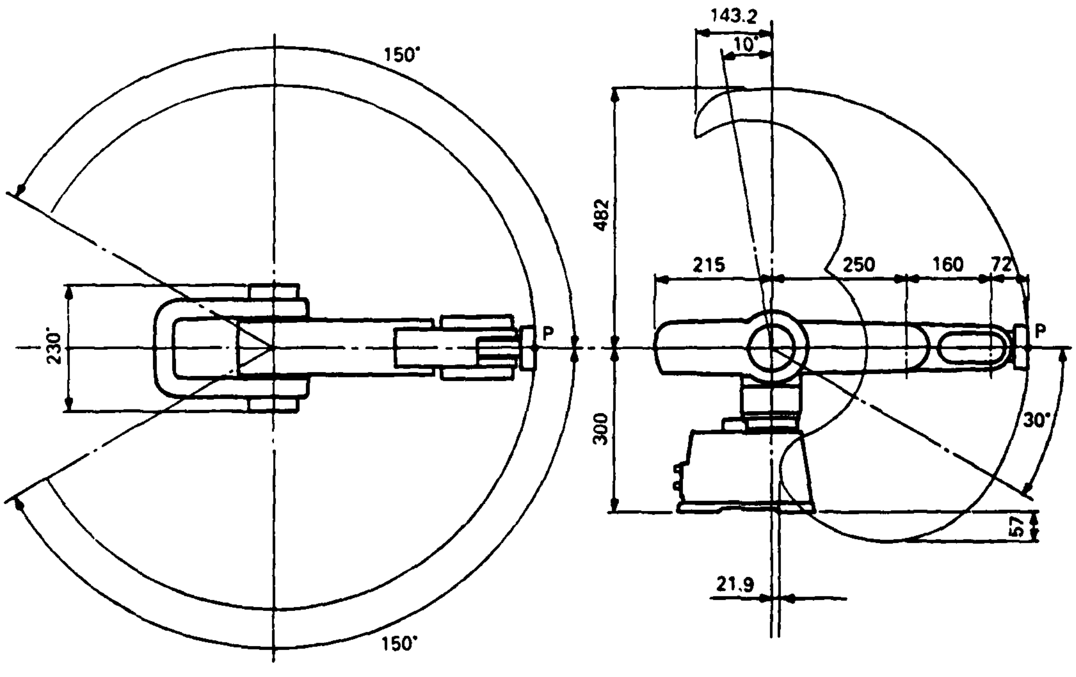


FIG. 3. - Operational space dimensions (measured in millimeters)

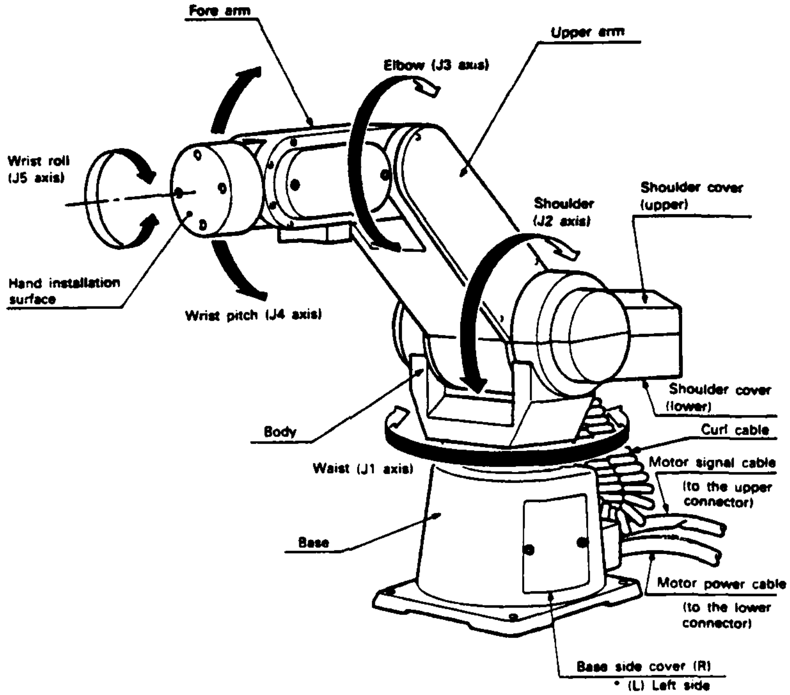


FIG. 2. - Five degrees of freedom

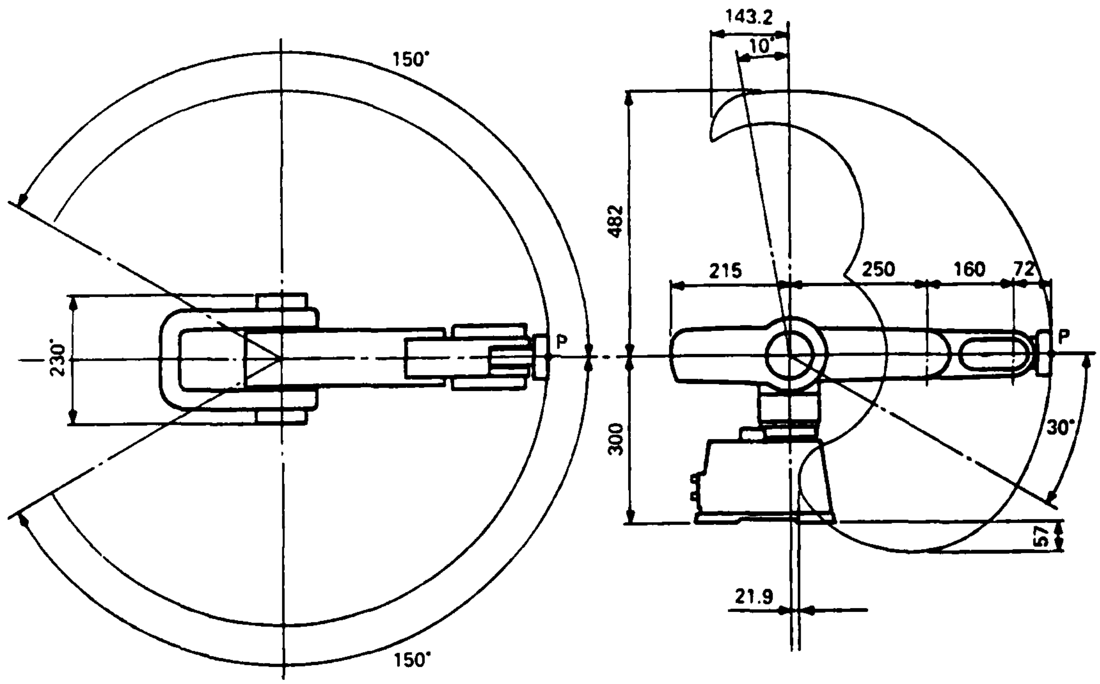


FIG. 3. - Operational space dimensions (measured in millimeters)

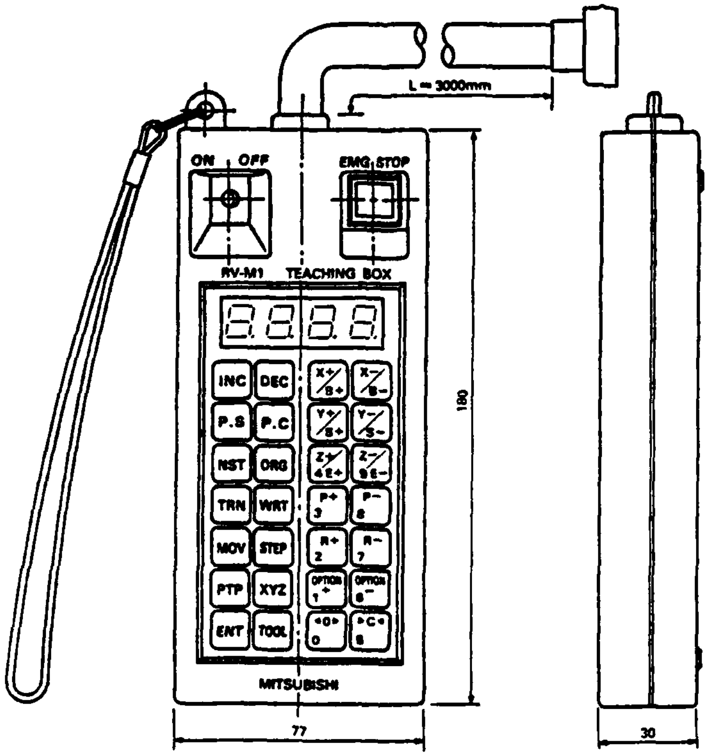


FIG. 4. - Teaching box

<u>Zenith Personal Computer</u>

The Zenith personal computer is connected directly to the robot drive unit. It has the following specifications:

1. 20 megabyte hard drive
2. 640 kilobyte RAM
3. EGA monitor
4. 5 1/4" disk drive (A drive)
5. 3 1/2" disk drive (B drive)
6. software: QuickBASIC (F6 selection on main menu)

STANDARD OPERATING PROCEDURES

Workcell start-up

Both equipment and personnel safety must be strictly observed whenever working in the CEM Robotics Laboratory. Prior to start-up, the system configuration should be as follows:

- both computer and robot arm are uncovered
- teaching box switch is set to *ON*
- robot arm operational space is clear of all obstructions.

In starting up the workcell, perform the following procedure:

- PLUG DRIVE UNIT POWER CORD INTO POWER STRIP
- CLOSE MAIN POWER CIRCUIT BREAKER
- VERIFY THAT TEACHING BOX IS IN THE *ON* POSITION. NEST SKIBBY BY DEPRESSING THE *NST* AND *ENT* BUTTONS ON THE TEACHING BOX. NESTING IS EXTREMELY IMPORTANT BECAUSE IT ALLOWS THE MATCHING OF THE ROBOT'S MECHANICAL ORIGIN WITH THE CONTROL SYSTEM'S ORIGIN (SEE FIG. 5)
- TURN ON COMPUTER CPU AND MONITOR
- AFTER NESTING, SWITCH TEACHING BOX TO *OFF* IF COMPUTER CONTROL IS DESIRED.

Safety Inspection

Prior to either manual or programmed operation of the robot, perform the following safety inspection:

- verify that all obstructions are removed and all personnel are located outside the robot arm's operational space
- position the emergency stop button in a location which is easily accessible.

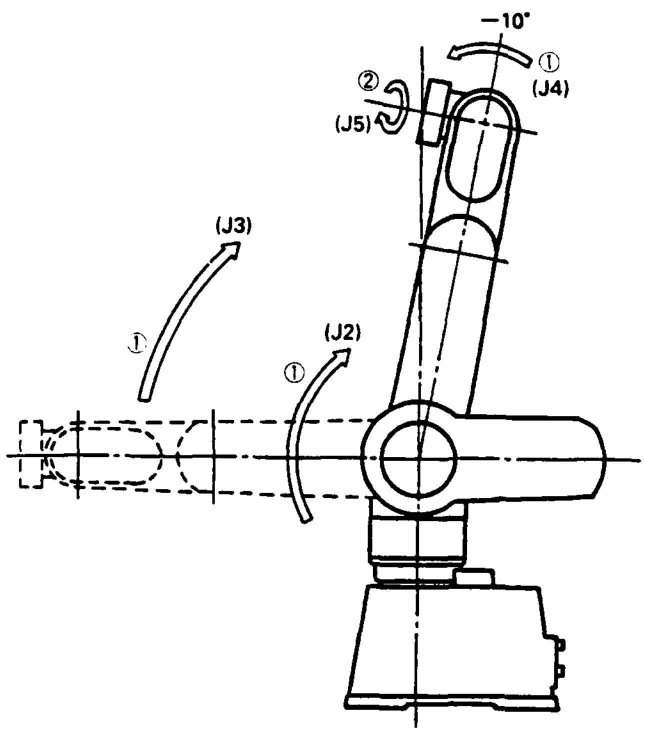


FIG. 5. - Nesting position

Teaching Box Operating Procedures

When the teaching box switch is in the *ON* position, the movement of the robot can be controlled entirely from the numeric keyboard.

The teaching box has multiple symbols which, when depressed, initiate joint and axes movements. Pages 2-18 through 2-21 of the instruction manual describe the functions associated with each teaching box key.

Personal Computer Operating Procedures

When the teaching box switch is in the *OFF* position, the movement of the robot can be controlled entirely by commands sent from the computer.

All robot commands are sent to the drive unit with the use of QuickBASIC. From the computer main menu screen, select QuickBASIC by depressing the **F6** key. Verify positive control of the robot by performing the following procedure:

1. VERIFY THAT TEACHING BOX SWITCH IS IN THE *OFF* POSITION
2. IN QUICKBASIC, TYPE THE FOLLOWING NEST COMMAND:
   LPRINT "NT"
3. EXECUTE THE NESTING COMMAND
4. VERIFY THAT THE ROBOT ARM NESTS UPON RECEIPT OF THE COMMAND.

A complete listing of commands can be found on pages 3-1 through 3-72 of the instruction manual.

QUICKBASIC PROGRAMMING

QuickBASIC is used to organize a sequence of robot commands to perform specific work tasks. It can be selected from the computer main menu screen by depressing the **F6** key.

Sample Screen Presentation

All automated work task programs should incorporate standardized computer screen presentations in their QuickBASIC programs in order to introduce and communicate the objectives of the program, as well as to prompt the user for keyboard input if required.

Included in appendix A are standardized computer screen presentations used to introduce and to communicate the objectives of a blocklaying demonstration program. A copy of this QuickBASIC program is included in appendix B.

Sample Articulated System Program

When operating the robot in the articulated system, the movements are defined by individual joint movements and pre-set positions. These positions are stored in the drive unit RAM in the form of a position number between 001 to 629. An example of a program which makes use of the articulated system is the blocklaying demonstration program in appendix B. Throughout the program, "MO XXX" (move commands) are used to direct the robot to pre-defined numerical positions. Fig. 6 shows the robot axis operations in the articulated system.

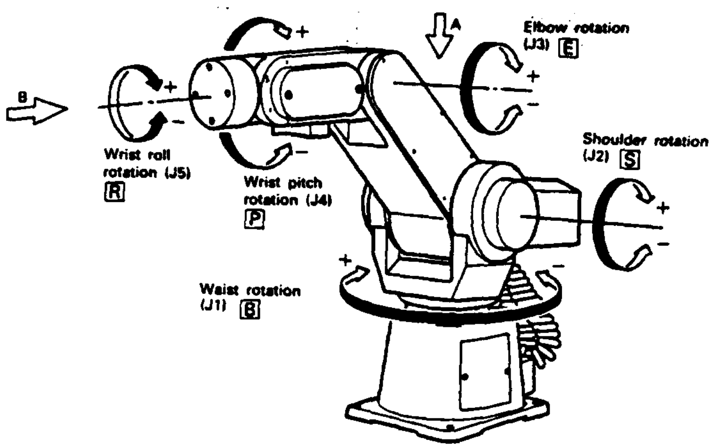


FIG. 6. - Articulated system operations

<u>Sample Cartesian Coordinate System Program</u>

The automated excavtor demonstration program (appendix C) operates entirely in the cartesian coordinate system. In this control mode, the robot's movements are defined in terms of x, y and z-axis coordinates as well as wrist pitch and roll. Fig. 7 shows the robot arm's operation in the cartesian coordinate system. Fig. 8 shows the orientation of the x, y and z-axis with respect to the origin (located at the center of the robot arm base). The point from which the cartesian coordinates are referenced is called the "tool center point". This point is defined by the tool length command "TL XXX", where XXX is the length of the tool (i.e. hand gripper, excavation bucket, etc) in millimeters.

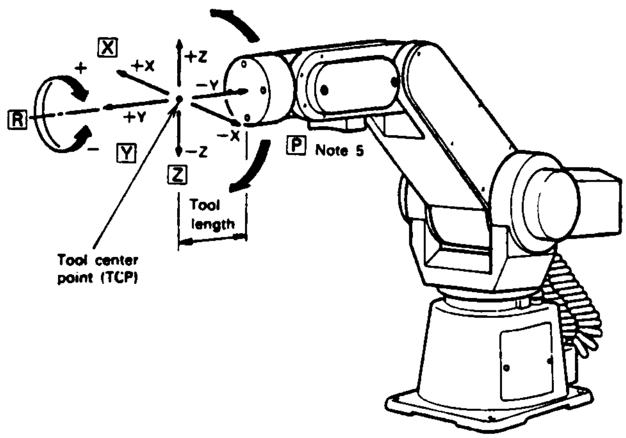


FIG. 7. - Cartesian coordinate system operations

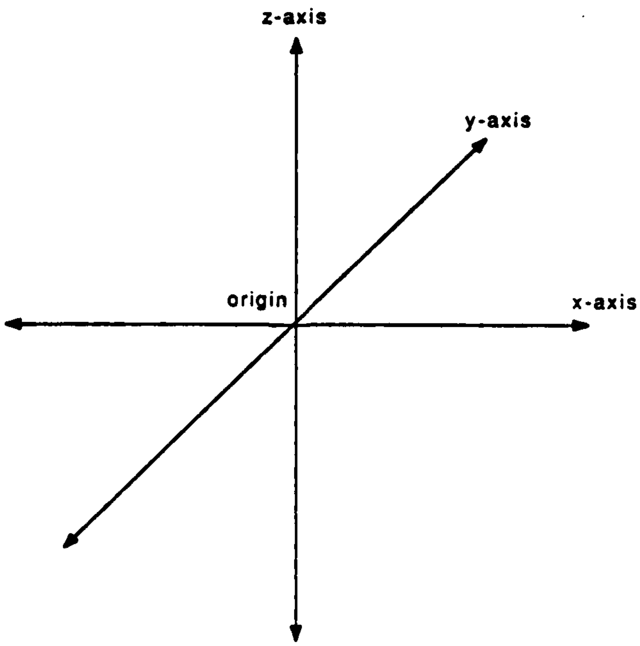


FIG. 8. - x, y and z-axis orientation

Fundamental Program Commands

Whether operating the robot in the articulated or the cartesian coordinate system, several fundamental commands must be included at the beginning of your program to ensure that the robot is operated safely. They are the following:

1. The introductory computer screen presentation must include the nesting of the robot to verify that the robot is under computer control.

   (**LPRINT "NT"**)

2. A tool length must be defined prior to any movement commands. If no tool length is defined, serious damage to the robot may occur as it maneuvers through the work envelope without consideration of its tool extension.

   (**LPRINT "TL XXX"**); XXX - millimeters

3. The speed of the robot´s movements must be defined prior to any robot movements.

   (**LPRINT "SP X"**); X - 0 to 9

SYSTEM SECURING PROCEDURES

Securing procedures

At the conclusion of all programming sessions, the robot must be properly secured in order to avoid any damage to system equipment. When securing the system, perform the following procedure:

- VERIFY THAT THE TEACHING BOX IS IN THE *ON* POSITION. NEST THE ROBOT BY DEPRESSING THE *NST* AND *ENT* BUTTONS
- OPEN MAIN POWER CIRCUIT BREAKER
- UNPLUG THE DRIVE UNIT POWER CORD FROM THE POWER STRIP
- TURN OFF THE COMPUTER MONITOR AND CPU
- COVER ROBOT AND COMPUTER WITH PLASTIC COVERING.

TECHNICAL ASSISTANCE

If technical assistance is required to resolve system or programming problems, contact Mr. John Bollinger of ARC, Inc.

Phone: (317) 254-1841

Address: AUTOMATION, ROBOTICS, AND COMMUNICATIONS, INC.
P. O. Box 55206
Indianapolis, Indiana 46220

Another good source of technical assistance is RIXAN ASSOCIATES.

Phone: (513) 222-0011

Address: RIXAN ASSOCIATES
5062 Wadsworth Road
Dayton, Ohio 45414

APPENDIX A

Standardized Computer Screen Presentations

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WELCOME TO THE CONSTRUCTION ENGINEERING AND MANAGEMENT DIVISION
ROBOTICS LABORATORY
PURDUE UNIVERSITY

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CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

This program emulates the laying of a block wall

Press SPACE BAR to nest SKIBBY

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
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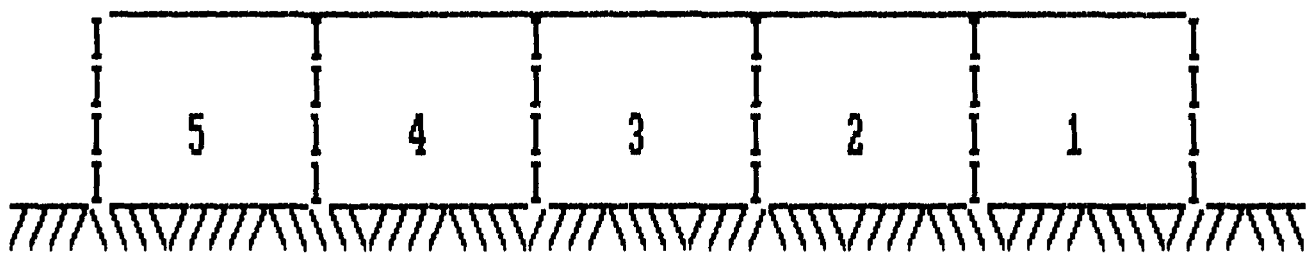

Original block configuration

Press SPACE BAR to view completed wall section

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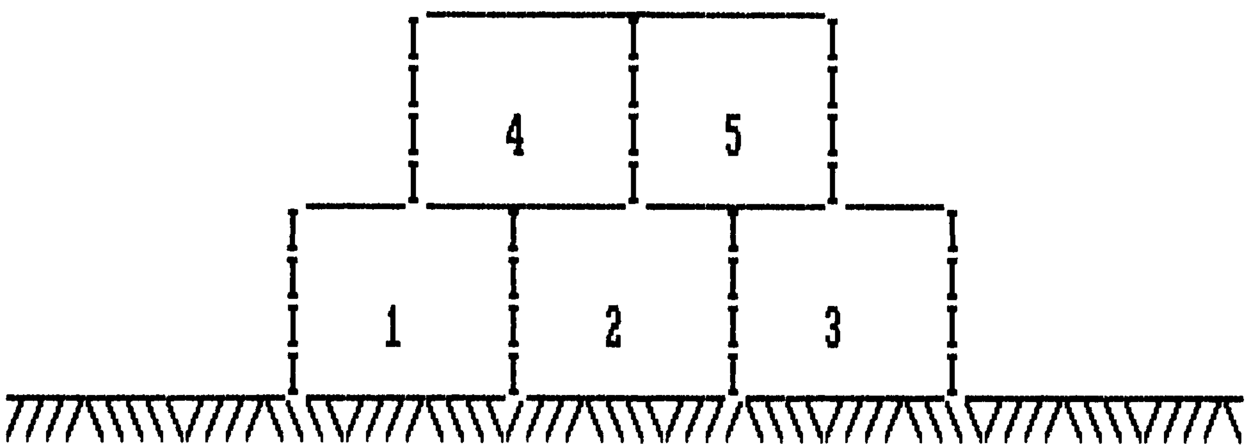

Completed wall section

Press SPACE BAR to begin blocklaying

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CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Laying of block 1 in progress

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Block wall is completed

Press any key to nest SKIBBY

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Block wall is completed

Press any key to continue

APPENDIX B

Blocklaying Demonstration Program

```
'************************BLOCK4 WALL BUILDING PROGRAM***************************
' CNE ROBOTICS LABORATORY                                          BLOCK4.BAS
  SPRING 1990

' This QuickBASIC program directs SKIBBY to build a simulated brick wall.
  The program was originally written by John Crane as part of an independent
  research project under the direction of Professor M. J. Skibniewski.
' The program references pre-set positions within the work envelope to pick
  up and lay simulated masonry block to form a simulated wall two courses
  high.
'*****************************************************************************
DECLARE SUB INTRODUCTION ()
 ECLARE SUB BLOCKINTRO (BLOCK%)
 ECLARE SUB FINALSCREEN ()

 CREEN 2

BLOCK% = 0

 LS

CALL INTRODUCTION

 PRINT "SP 5"
'Set speed equal to 5


'SKIBBY begins by picking up and laying block 1
 LOCK% = 1
 ALL BLOCKINTRO(BLOCK%)
 PRINT "MO 400"
LPRINT "MO 401"
 PRINT "MO 450"
 PRINT "MO 451"
LPRINT "MO 452"
 PRINT "MO 453"
 PRINT "MO 454"
 PRINT "MO 455"
LPRINT "MO 456"
 PRINT "MO 457"

'SKIBBY picks up and lays block 2
 LOCK% = 2
 ALL BLOCKINTRO(BLOCK%)
LPRINT "MO 400"
 PRINT "MO 401"
 PRINT "MO 440"
 PRINT "MO 441"
LPRINT "MO 442"
 PRINT "MO 443"
 PRINT "MO 444"
LPRINT "MO 445"
 PRINT "MO 446"
 PRINT "MO 447"

'SKIBBY picks up and lays block 3
 LOCK% = 3
 ALL BLOCKINTRO(BLOCK%)
LPRINT "MO 400"
 PRINT "MO 401"
```

```
LPRINT "MO 430"
 PRINT "MO 431"
 PRINT "MO 432"
LPRINT "MO 433"
 PRINT "MO 434"
 PRINT "MO 435"
LPRINT "MO 436"
LPRINT "MO 437"

 SKIBBY picks up and lays block 4
BLOCK% = 4
 ALL BLOCKINTRO(BLOCK%)
 PRINT "MO 400"
LPRINT "MO 401"
 PRINT "MO 420"
 PRINT "MO 421"
 PRINT "MO 422"
LPRINT "MO 423"
 PRINT "MO 424"
 PRINT "MO 425"
LPRINT "MO 426"
 PRINT "MO 427"

'SKIBBY picks up and lays block 5
BLOCK% = 5
 ALL BLOCKINTRO(BLOCK%)
 PRINT "MO 400"
LPRINT "MO 401"
 PRINT "MO 410"
 PRINT "MO 411"
LPRINT "MO 412"
 PRINT "MO 413"
 PRINT "MO 414"
LPRINT "MO 415"
LPRINT "MO 416"
 PRINT "MO 417"
 PRINT "MO 418"
LPRINT "MO 419"
 PRINT "MO 299"

CALL FINALSCREEN

 OCATE 18, 15
 'RINT "                                                      "
```

```
'******************************INRTODUCTION*********************************
'SUBROUTINE INTRODUCTION

'This subroutine introduces the program and prompts the user to press any key
'to begin the blocklaying process
'****************************************************************************
JB INTRODUCTION

CREEN 2

CLS

 Draw box outline for program introduction
LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 Print introduction screen
LOCATE 5, 8
PRINT "*************************************************************"
 OCATE 6, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 7, 8
 RINT "*************************************************************"
 OCATE 9, 8
PRINT "WELCOME TO THE CONSTRUCTION ENGINEERING AND MANAGEMENT DIVISION"
 OCATE 10, 8
 RINT "                      ROBOTICS LABORATORY"
LOCATE 11, 8
PRINT "                       PURDUE UNIVERSITY"
 OCATE 13, 8
PRINT "*************************************************************"
LOCATE 14, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 15, 8
PRINT "*************************************************************"

 OCATE 17, 8
PRINT "       This program simulates the laying of a block wall"

 OCATE 20, 8
 RINT "                  Press SPACE BAR to nest SKIBBY"

 O UNTIL INKEY$ <> ""
 OOP

'PRINT "NT"

CLS

 Draw original block line up
 INE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 OCATE 3, 8
PRINT "*************************************************************"
LOCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 5, 8
PRINT "*************************************************************"
```

```
'
LOCATE 10, 8
PRINT "     ____________________________________________________"
OCATE 11, 8
PRINT "     I          I          I          I          I          I "
LOCATE 12, 8
RINT "     I          I          I          I          I          I "
OCATE 13, 8
PRINT "     I    5     1    4     I    3     I    2     I    1     1"
OCATE 14, 8
RINT "____I__________1__________I__________I__________I__________1_____"
LOCATE 15, 8
PRINT "////\\\\////\\\\////\\\\////\\\\////\\\\////\\\\////\\\\////\\\\"

LOCATE 19, 8
PRINT "                         Original block configuration"

OCATE 21, 8
PRINT "          Press SPACE BAR to view completed wall section"

O UNTIL INKEY$ <> ""
LOOP

LS

'Draw picture of completed wall section
INE (10, 6)-(610, 190), , B
INE (14, 8)-(606, 188), , B

'
OCATE 3, 8
PRINT "****************************************************************"
LOCATE 4, 8
RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
OCATE 5, 8
PRINT "****************************************************************"

OCATE 7, 8
PRINT "                         ____________________"
LOCATE 8, 8
RINT "                         I          I          I"
LOCATE 9, 8
PRINT "                         I          I          I"
OCATE 10, 8
RINT "                         I    4     I    5     I"
LOCATE 11, 8
PRINT "                   _____I__________I__________I_____"
OCATE 12, 8
PRINT "                   I          I          I          I"
LOCATE 13, 8
RINT "                   I          I          I          I"
OCATE 14, 8
PRINT "                   I    1     I    2     I    3     I"
OCATE 15, 8
RINT "______________I__________I__________I__________I______________"
LOCATE 16, 8
PRINT " ////\\\\////\\\\////\\\\////\\\\////\\\\////\\\\////\\\\////\"
OCATE 19, 8
RINT "                         Completed wall section"

OCATE 21, 8
```

```
PRINT "                    Press SPACE BAR to begin blocklaying"

 O UNTIL INKEY$ <> ""
LOOP

 ND SUB
```

```
'********************************BLOCKINTRO**********************************
 SUBROUTINE BLOCKINTRO

'This program prints the block number which SKIBBY is working on at the time
'*****************************************************************************
 UB BLOCKINTRO (BLOCK%)

CLS

    LINE (10, 6)-(610, 190), , B
    LINE (14, 8)-(606, 188), , B

    LOCATE 3, 8
    PRINT "***********************************************************"
    LOCATE 4, 8
    PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
    LOCATE 5, 8
    PRINT "***********************************************************"

    LINE (120, 90)-(510, 120), , B
    LINE (124, 92)-(506, 118), , B

    LOCATE 14, 25
    PRINT " Laying of block "; BLOCK%; " in progress"

 ND SUB
```

```
'******************************FINAL SCREEN***********************************
'SUBROUTINE FINALSCREEN

'This subroutine prints the final screen
'****************************************************************************
 UB FINALSCREEN

CLS

 INE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 OCATE 3, 8
 RINT "***************************************************************"
LOCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 5, 8
PRINT "***************************************************************"

 INE (120, 90)-(510, 120), , B
LINE (124, 92)-(506, 118), , B

 OCATE 14, 24
 RINT "      Block wall is completed"

 OCATE 18, 8
 RINT "                        Press any key to nest SKIBBY"

DO UNTIL INKEY$ <> ""
 OOP

LPRINT "NT"

 ND SUB
```

APPENDIX C

Automated Excavator Demonstration Program

```
'****************************AUTOMATED EXCAVATOR*********************************
' SKIBBY2.BAS                                                     JAMES G. CRUZ
' SUMMER 1990
'
'This demonstration program allows the user to input the perimeter dimensions
'of a building foundation and, with the input, direct the excavator to carry
'out the exavation.  An excavation depth is given at 50 mm.
'*********************************************************************************

'Initialize all subroutines
DECLARE SUB INTRODUCTION (XDIM%, YDIM%)
DECLARE SUB XYDIMCALC (XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)
DECLARE SUB SIDEINTRO (SIDE%, LENGTH%)
DECLARE SUB TURNCORNER (SIDE%)
DECLARE SUB FINALSCREEN ()
DECLARE SUB EXCAVATE1 ()
DECLARE SUB EXCAVATE2 ()
DECLARE SUB MOVESKIBBY ()

'Initialize all variables
J% = 1
SIDE% = 1
SIDE1% = 0
SIDE2% = 0
REMAIN1% = 0
REMAIN2% = 0
XDIM% = 0
YDIM% = 0
L% = 0
REMAIN11% = 0
LENGTH% = 0

CLS

'Call introductory screens
CALL INTRODUCTION(XDIM%, YDIM%)

'Calculcate the required number of full 190 mm cycles/side
CALL XYDIMCALC(XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)

FOR J% = 1 TO 2

   'Perform excavation of sides 1 and 2, and then sides 3 and 4

   'Begin excavation of side
    FOR X% = 1 TO SIDE1%
       'SKIBBY completes two 95 mm passes for a total length of 190 mm
        LENGTH% = 190
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        CALL EXCAVATE2
       'Notify user that SKIBBY is re-positioning
        CALL MOVESKIBBY
    NEXT X%

 IF REMAIN1% > 0 THEN

   'Remaining length of side is completed
    IF REMAIN1% >= 95 THEN
        LENGTH% = 95
```

```
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        LPRINT "MP 155, 0, 200, -145, 180"
        CALL MOVESKIBBY
    END IF

    IF REMAIN1% >= 95 THEN
       REMAIN11% = REMAIN1% - 95
    ELSE
       REMAIN11% = REMAIN1%
    END IF

       LENGTH% = REMAIN11%
       CALL SIDEINTRO(SIDE%, LENGTH%)
       CALL EXCAVATE2
 LSE
 ND IF

    CALL TURNCORNER(SIDE%)
    SIDE% = SIDE% + 1

    FOR Y% = 1 TO SIDE2%
       'Begin excavation of side
       'SKIBBY completes two 95 mm passes for a total length of 190 mm
        LENGTH% = 190
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        CALL EXCAVATE2
        CALL MOVESKIBBY
    NEXT Y%

 IF REMAIN2% > 0 THEN

    IF REMAIN2% >= 95 THEN
       LENGTH% = 95
       CALL SIDEINTRO(SIDE%, LENGTH%)
       CALL EXCAVATE1
       LPRINT "MP 155, 0, 200, -145, 180"
       CALL MOVESKIBBY
    END IF

    IF REMAIN2% >= 95 THEN
       REMAIN11% = REMAIN2% - 95
    ELSE
       REMAIN11% = REMAIN2%
    END IF

   'Call EXCAVATE2 to complete footing for this side
    LENGTH% = REMAIN11%
    CALL SIDEINTRO(SIDE%, LENGTH%)
    CALL EXCAVATE2

 ELSE
 END IF

    CALL TURNCORNER(SIDE%)
    SIDE% = SIDE% + 1

NEXT J%
```

```
CALL FINALSCREEN
```

```
'********************************INTRODUCTION*************************************
' SUBROUTINE INTRODUCTION
'
' This subroutine prints the program introduction and receives dimensional
' input
' ********************************************************************************
S_B INTRODUCTION (XDIM%, YDIM%)

S REEN 2

'Draw box outline for program introduction
L'NE (10, 6)-(610, 190), , B
I NE (14, 8)-(606, 188), , B

'Print introduction screen
I CATE 5, 8
I INT "*****************************************************************"
LOCATE 6, 8
P INT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
I CATE 7, 8
PRINT "*****************************************************************"
LOCATE 9, 8
I INT "WELCOME TO THE CONSTRUCTION ENGINEERING AND MANAGEMENT DIVISION"
L CATE 10, 8
PRINT "                          ROBOTICS LABORATORY"
I CATE 11, 8
I INT "                           PURDUE UNIVERSITY"
LOCATE 13, 8
PRINT "*****************************************************************"
: CATE 14, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 15, 8
: INT "*****************************************************************"

LOCATE 17, 5
RINT "This program simulates the excavation of building foundation footings."

LOCATE 20, 8
PRINT "                     Press SPACE BAR to nest SKIBBY"
) UNTIL INKEY$ <> ""
OOP
'Nest SKIBBY prior to start of excavation
PRINT "NT"

'Set speed equal to 5
PRINT "SP 5"

Set tool length for bucket at 100 mm
LPRINT "TL 100"

Nest bucket until ready to excavate
LPRINT "MP 155, 0, 200, -145, 180"

LS
'Define SKIBBY's starting position
LINE (10, 6)-(610, 190), , B
INE (14, 8)-(606, 188), , B

LOCATE 3, 8
RINT "*****************************************************************"
```

```
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "******************************************************************"

LOCATE 7, 8
PRINT "                ____________side 3_____________"
LOCATE 8, 8
PRINT "               1                                1"
LOCATE 9, 8
PRINT "            s  1                                1  s"
LOCATE 10, 8
PRINT "            i  1                                1  i"
LOCATE 11, 8
PRINT "            d  1                                1  d"
LOCATE 12, 8
PRINT "            e  1                                1  e"
LOCATE 13, 8
PRINT "               1                                1"
LOCATE 14, 8
PRINT "            4  1                                1  2"
LOCATE 15, 8
PRINT "               1                                1"
LOCATE 16, 8
PRINT "               1____________side 1_____________1"
LOCATE 17, 8
PRINT "               x - starting point"

LOCATE 19, 8
PRINT "                       FOUNDATION PLAN VIEW"

LOCATE 21, 8
PRINT "           Press SPACE BAR to view footing section"

DO UNTIL INKEY$ <> ""
LOOP

CLS

 Define footing depth
LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B


LOCATE 3, 8
PRINT "******************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "******************************************************************"

LOCATE 7, 8
PRINT "      _____     ________                        ___________"
LOCATE 8, 8
PRINT "        I        ////\\I                         I\////\\\\/"
LOCATE 9, 8
PRINT "        I          \///\I                        I/\\\\"
LOCATE 10, 8
PRINT "      50 mm        \\\\/I                        I\\///"
LOCATE 11, 8
```

```
PRINT "         I          ////\I                      I/\\\\"
 OCATE 12, 8
 RINT "         I         /////\I                      I\\///"
LOCATE 13, 8
PRINT "       __I__        \\\\//I______________________I\\///\"
 OCATE 14, 8
 RINT "                    //////\\///////\\\\\/////\\\\\/////\\"

 OCATE 16, 8
PRINT "                                 FOOTING SECTION VIEW"

 OCATE 18, 8
PRINT "                               Excavation depth is 50 mm"

 OCATE 20, 8
 RINT "          Press SPACE BAR to enter foundation dimensions"

 O UNTIL INKEY$ <> ""
 OOP

 LS

 OCATE 23, 8

 Define foundation dimensions
 INE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 OCATE 3, 8
PRINT "********************************************************************"
LOCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 5, 8
PRINT "********************************************************************"

 OCATE 7, 8
PRINT "          ___      ________________________________"
LOCATE 8, 8
 RINT "           1      1                                1"
 OCATE 9, 8
PRINT "           1      1                                1"
 OCATE 10, 8
 RINT "           1      1                                1"
LOCATE 11, 8
 RINT "           1      1                                1"
 OCATE 12, 8
PRINT "           Y      1                                1"
LOCATE 13, 8
 RINT "           1      1                                1"
 OCATE 14, 8
PRINT "           1      1                                1"
 OCATE 15, 8
 RINT "           1      1                                1"
LOCATE 16, 8
PRINT "          _1_     1________________________________1"

LOCATE 18, 8
PRINT "                               FOUNDATION PLAN VIEW"
```

```
LOCATE 21, 8
INPUT "       Please enter the foundation Y - dimension (mm): ", YDIM%

CLS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "*************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "*************************************************************"

LOCATE 7, 8
PRINT "                   1-------------- X --------------1"
LOCATE 9, 8
PRINT "                    _________________________________"
LOCATE 10, 8
PRINT "                   1                                 1"
LOCATE 11, 8
PRINT "                   1                                 1"
LOCATE 12, 8
PRINT "                   1                                 1"
LOCATE 13, 8
PRINT "                   1                                 1"
LOCATE 14, 8
PRINT "                   1                                 1"
LOCATE 15, 8
PRINT "                   1                                 1"
LOCATE 16, 8
PRINT "                   1                                 1"
LOCATE 17, 8
PRINT "                   1                                 1"
LOCATE 18, 8
PRINT "                   1_________________________________1"

LOCATE 20, 8
PRINT "                         FOUNDATION PLAN VIEW"
LOCATE 22, 8

INPUT "       Please enter the foundation X - dimension (mm): ", XDIM%

CLS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "*************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "*************************************************************"


LINE (120, 90)-(510, 120), , B
LINE (124, 92)-(506, 118), , B
```

```
LOCATE 14, 19
PRINT "Press SPACE BAR to begin excavation program"

DO UNTIL INKEY$ <> ""
LOOP

END SUB
```

```
'****************************CYCLE CALCULATIONS*******************************
'SUBROUTINE XYDIMCALC

'This subroutine calculates the number of cycles which will be required to
'excavate all four sides of the foundation.
'*****************************************************************************
SUB XYDIMCALC (XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)

'Calculate the number of complete cycles required to excavate sides 1 and 3
SIDE1% = INT(XDIM% / 190)

'Calculate remaining length required to be excavated on sides 1 and 3
REMAIN1% = XDIM% - (SIDE1% * 190)

'Calculate the number of complete cycles required to excavate sides 2 and 4
SIDE2% = INT(YDIM% / 190)

'Calculate remaining length required to be excavated on sides 2 and 4
REMAIN2% = YDIM% - (SIDE2% * 190)

END SUB
```

```
'*******************************SIDE INTRODUCTION*****************************
'SUBROUTINE SIDEINTRO

 This subroutine displays the "excavation in progress" screen
'****************************************************************************
SUB SIDEINTRO (SIDE%, LENGTH%)

CLS

    LINE (10, 6)-(610, 190), , B
    LINE (14, 8)-(606, 188), , B

    LOCATE 3, 8
    PRINT "*****************************************************************"
    LOCATE 4, 8
    PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
    LOCATE 5, 8
    PRINT "*****************************************************************"

    LINE (120, 90)-(510, 120), , B
    LINE (124, 92)-(506, 118), , B

    LOCATE 14, 25
    PRINT "Excavation of side "; SIDE%; " in progress"

    LOCATE 20, 16
    PRINT ""; LENGTH%; " mm footing will be completed on this pass"

END SUB
```

```
'*******************************TURNCORNER*****************************************
'SUBROUTINE TURNCORNER

 This subroutine displays the fact that the excavator is turning the corner,
're-positioning for the next side.
 ***************************************************************************
 UB TURNCORNER (SIDE%)

HTONE = 780
 TONE = 329
 % = 0

 LS
     LINE (10, 6)-(610, 190), , B
     LINE (14, 8)-(606, 188), , B

     LOCATE 3, 8
     PRINT "*********************************************************************"
     LOCATE 4, 8
     PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
     LOCATE 5, 8
     PRINT "*********************************************************************"

     LINE (120, 90)-(510, 120), , B
     LINE (124, 92)-(506, 118), , B

     LOCATE 14, 24

     PRINT "Excavation of side "; SIDE%; " complete"

     IF SIDE% = 4 THEN
        LOCATE 20, 25
        PRINT "Press SPACE BAR to nest SKIBBY"
        DO UNTIL INKEY$ <> ""
        LOOP
        LPRINT "NT"
     ELSE
        LOCATE 18, 23
        PRINT "SKIBBY is re-positioning to next side"
        LOCATE 20, 19
        PRINT "Press SPACE BAR when SKIBBY is re-positioned"

        DO UNTIL T% = 15
           SOUND HTONE, 5
           SOUND LTONE, 5
           T% = T% + 1
        LOOP

        DO UNTIL INKEY$ <> ""
        LOOP

     END IF

 ND SUB
```

```
'******************************FINAL SCREEN************************************
'SUBROUTINE FINALSCREEN

'This subroutine displays the final program screen, informing the user that
'the excavation has been completed.
'******************************************************************************
SUB FINALSCREEN

CLS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "*********************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "*********************************************************************"

LINE (120, 90)-(510, 120), , B
LINE (124, 92)-(506, 118), , B

LOCATE 14, 24
PRINT "Foundation footings are completed"

END SUB
```

```
'**************************PERFORM EXCAVATION CYCLE*****************************
' ;UBROUTINE EXCAVATE1
'
'This program excavates 95 mm (95 mm per bucket pass) to a depth of 50 mm.
'*******************************************************************************
! /B EXCAVATE1

'Begin first bucket pass which excavates 95mm length

    'Begin excavation process
     LPRINT "MP 430, 0, 520, -10, 180"

    'Begin excavation motion
     LPRINT "MP 503, 0, 146, -45, 180"

     LPRINT "SP 3"
    'Pivot bucket
     LPRINT "MP 476, 0, 95, -60, 180"

    'Draw bucket towards SKIBBY
     LPRINT "MP 460, 0, 86, -70, 180"
     LPRINT "MP 418, 0, 75, -80, 180"
     LPRINT "MP 380, 0, 53, -95, 180"

    'Scoop up
     LPRINT "MP 155, 0, 200, -145, 180"

     LPRINT "SP 5"
    'Prepare to rotate and deposit

     LPRINT "MP -50, 155, 200, -145, 180"

    'Extend boom and rotate bucket to deposit into spoils pile
     LPRINT "MP -100, 450, 520, 0, 180"

 ND SUB
```

```
'**************************PERFORM EXCAVATION CYCLE****************************
 SUBROUTINE EXCAVATE2
'
'This program excavates 95 mm (95 mm per bucket pass) to a depth of 50 mm.
 *********************************************************************************
SUB EXCAVATE2

 Begin second bucket pass which excavates 95mm

    'Begin excavation process
     LPRINT "MP 380, 0, 520, -10, 180"

    'Begin excavation motion
     LPRINT "MP 408, 0, 146, -45, 180"

     LPRINT "SP 3"
    'Pivot bucket
     LPRINT "MP 380, 0, 95, -60, 180"

    'Draw bucket towards SKIBBY
     LPRINT "MP 345, 0, 75, -80, 180"
     LPRINT "MP 285, 0, 65, -90, 180"
     LPRINT "MP 230, 0, 50, -125, 180"

    'Scoop up
     LPRINT "MP 155, 0, 200, -145, 180"

     LPRINT "SP 5"
    'Prepare to rotate and deposit

     LPRINT "MP -50, 155, 200, -145, 180"

    'Extend boom and rotate bucket to deposit into spoils pile
     LPRINT "MP -100, 450, 520, 0, 180"

     LPRINT "MP 155, 0, 200, -145, 180"

END SUB
```

```
'*******************************MOVE SKIBBY****************************************
'SUBROUTINE MOVESKIBBY
'
'This subroutine provides screen display which notifies user that SKIBBY is
'backing up in order to re-position itself for another cycle
'**********************************************************************************
SUB MOVESKIBBY

HTONE = 780
LTONE = 329
T% = 0
CLS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "*****************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "*****************************************************************"


LINE (120, 90)-(510, 120), , B
LINE (124, 92)-(506, 118), , B

LOCATE 14, 25
PRINT "Standby while SKIBBY re-positions"

DO UNTIL T% = 10
   SOUND HTONE, 5
   SOUND LTONE, 5
   T% = T% + 1
LOOP

END SUB
```

APPENDIX D

Automated Excavator Program Manual

Automated Excavator Program Manual

CEM Robotics Laboratory
MoveMasterEX Industrial Micro-Robot System

Division of Construction Engineering and Management
School of Civil Engineering
Purdue University

TABLE OF CONTENTS

INTRODUCTION

This program manual was written to provide background information regarding the development of the automated excavator demonstration program as well as to provide set-up instructions for its safe execution.

Before attempting to set up the workcell and execute this program, please review the Mitsubishi MoveMasterEX Industrial Micro-Robot System (Model RV-M1) Instruction Manual and the CEM Robotics Laboratory User's Manual. A working knowledge of the robot system is required in order to minimize the possibility of equipment damage and/or personnel injury.

At the completion of the excavation program, you may notice that a thin film of dirt has developed on the work table and on the robot arm. If this occurs, secure the system and wipe down the workcell.

AUTOMATED EXCAVATOR PROGRAM DESCRIPTION

Cartesian Coordinate System

The robot arm can be operated either in the articulated or the cartesian coordinate system. In the articulated system, the movements of the robot arm are determined by pre-defined positions which are stored in the drive unit RAM. The command most commonly used to initiate movements in this system is the "MO XXX" or move command.

When operating in the cartesian coordinate system, movements of the robot arm are determined by positions which are referenced to x, y and z-axis coordinates within the operating envelope. The command most commonly used in this operating system is the "MP XXX, YYY, ZZZ, PPP, RRR" or move position command. The command moves the end of the "tool" to a position whose coordinates (position and angle) are specified as follows:

XXY	x-axis coordinate
YYY	y-axis coordinate
ZZZ	z-axis coordinate
PPP	pitch angle (wrist)
RRR	roll angle (wrist)

The tool in this program is defined in the program as the excavator bucket. This means that the coordinates and angles given in the "MP" command are measured to the end of the excavator bucket. This is defined in the program by the "TL XXX" or tool length command. The length XXX, as with all other dimension parameters, is given in millimeters. Fig. 1 shows the orientation of the x, y and z-axes with respect to the robot origin, which is located at the center of the robot arm base.

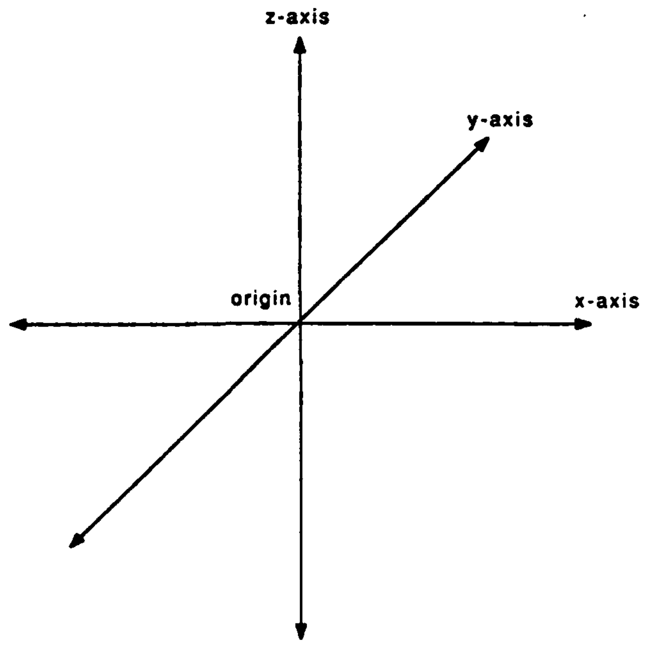


FIG. 1. - x, y and z-axis orientation

Automated Excavator Program Description

The automated excavator program prompts the user, through computer screen presentations, for foundation dimensions. With the inputted information, it calculates the number of excavation passes that are required for the completion of each foundation side. Once the user initiates the excavation process, the computer keeps the user informed, once again through computer screen presentations, as to the status of the excavation in terms of side in progress and length (in millimeters) being excavated. After the robot completes a full pass, it nests its bucket and informs the user that the excavator is simulating re-positioning itself along the foundation perimeter. When a foundation side is completed, the bucket is again nested and the user is informed that the excavator is simulating re-positioning itself along the next foundation side and aligning itself for the next sequence of passes. At the completion of the final foundation side, the user is informed that the footings are completed and that nesting of the robot arm is requested.

The coordinates of the robot arm movements allow for the excavation to a depth of 50 millimeters and a length of 190 millimeters per full pass. A full pass is composed of two 95 millimeter passes, with each full pass ending in the nesting of the bucket.

In those cases in which the foundation dimensions are not multiples of 190 millimeters, the program calculates the number and the length of each side's passes and also informs the user that the excavator is adjusting its position to complete these lengths. For example, for a foundation with dimensions of 500 millimeters by 600 millimeters, the following excavation sequence will be executed:

500 mm sides

190 mm (adjust position)

190 mm (adjust position)

95 mm (adjust position)

25 mm (relocate to next side)

600 mm sides

190 mm (adjust position)

190 mm (adjust position)

190 mm (adjust position)

30 mm (relocate to next side)

QuickBASIC Program

The automated excavator program consists of one main routine, with seven subroutines contained within. The program is written as follows:

a. seven subroutines are initialized.

b. all variables are initialized.

c. SUBROUTINE INTRODUCTION - introductory screens (standardized formats) are presented describing the excavation program. Foundation dimensions are requested from user. User intiates nesting to verify computer control. Robot speed is defined. Length of bucket is defined for use in cartesian coordinate reference.

d. SUBROUTINE XYDIMCALC - exact number of excavation passes are calculated based on user inputs.

e. SUBROUTINE SIDEINTRO - informs user of the length being excavated and the side in progress.

f. SUBROUTINES EXCAVATE1 AND EXCAVATE2 - define the "MP" commands which make up the 190 millimeter excavation cycle.

g. SUBROUTINE MOVESKIBBY - informs user that an excavation pass has been completed and that SKIBBY is re-positioning along the foundation perimeter.

h. SUBROUTINE TURNCORNER - informs user that a side has been completely excavated and that SKIBBY is relocating to the next side.

i. SUBROUTINE FINALSCREEN - informs user that the excavation has been executed successfully. Nesting of SKIBBY is executed.

All complete set of screen presentations is provided in appendix A. These presentations are standardized for all future robotics programs. A copy of the QuickBASIC program is provided in appendix B.

WORKCELL DESCRIPTION

Several modifications must be made to the workcell in order to properly run the automated excavator program. Fig. 2 is a plan view of the original workcell configuration.

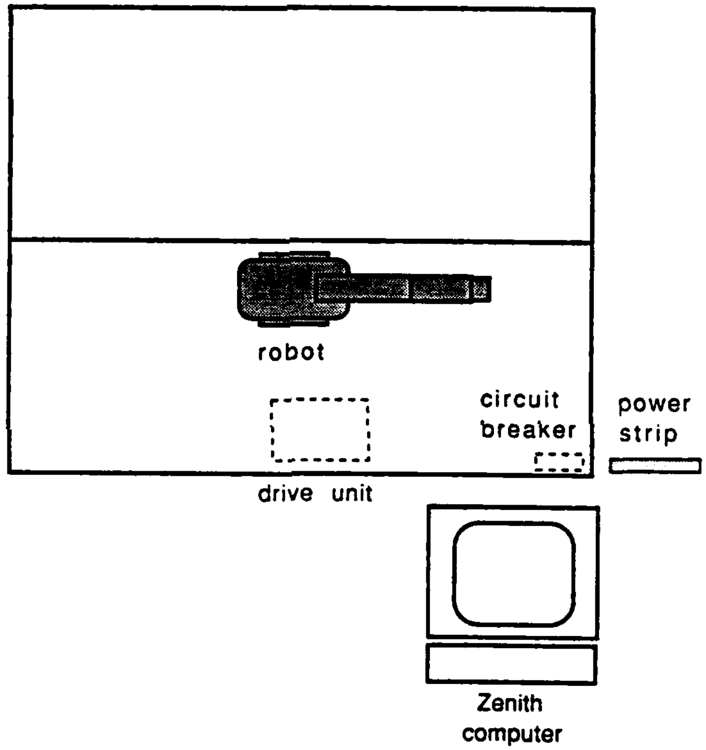


FIG. 2. - Original workcell configuration

Simulated Construction Site

Fig. 3 is a plan view of the simulated construction site, complete with excavation and spoil site sandboxes.

The following procedure should be followed when making the workcell modifications:

1. VERIFY THAT THE MAIN POWER BREAKER IS OPEN.
2. UNPLUG THE MOTOR-OPERATED HAND FROM THE ROBOT FORE ARM. UNSCREW THE HAND FROM THE WRIST PLATE (TWO SCREWS).

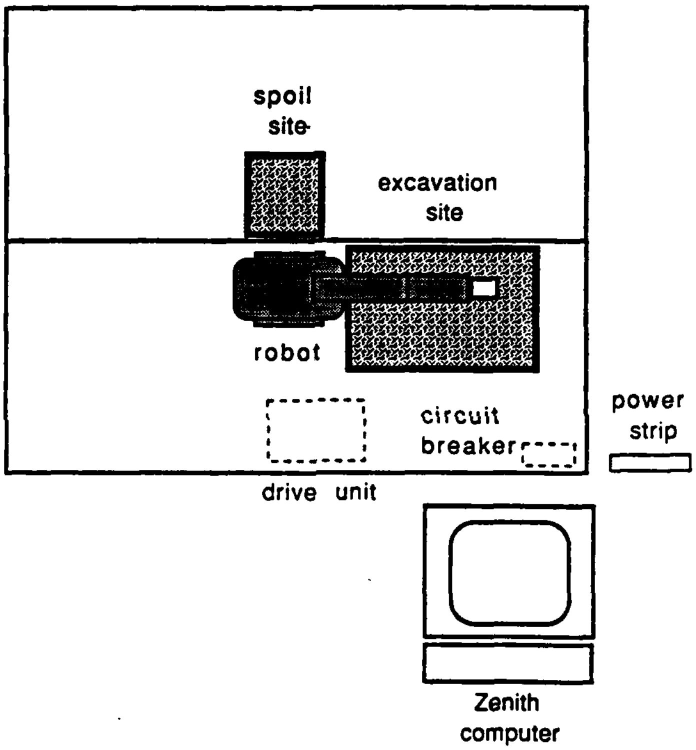


FIG. 3. - Simulated construction site

FASTEN THE EXCAVATOR BUCKET BRACKET ONTO THE WRIST PLATE WITH THE SAME TWO MOTOR-OPERATED HAND SCREWS. FASTEN THE BUCKET TO THE BRACKET WITH THE FOUR BUCKET SCREWS.

3. POSITION THE EXCAVATION AND SPOIL SITE SANDBOXES

ALONGSIDE THE ROBOT BASE AS SHOWN IN FIG. 3. THE SANDBOXES SHOULD TOUCH THE ROBOT BASE.

4. VERIFY THAT ALL OBSTRUCTIONS ARE REMOVED FROM THE OPERATING ENVELOPE BEFORE CLOSING THE MAIN POWER BREAKER.

Upon completion of the excavation program, dump the excavated sand from the spoil site sandbox back into the excavation site sandbox.

RUNNING THE AUTOMATED EXCAVATOR PROGRAM

Selecting QuickBASIC

With the simulated construction site properly set up, the automated excavator program can now be safely executed. Before executing the program however, the computer must first be placed in QuickBASIC mode. This is accomplished by performing the following procedure:

1. FROM THE COMPUTER MAIN MENU SCREEN, DEPRESS **F6**

Running The QuickBASIC Program

Follow the procedures listed below to call up the automated excavator program from the QuickBASIC files and to run it. It is assumed that the user is already in QuickBASIC mode.

1. VERIFY THAT ALL OBSTRUCTIONS HAVE BEEN REMOVED FROM THE OPERATING ENVELOPE.
2. OPEN UP THE **SKIBBY2.BAS** PROGRAM BY USING THE **FILE** SUBMENU.
3. SWITCH THE TEACHING BOX SWITCH TO THE *OFF* POSITION.
4. EXECUTE THE **SKIBBY2.BAS** PROGRAM BY USING THE **RUN** SUBMENU.
5. UPON EXECUTION OF THE PROGRAM, THE FOLLOWING COMPUTER SCREEN PRESENTATIONS WILL BE DISPLAYED:
    a. Introductory screen - press SPACEBAR to nest.
    b. Foundation plan view.
    c. Footing section view.
    d. Foundation plan view - enter y-dimension.

e. Foundation plan view - enter x-dimension.

f. Press SPACEBAR to begin excavation program.

g. Excavation information screen - reports side and length in progress.

h. Re-positioning information screen.

i. Excavation of side complete. Press SPACEBAR to continue to next side.

j. Excavation of side 4 complete. Press SPACEBAR to nest.

h. Foundation footings are completed. Press any key to return to QuickBASIC.

6. SAVE **SKIBBY2.BAS** PROGRAM BY USING THE **FILE** SUBMENU.

APPENDIX A

Computer Screen Presentations

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

WELCOME TO THE CONSTRUCTION ENGINEERING AND MANAGEMENT DIVISION
ROBOTICS LABORATORY
PURDUE UNIVERSITY

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

This program emulates the excavation of building foundation footings.

Press SPACE BAR to nest SKIBBY

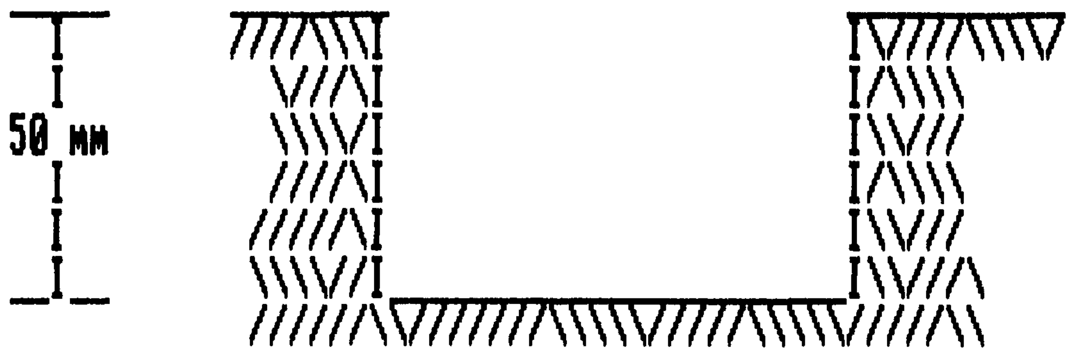
```
************************************************************
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
************************************************************

             ____________side 3_____________
            l                               l
       s    l                               l    s
       i    l                               l    i
       d    l                               l    d
       e    l                               l    e
            l                               l
       4    l                               l    2
            l                               l
            l____________side 1_____________l
            x - starting point

                    FOUNDATION PLAN VIEW

           Press SPACE BAR to view footing section
```

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

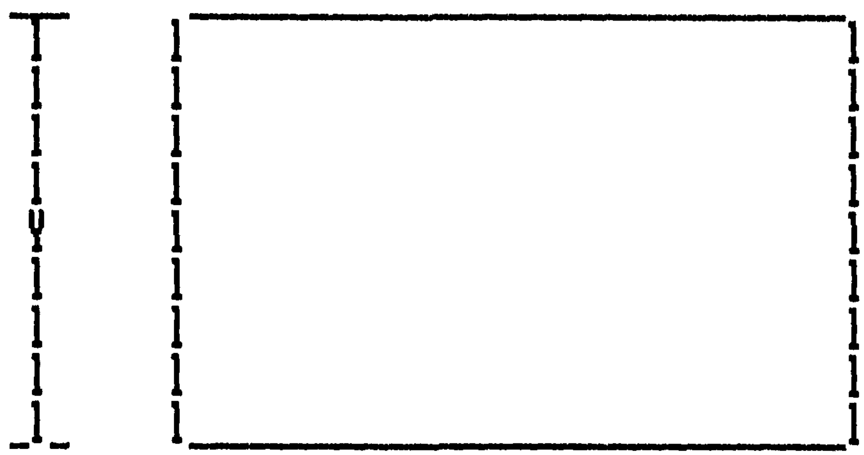


FOOTING SECTION VIEW

Excavation depth is 50 mm

Press SPACE BAR to enter foundation dimensions

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****



FOUNDATION PLAN VIEW

Please enter the foundation Y - dimension (mm):

```
***************************************************************
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
***************************************************************

                  |------------- X -------------|
```

FOUNDATION PLAN VIEW

Please enter the foundation X - dimension (mm):

```
***************************************************************
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
***************************************************************
```

Press SPACE BAR to begin excavation program

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Excavation of side 1 in progress

95 mm footing will be completed on this pass

```
***************************************************************
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
***************************************************************
```

Standby while SKIBBY re-positions

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Excavation of side 1 complete

SKIBBY is re-positioning to next side

Press SPACE BAR when SKIBBY is re-positioned

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Excavation of side 4 complete

Press SPACE BAR to nest SKIBBY

****
CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM
****

Foundation footings are completed

Press any key to continue

APPENDIX B

Automated Excavator Program

```
'***************************AUTOMATED EXCAVATOR********************************
' SKIBBY2.BAS                                                   JAMES G. CRUZ
  SUMMER 1990

'This demonstration program allows the user to input the perimeter dimensions
 of a building foundation and, with the input, direct the excavator to carry
 out the exavation.  An excavation depth is given at 50 mm.
'*****************************************************************************

 Initialize all subroutines
DECLARE SUB INTRODUCTION (XDIM%, YDIM%)
DECLARE SUB XYDIMCALC (XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)
 ECLARE SUB SIDEINTRO (SIDE%, LENGTH%)
_ECLARE SUB TURNCORNER (SIDE%)
DECLARE SUB FINALSCREEN ()
 ECLARE SUB EXCAVATE1 ()
 ECLARE SUB EXCAVATE2 ()
DECLARE SUB MOVESKIBBY ()

 Initialize all variables
J% = 1
SIDE% = 1
 IDE1% = 0
 IDE2% = 0
REMAIN1% = 0
 EMAIN2% = 0
 DIM% = 0
YDIM% = 0
XL% = 0
 EMAIN11% = 0
_ENGTH% = 0

 LS

'Call introductory screens
CALL INTRODUCTION(XDIM%, YDIM%)

'Calculcate the required number of full 190 mm cycles/side
CALL XYDIMCALC(XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)

 OR J% = 1 TO 2

   'Perform excavation of sides 1 and 2, and then sides 3 and 4

   'Begin excavation of side
    FOR X% = 1 TO SIDE1%
       'SKIBBY completes two 95 mm passes for a total length of 190 mm
        LENGTH% = 190
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        CALL EXCAVATE2
       'Notify user that SKIBBY is re-positioning
        CALL MOVESKIBBY
    NEXT X%

 IF REMAIN1% > 0 THEN

   'Remaining length of side is completed
    IF REMAIN1% >= 95 THEN
        LENGTH% = 95
```

```
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        LPRINT "MP 155, 0, 200, -145, 180"
        CALL MOVESKIBBY
    END IF

    IF REMAIN1% >= 95 THEN
       REMAIN11% = REMAIN1% - 95
    ELSE
       REMAIN11% = REMAIN1%
    END IF

       LENGTH% = REMAIN11%
       CALL SIDEINTRO(SIDE%, LENGTH%)
       CALL EXCAVATE2
 ELSE
 END IF

    CALL TURNCORNER(SIDE%)
    SIDE% = SIDE% + 1

    FOR Y% = 1 TO SIDE2%
       'Begin excavation of side
       'SKIBBY completes two 95 mm passes for a total length of 190 mm
        LENGTH% = 190
        CALL SIDEINTRO(SIDE%, LENGTH%)
        CALL EXCAVATE1
        CALL EXCAVATE2
        CALL MOVESKIBBY
    NEXT Y%

 IF REMAIN2% > 0 THEN

    IF REMAIN2% >= 95 THEN
       LENGTH% = 95
       CALL SIDEINTRO(SIDE%, LENGTH%)
       CALL EXCAVATE1
       LPRINT "MP 155, 0, 200, -145, 180"
       CALL MOVESKIBBY
    END IF

    IF REMAIN2% >= 95 THEN
       REMAIN11% = REMAIN2% - 95
    ELSE
       REMAIN11% = REMAIN2%
    END IF

   'Call EXCAVATE2 to complete footing for this side
    LENGTH% = REMAIN11%
    CALL SIDEINTRO(SIDE%, LENGTH%)
    CALL EXCAVATE2

 ELSE
 END IF

    CALL TURNCORNER(SIDE%)
    SIDE% = SIDE% + 1

NEXT J%
```

```
CALL FINALSCREEN
```

```
'*****************************INTRODUCTION***********************************
' SUBROUTINE INTRODUCTION

' This subroutine prints the program introduction and receives dimensional
' input
 ****************************************************************************
 JB INTRODUCTION (XDIM%, YDIM%)

 CREEN 2

'Draw box outline for program introduction
LINE (10, 6)-(610, 190), , B
 INE (14, 8)-(606, 188), , B

'Print introduction screen
 OCATE 5, 8
 RINT "*****************************************************************"
LOCATE 6, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 7, 8
PRINT "*****************************************************************"
LOCATE 9, 8
 RINT "WELCOME TO THE CONSTRUCTION ENGINEERING AND MANAGEMENT DIVISION"
 OCATE 10, 8
PRINT "                         ROBOTICS LABORATORY"
 OCATE 11, 8
 RINT "                          PURDUE UNIVERSITY"
LOCATE 13, 8
PRINT "*****************************************************************"
 OCATE 14, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 15, 8
 RINT "*****************************************************************"

LOCATE 17, 5
PRINT "This program simulates the excavation of building foundation footings."

LOCATE 20, 8
PRINT "                    Press SPACE BAR to nest SKIBBY"
 O UNTIL INKEY$ <> ""
LOOP
'Nest SKIBBY prior to start of excavation
 PRINT "NT"

'Set speed equal to 5
 PRINT "SP 5"

'Set tool length for bucket at 100 mm
LPRINT "TL 100"

 Nest bucket until ready to excavate
LPRINT "MP 155, 0, 200, -145, 180"

 LS
'Define SKIBBY's starting position
LINE (10, 6)-(610, 190), , B
 INE (14, 8)-(606, 188), , B

LOCATE 3, 8
 RINT "*****************************************************************"
```

```
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 5, 8
 RINT "*****************************************************************"

 OCATE 7, 8
 RINT "                 _____________side 3______________"
LOCATE 8, 8
PRINT "                1                                  1"
 OCATE 9, 8
 RINT "             s  1                                  1  s"
LOCATE 10, 8
 RINT "             i  1                                  1  i"
 OCATE 11, 8
PRINT "             d  1                                  1  d"
 OCATE 12, 8
 RINT "             e  1                                  1  e"
LOCATE 13, 8
PRINT "                1                                  1"
 OCATE 14, 8
 RINT "             4  1                                  1  2"
LOCATE 15, 8
 RINT "                1                                  1"
 OCATE 16, 8
PRINT "                1_____________side 1______________1"
 OCATE 17, 8
 RINT "                x - starting point"

LOCATE 19, 8
 RINT "                        FOUNDATION PLAN VIEW"

LOCATE 21, 8
 RINT "            Press SPACE BAR to view footing section"

DO UNTIL INKEY$ <> ""
 OOP

 LS

 Define footing depth
 INE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B


LOCATE 3, 8
PRINT "*****************************************************************"
 OCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
 RINT "*****************************************************************"

LOCATE 7, 8
PRINT "    _____     ________                             ___________"
 OCATE 8, 8
 RINT "      I       ////\\\I                             I\////\\\\/"
LOCATE 9, 8
 RINT "      I         \///\I                             I/\\\\"
 OCATE 10, 8
PRINT "    50 mm       \\\\/I                             I\\///"
 OCATE 11, 8
```

```
PRINT "        I          ////\I                         I/\\\\"
LOCATE 12, 8
PRINT "        I         /////\I                         I\\///"
LOCATE 13, 8
PRINT "      __I__       \\\\//I_______________________I\\///\"
LOCATE 14, 8
PRINT "                  //////\\////////\\\\\/////\\\\\\//////\\"

LOCATE 16, 8
PRINT "                           FOOTING SECTION VIEW"

LOCATE 18, 8
PRINT "                         Excavation depth is 50 mm"

LOCATE 20, 8
PRINT "          Press SPACE BAR to enter foundation dimensions"

DO UNTIL INKEY$ <> ""
LOOP

CLS

LOCATE 23, 8

 Define foundation dimensions
LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "************************************************************"

LOCATE 7, 8
PRINT "          ___      _________________________________"
LOCATE 8, 8
PRINT "           1      1                                 1"
LOCATE 9, 8
PRINT "           1      1                                 1"
LOCATE 10, 8
PRINT "           1      1                                 1"
LOCATE 11, 8
PRINT "           1      1                                 1"
LOCATE 12, 8
PRINT "           Y      1                                 1"
LOCATE 13, 8
PRINT "           1      1                                 1"
LOCATE 14, 8
PRINT "           1      1                                 1"
LOCATE 15, 8
PRINT "           1      1                                 1"
LOCATE 16, 8
PRINT "          _1_     1_________________________________1"

LOCATE 18, 8
PRINT "                          FOUNDATION PLAN VIEW"
```

```
LOCATE 21, 8
TNPUT "       Please enter the foundation Y - dimension (mm): ", YDIM%

LS

 INE (10, 6)-(610, 190), , B
 INE (14, 8)-(606, 188), , B

 OCATE 3, 8
 RINT "***************************************************************"
LOCATE 4, 8
PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
 OCATE 5, 8
 RINT "***************************************************************"

 OCATE 7, 8
 RINT "                1-------------- X --------------1"
LOCATE 9, 8
PRINT "                 __________________________________"
 OCATE 10, 8
 RINT "                1                                 1"
LOCATE 11, 8
 RINT "                1                                 1"
 OCATE 12, 8
PRINT "                1                                 1"
 OCATE 13, 8
 RINT "                1                                 1"
LOCATE 14, 8
PRINT "                1                                 1"
 OCATE 15, 8
 RINT "                1                                 1"
LOCATE 16, 8
 RINT "                1                                 1"
 OCATE 17, 8
PRINT "                1                                 1"
 OCATE 18, 8
 RINT "                1_________________________________1"

 OCATE 20, 8
 RINT "                          FOUNDATION PLAN VIEW"
LOCATE 22, 8

 NPUT "       Please enter the foundation X - dimension (mm): ", XDIM%

LS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 OCATE 3, 8
PRINT "***************************************************************"
 OCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "***************************************************************"


LINE (120, 90)-(510, 120), , B
 INE (124, 92)-(506, 118), , B
```

```
LOCATE 14, 19
 RINT "Press SPACE BAR to begin excavation program"

DO UNTIL INKEY$ <> ""
 OOP

END SUB
```

```
'****************************CYCLE CALCULATIONS******************************
'SUBROUTINE XYDIMCALC

 This subroutine calculates the number of cycles which will be required to
'excavate all four sides of the foundation.
 ****************************************************************************
 UB XYDIMCALC (XDIM%, YDIM%, SIDE1%, SIDE2%, REMAIN1%, REMAIN2%)

'Calculate the number of complete cycles required to excavate sides 1 and 3
 IDE1% = INT(XDIM% / 190)

'Calculate remaining length required to be excavated on sides 1 and 3
 EMAIN1% = XDIM% - (SIDE1% * 190)

'Calculate the number of complete cycles required to excavate sides 2 and 4
 IDE2% = INT(YDIM% / 190)

'Calculate remaining length required to be excavated on sides 2 and 4
REMAIN2% = YDIM% - (SIDE2% * 190)

_ND SUB
```

```
'*****************************SIDE INTRODUCTION*****************************
'SUBROUTINE SIDEINTRO

'This subroutine displays the "excavation in progress" screen
'***************************************************************************
 UB SIDEINTRO (SIDE%, LENGTH%)

CLS

    LINE (10, 6)-(610, 190), , B
    LINE (14, 8)-(606, 188), , B

    LOCATE 3, 8
    PRINT "*****************************************************************"
    LOCATE 4, 8
    PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
    LOCATE 5, 8
    PRINT "*****************************************************************"

    LINE (120, 90)-(510, 120), , B
    LINE (124, 92)-(506, 118), , B

    LOCATE 14, 25
    PRINT "Excavation of side "; SIDE%; " in progress"

    LOCATE 20, 16
    PRINT ""; LENGTH%; " mm footing will be completed on this pass"

END SUB
```

```
'******************************TURNCORNER*************************************
'SUBROUTINE TURNCORNER

 This subroutine displays the fact that the excavator is turning the corner,
're-positioning for the next side.
 ***************************************************************************
 UB TURNCORNEk (SIDE%)

"TONE = 780
 TONE = 329
 ɪ% = 0

 LS
     LINE (10, 6)-(610, 190), , B
     LINE (14, 8)-(606, 188), , B

     LOCATE 3, 8
     PRINT "*************************************************************"
     LOCATE 4, 8
     PRINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
     LOCATE 5, 8
     PRINT "*************************************************************"

     LINE (120, 90)-(510, 120), , B
     LINE (124, 92)-(506, 118), , B

     LOCATE 14, 24

     PRINT "Excavation of side "; SIDE%; " complete"

     IF SIDE% = 4 THEN
        LOCATE 20, 25
        PRINT "Press SPACE BAR to nest SKIBBY"
        DO UNTIL INKEY$ <> ""
        LOOP
        LPRINT "NT"
     ELSE
        LOCATE 18, 23
        PRINT "SKIBBY is re-positioning to next side"
        LOCATE 20, 19
        PRINT "Press SPACE BAR when SKIBBY is re-positioned"

        DO UNTIL T% = 15
           SOUND HTONE, 5
           SOUND LTONE, 5
           T% = T% + 1
        LOOP

        DO UNTIL INKEY$ <> ""
        LOOP

     END IF

 ND SUB
```

```
'****************************FINAL SCREEN**********************************
SUBROUTINE FINALSCREEN

'This subroutine displays the final program screen, informing the user that
'the excavation has been completed.
**************************************************************************
JB FINALSCREEN

LS

LINE (10, 6)-(610, 190), , B
INE (14, 8)-(606, 188), , B

LOCATE 3, 8
PRINT "***************************************************************"
OCATE 4, 8
RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
RINT "***************************************************************"

LINE (120, 90)-(510, 120), , B
INE (124, 92)-(506, 118), , B

LOCATE 14, 24
PRINT "Foundation footings are completed"

ND SUB
```

```
'**************************PERFORM EXCAVATION CYCLE*****************************
'SUBROUTINE EXCAVATE1

'This program excavates 95 mm (95 mm per bucket pass) to a depth of 50 mm.
'******************************************************************************
 UB EXCAVATE1

'Begin first bucket pass which excavates 95mm length

    'Begin excavation process
     LPRINT "MP 430, 0, 520, -10, 180"

    'Begin excavation motion
     LPRINT "MP 503, 0, 146, -45, 180"

     LPRINT "SP 3"
    'Pivot bucket
     LPRINT "MP 476, 0, 95, -60, 180"

    'Draw bucket towards SKIBBY
     LPRINT "MP 460, 0, 86, -70, 180"
     LPRINT "MP 418, 0, 75, -80, 180"
     LPRINT "MP 380, 0, 53, -95, 180"

    'Scoop up
     LPRINT "MP 155, 0, 200, -145, 180"

     LPRINT "SP 5"
    'Prepare to rotate and deposit

     LPRINT "MP -50, 155, 200, -145, 180"

    'Extend boom and rotate bucket to deposit into spoils pile
     LPRINT "MP -100, 450, 520, 0, 180"

¯ND SUB
```

```
'*************************PERFORM EXCAVATION CYCLE****************************
'SUBROUTINE EXCAVATE2

This program excavates 95 mm (95 mm per bucket pass) to a depth of 50 mm.
'*****************************************************************************
 UB EXCAVATE2

'Begin second bucket pass which excavates 95mm

    'Begin excavation process
     LPRINT "MP 380, 0, 520, -10, 180"

    'Begin excavation motion
     LPRINT "MP 408, 0, 146, -45, 180"

     LPRINT "SP 3"
    'Pivot bucket
     LPRINT "MP 380, 0, 95, -60, 180"

    'Draw bucket towards SKIBBY
     LPRINT "MP 345, 0, 75, -80, 180"
     LPRINT "MP 285, 0, 65, -90, 180"
     LPRINT "MP 230, 0, 50, -125, 180"

    'Scoop up
     LPRINT "MP 155, 0, 200, -145, 180"

     LPRINT "SP 5"
    'Prepare to rotate and deposit

     LPRINT "MP -50, 155, 200, -145, 180"

    'Extend boom and rotate bucket to deposit into spoils pile
     LPRINT "MP -100, 450, 520, 0, 180"

     LPRINT "MP 155, 0, 200, -145, 180"

END SUB
```

```
'******************************MOVE SKIBBY***************************************
'SUBROUTINE MOVESKIBBY

 This subroutine provides screen display which notifies user that SKIBBY is
'backing up in order to re-position itself for another cycle
 ********************************************************************************
 UB MOVESKIBBY

"TONE = 780
 LTONE = 329
T% = 0
CLS

LINE (10, 6)-(610, 190), , B
LINE (14, 8)-(606, 188), , B

 OCATE 3, 8
PRINT "*************************************************************************"
LOCATE 4, 8
 RINT "CEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEMCEM"
LOCATE 5, 8
PRINT "*************************************************************************"


 INE (120, 90)-(510, 120), , B
 INE (124, 92)-(506, 118), , B

  CATE 14, 25
 RINT "Standby while SKIBBY re-positions"

 O UNTIL T% = 10
   SOUND HTONE, 5
   SOUND LTONE, 5
   T% = T% + 1
LOOP

 ND SUB
```