N91-20035

p. 52

1990 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

SOME ASPECTS OF ROBOTICS CALIBRATION, DESIGN AND CONTROL

PREPARED BY:	Dr. Hazem Tawfik
ACADEMIC RANK:	Associate Professor
UNIVERSITY AND DEPARTMENT:	State University of New York - Farmingdale Mechanical Engineering Technology
NASA/KSC	
DIVISION:	Mechanical Engineering
BRANCH:	Special Projects (RADL)
NASA COLLEAGUE:	Mr. V. Leon Davis
DATE:	August 8, 1990
CONTRACT NUMBER:	University of Central Florida NASA-NGT-60002 Supplement: 4

ACKNOWLEDGEMENTS

I would like to thank my KSC colleague Mr. Leon Davis for giving me such a wonderful opportunity to participate in the interesting activities taking place in his robotics section at KSC. Also, thanks should be extended to the whole robotics engineering team for their cooperation; especially the coop student Mr. Tom Woods.

I am also grateful to the UCF program director Dr. Loren Anderson for making the summer program as much fun as it was a challenge. Ms. Kari Baird's enthusiasm and helpfulness was very much appreciated.

Many thanks to the NASA/KSC summer program director Dr. Mark Beymer for his friendliness.

ABSTRACT

The main objective of this project was to introduce the reader to techniques in the areas of testing and calibration, design, and control of robotics systems. A statistical technique was described to analyze a robot's performance and provide quantitative three dimensional evaluation of its repeatability, accuracy, and linearity. Based on this analysis; a corrective action should be taken to compensate for any existing error(s) and enhance the robot's overall accuracy and performance.

A comparison between robotics simulation software packages that were commercially available (SILMA, IGRIP) and that of KSC (ROBSIM) was also included in this report. These computer codes simulated the kinematics and dynamics patterns of various robotics arms geometry to help the design engineer in sizing and building the robot manipulator and its control system.

Finally, this report provided a brief discussion on an adaptive control algorithm.

SUMMARY

Robots are becoming increasingly viable in various applications within NASA/KSC. Most of these applications require more precision and sensory sophistication such as remote umbilical, radiator, tile, payload inspection etc. The mechanical structure of a robot manipulator usually consists of a number of interacting links and joints with separate drive and control systems. Therefore, the various sources of error that each joint could experience will result in a cumulative error and inaccuracy in the positioning of the end effector's tool center point.

Accordingly, a simple and straight forward technique to calibrate a robot and analyze its performance was deemed necessary.

The present report gives a detailed description of both the hardware and software that are used in the development of a statistical technique that provides a three dimensional evaluation of the robot's overall repeatability, accuracy, and linearity. Based on the obtained results and analysis, corrective measures could be taken such that the robot's inverse and forward kinematic software and/or control system would account for the errors to enhance accuracy and performance. In addition, for trouble shooting an operational problem, this technique could also be conducted to examine the accuracy of every individual joint that will help trace and rectify the problem.

The second part of this project provides a comparison between two commercially available computer codes (SILMA and IGRIP) and NASA's (ROBSIM) program. This comparison will help NASA/KSC make a decision regarding the selection of a computer simulation package for the robotics kinematics, dynamics, and control system. Such a package is very useful for an engineer during the design stage to size the various components of a robotics system. The SILMA package was found to be the easiest to use and equipped with the best graphical display that could be integrated with various work stations.

The third part of the report gives a brief discussion on the adaptive control algorithm for the radiator inspection robot. Because of the variation in the manipulator's inertia through the robot trajectory, the torque requirement at the joints will also change with the robot's position. Accordingly, the PID loop optimum gains will also change. The proposed algorithm is based on a closed form polynomial of the 8th order or more to yield the optimum gain values for the PID loop that corresponds with robot location.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

IGRIP	-	Interactive Graphics Robot Instruction Program
KSC	-	Kennedy Space Center
LaRC	-	Langley Research Center
RADL	-	Robotics Applications Development Laboratory
ROBSIM	-	ROBotics SIMulation program
TCP	-	Tool Center Point

LIST OF ILLUSTRATIONS

I INTRODUCTION

1.1 ROBOTICS IN INDUSTRY

The economical value of the use of robots in industry has been proven because robots increase productivity, enhance quality, and reduce the price per units. Most of the industrial applications require high precision and sensory sophistication such as assembly, deburring etc. However, due to operational, environmental, and manufacturing factors the robot's accuracy deteriorates. Accordingly, initial and periodical testing and calibration of robots is a very important task. Since the beginning of the use of robots in industry back in the 70's until the present time there is no satisfactory calibration and testing scheme to examine the robot's performance and accuracy. The present report provides a detailed description of a precise, simple, and straight forward technique that evaluates the repeatability, relative accuracy, and linearity.

1.2 ROBOTICS At NASA/KSC

As soon as the shuttle returns back from a space mission and rolls into the Orbit Processing Facility it goes through rigorous inspection, service and maintenance routines. Some of these inspection routines lend themselves well as a robotics application such as the radiator, tiles, etc. Also, in the shuttle program at KSC there are other robotics applications that are still in the research and development stage such as remote umbilical connection, payload inspection, etc. In addition, robots are currently used in other processes at KSC such as the coat removing process of the booster rockets using water jets after having been picked up from the ocean.

All these robots previously indicated require routine calibration and testing every four to six months depending on the accuracy requirement of the task to be accomplished. The technique described in this report will not only calibrate the robot but also will help the trouble shooting process by testing each individual joint separately.

1.3 WHEN TO CALIBRATE AND TEST A ROBOT?

Any robot should be tested as indicated in the following:

- After Initial Instalation
- Periodically During Operation
- Trouble Shooting A Problem

II ROBOTICS CALIBRATION AND TESTING

2.1 SOURCES OF ERRORS

The robot manipulator is simply described as an open chain that consists of a number of links and joints to provide the arm with a certain degree of freedom (DOF). The manipulator is fitted to a firm base at one end and an end effector is mounted to the other end of the arm. The arm is designed to provide accurate positioning of the end effector's tool center point (TCP) in the space to conduct certain tasks such as material handling, welding, visual inspection etc.

However, the cumulative errors in all links and joints combined with the possible inaccuracy of the robot's control system will result in an overall error in the location of the TCP. These sources of error could be summarized in the following:

- Servo positioning error (Due to linearization)
- Variations in the links dimensions due to manufacturing tolerances.
- Backlash and wear in the joints due to operation
- Arm deflection due to its flexibility and variation in the environment temperature.
- The zero of the encoder does not coincide with the zero of the joint.
- Forward and inverse kinematics error due to linearization around a nominal operating point.

Accordingly, a simple and straight forward technique was found necessary to evaluate the overall error in the X,Y, and Z directions experienced by the end effector in the positioning of the TCP. The few robotics calibration techniques that are recently available in the literature can be described as rather complicated; and some of them do not reach an acceptable level of accuracy.

2.2 PARAMETERS OF TESTING AND CALIBRATION

The present robotics calibration techniques enjoy both precision and simplicity in the evaluation of the following calibration parameters:

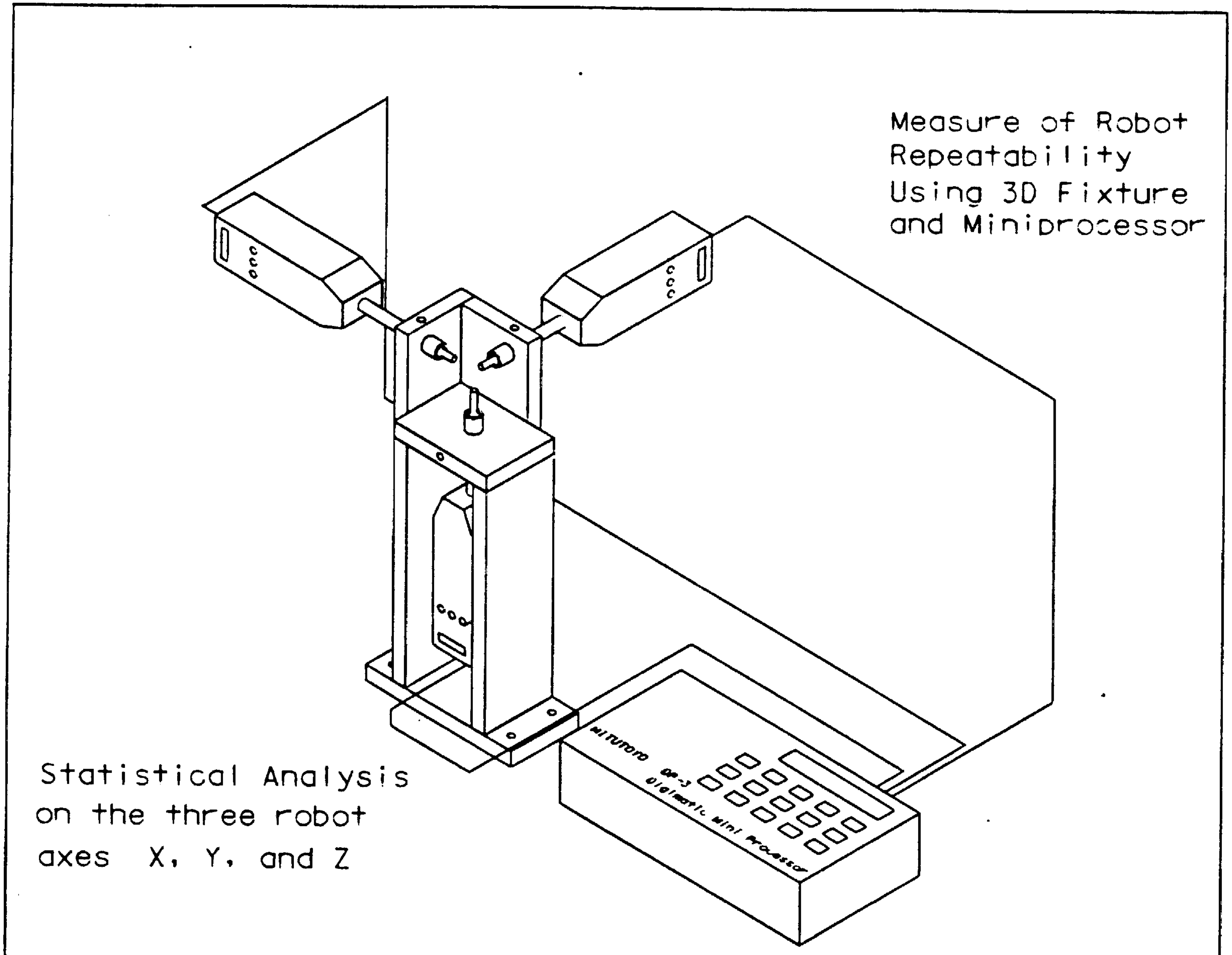


Figure 2-1 3D Fixture For measuring repeatability

E:\DGN\TAWFIK2.HLN Jul. 31, 1990 14:44:58

- Repeatability
- Accuracy
- Linearity

This report provides a detailed description of such a technique supported with illustrative figures and diagrams of both hardware and software that are used in the study, analysis, and evaluation of the previously mentioned parameters. This analysis will help the corrective action decision so the robot forward and inverse kinematic software as well as the control system will account for the calculated errors and improve the overall accuracy of the robot manipulator.

2.3 EVALUATION OF THE ROBOT'S REPEATABILITY IN THREE DIMENSIONAL X,Y,AND Z AXES

The repeatability of a robot is defined as how close the robot will locate the TCP to a previously taught position. A taught position means that the robot should be physically at this point and all the encoder or resolver readings are recorded. This means that the goal points are never specified in cartesian coordinates and the inverse kinematic computation never arises. Simply, repeatability is a teach and playback process. Therefore, the first step in the robot's calibration procedure is the examination of its repeatability. The measurement of the repeatability could be conducted using the calibration fixture with three dial or digimatic indicators as shown in Figure 2-1.

2.4 HARDWARE DESCRIPTION

The hardware consists of the following:

- 3D Calibration Fixture
- Cube With Blunt Front Corner
- Digimatic Mini Processor
- Digimatic Data Logger
- Digimatic Data Transmitter
- Digimatic Dial Indicator
- PC Computer With Math Co-processor and 640K memory
- Communication Cables

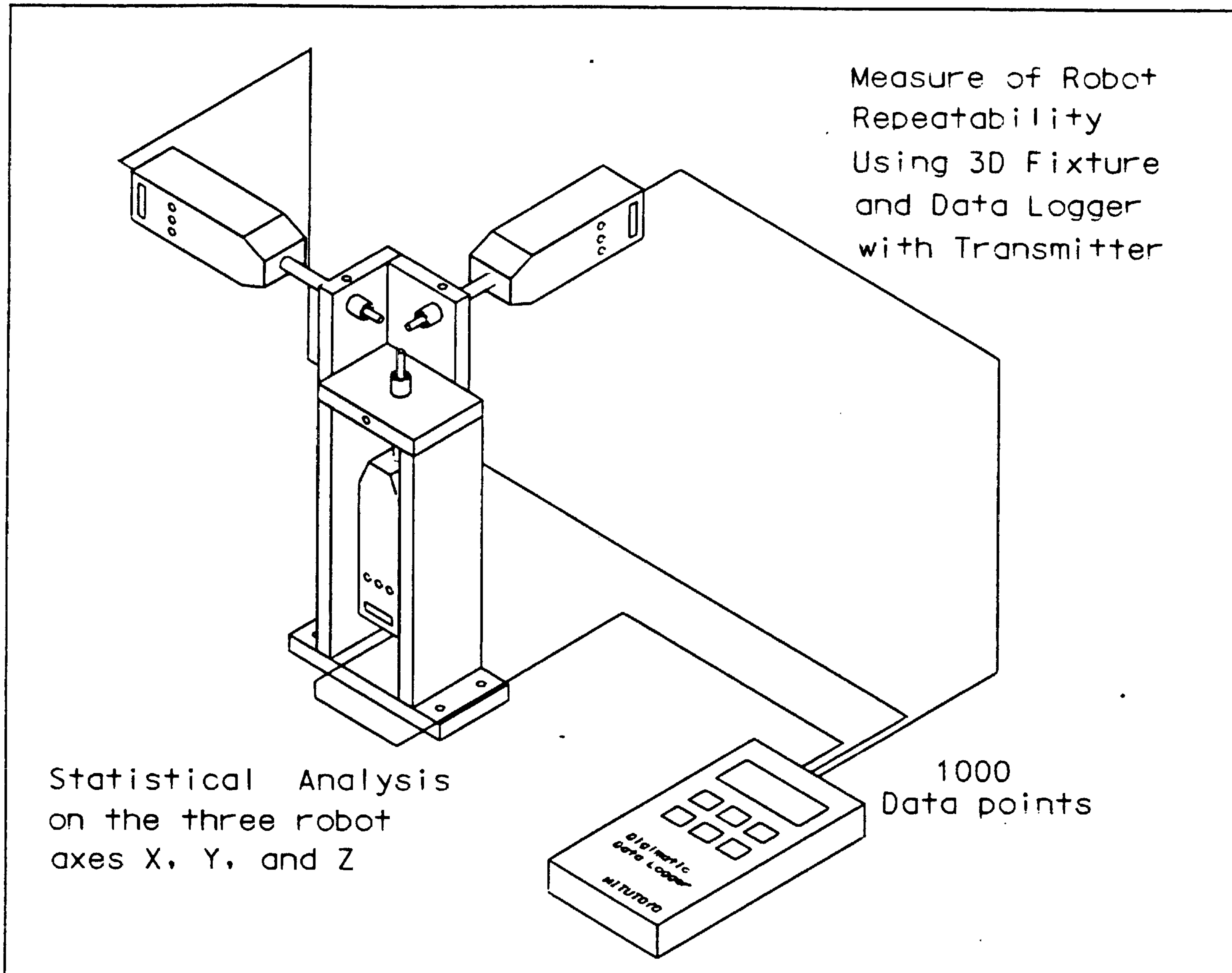


Figure 2-2 3D Fixture connected to Data Logger

E.\DGN\TAMFIK2.HLN Aug 01, 1990 11.02.28

ORIGINAL PAGE IS
OF POOR QUALITY

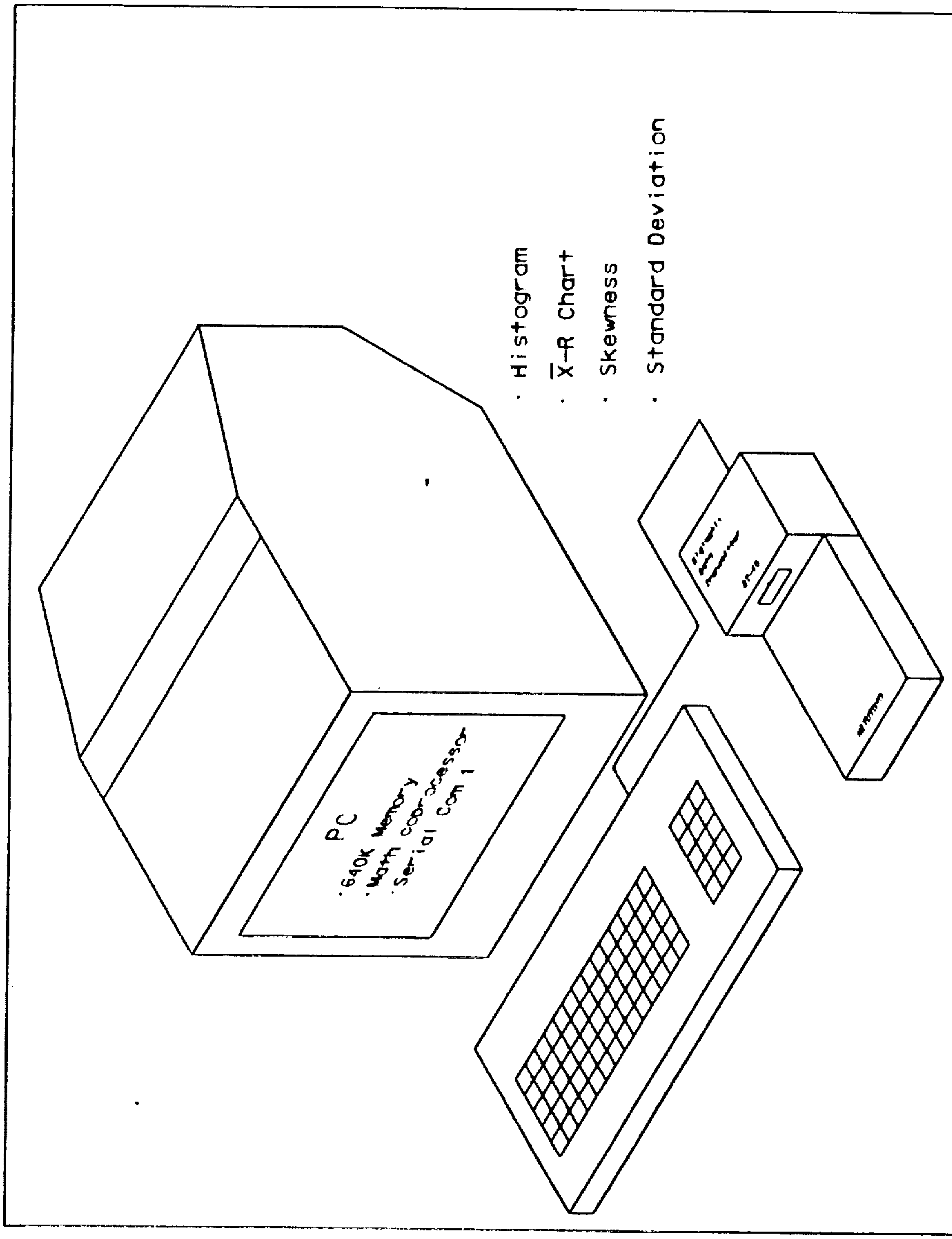


Figure 2-3 Data transmitted to Computer

E:\DGN\TAWFIK2.HLN Jul. 31, 1990 13.49.17

2.5 DESCRIPTION OF THE SOFTWARE

Two software packages are used to perform the required analyzes and evaluate the following statistical parameters:

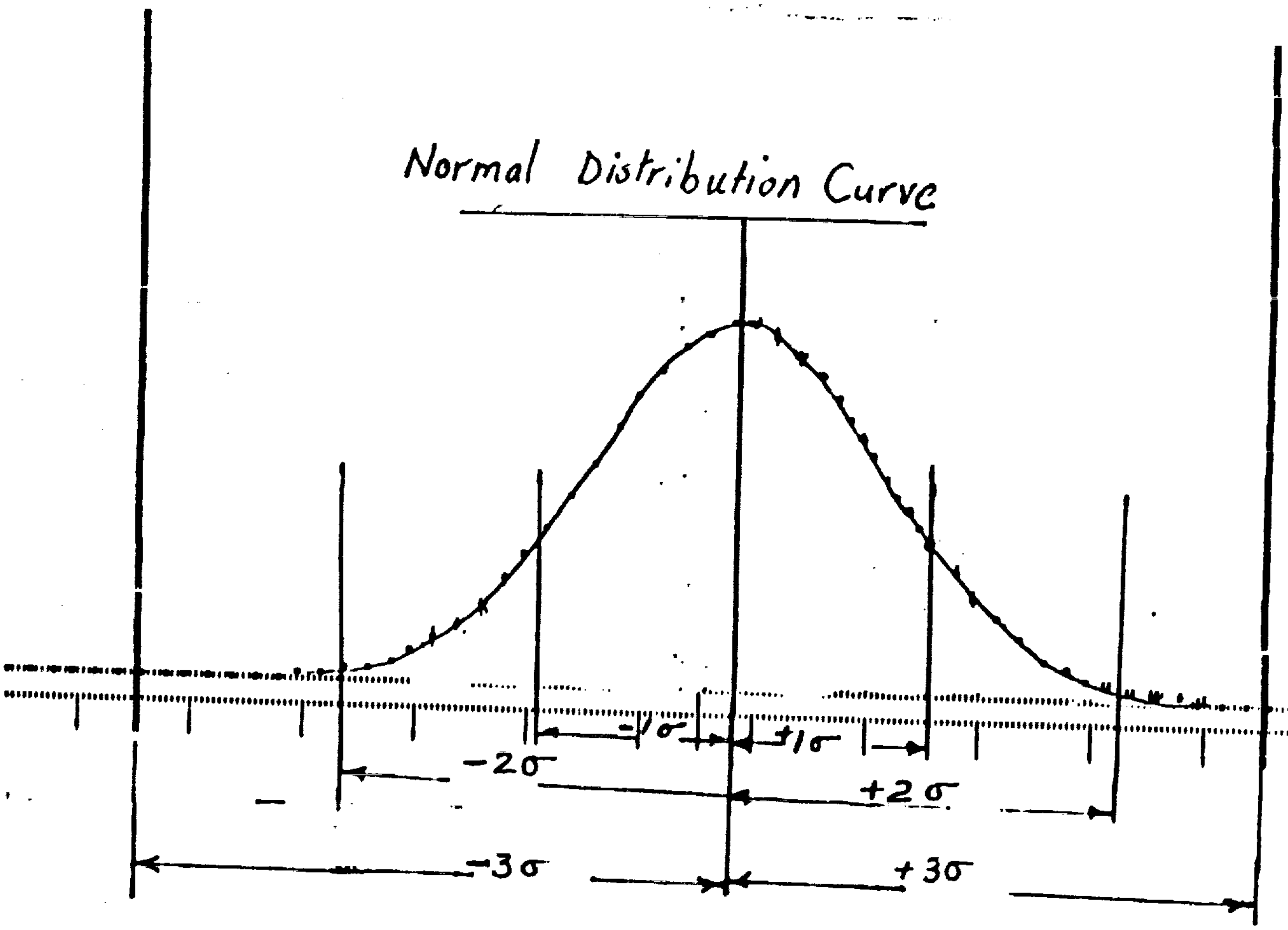
- Average or Mean
- Mode
- Standard Deviation
- Skewness
- Range

Also, these packages provide plots of the Histogram, and the Xbar-R charts.

2.6 EXPERIMENTAL PROCEDURE

The experimental procedure consists of the following steps:

- Bolt or clamp the 3D fixture to a surface plate within the work envelope of the robot.
- Install the digimatic dial indicators and lock them to the X,Y, and Z axes as shown in Figure 2-1.
- Mount a cube with a blunt front corner on the end effector of the robot under examination.
- Move the robot such that the cube will fit between the three indicators and cause approximately a 3/8 inch deflection in each indicator.
- Teach that position (A) to the robot controller
- Move the robot about one inch away from the fixture and teach that position (B) to the robot controller.
- Move the robot to any arbitrary position within the work envelope and return back to position (A) via position (B).
- Record or Dump the three indicators readings to the Data Logger device Figure 2-2 and then to the PC computer through the Data Transmitter device and RS232 communication board Figure 2-3.
- Repeat this process 25 to 30 times.



Between ±1σ   68% of the Data

±2σ   95% of the Data

±3σ   99% of the Data

Figure 2-4   Normal Distribution Curve

2.7 DATA ANALYSIS

The data analysis is mainly performed by the two previously mentioned software packages. Also, a numerical example is given later on in this report to support and clarify the procedure.

2.7.1 Visual Observation of the Histogram

The first step of the analysis is the visual observation of the histogram to determine the existence of any skewness. The value of the skewness parameter a_3 given by the software provides an estimate for the degree of skewness in the histogram as shown in the following:

$a_3 = 0$	Symmetrical Histogram (Figure 2-4)
$a_3 > 0$	Skewed to the right
$a_3 < 0$	Skewed to the left

If a_3 is close to the value of + 1 or higher this is an indication that the histogram is highly skewed to the right or to the left; this skewness is usually attributed to an instability in the robot's control system. A corrective action should be taken.

2.7.2 The Location of the Average Line (X bar)

If the average value does not coincide with the nominal value, this amount of error could be attributed to the linearization of the inverse kinematics software and/or the effect of the ambient temperature.

2.7.3 The Robotics Capability Index

When evaluating the robotics system to determine if it is capable of meeting the specification requirements of a certain task, three parameters have to be evaluated as defined by the following three equations, also see Figure 2-4:

$$C_p = \frac{USL-LSL}{6*\sigma}$$

$$C_{pk1}=\frac{USL-\overline{X}}{3*\sigma}$$

$$C_{pk2}=\frac{\overline{X}-LSL}{3*\sigma}$$

as

C_p = Robotics Capability Index (RCI)- The robot will be classified as capable of meeting the task's accuracy requirements if the value of this parameter equals unity or more. If the value of the RCI is less than unity the robot is classified as incapable of performing the task.

C_{pk1} = This parameter will indicate if the robotics system is experiencing any shift off the nominal value. Accordingly, the value of this parameter should exceed unity.

C_{pk2} = Similar to the previous parameter

USL = Upper specification Limit

LSL = Lower Specification Limit

Sigma = Standard Deviation

2.7.4 Xbar-R Chart

The Xbar-R Chart should be examined for out of control signs and/or patterns. Some of these patterns could be summarized in the following:

- One point above the UCL or below the LCL

  UCL = X bar + 3 sigma

  LCL = X bar - 3 sigma

- Seven points in the row going up or down
- Fifteen points in the row going up and down
- Two points out of three are in zone "C"

2.7.5 Numerical Example

Consider a robot that is used in the assembly of mechanical parts, the nature of the task requires robot's repeatability as 0.001 in.

The following table 2-1 shows 30 arbitrary data points chosen to numerically present the procedure and analyses for only one axis the X axis say. Also, a Histogram was drawn for this set of data as shown in Figure 2-5.

In this example the average (X-bar) = 0.00008 inch which also indicates the repeatability in the X direction.

Accordingly, Total Repeatability = SQR((X-barx)^2 + (X-bary)^2 + (X-barz)^2)

Skewness (a_3) = - 0.356

This value of the skewness parameter indicates that the robot's control system could be experiencing a certain degree of bias. However, if the value of a_3 exceeded unity a corrective action should be considered.

Robot Capability Index C_r = (USL LSL)/(6 * sigma)

USL = + 0.001 inch

LSL = - 0.001 inch

The Standard Deviation (sigma) = 0.00026

C_r = 1.28 (Robot is Capable)

C_{rk1} = (USL - X bar)/ (3*sigma)

= (.001 - .0008) / (3 * 0.00026) = 0.256

C_{rk2} = (X bar - LSL) / (3 * sigma)

= (.0008 - (- 0.001)) / (3 * 0.00026) = 2.3

Both C_{rk1} and C_{rk2} should be larger than unity for no corrective action

The current numerical example indicates that the robot needs adjustment.

X bar - R Charts

The data shown in table 2-1 are plotted in an X bar - R chart as depicted in Figure (2-6). The study of this X bar - R chart shows no patterns or signs of out of control as previously explained.

DATE PRINTED 08-02-1990

PAGE

BASIC STATISTICS COMPREHENSIVE REPORT ON hht1

PART DESCRIPTION: calib

LOT DESCRIPTION: calib

SUBGROUP NUMBER: 1 SUBGROUP CODE: 1 08-02-1990 19:14

FEATURE: A NO. SUBGROUPS: 1 NO. PIECES/SUBGROUP: 30

MAXIMUM: +0.00070 AVERAGE: +0.00008 MINIMUM: -0.0005(

UPPER SPEC: +0.00100 NOMINAL: +0.00000 LOWER SPEC: -0.0010(

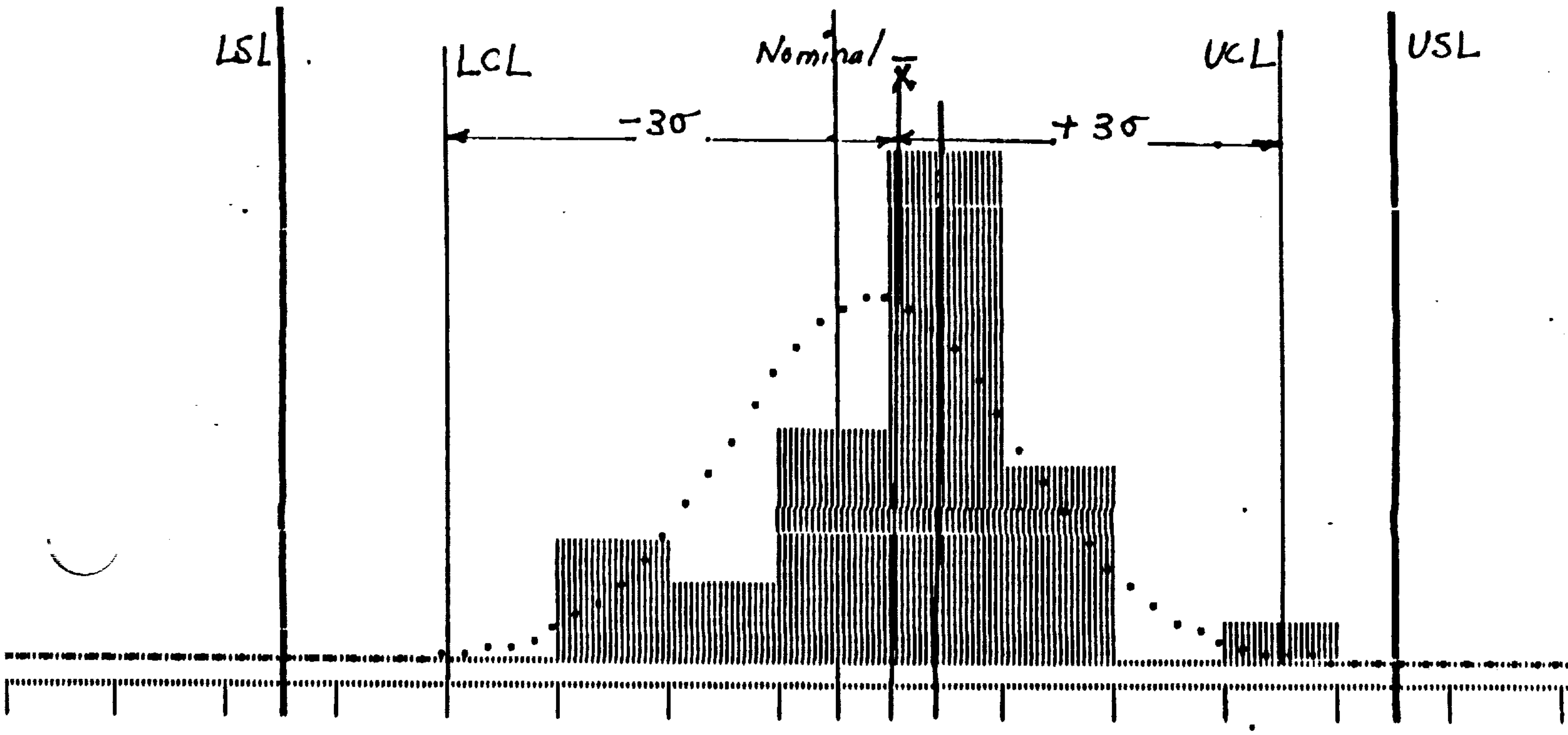
TOTAL NUMBER OF PIECES: 30 SIGMA: +0.00026 RANGE: 0.0012(

PIECES ABOVE UPPER SPEC: 0 PERCENT ABOVE UPPER SPEC: 0.00

PIECES BELOW LOWER SPEC: 0 PERCENT BELOW LOWER SPEC: 0.00

PIECE	MEASUREMENT	PIECE	MEASUREMENT	PIECE	MEASUREMEN
1	+0.00020	11	+0.00030	21	+0.00040
2	+0.00010	12	-0.00020	22	-0.00020
3	-0.00010	13	+0.00010	23	+0.00000
4	-0.00040	14	+0.00020	24	+0.00000
5	+0.00040	15	+0.00070	25	+0.00020
6	+0.00030	16	+0.00010	26	-0.00010
7	+0.00010	17	+0.00020	27	+0.00020
8	-0.00050	18	-0.00050	28	+0.00010
9	+0.00020	19	+0.00030	29	+0.00020
10	+0.00010	20	-0.00010	30	+0.00000

Table 2-1 Data Points Collected from One Axis of the 3D Fixture



MAX:	+0.00070	USL:	+0.00
(BAR:	+0.00008	NOM:	+0.00
MIN:	-0.00050	LSL:	-0.00
SIG:	+0.00026	RNG:	0.00
1ODE:	+0.00020	INTERVAL:	+0.00

Figure 2-5 Histogram

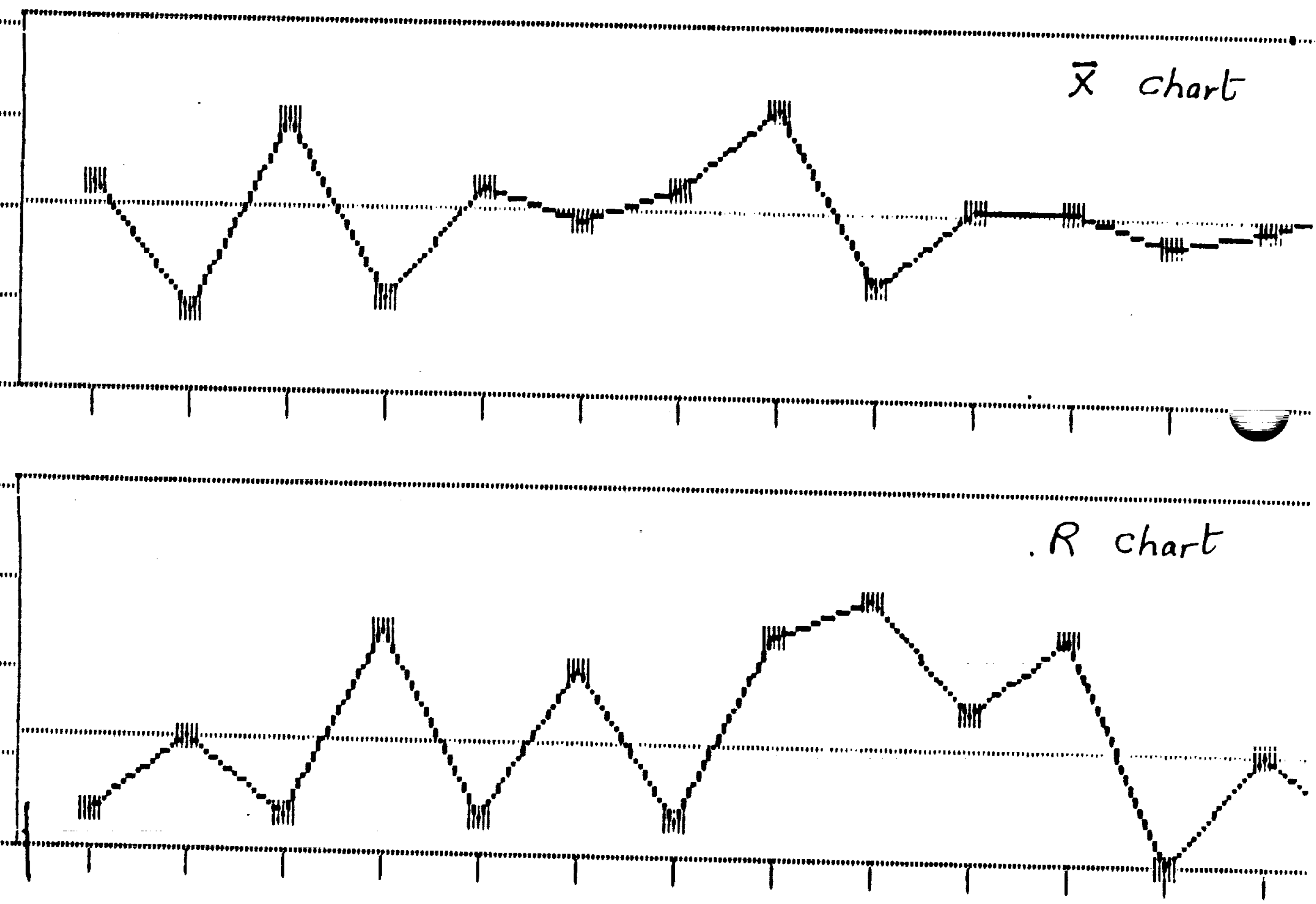


Figure 2-6 X̄-R charts

2.8 TESTING ROBOT'S ACCURACY IN THE THREE X,Y, and Z AXES

If the robot's repeatability is proven to be acceptable this will lead to the second step which is the checking of its accuracy. Accuracy, however, is defined as the precision with which a goal position, specified in cartesian terms, is attained. Accordingly, the inverse kinematics must be computed to find the required joint angle that yield the precise positioning of the TCP at the specified point. This will represent an additional source of error that will only influence the robot's accuracy but not its repeatability. Due to the linearization and approximation of most robotics inverse kinematic models associated with the possibility of more than one solution, robots in general are more repeatable than accurate.

Therefore, a good analytical technique, precise measurements and efficient data acquisition scheme are deemed necessary for detailed examination of any robot performance. Such a technique could also be used to trouble shoot an operational problem by monitoring the individual performance of the manipulator's joints.

According to the previous definition of accuracy the following two types should be considered they are as follows:

- Absolute Accuracy
  Measured with respect to the world coordinate system of the robot

- Relative Accuracy
  Measured in reference to any other coordinate system such as TCP, Encoders, etc.

The knowledge of the relative accuracy of a robot is much more important than the absolute in most applications. Therefore, this report is only concerned with the evaluation of the robot 's relative accuracy with respect to its encoder's reference points.

2.8.1 Experimental Set Up

The experimental set up is clearly exhibited in Figure (2-7) it consists of two 3D fixtures similar to that used in the repeatability measurement.

2.8.2 Experimental Procedure

The experimental procedure could be simply described in the following:

- Place the two fixtures as far apart as possible and still be within the work envelope of the robot.

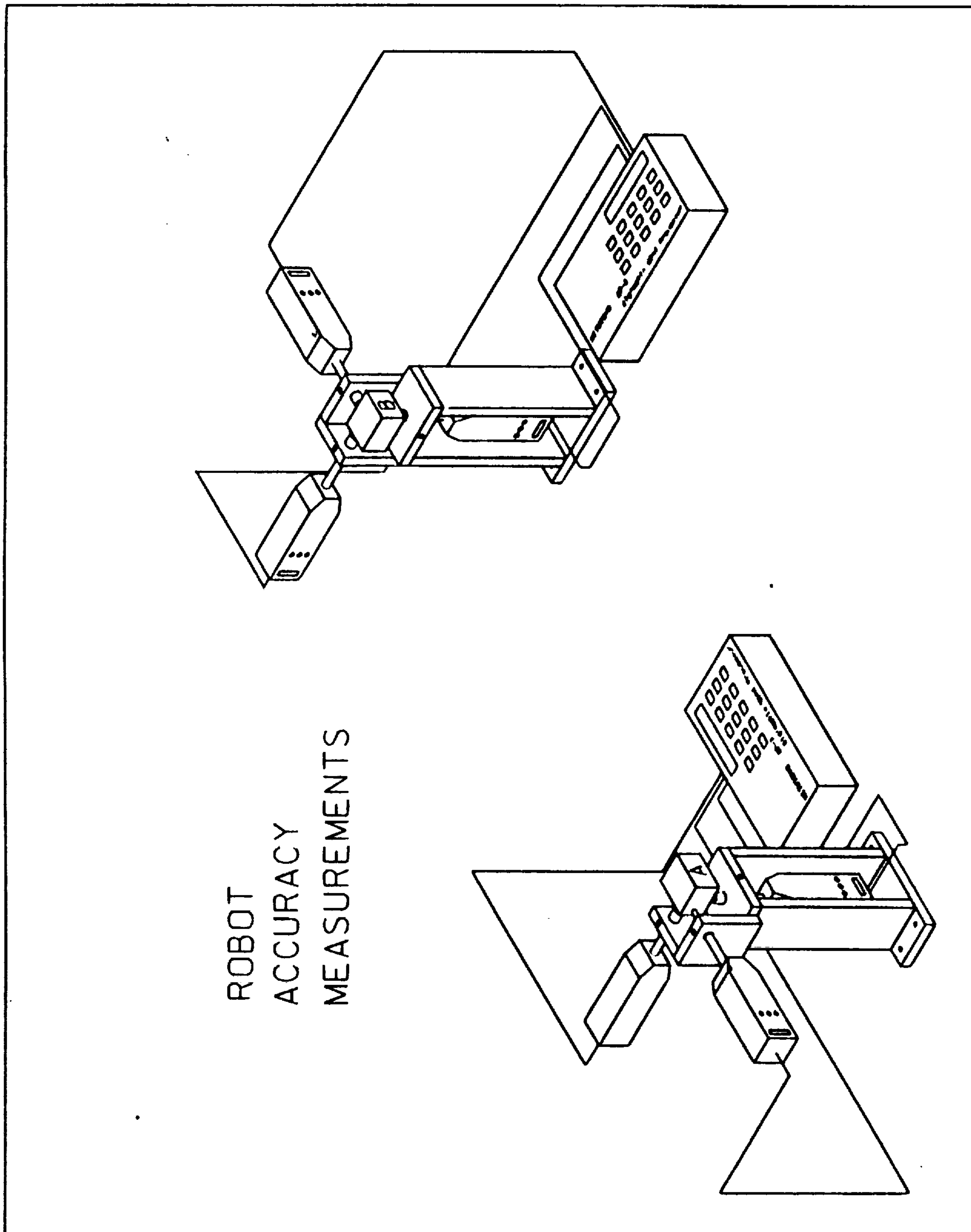


Figure 2-7 3D Robot Accuracy measurement set up

E:\DGN\TAWFIK2.HLN Jul. 31, 1990 13.19.33

- Place the blunt nose cube that is fitted to the end effector of the robot between the indicators of the first fixture to cause an approximate deflection of .5 inch in each indicator.

- Zero off the indicators and set this position as home for the robot arm i.e. all robot's encoders will read zero at this point.

- Move the arm to the second fixture and place the cube between the indicators tips to depress them for about .5 inch each.

- Read and record the teach pendent display of the X,Y, and Z coordinates of this second point.

- Zero off all indicators once more as well as set this position to home.

- Command the robot to go back to the first fixture through an inverse sign of the previously recorded point.

- Record or transmit the readings of the X,Y, and Z indicators to the computer for analysis and evaluation of the mean relative accuracy in each axis.

- Change the positions of these fixtures and repeat the procedure a few times to cover most of the work envelope.

- Evaluate the overall average accuracy in the direction of each axis.

2.8.3 Data Analysis

The analysis of the accuracy evaluation is similar to the previously described analysis for the evaluation of repeatability.

However, if the overall accuracy of each axis is within an acceptable range and the robot has not been classified as out of control, the error could be accounted for either in the control system gains or the inverse kinematic model of the robot. This will result in better accuracy and general improvement in the robot performance.

2.9 Testing of Robot's Linearity

The testing of the robot's linearity means examining its ability to move in straight line trajectories. To evaluate such ability an experimental set up is shown in Figure (2-8).

2.9.1 Equipment Requirement

The Equipment needed to evaluate the linearity of a robot consists of the following:

- Right angle holder for fitting two perpendicular indicators
- Parallel bar with parallelism and perpendicularity up to + 0.0001
- Linear scale with resolution of 0.0001 inch

2.9.2 Experimental Set Up

The experimental set up is summarized in the following:

- Mount the indicators on the holder such that they will be perpendicular to each other to few seconds
- Fit the combination of the holder and indicators to the end effector of the robot.
- Screw the linear scale to the side of the parallel bar
- Prepare a rigid connection between the linear scale and the indicator holder so the position of the TCP along the bar could be monitored.

2.9.3 Experimental procedure

The experimental procedure is as follows:

- Move the end effector until the indicators touch the horizontal and vertical surfaces of the parallel bar near one of its ends.
- Move further in till both indicators are depressed against the bar surfaces approximately .5 inch each.
- Connect the linear scale to the indicators holder
- Zero off the indicators as well as the linear scale and teach the robot this position (A)

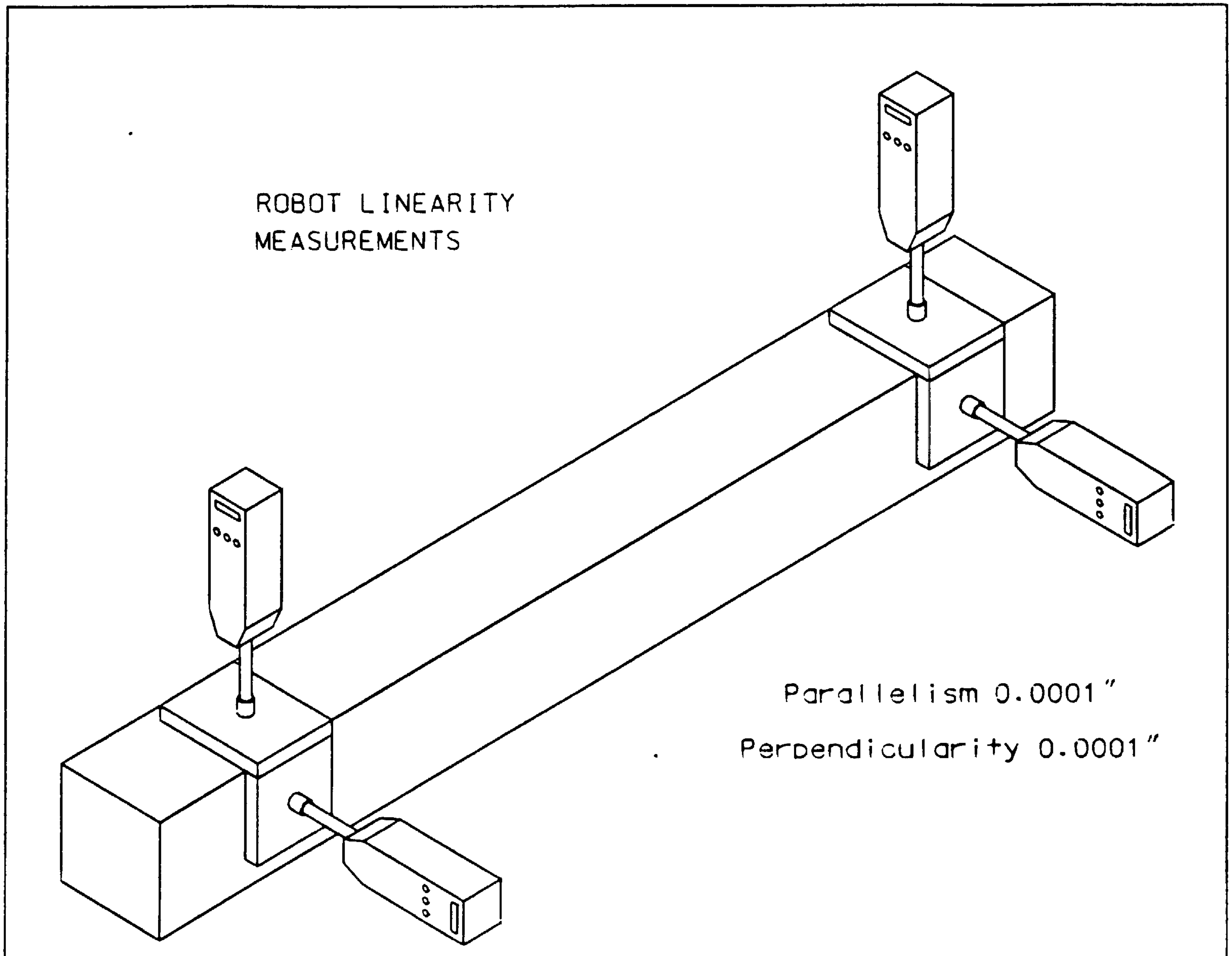


Figure 2-8 Experimental set up for linearity measurements

E:\DGN\TAWFIK2.HLN Aug. 01, 1990 13 06 53

- Move the end effector with the holder near the other end of the bar in a straight line motion to the best of the robots ability.

- Teach the robot this point (B)

- Zero off the indicators and the linear scale once more

- Command the robot to shuttle between (A) and (B) for 25 to 30 times

- Collect data through each stroke and perform analysis similar to that previously described to evaluate the robot's linearity.

III EVALUATION OF "ROBSIM" AND ITS USEABILITY AT NASA/KSC

3.1 Introduction

Due to the continuous expansion in the Robotics Application Development Laboratory (RADL) at KSC a good computer software package is needed to help the engineers design and size Robotics components. Currently, there are few packages that are commercially available as well as ROBSIM that is developed by NASA contractors.

Naturally, the ROBSIM package is available for any of NASA's Centers free of charge. However, the package that was given to KSC in 1989 or earlier, was found to be an incomplete according to Langley Research Center (LaRC) personnel. This was the reason that Dr. Gregory L. Tonkay could not use ROBSIM and give a fair evaluation of the package during his NASA/ASEE Summer Faculty Fellowship program in 1989. One of Dr. Tonkay concluding remarks was that " ROBSIM is awkward to learn, and use".

3.2 Package evaluation

Although the package has been completed, according to KSC personnel, I still concur with Gregory's findings with regard to ROBSIM's poor interaction with the user and it is not user friendly.

Also, it has limited graphics capability using Evans & Shutherland as well as poor collision avoidance model.

On the other hand, one should not ignore ROBSIM's good points such as:

- It provides a wide range of robotics design and analysis capabilities
- It models the kinematics and dynamics patterns of a robot manipulator
- It simulates linear control system with a PID loop
- It provides adaptive control algorithm

A comparison between ROBSIM package and other packages that are commercially available is given in table (3-1) next page.

Table 3-1 Comparison Of Robotics Simulation Software

Feature	ROMSIM	IGRIP	SILMA
Ease of Use	Cumbersome, Difficult, May not be Free of Errors	Easy, Mouse-driven Menus	Easy, Mouse-driven Menus
Control System Simulation	Adaptive Control System Algorithm	Linear Control	Linear Control with PID Loop
Kinematic Solution	Internal Solution	Provide Multiple Arm Configuration And Allows Adding More Through C-Program	Provide efficient Closed Form Solutions for Inverse Kinematics of Multiple Configuration and Allows To Add New Robots Config. To The Cimstation Library
Dynamics	Requires Too Much Detailed Information To Generate Interactive Forces and Torques At The Joints.	The Robot Controller Could Be Connected to the Work Station and Directly Drive the Robot Model on the screen.	Simulate general Dynamics Of Manipulator, Compute Forces and Torques At Joints
Collision	Poor Model For Collision Avoidance	Collision Detection, Exact Intersection of Surfaces	Collision Detection, Min. Distance Analysis
Graphics	Poor Wireframe	Wireframe, Shaded Surfaces	Wireframe, Shaded Surfaces
Graphics Hardware	Evans & Shutherland For Full Graphics, VT 240 For Limited Graphics	Intergraph Workstation	Intergraph Workstation or Similar

Table 3-1 Comparison of Robotics Simulation Software (Cont.)

Feature	ROBSIM	IGRIP	SILMA
Workcell Integration	Not Available	Not Available	Generate Simulation Prog-rames for actual Workcell Devices
Animation	Not Available	Not Available	Graphical Representation Of Workcell Simulation
Cost	No Cost	$ 70,000 - 100,000	$ 70,000 - 100,000
Systems	VMS operating System		UNIX Environment

3.3 Results and Discussion

In view of the current study and the comparison table (3-1) one could come to the following recommendations:

- In case of budget availability IGRIP or SILMA package is recommended

- In case of budget unavailability a good manual should be prepared for ROBSIM so its inverse kinematic, Dynamics, and Control models could be easily used for calculating the torque requirements at the joints, arm configuration, control system specifications, etc.

IV ADAPTIVE ALGORITHM FOR THE CONTROL SYSTEM OF THE RADIATOR INSPECTION ROBOT

4.1 Introduction

The motors of the control system of the radiator inspection robot are currently being selected. The sizing of these motors are based on the maximum torque requirement calculations given be Todd Graham's planer model that is based on Kane's equations. Also, this model provides the interaction forces and moments at the joints that have been incorporated in the design and configuration of the control system.

4.2 The Servo Control System

The control system for the three joints of the robot arm are outlined in Figure 4-1. It could be noted that each joint is controlled with a similar system. However, the transfer function of the linearized inertia terms of each link and the interactive torques on each joint are different and varying with position and time. Therefore, the optimum PID loop gains that provide the most smooth and accurate operation with each joint control system will also vary with time and location.

However, for a repeatable task like that performed by the radiator inspection robot the optimum gains could be only related to the robot's positions.

4.3 Adaptive Algorithm

The proposed adaptive control algorithm is to overcome the effects of the position-varying manipulator dynamics on system performance by providing updated values of the control system gains. This could be achieved by finding the optimum gains at few positions through the robot's path that include both the beginning and end points Figure 4-2. MATRIXX7.1 could be used to find these gains. A least square or equivalent curve fitting technique will provide a polynomial that yields each gain as a function of joint location (q). For example:

$$K = a_0 + a_1 q + a_2 q^2 + a_3 q^3 + \dots\dots\dots\dots\dots\dots + a_n q^n$$

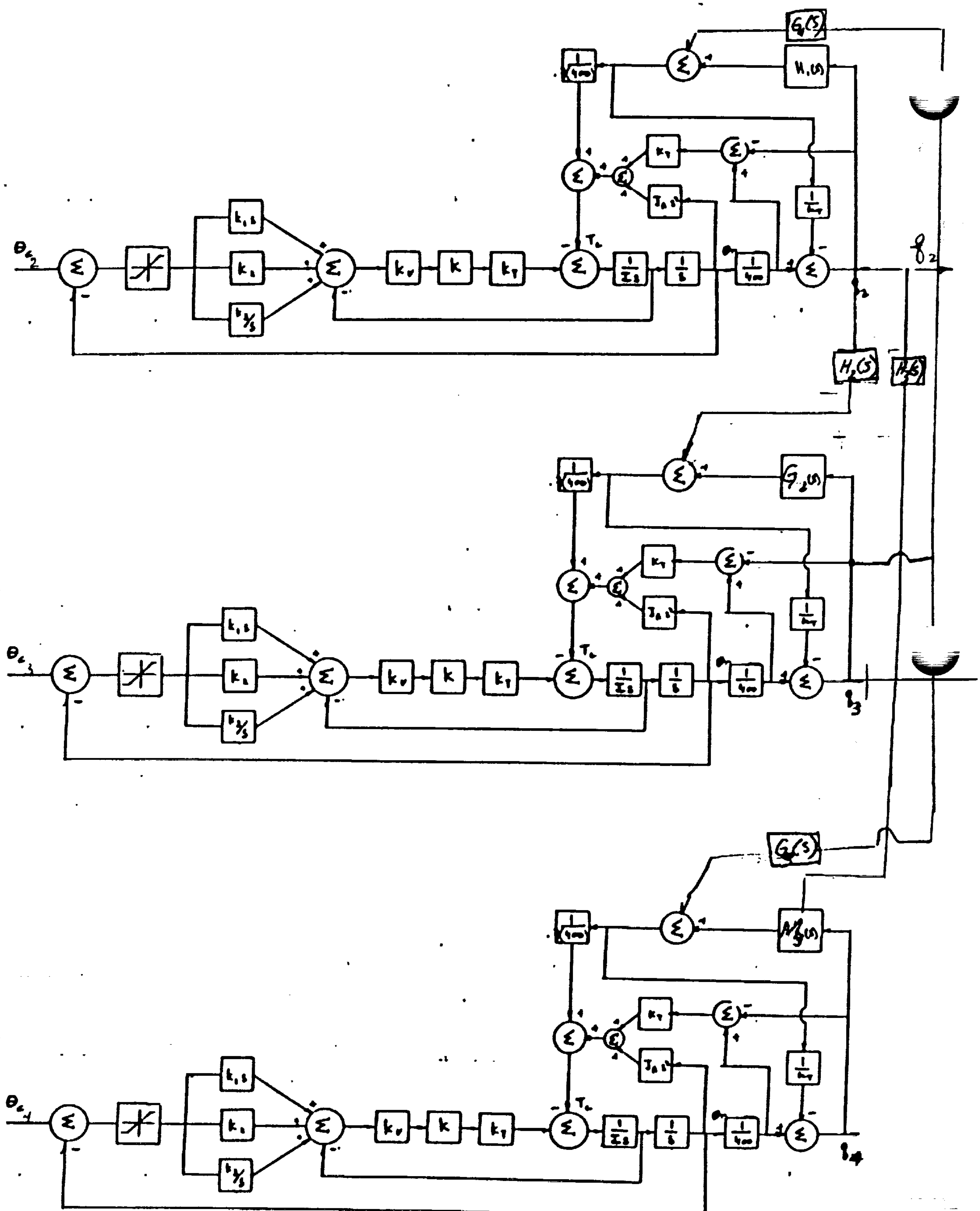


Figure 4-1 servo control System for Radiator Inspector Robot

ORBITER RADIATOR INSPECTION

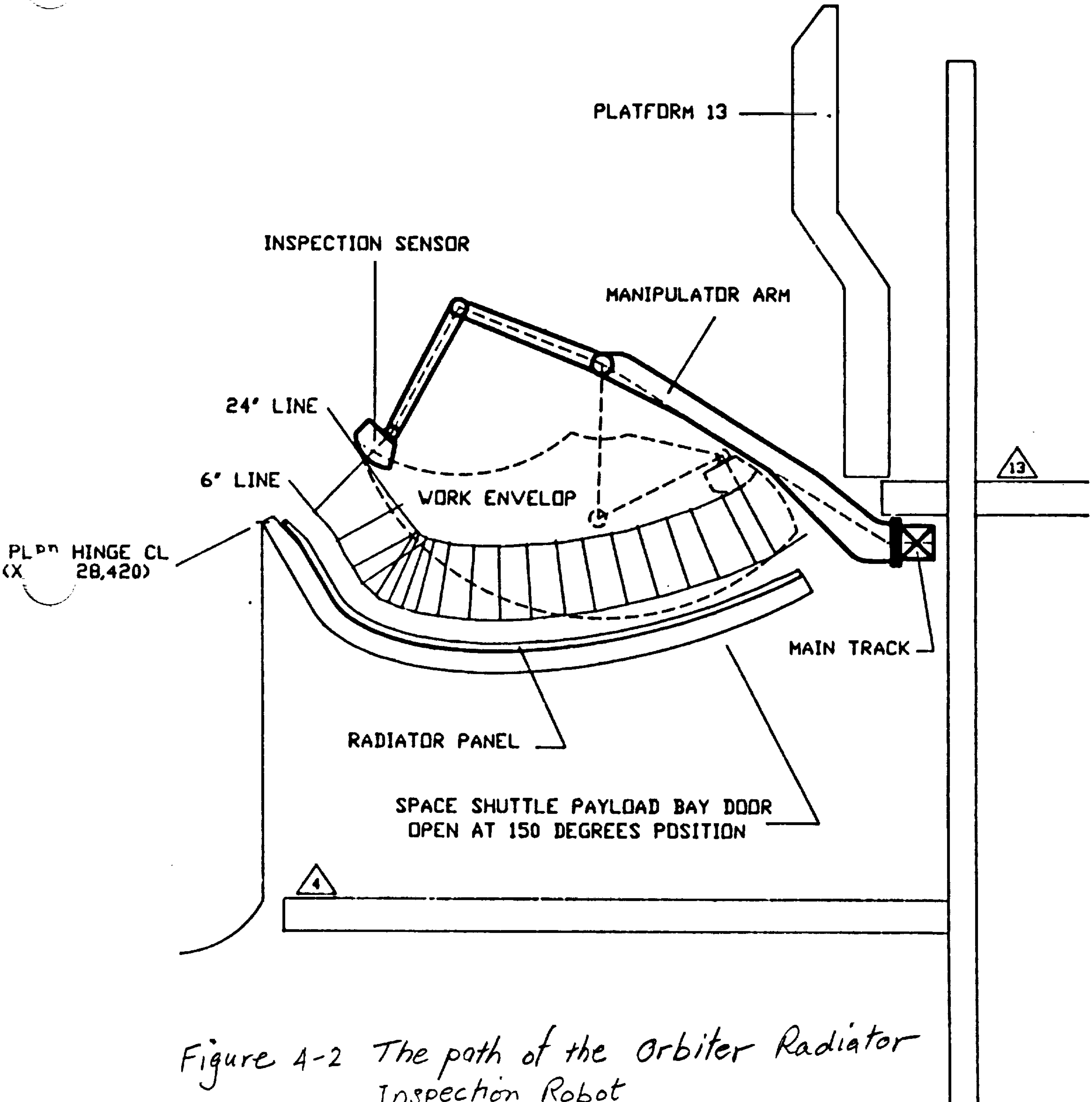


Figure 4-2 The path of the Orbiter Radiator Inspection Robot

V CONCLUSIONS

(1) A statistical technique could be used to calibrate, test, and trouble shoot a robot.

(2) The present technique provides a straight forward method to evaluate the robotics accuracy, repeatability, and linearity.

(3) In case of budget availability it would be advisable to obtain either SILMA or IGRIP as robotics design packages at RADL.

(4) In case of budget unavailability, a good manual should be developed for ROBSIM so its kinematics, dynamics, and control system packages could be used at RADL.

(5) An adaptive algorithm should be used with the radiator inspection robot's control system to minimize the servo system errors due to the variation of the inertia matrix with time and location.

REFERENCES

[1] Davis, Virgil Leon, " Systems Integration for the Kennedy Space Center Robotics Applications Development Laboratory" MS 87-482 SME Technical Report, 1987.

[2] Evaluation of Automated Decisionmaking Methodologies and Development of an Integrated Robotic System Simulation: Appendix A - Robsim User's Guide, NASA Contractor Report - 178051, March 1986

[3] Craig, John, " Introduction to Robotics Mechanics and Control", 1989 Addison-Wesley Publishing Company, Inc.

[4] Tawfik, Hazem "Computer Integrated Manufacturing Work Cell Process Capability", ASME Manufacturing International '90, Atlanta, Gorgia, March 1990.

[5] Kuo, Benjamin " Automatic Control Systems", Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1987.

[6] Nof, Shimon, " Handbook of Industrial Robotics", John Wiley & sons Inc.,1985.

1990 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

EVALUATION OF THE EFFECT OF LOW STRAIN RATE OVER TIME ON TITANIUM HOSE CLAMPS USED IN THE ORBITER

PREPARED BY: Mr. Delbert Taylor

ACADEMIC RANK: Instructor

UNIVERSITY AND DEPARTMENT: Murray State College
Engineering Technology

NASA/KSC

DIVISION: Materials Science Laboratory

BRANCH: Malfunction Analysis Branch

NASA COLLEAGUE: Mr. Charles Denaburg
Mr. Scott Murray

DATE: August 10, 1990

CONTRACT NUMBER: University of Central Florida
NASA-NGT-60002 Supplement: 4

ACKNOWLEDGEMENTS

I am extremely grateful for the opportunity to have participated in the 1989 and 1990 NASA/ASEE Summer Faculty Fellowship Programs. The experiences of the past two summers have been most enjoyable and rewarding.

First of all, I would like to thank the people at NASA/KSC and at the University of Central Florida for their hospitality and enthusiastic helpfulness. Special recognition for the overall planning and implementation of the program is given to Dr. Loren A. Anderson and Dr. E. Ramon Hosler, University of Central Florida Program Directors and their administrative assistant, Ms. Kari L. Baird; Kennedy Space Center Program Directors, Mr. Dennis W. Armstrong and Dr. Mark A. Beymer.

A special thanks to Bob Denaburg, Scott Murray, Gino Gaudino and Peter Marciniak for making room for me in their laboratory, and for providing their expertise, guidance and assistance throughout the project. The stimulating discussions about metallurgy and laboratory techniques have been inspirational.

Thanks to Mr. Charles W. Hoppesch, Chief of the Materials Science Laboratory, for making all the areas and equipment available for my use.

I would like to acknowledge the support of colleagues from my home institution, Murray State College, particularly, Dr. Clyde Kindell, President, Mr. Dennis Toews, Mr. Joe Reid and Mr. Bill Malone.

My acknowledgements would not be complete, however, without special mention of my wife, Vern. She continues to furnish help and support as always.

ABSTRACT

Titanium is available in both commercially pure and alloy grades. These grades can be grouped into three basic categories according to the predominant phase or phases in their microstructure. The titanium hose clamps are manufactured from single phase titanium, classified as being in the alpha category and designated as an unalloyed grade called commercially pure titanium. This commercially pure grade is characterized by a hexagonal, close-packed crystalline grain structure, is not heat treatable, is easily welded and is stable from room temperature up to 1625 degrees F. Commercially pure titanium is commonly used in applications where optimum corrosion resistance is desired and where high strength is not a factor. The failure of several commercially pure titanium hose clamps used in the orbiter is believed to be the result of strain over an extended period of time. This study will focus on the long time duration of low strain rate and evaluation of the results.

SUMMARY

Hose clamps manufactured out of commercially pure titanium reportedly failed in use aboard the orbiter. Subsequent tests indicate this failure may be due to sustained load cracking. The samples were analyzed by inductively coupled argon plasma emission spectrometric methods. The samples met the compositional requirements for commercially pure titanium. The samples contained hydrogen in the amount of approximately 30 ppm both in the strap and in the holder area. Scanning electron microscope fracture analysis depicts features characteristic of a brittle failure mode. The failure fracture appeared to initiate in the center of a spot weld and terminated with a fracture at the interface of the fusion zone and the heat affected zone. Additional tests were conducted to further investigate the slow strain embrittlement with emphasis on the detection of hydride precipitation in the leading edge of the crack. Test results indicate a loss of ductility and the embrittlement of the sample.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

FUZ	Fusion Zone
HAZ	Heat Affected Zone
HRB	Rockwell Hardness Number
ICAP	Inductively Coupled Argon Plasma
PPM	Parts per million
SEM	Scanning Electron Microscope
SLC	Sustained Load Cracking

I. INTRODUCTION

1.1 BACKGROUND

Titanium is commercially available in several different compositions and grades. Selection of the grade that is precisely correct for a specific application usually makes the difference between the safe profitable use of titanium in a high performance structure and a marginal application.

Titanium base alloys are similar to many other engineering metals. Pure titanium is soft, weak and very ductile. When alloyed with other elements, the titanium metal base is converted to a material with characteristics of high strength, stiffness, useable ductility, corrosion resistance and a lower density than other engineering materials. The most predominant of these characteristics in any given composition is a function of the alloying element selected (1).

Titanium has a hexagonal close-packed crystal grain structure called alpha, which transforms to a body centered cubic structure, called beta at 1625 degrees F. Alloying elements favor one or the other of the two structures. Aluminum, for example, stabilizes the alpha structure raising the transformation temperature from alpha to beta. Chrominum, iron, molybdenum, manganese and vanadium lower the transformation temperature making the beta phase stable at lower temperatures. Tin is considered neutral.

Titanium grades fall into three major classes depending on the phase or phases present in their microstructures. The three classes are alpha, beta, and the combination of phases referred to as alpha-beta. The alpha-beta class includes most of the titanium as used today.

Alpha alloys, the hexagonal structured compositions, possess the highest strength and oxidation resistance at elevated temperatures and the best weldability of the titanium grades. Room temperature strength levels, however, are the lowest. These compositions do not respond to heat treatment (2).

Within the alpha alloy classification are grades with high aluminum content, grades with such lean beta present to be almost pure alphas, and the commercially pure or unalloyed grades.

Commercially pure titanium was the first titanium melted and currently is produced in five different strength levels determined by the interstitials present, primarily oxygen.

Titanium alloys also have a great affinity to the beta stabilizing interstitial, hydrogen. There are basically two types of hydrogen embrittlement exhibited. These have been designated as impact embrittlement and low strain rate embrittlement. Sensitivity of titanium alloys to low strain rate embrittlement appears to increase with increasing strength, notch severity, alpha grain size, continuity of the beta phase and the hydrogen content (3).

In commercially pure titanium, as in all other metals, as the strength increases, toughness, ductility and formability decrease.

1.2 HOSE CLAMP FAILURES

Broken titanium hose clamps were found lying on the deck in the crew compartment of the orbiter. These clamps of various sizes are used to hold low pressure ducting in place. It was reported that the failures occurred during the installation tightening process. However, discussions with the system engineers and technicians indicated that some were found broken. Others had failed on reinstallation, having been stressed in use over a long period of time. It was reported that the failure occurred to a few being reinstalled, not representing a failure of all the reused clamps. The subject clamps, P?N ME277-0015, were manufactured by Aeroquip Manufacturing Company (4).

1.3 PRIOR INVESTIGATIVE RESULTS

An investigation of the failures was conducted by NASA/KSC Failure Analysis Lab (4). The investigation procedures included visual, metallography, scanning electron microscope (SEM) and analytical tests.

1.4 PRIOR CONCLUSIONS

The initial investigation concluded that the failure was due to sustained load cracking (SLC). Normally this type of fracture would be caused by an excess of one of the interstitial elements, primarily hydrogen and the precipitation of hydrides. The subject hose clamps were manufactured from commercially pure titanium (4).

1.5 OBJECTIVES

The overall objective of this investigation was to establish a similar type low strain rate under controlled conditions using the same type titanium hose clamps to establish the brittleness, hydrogen content and the changes in the microstructure.

II. TEST PROCEDURES

2.1 TESTS

The tests were conducted using the small hose clamps shown in Figures 2-1 and 2-2. Previous metallic samples selected from the clamps were dissolved in concentrated HCL and analyzed by inductively coupled plasma (ICAP) spectrometric methods. The subject material met the composition requirements for unalloyed titanium, essentially 100% Ti. This is the same criteria for the alpha class commonly called commercially pure titanium. Fracture surface samples were also analyzed using a scanning electron microscope for fractgraphic studies. The sample hose clamps were stressed by installing them around a piece of pipe. An Instron tensile testing machine was used to subject the clamps to a low strain rate of .002 inches per minute until the fracture point was reached.

2.2 TEST RESULTS

The failures of the hose clamps were primarily in the area where spot welding was performed between the strap and bolt-holding bracket. The fracture appeared to originate from the edge of a spot weld. The grains of the microstructure near the edge of a weld appeared to be distorted. Linear marks that can be attributed to the welding machine also were seen. The fracture surface showed dimples arranged in areas that appear to be separated by crack arrest lines. Many of the dimpled lines were elongated indicating that the origin of the fracture was at the center of the spot weld. This failure is in the area of the fusion zone (FUZ) and the heat affected zone (HAZ) interface (HAZ/FUZ) as shown in Figure 2-3. SEM photomicrographs of the fracture are shown in Figures 2-4 through 2-7. Most of the fracture surfaces had a sharp, faceted appearance which is indicative of brittle fracture. There was also a slight indication of fatigue in the area.

Metallographic samples were made of the HAZ and FUZ weld areas. These were compared with a sample from an unstressed clamp. There was no indication of any microstructure change which could contribute to the premature failure. The metallographic samples were primarily etched with Kroll's etchant for grain examination. Some were etched with an Hf-Hcl etchant to investigate for the presence of hydrides.

Hardness tests were conducted using a Universal Microhardness Tester. All values were converted to a Rockwell Hardness Number (HRN). All hardness readings fell within a range of HRB 92 to HRB 100. There was no noticeable hardness difference between the stressed and the unstressed samples.

Hydrogen analysis conducted by the Lewis Research Center of similar clamps, both stressed and unstressed, determined that the hydrogen level of the samples was approximately 30 ppm. The composition of the samples met the requirements for commercially pure titanium (99.2+%).

III. CONCLUSION

When subjected to a low strain rate over a period of time, commercially pure titanium hose clamps are subject to failure due to sustained load cracking (SLC). Although slow strain rate is most often observed in the alpha/beta class titanium, it has also been observed in the alpha and the beta class metals. The loss of ductility was pronounced at near room temperature. The embrittlement of the low strain rate can be attributed to the hydride precipitate that formed during the strain. This formation of the hydride took place in the area of the slip planes. The large volume of the hydride stressed the slip plan causing a crack. Beginning at the leading edge of the crack, this process is again repeated until complete failure occurs. Additional testing would be required to determine whether the hydride nucleation is initiated by the attainment of a critical stress or by the mount of strain developed in the metal.

REFERENCES

1. Donachie, M.J. Introduction to Titanium and Titanium Alloys. Source Book, ASM, 1982.

2. "A General Summary of the Physical Metallurgy of Titanium Alloys." TML Report No. 19, 1955.

3. Groeneveld, T.P., Fletcher, E.E., Elsea, A.R. A Study of Hydrogen Embrittlement of Various Alloys. Battelle Annual Report, 1966.

4. Metals Handbook, 9th Edition. Metallography and Microstructures. ASM, Vol. 9, 1985.

5. Metals Handbook, 9th Edition. Mechanical Testing. ASM, Vol. 8, 1985.

6. "Hydrogen Embrittlement Testing." ASM-STP543, 1974.

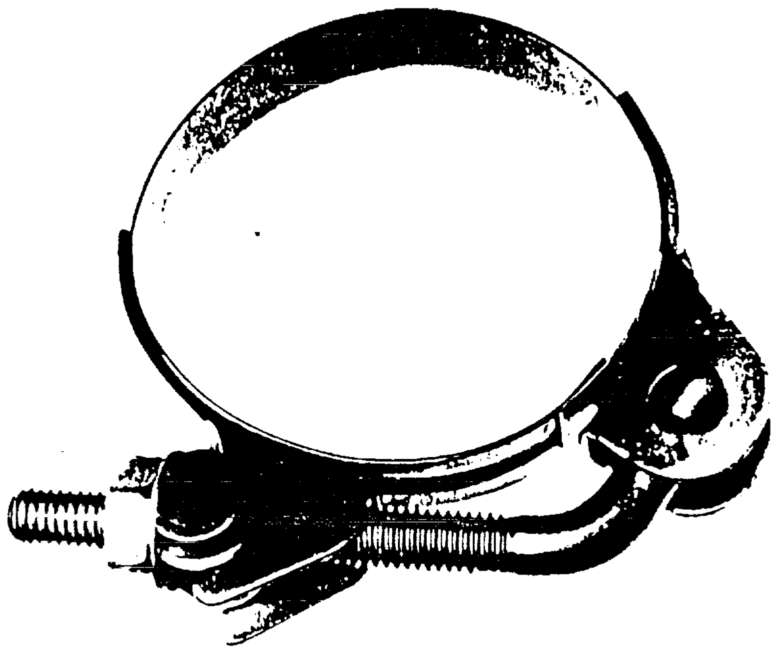


Figure 2-1. Titanium Hose Clamp

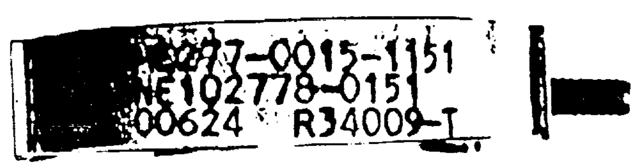


Figure 2-2. Titanium Hose Clamp Identification

ORIGINAL PAGE IS
OF POOR QUALITY

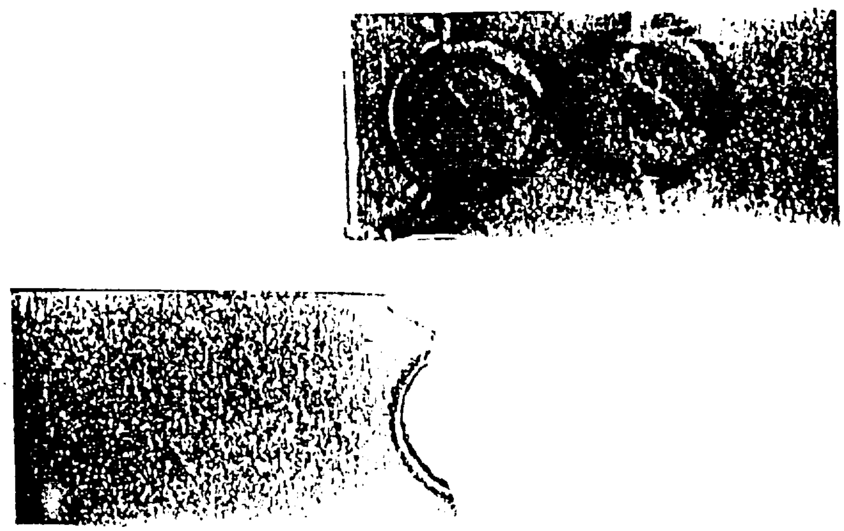


Figure 2-3. Weld Fracture

ORIGINAL PAGE IS
OF POOR QUALITY

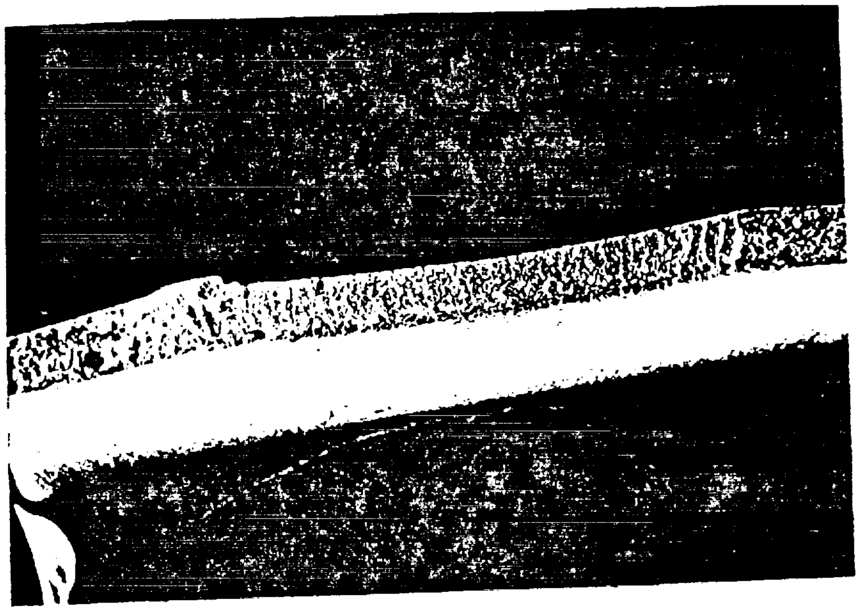


Figure 2-4. SEM Micrograph of Fracture, 17X

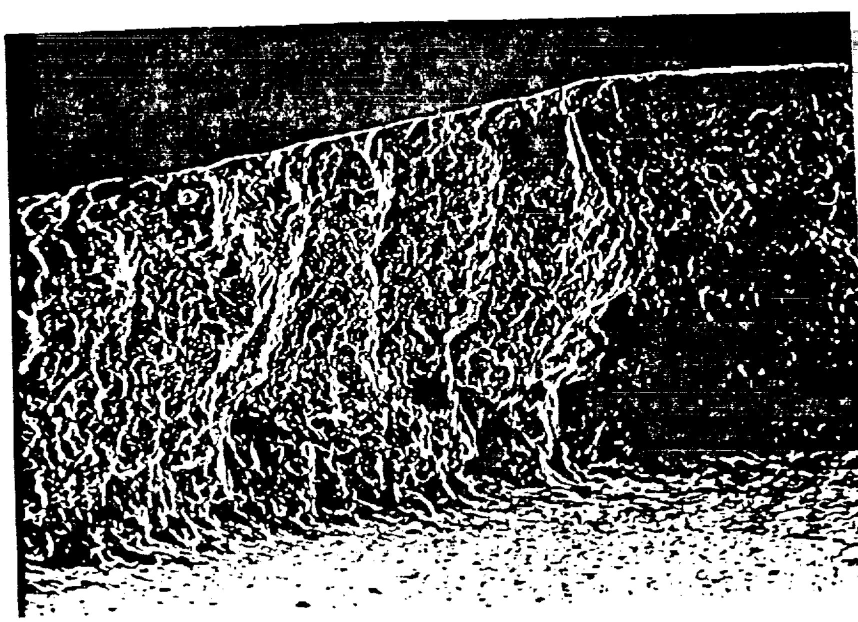


Figure 2-5. SEM Micrograph of Fracture, 107X

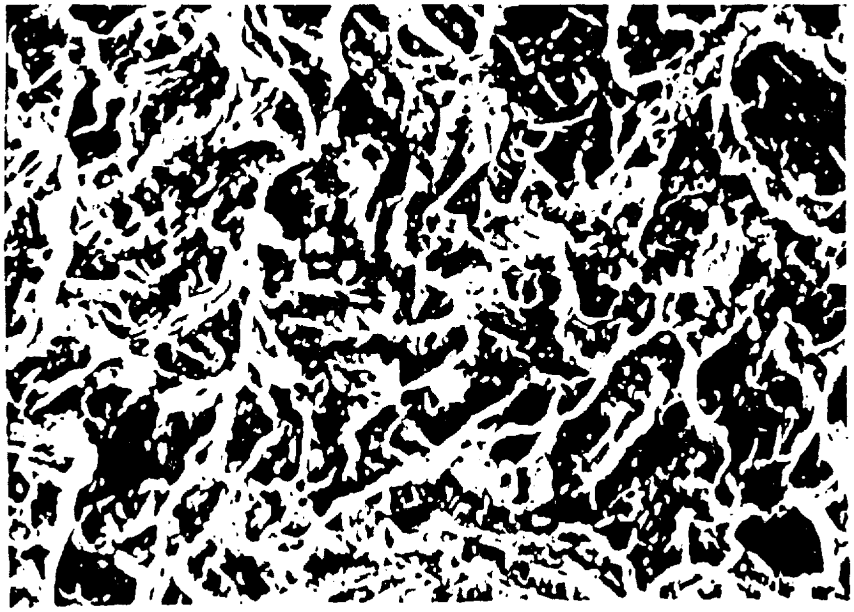


Figure 2-6. SEM Micrograph of Fracture, 1230X

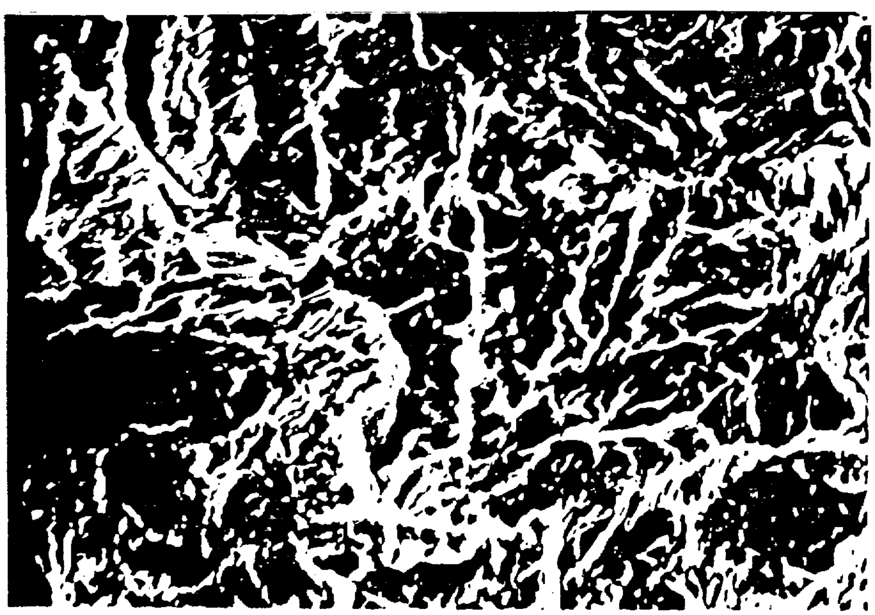


Figure 2-7. SEM Micrograph of Fracture, 1210X

ORIGINAL PAGE IS
OF POOR QUALITY