2016-01-01

Design Of Experiments-Based Scara Robot Parameter Evaluation For Embedding Electronics Into 3d Print

Sreekara Charith Boppana
University of Texas at El Paso, sboppana@miners.utep.edu

DESIGN OF EXPERIMENTS-BASED SCARA ROBOT PARAMETER EVALUATION FOR EMBEDDING ELECTRONICS INTO 3D PRINT

SREEKARA CHARITH BOPPANA

Master's Program in Industrial Engineering

APPROVED:

Tzu-Liang (Bill) Tseng, Ph.D., Chair

Amit J. Lopes, Ph.D.

Yirong Lin, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

DESIGN OF EXPERIMENTS-BASED SCARA ROBOT PARAMETER EVALUATION FOR EMBEDDING ELECTRONICS INTO 3D PRINT

by

SREEKARA CHARITH BOPPANA, B. Tech

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

Industrial, Manufacturing, and Systems Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

December 2016

Acknowledgements

I would like to express my deepest gratitude to my thesis committee chair Dr. Tseng Bill for the opportunity of being a part of his research team, and for his continuous assistance and support at each level of my master's journey. I sincerely thank my thesis committee Co-chair Dr. Amit Lopes for all his support and guidance; for sharing his dedication, knowledge, and passion for his work that highly motivated me to give my best effort in this presented research. I especially would like to thank my committee member – Dr. Yirong Lin for his time and providing feedback. I would like to thank Dr. Jamie Sanchez for sharing his experience knowledge in my work. I would like to acknowledge Mr. Oscar Murga, who once was in my shoes, for teaching me how to operate the robot. My heartfelt appreciation to the faculty and staff of Industrial, Manufacturing and Systems Engineering Department for making my stay extremely enjoyable.

Finally, I must thank my parents for their blessings, love and constant encouragement throughout my master's program. Also, I would like to thank all my friends and family members who supported and motivated me all the time.

Abstract

Additive manufacturing processes combined with enhanced technologies for electronics production enables a highly flexible manufacturing of personalized 3D electronic devices. Due to the enormous progress within the last years, these technologies made their way from prototyping towards manufacturing. The growing request for products manufactured in batch size, making use of a robot to incorporate the electronic components necessary to make functional 3-Dimensional-Structural Electronics will extend the mass production possibilities. There is significant interest in automation of a process is which parameters are influential in the occurrence of assembly defects and which adjustments should be made to those variables to reduce assembly defects. The present study aimed at investigating the accuracy of the electronic parts mounted on the 3D printed board, and to what extent these factors are significant for the accurate assembly process. The full factorial experiment was conducted to illustrate and explain the findings in the parameter optimization. Finally, optimal settings for the robot are proposed for more accuracy and repeatability.

Table of Contents

List of Tables

List of Figures

List of Illustrations

Chapter 1: Introduction

Processing multiple material types with a single build type is becoming an emerging trend in the 3D printing [1], which will favor in print 3D structural electronics. It has the advantages of being able to produce 3D objects with the wires and circuitry embedded within the structural material, creating more complex structures, mass customization for biomedical companies to make perfect copies of anatomy, aerospace parts with radiation shielding capability etc.

One of the major challenges in bringing this technology to large scale production for end-use products are many of the electronics assemblies are manual. Embedding the components manually for hundreds is not an easy task for many products which causes human mistake and exhaustion. The surface mount component placement machines such as pick and place assembly robot solve the problem by aligning the electronic components, both as to angular orientation and coordinate(x,y) location for precise placement. Vacuum quills are used to travel to bin or feeder, pick up a component, properly orient the component and carry it to the 3D structure with the leads making the proper connection with the circuit connections which are created on the 3D structure. However, the electronic components must be placed accurately on the 3D structure, to ensure proper electrical contact, thus requiring correct angular orientation and lateral positioning.

Just-in-time is a philosophy which places importance on identifying and eliminating the defects before they occur than trying to decrease defects after they have occurred, which helps reduction of scrap and better process yields [2]. To achieve this, the manufacturing industries use many techniques to detect and to set the process correctly. Among them, Design of experiments is one.

A designed experiment is a test or series of tests in which purposeful changes are made to input variables of a process to get the response output [3]. Experimental design methods play a very useful role in process development and process troubleshooting, resulting in higher quality.

General Experimental Design techniques if implemented early in process development will result in the following results:

1) Improved process yields

2) Reduced Variables and closer conformance to nominal or target requirements

3) Reduced development time

4) Reduced overall costs

Experimental Design techniques are applied in this thesis is an effort to optimize the pick and place process. Primary interest was in determining the effects of the process variables. This would enable to optimize the variables affecting the process, thereby increasing process yields.

1.1 OBJECTIVE

The main objective of this thesis is to study the variables affecting the assembly process by conducting the series of experiments for the 3D Structured Electronics (SE) assembly. Minitab and Design Expert were used for carrying out experimentation and analysis of 3D SE assembly.

Minitab offers four types of designs: factorial designs, response surface designs, mixture designs, and Taguchi designs. The steps you follow in Minitab to create, analyze, and visualize a designed experiment are similar for all types. After you perform the experiment and enter the results, Minitab provides several analytical tools and graph tools to help you understand the results.

Design Expert is a commercial software package used to design and analyze industrial experiments. The software provides assistance in the proper choice of the experimental design and provides easily understood graphical procedures for interpreting the experimental results. Design expert offers a full range of factorial and fractional factorial designs at two levels. These designs are basic blocks for the successful use of statistical principles in an industrial environment.

Experimentation was carried out on Yamaha SCARA robot 180x with an arm length of 180 mm with using Cognex vision system located in the Department of Industrial, Manufacturing, and Systems Engineering at University of Texas at El Paso. The chapter covering experimentation will describe Yamaha SCARA robot 180x as well as Cognex vision system. The following chapters explain the methodology and results.

Chapter 2: Theoretical Background

2.1 3D PRINTING OF STRUCTURAL ELECTRONICS

3D printing (3DP), also known as additive manufacturing, is the technology used for the rapid production of 3D objects directly from digital computer-aided design (CAD) files. It has existed in some form since the 1980s [4]. In the past two decades of research and development, we have seen the progression of a variety of different additive manufacturing processes and materials because of the ability to print a broad range of structures with accuracy and reasonable cost. With 3D printing, it will be possible to fabricate a part from scratch in just a few hours. It enables developers and designers to proceed from the monitor flat screen to the exact three-dimensional part.

Researchers have been creating and developing new ways of utilizing the 3D printing or AM technology to create 3D Structural Electronics (3DSE), because of the advantages of 3D printing that include ease of duplicating products, low cost, and product security considerations. 3DSE is an area in which electronic devices and connections happen in a three-dimensional part. Leading research in 3DSE is taking place at the W. M. Keck Center for 3D Innovation of The University of Texas at El Paso.

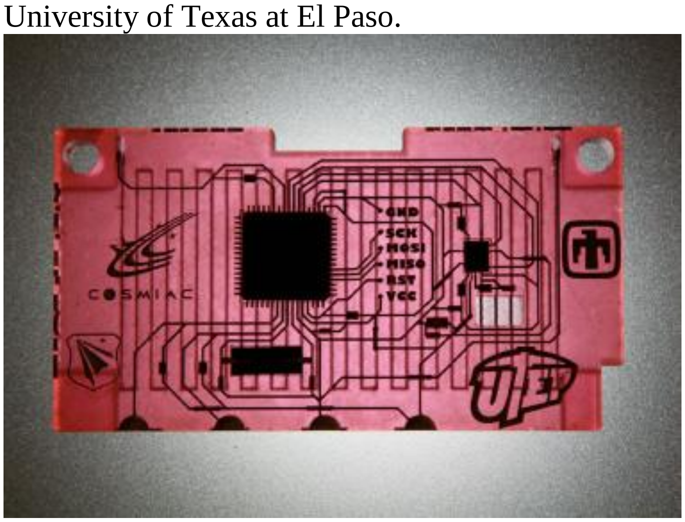


Figure 2.1: 3D printed circuit board (Source: W.M.Keck center)

2.2 IMPLEMENTATION OF AUTOMATION FOR 3D STRUCTURAL ELECTRONICS

The International society of automation defined automation as "the creation and application of technology to monitor and control the production and delivery of products and services". The use of automation in the assembly process of printed circuit boards began twenty years ago, through either semimanual processes or fully automated processes. Ongoing research is going on factors significant for the accurate assembly process. Incorporating electronic components to additive manufacturing to create 3D-SE and thereby replacing Printed circuit boards as the production of 3D-SE is an inexpensive alternative. The use of a robot to incorporate the electronic components necessary to make functional 3d-SE will extend the mass production possibilities.

2.2.1 Experimental Setup

The Electronic components of different sizes and shapes were selected randomly to conduct the experiment. Yamaha SCARA yx180 model used in this experiment performs the Pick and place of the electronic components from the feeder to the electronic component slots in order to test the accuracy.

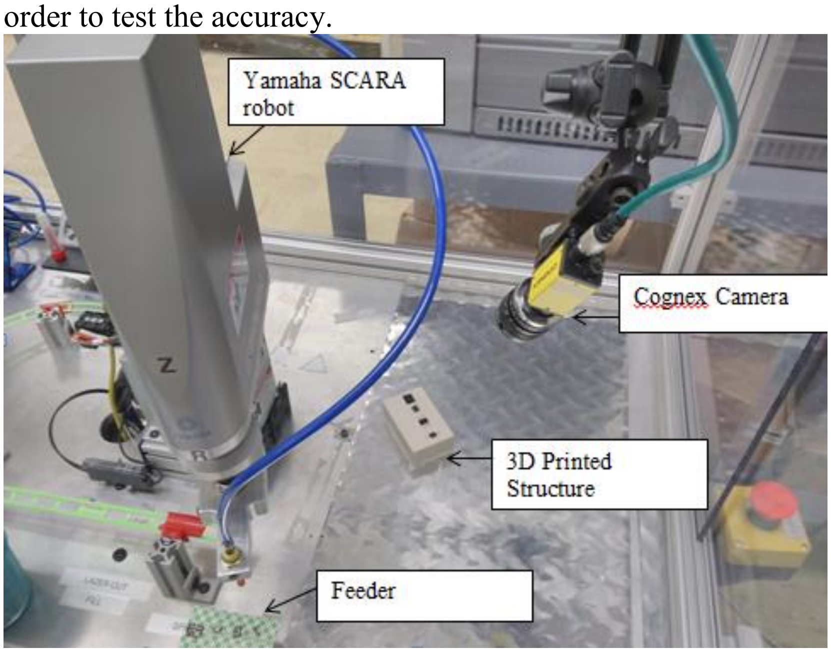


Figure 2.2: Automation Station with electronic components assembled

2.2.2 Machine Vision system

Machine vision is the technology and methods used to provide imaging-based automatic inspection and analysis for applications such as automatic inspection, process control, and guidance in the industry. Machine vision system is used in this experiment to inspect the assembly process and also to measure the accuracy.

Any selected initial image can be set as a standard image in the vision system. For this research, four model regions of images representing the electronic components are given as the standard image. When the multiple runs are performed the vision system compares the new image with the standard one and gives the accuracy score.

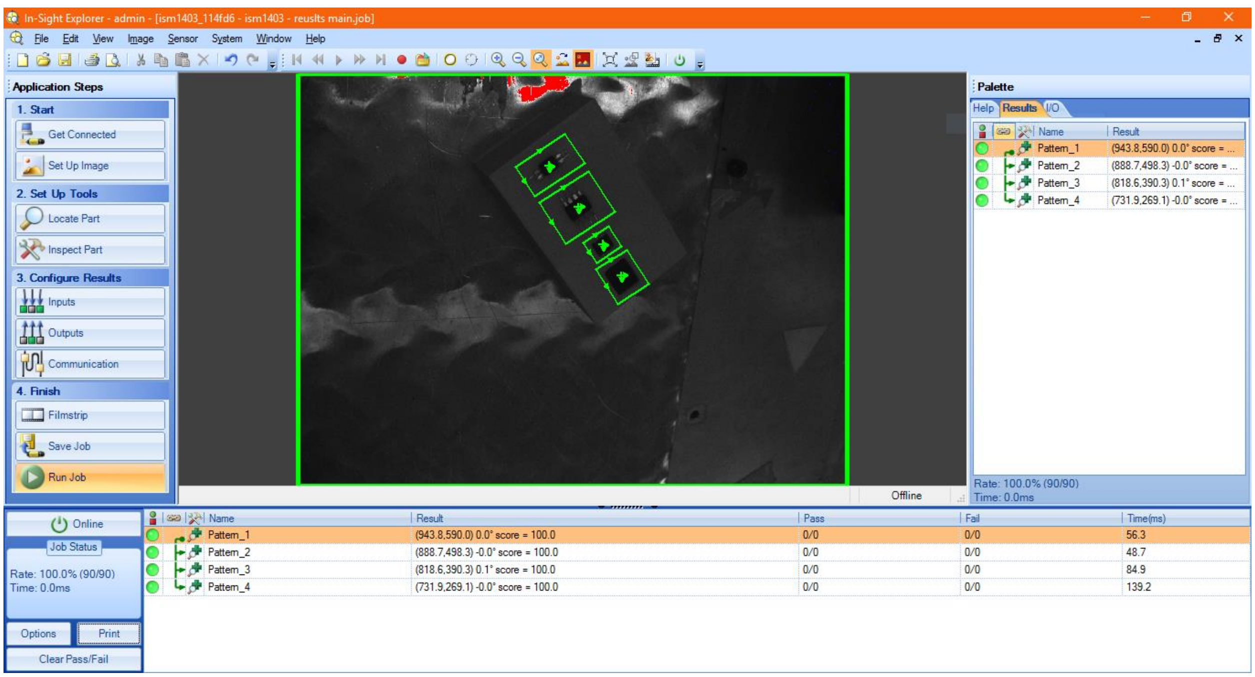


Figure 2.3: Insight explorer machine vision system

Chapter 3: Research Methodology

3.1 General

This chapter describes the methodology proposed to evaluate the process variables that are encountered in embedding electronics into 3D print. A robot was actually operated and evaluated at various levels of the variables. Section 3.2 gives the explanation about the design of experiments and Section 3.3 gives the application of Design of Experiments to this thesis.

3.2 Design of Experiments

Statistical design of experiments refers to the process of planning an experiment so that appropriate data is collected and analyzed by statistical methods which result in valid conclusions [3, 7]. Statistical analysis is the best approach for solving a problem when the data is subjected to experimental errors.

Standard assumptions of most statistical treatments are as follows

1) The observation must be a fair sample of the population about which inferences are desired.

2) The observations are of constant variance, are statistically independent, and are normally distributed.

3) Few or no bad values will be produced, and few missing values.

Many Industrial experiments involve a study of the effects of two or more factors. Each of the factors may have more than two levels. In order to carry out experimentation so as to study the effects of the factors at each level, the total number of experiments that have to be carried will be very high. In addition to that when a factor is kept at the same level and if the other factors are varied from one level to the other level the basic principle of Randomization is being lost, to avoid such kind of difficulties it is very helpful to carry out factorial designs.

Factorial Experimentation is suitable for the following reasons:

1) The main Objective for the experimentation was to determine quickly the effect of each of the number of factors over a specified range.

2) To carry out investigations over the interactions among all the effects of factors.

3) To carry out the experiments so as to give recommendations which apply over a range of conditions.

The factorial design has been applied to this problem because of its versatility of studying the effects of all the individual factors, its levels accurately for the process. Another advantage of using this factorial design for this problem is that it is possible to change all the factors over their ranges without losing the randomization. The reason for choosing the particular design depends on the number of factors that are to be studied. This also depends on the total number of levels for each factor and the total number of experiments that are to be carried in the process.

3.1.1 Advantages of Factorial Design

Factorial Designs are more efficient than one-factor-at-a-time experiments to determine the impact of two or more factors on a response. A factorial design is also efficient even if there are interactions between the factors in the experiment.

Factorial Designs allow each effect of the factor to be estimated at several levels of the other factors and to yield conclusions which are valid over a range of experimental conditions. A Factorial Design is one in which for each complete trial or replication of the levels of factors are investigated without loss of randomization. Factorial Design is very efficient for Industrial Experiments.

A factor is an independent variable which has to be studied in an experiment. An effect of a factor is defined as the change in response produced by a change in the level of the factor. This is called Main effect. An interaction is said to be occurring in the experiments if the difference in response between the levels of one factor is not the same at all levels of the other factors

An interaction is said to be not occurring if the response that is to be measured for factor A at all levels of factor B is not dependent on factor B.

The basic principles of randomization and replication were followed in the experiments done on Keyboards

Randomization is the process by which the order of the individual runs of the experiment is randomly determined. Randomization tends to average out the effects of extraneous factors in an experiment that are not under specific control. Replication is the number of observations or sample size per treatment combinations. A factorial experiment is one where all levels of a given factor or treatment are combined with all other factors in an experiment. A factor is an independent variable to be studied in an experiment. A level of a factor is a particular value of that factor. A mathematical model for the four-factor experiments can be written as follows.

3.1.2 Four-Factor Experimental Model

The four-factorial experiment involves four factors or treatments. The general model has ‘a’ level of factor A, 'b' levels of factor B, 'c' levels of factor C, 'd' levels of factor D and n replicates. The observations can be described as a statistical model as follows:

$$Yijklm=U+A_i+B_j+AB_{ij}+C_k+AC_{ik}+BC_{jk}+ABC_{ijk}+D_l+AD_{il}+BD_{jl}+ABDi_{dl}+CD_{kl}+ ACD_{ikl}+BCD_{jkl}+ABCD_{ijkl}+E_{ijklm}$$

U = overall mean effect

A_i; = effect of ith level of factor A

B_j = effect of jth level of factor B

AB_{ij} = interaction between factors A and B

C_k = effect of kth level of factor C

AC_{ik} = interaction between factors A and C

BC_{jk} = interaction between factors B and C

ABC_{ijk} = interaction between factors A, B and C

D_l= interaction between factors A and D

BD_j; = interaction between factors B and D

ABD_{jj}; = interaction between factors A, B, and D

CD_{kl} = interaction between factors C and D

ACD_{ikl} = interaction between factors A, C, and D

BCD_{jkl} = interaction between factors B, C, and D

$ABCD_{ijkl}$ = the four factor (ABCD) interaction

E_{ijkim} = random error component

This experimental model was used in the experiments carried over for the UV coating machine. In this experiment, four factors were studied. The experimentation is described in detail in the next chapter.

The experiments were run and the Analysis of Variance (ANOVA) for each was computed using the Design expert software. Plots of probability and residuals were also analyzed.

3.3 METHODOLOGY FOR DOE

The methodology of DOE is fundamentally divided into four phases [10]. These are:

1. Planning phase
2. Designing phase
3. Conducting phase
4. Analyzing phase

3.3.1 Planning phase

The step-by-step procedure outlined by Montgomery was followed during the planning phase of the experiments. The planning phase is made of problem recognition, selection of response, selection of process variables, classification of process variables, and determining the levels of process variables [6].

(a) *Problem recognition*: A clear statement of the problem can create a better understanding of what needs to be done. Finding pick and place process spread of electronic components using SCARA robot and finding optimal settings to reduce process spread, which leads to poor capability.

(b) *Selection of response:* The selection of a suitable response for the experiment is critical to the success of any industrial designed experiment. For electronic components assembly, accuracy is one of the major quality characteristics. So, the response variables to be analyzed later were selected as the accuracy of the assembly process. In this research work, we used the Cognex vision system to measure the accuracy by Patmax pattern as explained in the previous chapter. Few trail runs are done on the vision system to see for stability and robustness to environmental changes.

(c) *Selection of Process variables*:To identify potential design parameters, use of engineering knowledge, cause and effect analysis and brainstorming are used. As a result of this planning, the control variables, held constant variables and nuisance factors were determined. The control variables i.e, the factors to be varied during the experiments, were chosen based on the working knowledge of the robot. The illustration 3.1 shows the classification of the variables considered in the experiment.

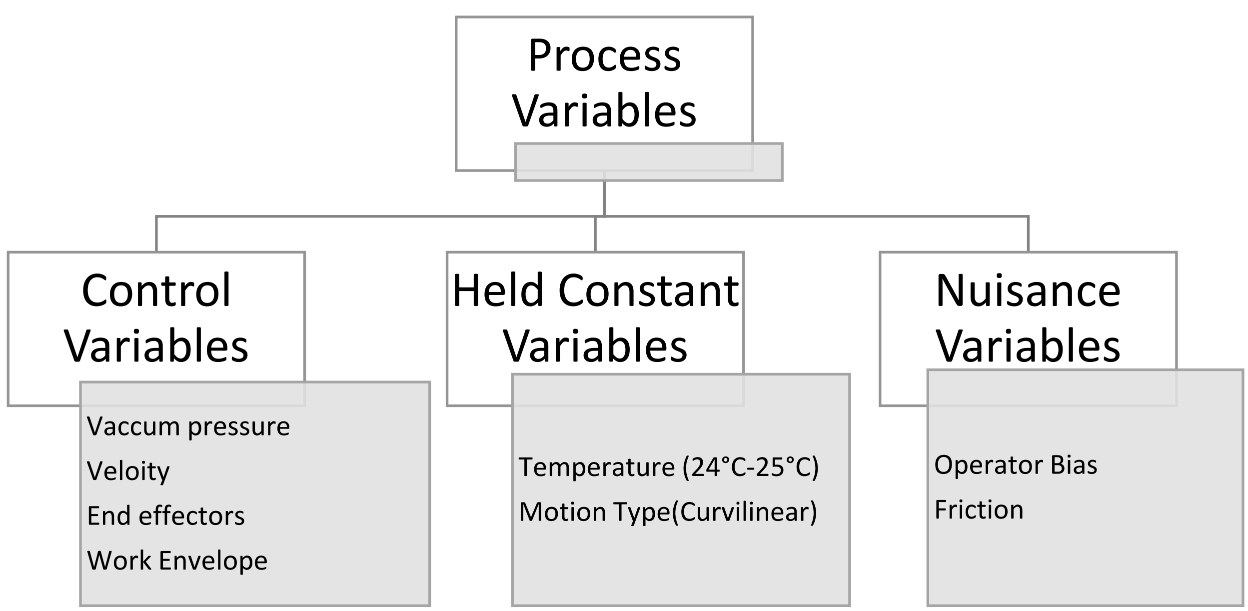


Illustration 3.1: Process variables of the Pick and place the assembly of electronic components.

(d) *Determining the levels of process variables*: There are two qualitative (type of vacuum end effectors, Work envelope) and two quantitative (vacuum pressure, velocity) variables in this experiment. All the four variables are studied at three levels as the decision was made to use three-level factorial designs.

Table 3.1: Levels of variables used in the experiment.

Variable name	**Units**	**Level 1**	**Level 2**	**Level 3**
Vacuum Pressure	Psi	50	70	90
Velocity	Mm/s	9	45	180
Type of Vacuum gripper		Xp-B5	XP-B8	XP-B10
Position & shape of part		PAT1	PAT2	PAT3

3.3.2 Designing phase

The full factorial design is considered based on the variables and number of levels. Selection of sample size is one of the most important aspects of any experimental design. Three replicates of the experiment are conducted and blocking is used to reduce the variability caused by noise factors or nuisance factors. The Same operator took the results over the experiment to remove operator to operator variability.

3.3.3 Conducting phase

Several considerations are recognized after performing the experimental trials

- Ensuring the experiment is not affected by external sources of noise like humidity and temperature.
- Record the observed response variables on the prepared data sheet.

- Attention was paid to variables which should be "held constant" so that they won't inflate the error in the experimental results.

Randomized Experimental runs are conducted based on the run order generated by the Design Expert software. The run order for the experiment can be seen in Appendix IV.

Table 3.2: Design layout with Accuracy score

Std. order	Block	Run	Vacuum pressure	Velocity	Type of Vacuum Gripper	Position & shape of part	Accuracy Score
1	Block 1	46	50	9	5	PAT1	92.9
2	Block 1	18	70	9	5	PAT1	100
3	Block 1	58	90	9	5	PAT1	92.4
4	Block 1	20	50	45	5	PAT1	85.4
5	Block 1	78	70	45	5	PAT1	95.8
6	Block 1	76	90	45	5	PAT1	65.9
7	Block 1	72	50	180	5	PAT1	91.4
8	Block 1	13	70	180	5	PAT1	83.2
9	Block 1	8	90	180	5	PAT1	82.4
10	Block 1	31	50	9	8	PAT1	100
11	Block 1	70	70	9	8	PAT1	93.6
12	Block 1	68	90	9	8	PAT1	88.4
13	Block 1	52	50	45	8	PAT1	88.6
14	Block 1	5	70	45	8	PAT1	95.7
15	Block 1	65	90	45	8	PAT1	76.1
16	Block 1	54	50	180	8	PAT1	98.9
17	Block 1	6	70	180	8	PAT1	100
18	Block 1	32	90	180	8	PAT1	97.6
19	Block 1	45	50	9	10	PAT1	87.5
20	Block 1	48	70	9	10	PAT1	89.5
21	Block 1	74	90	9	10	PAT1	86.5
22	Block 1	34	50	45	10	PAT1	74
23	Block 1	24	70	45	10	PAT1	100
24	Block 1	11	90	45	10	PAT1	97.8
25	Block 1	40	50	180	10	PAT1	100
26	Block 1	57	70	180	10	PAT1	100
27	Block 1	17	90	180	10	PAT1	100
28	Block 1	39	50	9	5	PAT2	81.1
29	Block 1	44	70	9	5	PAT2	97
30	Block 1	27	90	9	5	PAT2	68.8
31	Block 1	2	50	45	5	PAT2	100
32	Block 1	77	70	45	5	PAT2	86.2

33	Block 1	21	90	45	5	PAT2	75
34	Block 1	7	50	180	5	PAT2	100
35	Block 1	61	70	180	5	PAT2	60.5
36	Block 1	51	90	180	5	PAT2	86.5
37	Block 1	63	50	9	8	PAT2	100
38	Block 1	37	70	9	8	PAT2	100
39	Block 1	50	90	9	8	PAT2	99.7
40	Block 1	33	50	45	8	PAT2	88.7
41	Block 1	60	70	45	8	PAT2	100
42	Block 1	41	90	45	8	PAT2	98
43	Block 1	9	50	180	8	PAT2	97.3
44	Block 1	38	70	180	8	PAT2	100
45	Block 1	28	90	180	8	PAT2	100
46	Block 1	23	50	9	10	PAT2	100
47	Block 1	79	70	9	10	PAT2	100
48	Block 1	22	90	9	10	PAT2	100
49	Block 1	42	50	45	10	PAT2	96.9
50	Block 1	19	70	45	10	PAT2	100
51	Block 1	53	90	45	10	PAT2	100
52	Block 1	15	50	180	10	PAT2	100
53	Block 1	10	70	180	10	PAT2	100
54	Block 1	75	90	180	10	PAT2	100
55	Block 1	4	50	9	5	PAT3	98.2
56	Block 1	81	70	9	5	PAT3	100
57	Block 1	71	90	9	5	PAT3	100
58	Block 1	55	50	45	5	PAT3	96.2
59	Block 1	66	70	45	5	PAT3	84.5
60	Block 1	16	90	45	5	PAT3	98.3
61	Block 1	1	50	180	5	PAT3	100
62	Block 1	69	70	180	5	PAT3	100
63	Block 1	25	90	180	5	PAT3	99.9
64	Block 1	56	50	9	8	PAT3	97.7
65	Block 1	47	70	9	8	PAT3	89.6
66	Block 1	36	90	9	8	PAT3	94.7
67	Block 1	35	50	45	8	PAT3	100
68	Block 1	30	70	45	8	PAT3	98.5
69	Block 1	43	90	45	8	PAT3	85.8
70	Block 1	29	50	180	8	PAT3	0
71	Block 1	14	70	180	8	PAT3	95.8
72	Block 1	59	90	180	8	PAT3	100
73	Block 1	49	50	9	10	PAT3	98
74	Block 1	73	70	9	10	PAT3	92.7
75	Block 1	80	90	9	10	PAT3	82.2
76	Block 1	26	50	45	10	PAT3	95.4
77	Block 1	67	70	45	10	PAT3	96

78	Block 1	3	90	45	10	PAT3	95.5
79	Block 1	64	50	180	10	PAT3	0
80	Block 1	62	70	180	10	PAT3	100
81	Block 1	12	90	180	10	PAT3	99.5
82	Block 2	144	50	9	5	PAT1	71.6
83	Block 2	141	70	9	5	PAT1	100
84	Block 2	128	90	9	5	PAT1	81.9
85	Block 2	82	50	45	5	PAT1	90.5
86	Block 2	105	70	45	5	PAT1	71.6
87	Block 2	126	90	45	5	PAT1	71.6
88	Block 2	98	50	180	5	PAT1	92.4
89	Block 2	115	70	180	5	PAT1	95.7
90	Block 2	99	90	180	5	PAT1	90.2
91	Block 2	153	50	9	8	PAT1	92.1
92	Block 2	158	70	9	8	PAT1	91.7
93	Block 2	107	90	9	8	PAT1	89.4
94	Block 2	152	50	45	8	PAT1	73.4
95	Block 2	139	70	45	8	PAT1	99
96	Block 2	135	90	45	8	PAT1	99.7
97	Block 2	117	50	180	8	PAT1	100
98	Block 2	148	70	180	8	PAT1	100
99	Block 2	136	90	180	8	PAT1	98.9
100	Block 2	162	50	9	10	PAT1	93.5
101	Block 2	129	70	9	10	PAT1	82.4
102	Block 2	143	90	9	10	PAT1	100
103	Block 2	86	50	45	10	PAT1	97.9
104	Block 2	84	70	45	10	PAT1	92.2
105	Block 2	110	90	45	10	PAT1	100
106	Block 2	113	50	180	10	PAT1	100
107	Block 2	160	70	180	10	PAT1	99.7
108	Block 2	147	90	180	10	PAT1	100
109	Block 2	146	50	9	5	PAT2	91.4
110	Block 2	122	70	9	5	PAT2	76.1
111	Block 2	119	90	9	5	PAT2	61.8
112	Block 2	95	50	45	5	PAT2	85.6
113	Block 2	106	70	45	5	PAT2	100
114	Block 2	159	90	45	5	PAT2	83
115	Block 2	88	50	180	5	PAT2	100
116	Block 2	155	70	180	5	PAT2	99.5
117	Block 2	138	90	180	5	PAT2	66.7
118	Block 2	133	50	9	8	PAT2	99
119	Block 2	157	70	9	8	PAT2	100
120	Block 2	90	90	9	8	PAT2	92.4
121	Block 2	125	50	45	8	PAT2	66.2
122	Block 2	123	70	45	8	PAT3	100

123	Block 2	150	90	45	8	PAT2	100
124	Block 2	83	50	180	8	PAT2	100
125	Block 2	101	70	180	8	PAT2	100
126	Block 2	111	90	180	8	PAT2	100
127	Block 2	112	50	9	10	PAT2	100
128	Block 2	161	70	9	10	PAT2	100
129	Block 2	103	90	9	10	PAT2	100
130	Block 2	130	50	45	10	PAT2	100
131	Block 2	100	70	45	10	PAT2	100
132	Block 2	114	90	45	10	PAT2	100
133	Block 2	96	50	180	10	PAT2	65.1
134	Block 2	151	70	180	10	PAT2	97
135	Block 2	127	90	180	10	PAT2	100
136	Block 2	120	50	9	5	PAT3	71.6
137	Block 2	85	70	9	5	PAT3	100
138	Block 2	137	90	9	5	PAT3	100
139	Block 2	89	50	45	5	PAT3	99.5
140	Block 2	124	70	45	5	PAT3	97
141	Block 2	97	90	45	5	PAT3	99.6
142	Block 2	93	50	180	5	PAT3	98.2
143	Block 2	91	70	180	5	PAT3	100
144	Block 2	116	90	180	5	PAT3	97.1
145	Block 2	121	50	9	8	PAT3	99.5
146	Block 2	140	70	9	8	PAT3	91.8
147	Block 2	109	90	9	8	PAT3	90.2
148	Block 2	131	50	45	8	PAT3	89.2
149	Block 2	104	70	45	8	PAT3	97.2
150	Block 2	87	90	45	8	PAT3	98.7
151	Block 2	92	50	180	8	PAT3	0
152	Block 2	102	70	180	8	PAT3	99.8
153	Block 2	108	90	180	8	PAT3	98.3
154	Block 2	94	50	9	10	PAT3	94.1
155	Block 2	145	70	9	10	PAT3	98.4
156	Block 2	134	90	9	10	PAT3	100
157	Block 2	142	50	45	10	PAT3	94.9
158	Block 2	118	70	45	10	PAT3	97.4
159	Block 2	149	90	45	10	PAT3	97.4
160	Block 2	154	50	180	10	PAT3	0
161	Block 2	156	70	180	10	PAT3	99.5
162	Block 2	132	90	180	10	PAT3	100
163	Block 3	233	50	9	5	PAT1	76.4
164	Block 3	189	70	9	5	PAT1	78.8
165	Block 3	198	90	9	5	PAT1	92.2
166	Block 3	193	50	45	5	PAT1	93
167	Block 3	205	70	45	5	PAT1	71.5

168	Block 3	204	90	45	5	PAT1	74.5
169	Block 3	168	50	180	5	PAT1	74.1
170	Block 3	200	70	180	5	PAT1	97.7
171	Block 3	229	90	180	5	PAT1	72.2
172	Block 3	163	50	9	8	PAT1	91.3
173	Block 3	177	70	9	8	PAT1	96.3
174	Block 3	197	90	9	8	PAT1	93.5
175	Block 3	191	50	45	8	PAT1	100
176	Block 3	236	70	45	8	PAT1	100
177	Block 3	199	90	45	8	PAT1	81.8
178	Block 3	231	50	180	8	PAT1	97.9
179	Block 3	206	70	180	8	PAT1	99.8
180	Block 3	212	90	180	8	PAT1	73.9
181	Block 3	215	50	9	10	PAT1	91.6
182	Block 3	226	70	9	10	PAT1	89.4
183	Block 3	203	90	9	10	PAT1	88
184	Block 3	210	50	45	10	PAT1	100
185	Block 3	196	70	45	10	PAT1	91.3
186	Block 3	180	90	45	10	PAT1	100
187	Block 3	185	50	180	10	PAT1	91.1
188	Block 3	228	70	180	10	PAT1	100
189	Block 3	173	90	180	10	PAT1	100
190	Block 3	224	50	9	5	PAT2	100
191	Block 3	217	70	9	5	PAT2	93.3
192	Block 3	240	90	9	5	PAT2	78.4
193	Block 3	176	50	45	5	PAT2	93
194	Block 3	222	70	45	5	PAT2	0
195	Block 3	194	90	45	5	PAT2	61.8
196	Block 3	195	50	180	5	PAT2	74.1
197	Block 3	178	70	180	5	PAT2	100
198	Block 3	230	90	180	5	PAT2	84.3
199	Block 3	174	50	9	8	PAT2	99.7
200	Block 3	172	70	9	8	PAT2	100
201	Block 3	208	90	9	8	PAT2	100
202	Block 3	238	50	45	8	PAT2	99.9
203	Block 3	223	70	45	8	PAT2	78.4
204	Block 3	218	90	45	8	PAT2	99
205	Block 3	165	50	180	8	PAT2	99.9
206	Block 3	221	70	180	8	PAT2	99.7
207	Block 3	182	90	180	8	PAT2	99.7
208	Block 3	170	50	9	10	PAT2	100
209	Block 3	187	70	9	10	PAT2	100
210	Block 3	225	90	9	10	PAT2	100
211	Block 3	171	50	45	10	PAT2	100
212	Block 3	164	70	45	10	PAT2	100

213	Block 3	175	90	45	10	PAT2	94.6
214	Block 3	235	50	180	10	PAT2	0
215	Block 3	211	70	180	10	PAT2	100
216	Block 3	242	90	180	10	PAT2	100
217	Block 3	192	50	9	5	PAT3	96.1
218	Block 3	190	70	9	5	PAT3	100
219	Block 3	169	90	9	5	PAT3	92.5
220	Block 3	181	50	45	5	PAT3	95.7
221	Block 3	186	70	45	5	PAT3	89.1
222	Block 3	227	90	45	5	PAT3	98.3
223	Block 3	220	50	180	5	PAT3	99.8
224	Block 3	202	70	180	5	PAT3	99.8
225	Block 3	209	90	180	5	PAT3	88.7
226	Block 3	232	50	9	8	PAT3	96.5
227	Block 3	166	70	9	8	PAT3	96.1
228	Block 3	201	90	9	8	PAT3	94.8
229	Block 3	207	50	45	8	PAT3	98.7
230	Block 3	243	70	45	8	PAT3	91.5
231	Block 3	237	90	45	8	PAT3	96.9
232	Block 3	219	50	180	8	PAT3	99.9
233	Block 3	179	70	180	8	PAT3	99.2
234	Block 3	184	90	180	8	PAT3	95.7
235	Block 3	213	50	9	10	PAT3	87.9
236	Block 3	216	70	9	10	PAT3	92.1
237	Block 3	239	90	9	10	PAT3	99.1
238	Block 3	167	50	45	10	PAT3	96.7
239	Block 3	188	70	45	10	PAT3	91.8
240	Block 3	234	90	45	10	PAT3	95.8
241	Block 3	183	50	180	10	PAT3	0
242	Block 3	214	70	180	10	PAT3	100
243	Block 3	241	90	180	10	PAT3	93.9

Analyzing phase and results are discussed in the following chapter.

Chapter 4: Data Analysis and Results

The custom full factorial design was analyzed using Minitab software. Normal probability plot of the standardized residuals from the analysis shows that data is not normally distributed. As the process has many values close to the natural limit, the data is skewed.

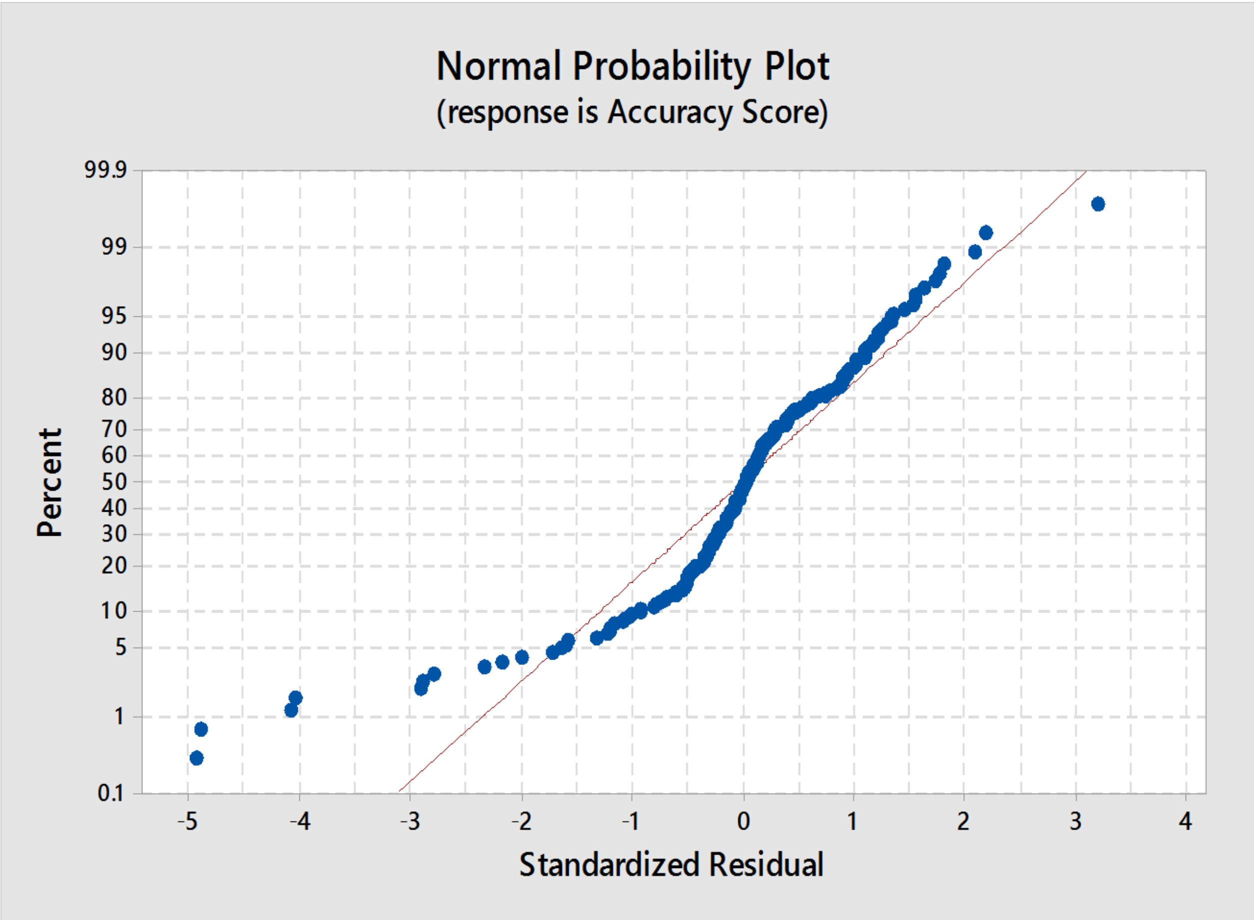


Figure 4.1: Normal Probability plot of Residuals for Accuracy Score

The accuracy score was transformed using Box-Cox Transformation. From the Box-Cox plot, it is evident that transformation should be considered as the confidence interval for λ does not include 1.

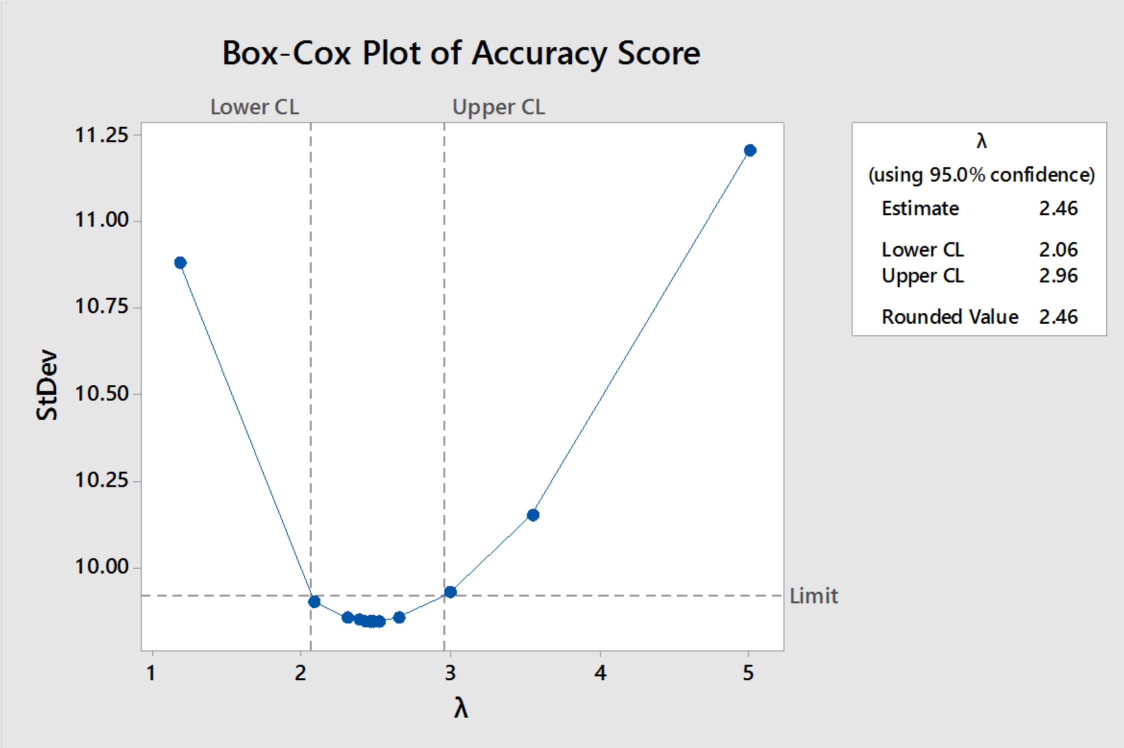


Figure 4.2 Box-Cox Plot of Accuracy Score

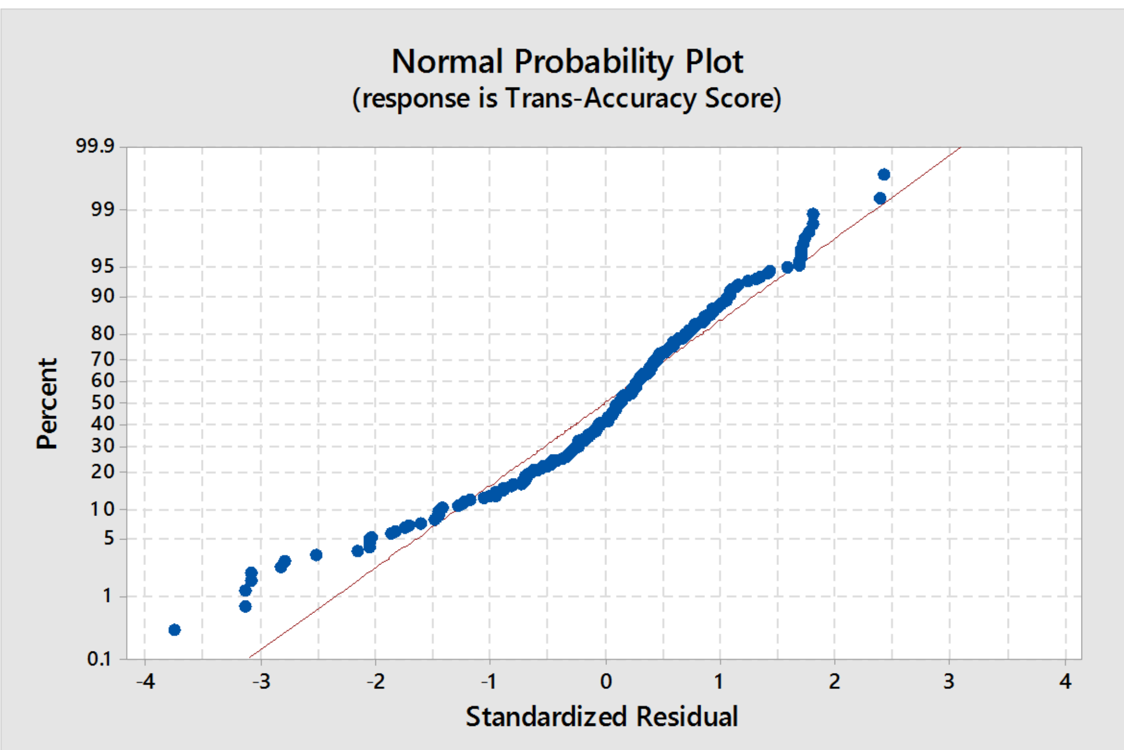


Figure 4.3: Normal Probability plot of the transformed response

4.1 ANALYSIS OF VARIANCE (ANOVA)

Table 4.1: Analysis of variance table

Source	DF	Adj SS	Adj MS
Model	32	34076384323	1064887010
Linear	8	8103073255	1012884157
Vacuum Pressure	2	2239080204	1119540102
Velocity	2	146693827	73346914
Type of Vacuum gripper	2	4966570645	2483285323
Position & Shape of part	2	743020400	371510200
2-Way Interactions	24	25961754765	1081739782
Vacuum Pressure*Velocity	4	4606268499	1151567125
Vacuum Pressure*Type of Vacuum gripper	4	4866562363	1216640591
Vacuum Pressure*Position & Shape of part	4	2665894581	666473645
Velocity*Type of Vacuum gripper	4	2062432382	515608095
Velocity*Position & Shape of part	4	2907184048	726796012
Type of Vacuum gripper*Position & Shape of part	4	8867895045	2216973761
Error	210	54050558358	257383611
Lack-of-Fit	48	21150843846	440642580
Pure Error	162	32899714512	203084657
Total	242	88126942681	

Source	F-Value	P-Value
Model	4.14	0.000
Linear	3.94	0.000
Vacuum Pressure	4.35	0.014
Velocity	0.28	0.752
Type of Vacuum gripper	9.65	0.000
Position & Shape of the part	1.44	0.238
2-Way Interactions	4.20	0.000
Vacuum Pressure*Velocity	4.47	0.002
Vacuum Pressure*Type of Vacuum gripper	4.73	0.001
Vacuum Pressure*Position & Shape of the part	2.59	0.038
Velocity*Type of Vacuum gripper	2.00	0.095
Velocity*Position & Shape of the part	2.82	0.026
Type of Vacuum gripper*Position & Shape of the part	8.61	0.000
Error		
Lack-of-Fit	2.17	0.00

4.1.1 Interaction Effects

The model contains six interaction effects which must be evaluated first. The p-value of 0.097 for the velocity by gripper type interaction is not less 0.05. Therefore, there is no significant interaction effect. That is, there is no evidence that the velocity of the robot on the accuracy of the assembly depends on the type of the gripper. Also interaction between 1) vacuum pressure and velocity 2) vacuum pressure and gripper type 3) velocity and position and shape of part 4) gripper type and position and shape of part 5) vacuum pressure and position and shape of part

4.1.2 Main effects

The model contains two main effects (vacuum pressure and gripper type) that can be evaluated in the presence of a significant interaction. The p-value of vacuum pressure and gripper type effect on accuracy score are less than 0.05. Therefore, you conclude that there is a significant effect.

The p-values of velocity and position and shape of the part are not less than 0.05. That is, there is no evidence that accuracy score depends on the velocity and position and shape of the part.

4.2 FACTORIAL PLOTS

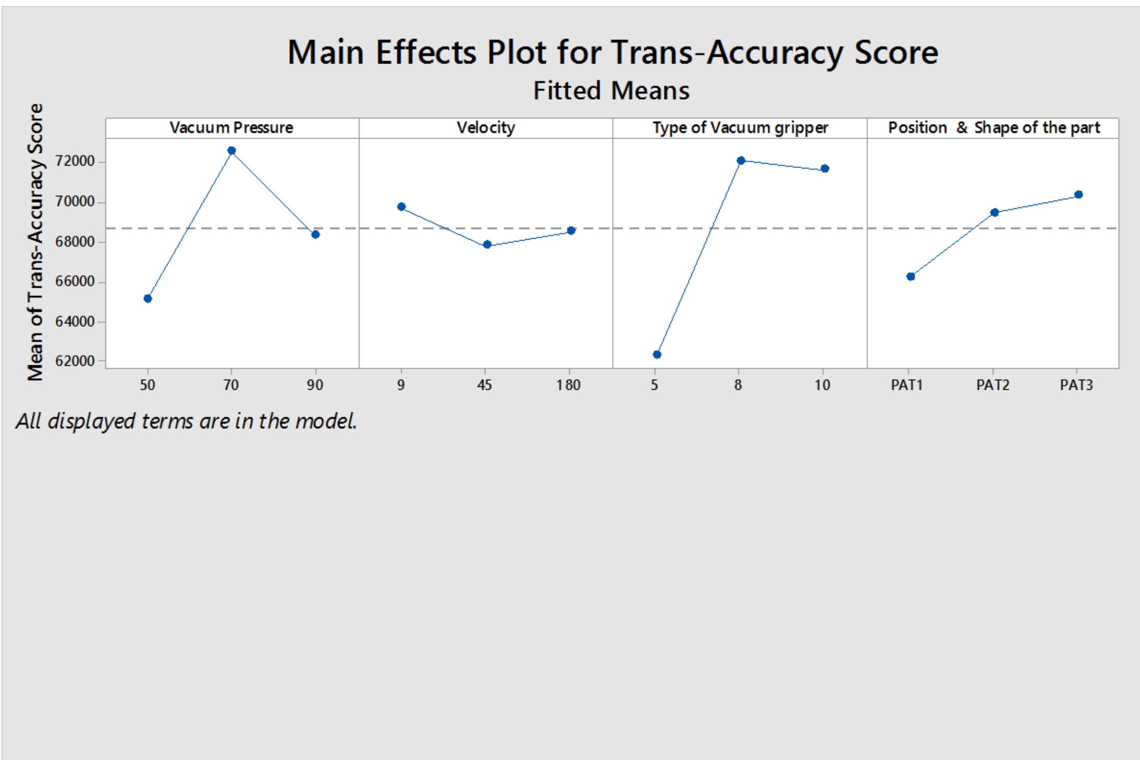


Figure 4.4 Main Effects plot for Transformed Accuracy score

The main effects plot is most useful when there are several categorical variables. It helps to compare the changes in the level means to see which categorical variable influences the response the most. The main effect is present when the mean of the response changes at the different levels of the variable [11]. For a variable with two levels, the mean is higher at one level of the variable than at another level. This difference is the main effect. The main effects are only interpretable if the interaction effects are not significant.

Minitab creates the main effects plot by plotting the fitted mean for each value of a variable in the model. Minitab can plot data means for variables that are not in the model. A line

connects the points for each variable. Look at the line to determine whether or not the main effect is present for a variable. When the line is horizontal (parallel to the x-axis), then there is no main effect present [6]. Each level of the variable affects the response in the same way, and the response mean is the same across all levels. When the line is not horizontal (parallel to the x-axis), then there is a main effect present. Different levels of the categorical variable affect the response differently. The greater the difference in the vertical positions of the plotted points, the greater the magnitude of the main effect [10]. To determine if a difference is statistically significant, check the p-value of the term in the analysis of variance table. By comparing the slopes of the lines, you can compare the relative magnitude of the effects. Minitab also draws a reference line at the overall mean. Factorial plots do not use the data in the worksheet for the fitted means. Instead, Minitab estimates the fitted means based on a stored model. Factorial plots are accurate only if the model represents the true relationships [11]

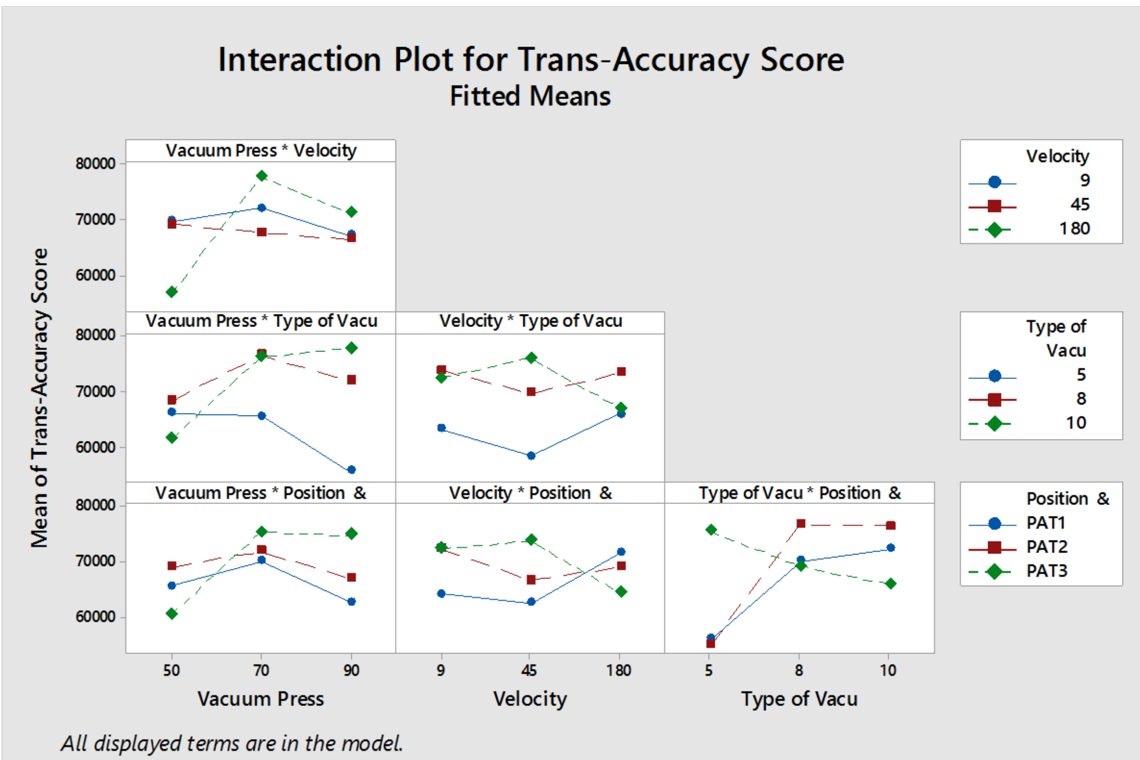


Figure 4.5 Interaction plot for Trans-Accuracy Score.

Chapter 5: Conclusions and Recommendations

5.1 CONCLUSIONS

The following conclusions can be drawn from the experiment:

1) In the factorial experiments that are conducted for the assembly process, the results show that vacuum pressure and type of vacuum gripper plays a very important role. In addition to that, the interaction of 1) vacuum pressure and velocity 2) vacuum pressure and gripper type 3) velocity and position and shape of part 4) gripper type and position and shape of the part also play an equally important role. This is supported by the ANOVA table too.

2) Although velocity plays an important role in assembling the electronic components surprisingly, the analysis does not prove it. From the residual plot, it was evident that there is still room for improvement of the model by adding additional variables.

3) Optimum Settings of the robot used for the experiment are found out by using response surface design. At the optimal settings counter-plots of accuracy score are prepared to analyze the interaction

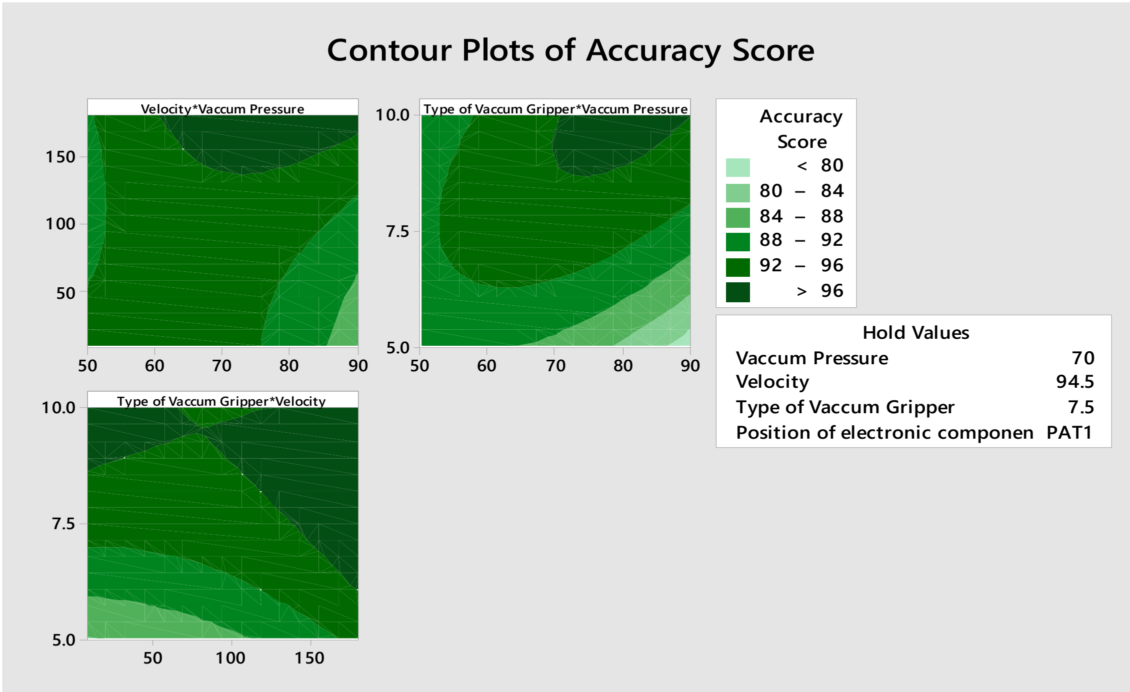


Figure: 5.1.1 Contour plots of accuracy score

5.2 RECOMMENDATIONS

A better gripping arm has to be designed by calculating the adhesion forces acting on the micro parts. An optical sensor will help automatic pick and orientation of the micro parts. The experiment only investigated the accuracy of the pick and place of micro objects. For a better understanding of the process, other quality characteristics like repeatability have to be studied.

References

[1] Gordon, R. (2015). Trends in Commercial 3D Printing and Additive Manufacturing. *3D Printing and Additive Manufacturing, 2*(2), 89-90. doi: 10.1089/3dp.2015.28999.rgo

[2] Golhar, D. Y., & Stamm, C. L. (1991). The just-in-time philosophy: A literature review. *International Journal of Production Research, 29*(4), 657-676. doi:10.1080/00207549108930094

[3] Czitrom, V. (1999). One-Factor-at-a-Time versus Designed Experiments. *The American Statistician*, *53*(2), 126-131. doi:10.1080/00031305.1999.10474445

[4] Goswami, A., Quaid, A., Peshkin, M., "Complete Parameter Identification of a Robot from Partial Pose Information", Proceedings of the 1993 IEEE International Conference on Robotics and Automation, (1) 168-173, 1993.

[5] Schubert, C., Langeveld, M. C., & Donoso, L. A. (2013). Innovations in 3D printing: A 3D overview from optics to organs. *British Journal of Ophthalmology*, *98*(2), 159-161. doi:10.1136/bjophthalmol-2013-304446

[6] Mehrez, A., Hu, M., Offodile, O.F. "Multivariate Economic Analysis of Robot Performance Repeatability and Accuracy", Journal of Manufacturing Systems, 15(4) 215-226, 1996.

[7] ISO 9283 – "Manipulating industrial robots. Performance criteria and related test methods". ISO, Geneva 1998.

[8] Montgomery, D.C. Design and Analysis of Experiments, 6th edition, Wiley, 2005

[9] Espalin, D., Muse, D. W., MacDonald, E., & Wicker, R. B. (2014). 3D Printing multifunctionality: structures with electronics. The International Journal of Advanced Manufacturing Technology, 72(5-8), 963-978.

[10] Young, K., & Pickin, C. G. (2000). Accuracy assessment of the modern industrial robot. *Industrial Robot: An International Journal, 27*(6), 427-436. doi:10.1108/01439910010378851

[11] Zhang, X. P., Yan, W. C., Zhu, W., & Wen, T. (2011). A Design of End Effector for Measuring Robot Orientation Accuracy and Repeatability. *AMM Applied Mechanics and Materials*, *137*, 382-386. doi:10.4028/www.scientific.net/amm.137.382

[12] Hicks, Charles. Fundamental Concepts in the Design of Experiments. 3rd ed. PP. 15 - 35. Holt, Rinehart and Winston, Inc., 1982.

[13] Grant, Eugene, and Richard Leavenworth. Statistical Qua1ity Control. 5th ed. PP. 152 - 170.

New York:McGraw Hill, Inc., 1980.

Appendix I- Yamaha SCARA YK180X Specifications

YK180X

Standard type: Tiny type

Arm length 180mm | Maximum payload 1kg

Ordering method

YK180X - 100 - [ ] - RCX340-4 [ ] - [ ] - [ ] - [ ] - [ ] - [ ] - [ ]

Model - Z axis stroke (100: 100mm) - Cable (3L: 3.5m / 5L: 5m / 10L: 10m) - Controller / Number of controllable axes - Safety standard - Option A (OP.A) - Option B (OP.B) - Option C (OP.C) - Option D (OP.D) - Option E (OP.E) - Absolute battery

Specify various controller setting items. RCX340 ▶ P.494

RCX240S [ ] - [ ] - [ ] - [ ] - [ ] - BB

Controller - CE Marking - Expansion I/O - Network option - iVY System - Gripper - Battery

Specify various controller setting items. RCX240/RCX240S ▶ P.481

Specifications

			X-axis	Y-axis	Z-axis	R-axis
Axis specifications	Arm length		71 mm	109 mm	100 mm	-
	Rotation angle		+/-120 °	+/-140 °	-	+/-360 °
AC servo motor output			50 W	30 W	30 W	30 W
Deceleration mechanism	Speed reducer		Harmonic drive	Harmonic drive	Ball screw	Harmonic drive
	Transmission method	Motor to speed reducer	Direct-coupled			
		Speed reducer to output	Direct-coupled			
Repeatability [Note 1]			+/-0.01 mm		+/-0.01 mm	+/-0.004 °
Maximum speed			3.3 m/sec		0.7 m/sec	1700 °/sec
Maximum payload			1.0 kg			
Standard cycle time: with 0.1kg payload [Note 2]			0.39 sec			
R-axis tolerable moment of inertia [Note 3]			0.01 kgm^2			
User wiring			0.1 sq × 6 wires			
User tubing (Outer diameter)			ϕ 3 × 2			
Travel limit			1.Soft limit 2.Mechanical stopper (X,Y,Z axis)			
Robot cable length			Standard: 3.5 m Option: 5 m, 10 m			
Weight (Excluding robot cable) [Note 4]			5.5 kg			
Robot cable weight			1.5 kg (3.5 m) 2.1 kg (5 m) 4.2 kg (10 m)			

Note 1. This is the value at a constant ambient temperature.
Note 2. When reciprocating 100mm in horizontal and 25mm in vertical directions.
Note 3. There are limits to acceleration coefficient settings. See P.522.
Note 4. The total robot weight is the sum of the robot body weight and the cable weight.

Controller

Controller	Power capacity (VA)	Operation method
RCX340 RCX240S	500	Programming / I/O point trace / Remote command / Operation using RS-232C communication

Note. "Harmonic" and "Harmonic drive" are the registered trademarks of Harmonic Drive Systems Inc.
Note. The movement range can be limited by changing the positions of X and Y axis mechanical stoppers. (The movement range is set to the maximum at the time of shipment.)
See our robot manuals (installation manuals) for detailed information.

Our robot manuals (installation manuals) can be downloaded from our website at the address below:
http://global.yamaha-motor.com/business/robot/

Appendix II- Vacuum Cups used in the experiment

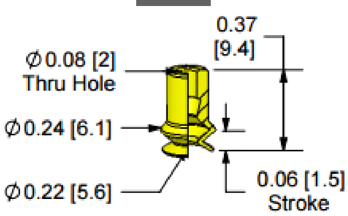
VACUUM CUPS
BELLOWS CUPS

	CUP SIZE	CUP MATERIAL[1]		FITTING		FILTER
XP-B	15	N	-	10M	-	
	5 = 5 mm	A = Ameriflex		See Cup Fitting section for available threads.		(Blank) = None
	8 = 8 mm	CS = Conductive Silicone				FD = PE Filter
	10 = 10 mm	D = Duramax				FS = SS Screen
	15 = 15 mm	N = Nitrile				See Cup Fitting Section for availability.
	20 = 20 mm	S = Silicone				
		V = Viton				

[1]All cups are available in Nitrile and Silicone.
Check availability for other materials before ordering.

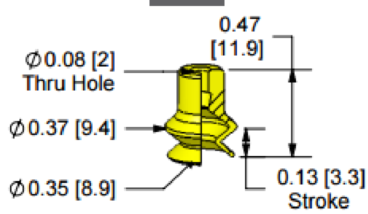
[2]All figures for shear load are 18"Hg. using a 0.5 coefficient of friction. Adjust coefficient of friction to suit your conditions, then apply a generous factor of safety (3:1 or greater) to shear loads.

XP-B5



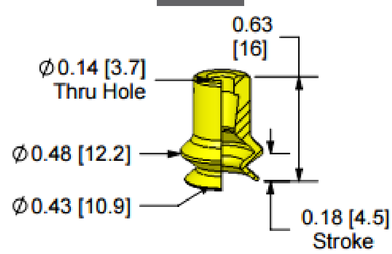
Cup Diameter	5 mm
Cup Weight: oz [g]	0.004 [0.11]
Internal Volume: cu in [cc]	0.01 [0.2]
Force @ 6" Hg: lb [n]	0.07 [0.3]
Force @ 18" Hg: lb [n]	0.10 [0.4]
Minimum Radius: in [mm]	0.06 [1.5]
Shear Load[2]: lb [n]	0.05 [0.2]

XP-B8



Cup Diameter	8 mm
Cup Weight: oz [g]	0.01 [0.3]
Internal Volume: cu in [cc]	0.01 [0.2]
Force @ 6" Hg: lb [n]	0.18 [0.8]
Force @ 18" Hg: lb [n]	0.36 [1.6]
Minimum Radius: in [mm]	0.07 [1.8]
Shear Load[2]: lb [n]	0.18 [0.8]

XP-B10



Cup Diameter	10 mm
Cup Weight: oz [g]	0.03 [0.9]
Internal Volume: cu in [cc]	0.03 [0.5]
Force @ 6" Hg: lb [n]	0.3 [1.3]
Force @ 18" Hg: lb [n]	0.8 [3.6]
Minimum Radius: in [mm]	0.16 [4.1]
Shear Load[2]: lb [n]	0.4 [1.7]

Appendix III – Program for the Robot

```
ACCEL 90              'SET ACELERATION FOR THE ENTIRE PROGRAM
DECEL 70              'SET DEC FOR THE ENTIRE PROGRAM
SPEED 60              'SET MAX SPEED THE ROBOT WILL RUN
MOVE P,P0,Z=0         'GO HOME EVERY TIME WE START CYCLE
DO2(2,1,0)=0          'TURN OFF ALL OUTPUTS
' TEST
'***INPUT AND OUTPUT DEFINITION***
'  INPUT 20, 21 AND 22 ARE PROGRAM SELECTION
'  INPUT 23 IS START CYCLE
'  INPUT 24 IS PRESSURE OK
'  INPUT 36 AND 37 ARE FOR COLOR CAMERA
'  OUTPUT 20 IS FOR DONE
'  OUTPUT 21 IS FOR VACUUM ON
'  OUTPUT 22 IS FOR LASER ON
'  OUTPUT 27 IS FOR COLOR CAMERA
************************PROGRAM*********************************
*MAIN:                'MAIN PROGRAM
DO2(0)=1              'ROBOT READY AND IN AUTO
IF DI(23)=0 THEN GOTO *MAIN     'WAIT FOR SET CYCLE
'THE COMMAND BCD IS INPUTS DI20, DI21 AND DI22
'COMMAND BCD 0 = RUN PICK_N_PLACE PROGRAM
IF DI2(2,1,0)=0 THEN GOSUB *PICK_N_PLACE
GOTO *MAIN
'**************************SUBRUTINES*****************************
*TURN_VACC_ON:
DELAY 100             'DELAY 100 MS
DO2(1)=1              'TURN VACCUM ON
DELAY 200             'WAIT 200 MS
RETURN
*TURN_VACC_OFF:
DELAY 100             'DELAY 100 MS
DO2(1)=0              'TURN VACCUM OFF
DELAY 200             'WAIT 200 MS
RETURN
*LASER_ON:
DO2(2)=1              'TURN LASER ON
DELAY 200             'WAIT 200 MS
RETURN
*LASER_OFF:
DO2(2)=0              'TURN LASER ON
DELAY 200             'WAIT 200 MS
RETURN
```

```
'***************************PICK_N_PLACE************************
*PICK_N_PLACE:
MOVE P, P1000, Z=0
DO2(1)=1
MOVE P, P1001, Z=0
DO2(1)=0
DELAY 200
MOVE P,P1002, Z=0
DO2(1)=1
MOVE P,P1003, Z=0
DO2(1)=0
MOVE P,P1004, Z=0
DO2(1)=1
MOVE P,P1005, Z=0
DO2(1)=0
MOVE P,P1006, Z=0
DO2(1)=1
MOVE P,P1007, Z=0
DO2(1)=0
RETURN
```

Vita

Sreekara Charith Boppana was born on 29th January 1993 in Challapalli, Andhra Pradesh, India. The only child of Kamalakar Boppana and Vijaya Boppana, he graduated from the K L University, Vijayawada, in the fall of 2014, with a bachelor's degree in Mechanical Engineering. He worked as Trainee Engineer in Vizag Steel Plant in the summer of 2012 and 2013. He worked as a Quality engineer in the HMT Machine Tools Ltd., until Dec 2014. He entered the graduate school at the Wayne State University at Detroit, in the winter of 2015 for a master's degree in Industrial engineering. He later transferred to the University of Texas at El Paso in fall 2015. While pursuing his master's degree, he worked as an Event staff for CSC El Paso. He also worked as Research Assistant in IMSE Department, UTEP.

Contact Information: sboppana@miners.utep.edu

This thesis/dissertation was typed by Sreekara Charith Boppana.