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E-Quality Design Of Experiments For Structural Electronics

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E-QUALITY DESIGN OF EXPERIMENTS FOR STRUCTURAL ELECTRONICS

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Dedication

First of all, I would like to dedicate this thesis to my family that has always supported me. To my mom Blanca Margarita Torres, who never thought that I will graduate from high school, my dad Norberto Aurelio Murga that always taught me to go farther and that it was possible to accomplish anything that you want, and my sister Blanca Margarita Murga who has inspired me to always push my limits at school. They have been pushing, motivating, advising and caring me the whole journey.

Also, I would like to dedicate this thesis to my loving girlfriend Tania Moreno who has been a huge motivation to finish my bachelor and today my masters. Also, for helping me with homework and studying as well as understanding my absenteeism and high levels of stress at home.

Finally, I would like to thank everybody that believed in me and supported me in this great journey.

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by

OSCAR ALEJANDRO MURGA TORRES, B.S..

THESIS

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Abstract

Additive Manufacturing (AM) is a technology utilized for creating complex parts by adding layers of material in order to create a three dimensional functional part. This technology has been pushed to a new level of functionality where mechanical parts are combined with electronic components to create Three-Dimensional Structural Electronics (3DSE) systems. This new technology has been used to replace Printed Circuit Boards (PCB), for 3D SE are light weight and can be created in any desired shape. Computer Aided Design (CAD) software is used to design the part and a Fused Deposition Modeling (FDM) machine is used to 3D print the part with slots for the electronic components to be embedded. Researchers have been working on embedding electronic components for several years, but so far all the embedding of components is done manually. The research presented in this paper provides a new approach for embedding electronics by utilizing a Yamaha SCARA robot in order to automate the pick and place process. Automated placement of electronic components is an ongoing research area, and in this paper a design of experiment (DOE) is conducted to measure accuracy on the Yamaha SCARA robot in order to facilitate accurate placement of electronic components.

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Chapter 1: Introduction

The field of manufacturing is driven by consumer/costumer demand for a higher quality product at a lower cost. The manufacturer must keep evolving with technology to fit customer needs and at the same time maintain a high profit by reducing operating cost. Technology offers new pathways to achieve these goals through automation. In the last couple of decades, the industry has utilized the field of automation and robotics to lower the cost of manual labor and increase the quality of the product, automation is expanding across industries at a rate that is exceeded only by the growth of internet [1]. When done correctly may be an efficient approach to maintain the balance between the demand of the consumer and the efficiency of the manufacturer. Automation, can be defined as the use of machinery or equipment in a manufacturing process, industrial robots are the mere example of automation. To facilitate automation, the *industrial* robot operates in a structured environment that is relatively well defined and can be engineered and modified for the best use of robotic technologies (in contrast with robots operating in unstructured environments such as space exploration missions, underwater missions, or nuclear disaster cleanup), therefore the design of the working area must be strategically thought for the best production results and cost efficiency. To that end, the uncertainties that exist in a structured environment can be identified and anticipated, and handled by the correct implementation of sensors, feeders, fixtures, sorting procedures, and other techniques [2].

An automatic system can be defined as a system which is able to repeat specific operation generally with a low degree of intellectual and manipulative levels, but that can be easily programmed in agreement with demands of productivity [3]. Robotics is the theory and practice of automation of tasks which, because of their nature, were previously thought to be reserved for man alone. Such work is characterized by an almost permanent interaction between the robotic device and the object (or environment) [4]. The need of automation in a manufacturing process is ideal for two main reasons: cost

savings and improving the quality of the product manufactured. Zandin (2001) explains how that flexibility is the main advantage of robots because it allows the manufacturer to utilize them for a vast variety of products of all sizes. It also allows for implementation of a wide range of productivity life cycles to accommodate to the demand of the product. Therefore as stated before, it is important to implement a design that fits the needs of one's specific product and justify every aspect of the design. For tasks that are repetitive, such as the case of embedding electronic components, a simpler pick and place devise may be the most effective and low cost solution. Other more difficult task may require a higher level of flexibility or even require a human operator with intelligence [2]. Therefore, when approaching the idea of automating a process one must consider the task, the intellectual levels required for the task and the potential of the robot that is being considered for the job. New robots have the capability of performing different jobs by being reprogramed; this means that they can substitute not one but several workers. Shin (2008) defines the advantages of these robots, the first one being flexibility which according to her modern robots can in many cases perform better than previews robots since they are able to perform more than one function such as welding, riveting, bonding and installing components [5]. Other benefits of robots are their precision, speed, accuracy and according to Shin, their ability to work 365 days.

Automation is not only a benefit for the manufacturing industry but for the safety of the worker and in the past it has been implemented entirely in the welding industry due to the injury risk that it represents for the human worker. Zandin (2001) states that robots are justified for task that have the 4-D characteristics which are dangerous, dirty, difficult and dull [2]. Research shows that a product spends 95 % of its time waiting and been transport to a different area, while only 5% of the time the product is on active production and robots can be utilized to speed up the moving time and as a consequence reduce production time [6].

The purpose of this research is to show the benefits of automating the electronic component placement for the purpose of building Three-Dimensional Structural Electronics (3D-SE) using Additive Manufacturing. Additive Manufacturing or 3-D printing is a technology where parts are created by adding material in layers in order to create a three dimensional part. Researchers are incorporating electronic components to additive manufacturing to create 3D-SE and replace Printed Circuit Boards (PCB). Gutierrez (2011) pioneer on 3D SE research, if the use of PCBs is eliminated, one can design the circuits on the surface of a conformal device, with that the size and volume of the device can be reduced and its shape optimized for a more efficient use [7]. In addition, the use of additive manufacturing for the production of 3D SE is an inexpensive alternative to the traditional PCB. 3-D printing is an automated process which requires minimal human interactions, aside from the design. The use of a robot to incorporate the electronic components necessary to make a functional 3D SE will extend the production possibilities and allow for as many changes and alterations as the consumer desires with minimal cost and quality repercussions. This research presents a design of experiment approach used to measure the significance of the factors interaction to achieve a high quality production of 3D-SE while using automated assembly of electronic components. In order to compare the final quality of component placement a machine Vision system will be utilized, to better understand the reliability and accuracy of the embedding technique.

Chapter 2: Theoretical Background

2.1 History of the Robot:

The vision of robotics has been around since the beginning of the 19^{th} century to depict a fictional character, an idea of a machine with human characteristics that will function on human command and never represent a hazard. Scott (2011) describes how the idea was transformed and turned into a reality initially by building “Shakey”, a robot built at the Stanford Research Institute that was able to perceive, model and interact with its environment, this robot represented the beginning of the “Artificial Intelligence” era. Later more sophisticated machines were created, those machines could be controlled through a computerized system. The first robotic arm was invented in 1969, this arm was controlled by a computer and had 6 degrees of freedom and five revolute joints. The new implementations added to the flexibility of its uses, and lead to the creation of the most current robots, that maximize the cost and quality of the manufacturer’s productions in a variety of industries.

Automation in the Industry grew around the scientific research, one of the first robots created for the industry was the “Versatran” which was distributed in 1963, and the use of this robot was specific to transfer of product. This robot was followed by the “Trallfa” robot, a robot with six degrees of freedom, capable of spray painting different surfaces; this robot was later on modified to be used on the welding and agriculture industry. Those robots proved to be efficient for the manufacturing industry and their processes. Since its introduction automation in the industry overlooks three main ideas: create a safe environment for the human worker, reduce cost and increase product quality.

2.2 Safe environment:

Automation was brought into the manufacturing industry with the idea of creating a safe environment in dangerous industries such a welding. Today maintaining a safe work environment continues to be one of the main goals of automation, and robots are more capable of performing tasks that can be difficult or endangering humans. One example of this is the use of the Microsoft’s Kinect motion sensing system (Perception Inc.), which utilizes scoops and suction cups to pick and drop boxes in a conveyor belt. This approach reduces injuries for workers in the loading industry such FedEx and

UPS, who have a high probability of suffering from back injuries. With the same purpose, Boeing utilizes giant robots to build their commercial jets, and they state that robots are more precise and the process is safer for workers [5]. When compared to the small scale of our research which consists on working with relatively small elements, one may consider that injuries are not something to be worried about; however injuries also come along through processes that become exhausting by repetition, which is the case of electronic component assembly.

By creating a safe environment the industry is not erasing manual labor from the map, and while the machines work on the assembly line 24 hours a day, 365 days a year, taking care of the precise heavy lifting work load, workers do simple tasks such as trimming extra material, threading wires and screwing fasteners. In that manner, manual labor continues to be required, without jeopardizing their safety and the quality of the product [8]. Boeing claims that even when using robots to build their aircraft the company struggles to obtain enough workers to keep their production of its 787 aircraft, and that automation only increases precision and is safer for workers. Alternatively, the robotic industry in continuously creating new jobs, in 2011 the International Federation of Robotics created 150, 000 employments worldwide in engineering and assembling jobs [8]. After a quantitative experimentation on automation and the effects of a mental load on manual labor Wei (1998) concluded that automation improves production efficiency and enhances operational safety.

2.3 REDUCED COST:

Cost reduction is leading factor in the manufacturing industry and automation is becoming an essential step on reducing manual labor cost, and improved new versions of robots can replace more than one worker and perform up to four functions instead of one. Robots can weld, rivet, bond and install components. For example, Shin (2008) explains how robots utilized in the lettuce packaging industry in California, work at speeds that they may replace five workers [5]. The efficiency of automation when introduced in to the manufacturing industry in a smart educated manner can bring huge profits to the company and there are cases where robotic automation costing 250,000, replaced 2 operators that were earning 50,000 dollars a year, and after the 15 year life of the robotic system the machine had produced a saving of 3.5 million dollars [8]. The Philips Electronics factory in Drachten

Netherlands has robotic arms that must remain enclosed on glass boxes due to the high speed work they produce, at no risk to human injury [8].

Automation has proven to be cost effective in a wide range of industries. One example of this is C & S, the one of the world's largest grocery wholesaler, which was able to reduce their warehouse space from half a million square feet to 30,000 square feet, and hundreds of worker to a few technicians who take care of the robots that work 24 hours, 365 days at a 25 miles per hour speed [8]. Robots are acquiring flexibility and becoming inexpensive, since 1990 the cost of automation has dropped to almost half [9]. As for electronic components assembly, Brandeau (2007) state that implementation of automation on electric component assembly has proven to be faster and cheaper and the advances need to be implemented on maximizing the performance of the robot to produce more than one distinct board [11].

2.4 INCREASE QUALITY:

For this research quality of component placement is being addressed and what automation can contribute to the assembly process. Robots are capable of performing tasks that could be considered difficult to humans; are precise and can slip wires into holes too small to be seen by the naked eye. Philips uses robots that are capable of bending wires with millimetric accuracy, and can put toothpick-thin spindles into even smaller holes and what is most important to our process these robots can grab miniature plastic gears and set them in housing, and snap plastic pieces in place. Robots can be accurate at high speeds without reaching exhaustion. Shin (2008) states that while humans can move a box every six seconds, a robot can perform the same task in one second and avoid back injury. The Tesla Company can have as many as eight robots working on the building of a single car without crashing each other [5], [8]. Although, most of those tasks can be performed through manual labor, these examples show how the same job can be done in a more precise manner and less time consuming by a robotic arm.

Genaidy (1988) compared the performance of a robot to that of 10 humans during 100 work cycles, and found out that although robots took about three time longer to perform a cycle (robot=10.01s, human=2.95s), the robot was consistent with its times with a standard deviation of .279s and a variation coefficient of 2.76%, on the other hand the human presented a standard deviation of .49s

and a variation coefficient of 16.63%. This shows that even when the robots performance is slower than that of the human, the robot continues to work at a constant speed even after long periods of time, while the human's performance is affected by exhaustion [10].

2.5 Implementation of automation for 3D Structural Electronics

The use of automation on the assembly process of printed circuit boards began twenty years ago, through either semimanual processes or fully automated processes. Researchers have been creating and developing new ways of utilizing the 3D printing or AM technology to create 3DSE, because of the advantages of 3D printing that include ease of duplicating products, low cost, and product security considerations [12]. 3DSE is an area in which electronic devices and connections happen in a three dimensional part. Leading research laboratory in 3DSE is taking place at the W. M. Keck Center for 3D Innovation of The University of Texas at El Paso. In order to be able to create an additive manufactured part a Stereolithograpy or Standard Triangulation Language (STL) file is required, and can be created with a design software such as Solidworks. Once the STL is created, it can be uploaded to the AM machine and to begin building the model. After the part is completed the support material is removed and the part is ready to use. For 3DSE the process varies from the original process and some extra steps are added. Before creating the CAD a design of the desired electronic component must be created and saved as .dxf file, the file is then imported to the CAD software and incorporated to the desired shape, finally it must be saved as a STL file and manufacture with the desire technology [7]. After the part is completed and cleaned, the electronic components are embedded and the conductive ink or wires are placed to connect the electronic components [8]. Three Dimensional Structural Electronics have revolutionized the electronic market; according to Fritz (1998) 3DSE are quickly to build, and can be created in small batches and small sizes [13]. Also, according to Espalin (2014) 3D printed parts with embedded electronics have the ability to be built in complex geometrically shapes [14]. Gutierrez (2011) proposed that this technology is very useful for spacecraft because AM can be conformed to any surface or volume [15]. On the other hand, 3DSE are complex parts that require care throughout the building process and high level of precision during the assembly process. Embedding electronic components within the 3DSE is not an easy task, for each component has a different challenge and it is important to

take into consideration tolerances, fixturing, and functionality [10]. In order to achieve the desired functionality and precision of the 3DSE building process the electronic components are placed manually, therefore all implementations on the CubeSat were done manually, however manual labor as proven to be inefficient and can vary from person to person [15]. By embedding the components manually is possible to achieve a product with high quality, but is time consuming, and introduces quality variables to the final product due to human mistake and exhaustion. As a result, after an extensive literature review about pick and place in 3DSE automating the assembly process of the electronic components in additive manufactured parts is an important research area.

Chapter 3: Proposed Methodology

3.1 General

This chapter describes the methodology proposed to automate the pick and place process for embedding electronic components. The first step is the pick and placement process with a robotic station includes analyzing several key factors. First, it necessary to know the station used for the pick and placement, including the robot used and the software to manipulate the robot (Section 3.2). Also, it is important to identify the components that will be placed with the robotic station (Section 3.3). After the robotic station has been identified and the Machine Vizio System has been described (Section 3.4). A precision test can be run as a key step to ensure the placement of the electronic components with required quality.

3.2 Machine setup

This research includes a design of experiments will be conducted to analyze and verify the accuracy of an automatic station. The robotic station consist of Yamaha SCARA YK350X (1), Yamaha SCARA YK180X (1), Yamaha Linear Actuator 850mm (1), Black and white Cognex camera (1) and Colored Cognex camera (1). Each robot can be operated either by its controller or through the computer utilizing the VIP WIN program (Figure 1.)

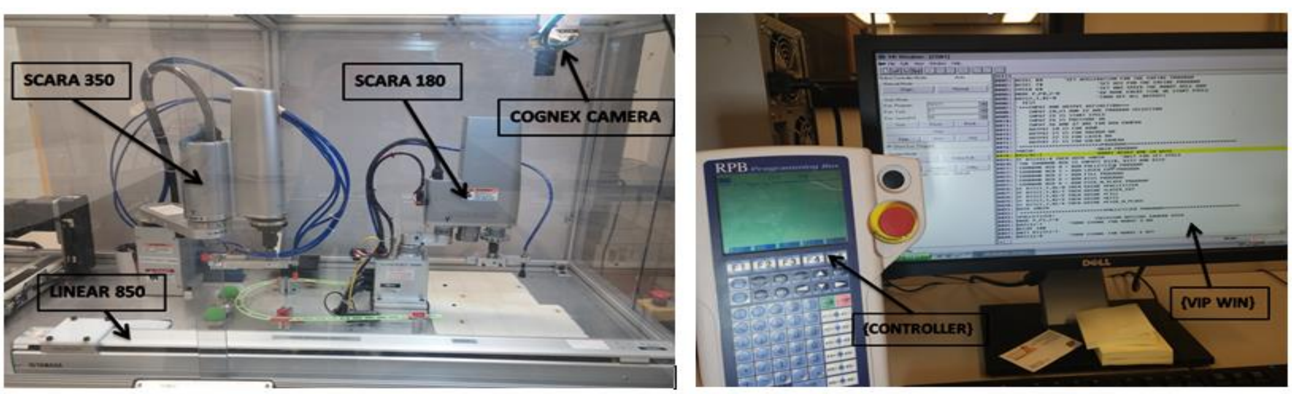

Figure 1 Automation Station with Components (Left), Controller with VIP WIN Program (Right)

Due to the limitation of the robotic station been incased, the space available to work is 23 inches by 16 inches as shown in Figure 2. However the space available for experimentation is further limited by

the range of the robotic arm which only extends up to 8.75 inches on the “X” and “Y” axis, and only allows for 4 inches on the “z” axis (Figure 2).

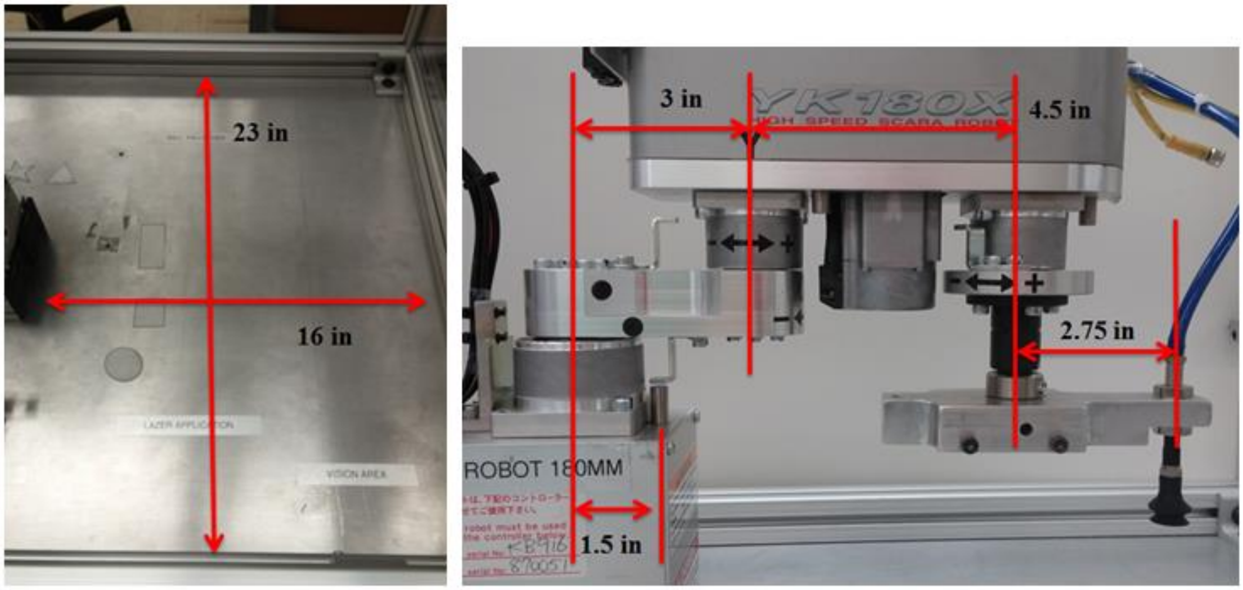

Figure 2 Robotic Platform Dimensions (Left), Robotic Arm Dimensions (Right)

The dimensions of the YK180X robot are critical because distance traveled is one of the factors to be considered to ensure good quality of component placement. Also, by knowing the dimensions of the robot it is possible to manipulate it so as to prevent any crash with its base or with another robot located on the vicinities.

3.3 Three Dimensional Printed Board

For this research a Fused Deposition Modeling (FDM) machine was utilized to create the AM part to embed the electronics. In order to create the part, it is necessary to follow a process chain that consists of eight steps. First, it is necessary to create a 3 dimensional design of the part using Computer Aided Design (CAD) program such as Solidworks. Figure 3 shows the blue print of the platform created to embed the electronic components. All the dimensions shown in Figure 3 were taken from the electronic components selected for this research (Figure 4).

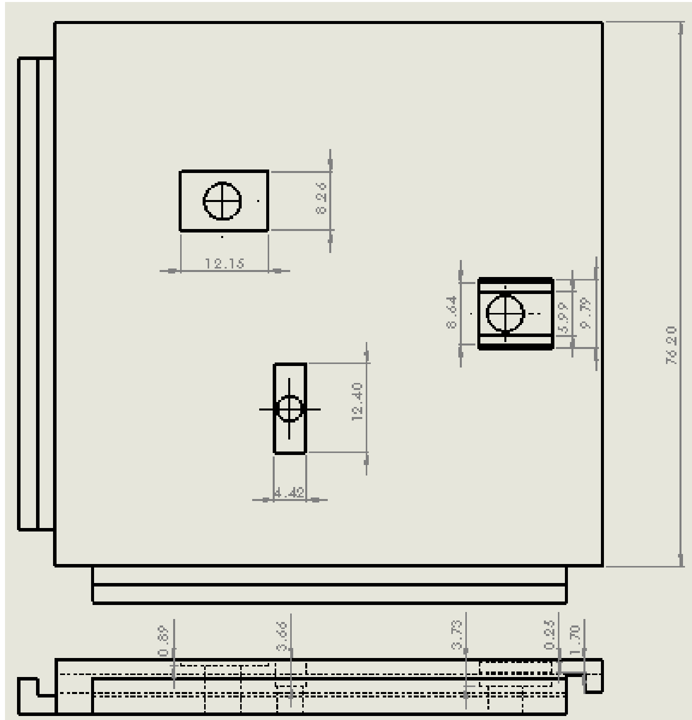

Figure 3 Blue print Embedded Electronic Platform

Figure 3 layout was randomly selected. The electronic component slots were placed vertically and horizontally in order to test the robotic arm placing components in both directions.

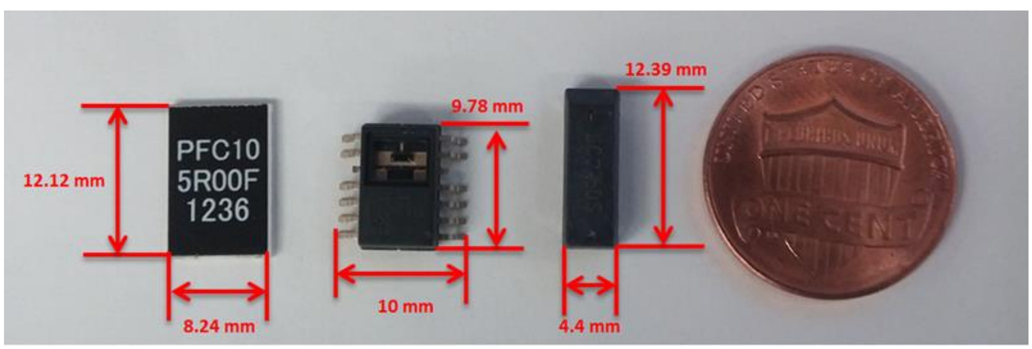

Figure 4 Electronic components Dimensions

From Figure 4 it is possible to observe the electronic components used. Also it is possible to see the different shapes of micro components available to embed. Finally the one cent coin on the right side of the image is for size reference.

After the 3D design is completed, it was necessary to convert the CAD design to a STL file which can be done using the same CAD software. The STL file was transferred to a computer connected to a FDM machine (Figure 5) where the orientation, layer resolution, and size can be adjusted.

Figure 5 Dimensions Elite Machine (FDM)

Orientation, layer resolution, and part size are some key parameters that will determine the build time and the amount of support material utilized. With a FDM Dimensions Elite, it is possible to create parts as large as 8 inch by 8 inch by 12 inch in height as shown in Figure 6. These dimensions are key in the process of building a part with any FDM machine because it is not possible to create parts larger than the building envelope.

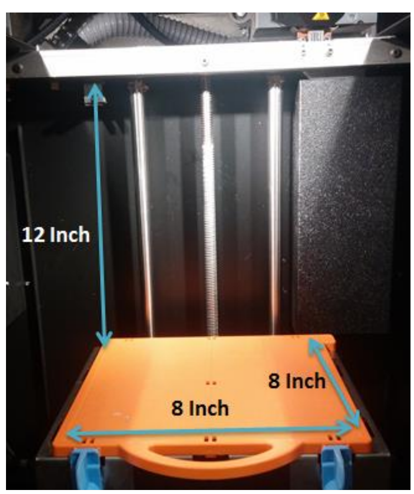

Figure 6 Building Space Dimensions

These dimensions are key in the process of building a part with any FDM machine because it is not possible to create parts larger than the building envelope.

Figure 7 shows the Catalyst software home page, where all the modifications of the orientation, layer resolution, and size can be done. Also, with this software it is possible to create several parts at the same time to save time and cost by clicking the option “Pack” (Figure 9).

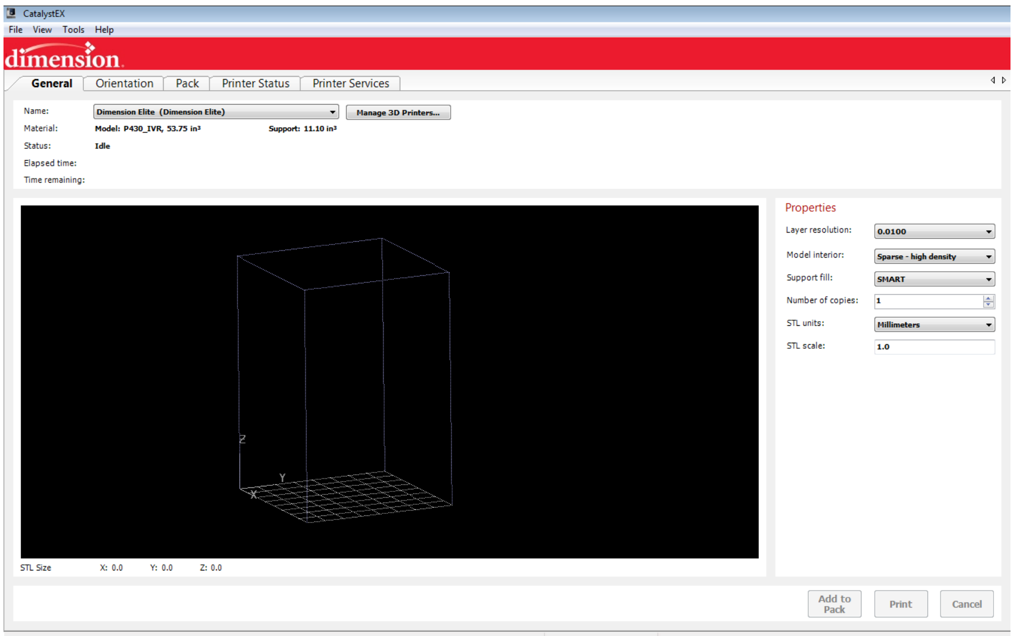

Figure 7 Catalyst Software Home page

As seen in Figure 7 (General Tab) it is possible to modify the layer resolution from 0.01 inches to 0.007 inches. Next, it is possible to modify the model density from low density to solid. Also, the units can be modify from millimeters to inches and finally the scale of the part can be modify. All these options can be find on the right side of the home page.

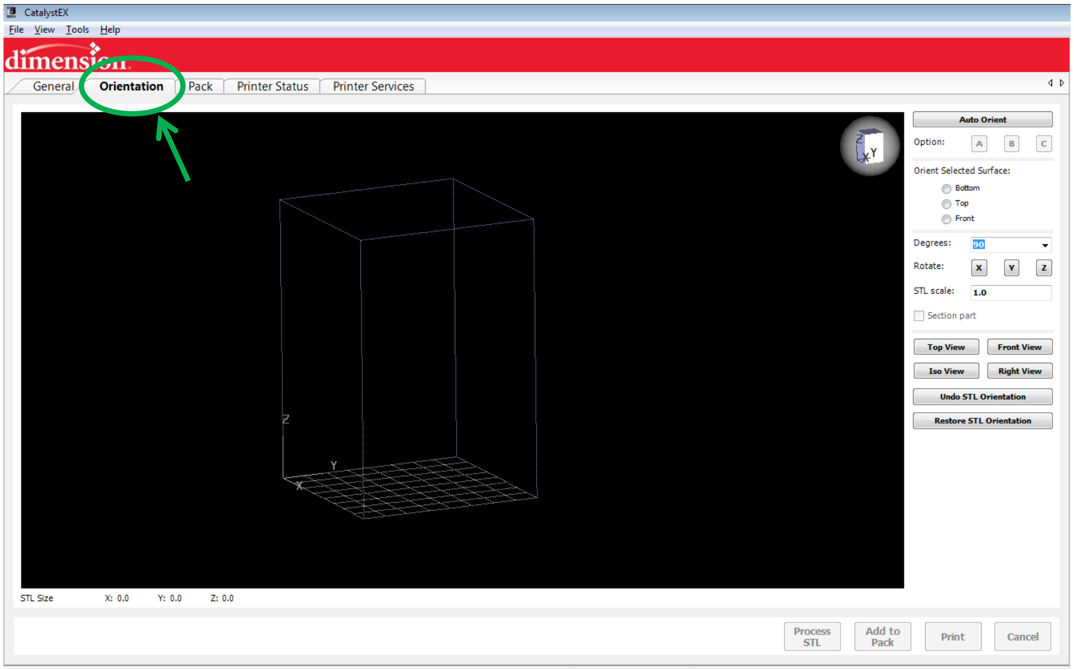

Figure 8 Catalyst Software Orientation Tab

Figure 8 shows the home page of the Orientation tab. In this page it is possible to change the build angle and orientation of the part. The part can be rotated on its X, Y and Z axis and from 30 degrees to 180 degrees. All the options can be find on the right side of the orientation page.

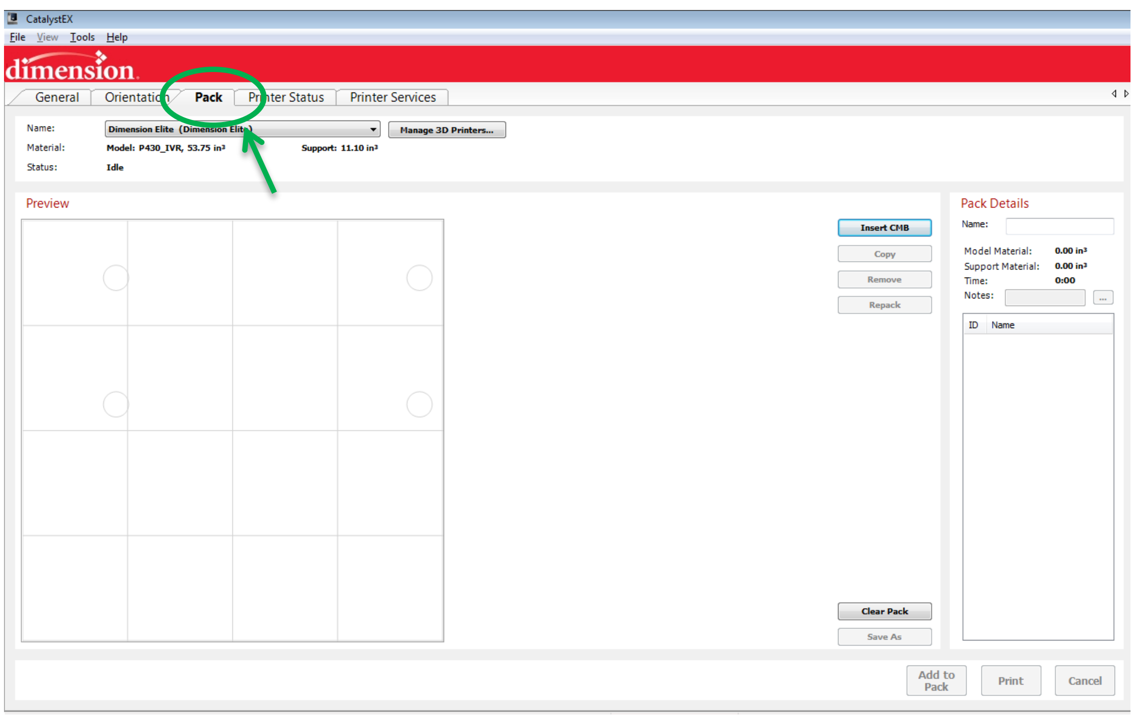

Figure 9 Catalyst Software Pack Tab

Figure 9 shows the Pack tab where multiple parts can be manufacture at the same time. On the right side of this page it is possible to find all the options. Some of the options used more frequent is copy and clear pack.

Next, the part is manufactured and once the product is completed it must undergo a post process to remove any support material if support material was used. The post process consists of submerging the manufactured part in a bath containing water and sodium hydroxide solution. This solution helps dissolve the support material when maintain at a temperature between 70 and 72 degree Celsius. Figure 10 shows the Support Cleaning Apparatus (SAC) used to remove the support material.

Figure 10 Support Cleaning Apparatus (SCA)

The SAC main components are the cover, display screen, housing and the sodium hydroxide solution. After the part is removed from the support cleaning apparatus it is rinsed with water to eliminate any residues of sodium hydroxide and dried using paper towels. Once completely dried the part is ready to embed the electronic component in, which are currently added manually and potentially in the future using a robotic arm. Figure 11 shows the manufactured part with the electronic components placed on their respective slots.

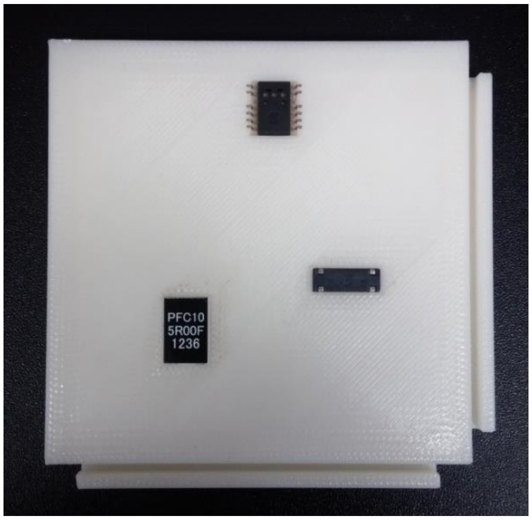

Figure 11 3D Printed Platform with Electronic Components Embedded (Top View)

For research purposes access holes were manufactured to the platform as shown on Figure 12 to facilitate easier release of the electronic components from the slots, since components are added by press fit.

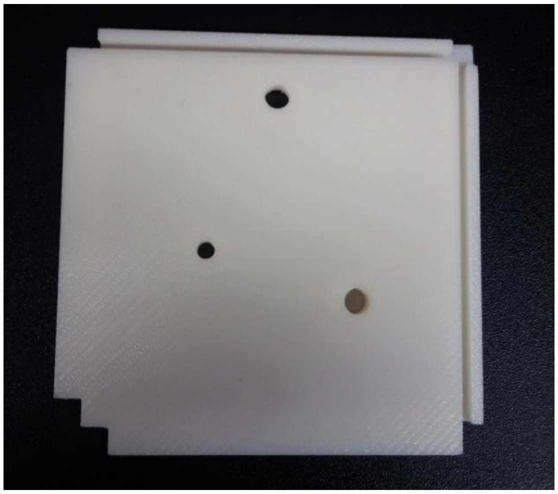

Figure 12 3D Printed Platform with Electronic Components Embedded (Bottom View)

3.4 Machine Vizio System (Cognex Camera)

The main purpose of this research is to compare the quality of component placement by hand and by automating the placement process. Before, performing any component placement experiment, it is necessary to adjust the machine vizio system to verify that the system is functional. In this section, experiments were performed to assure that the system is performing as required. Figure 13 shows the home page of the In-Sight Vizion System. From the home page of the system it is possible to connect to

any desired camera (In-Sight Network) also, it is possible to capture images or play live video. If an image is taken it is possible to test the image from the applications column and set up tab.

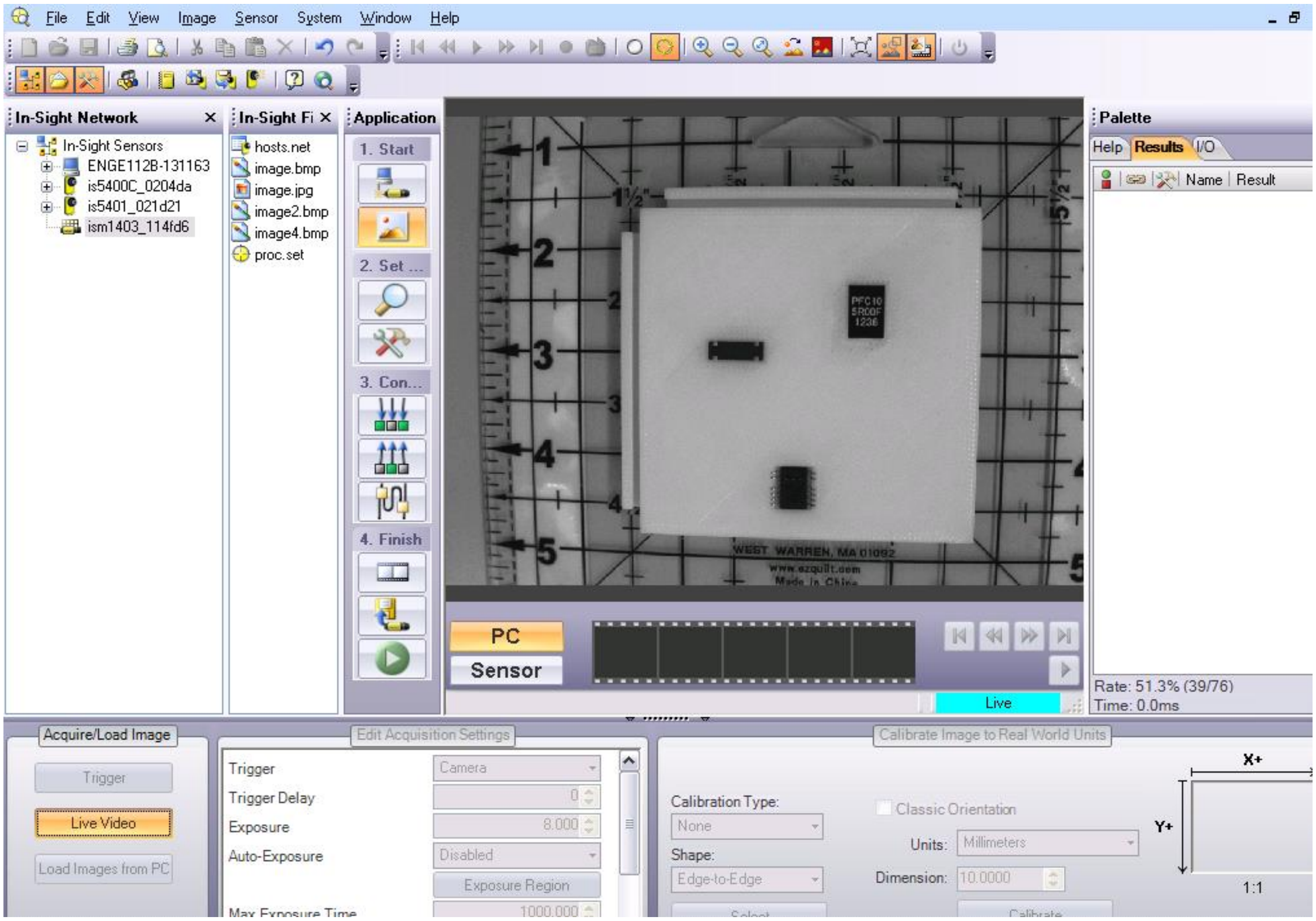

Figure 13 In-Sight Vizion System Homepage

The first experiment was to verify the electronic component placement quality utilizing the option of “Blob Testing”. For the blob testing it is necessary to select the area that wants to get evaluated as show in Figure 14. The selected area to be evaluated shows in green color and is composed of the three electronic components. Also, on the top right side of the In-Sight page it is possible to see the results in pixels.

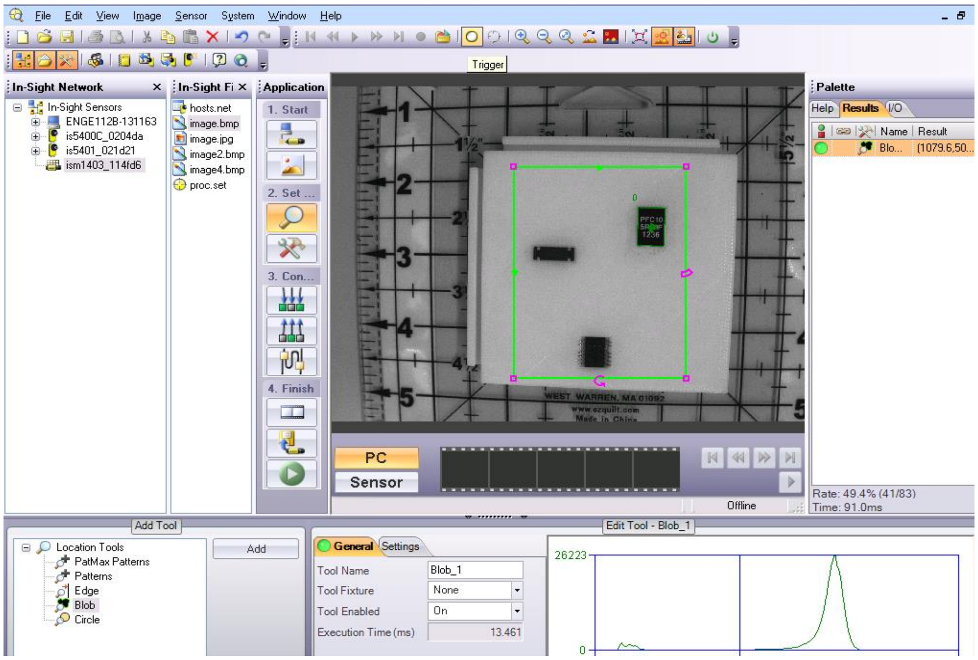

Figure 14 Machine Vizion System Blob Testing Area

After removing the components from the additive manufacture part it is possible to appreciate that the vision systems marks the part as a non-defective part (Figure 15) this can be concluded because the area selected keeps appearing in green and not in red.

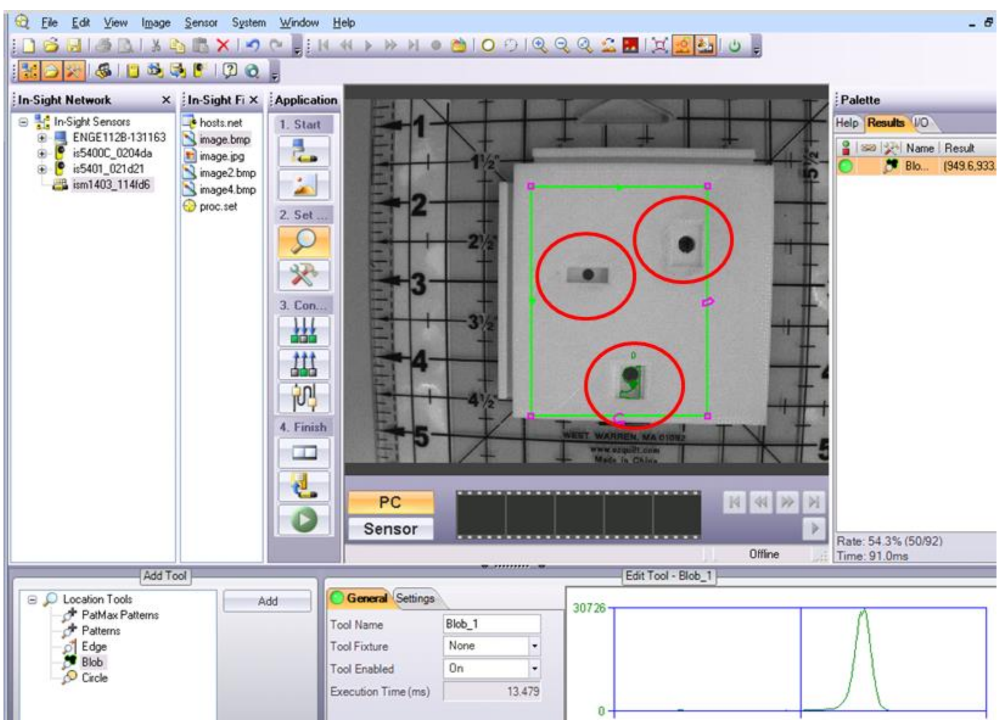

Figure 15 Machine Vizion System Blob Testing Error

Blob testing is not the best option to evaluate the quality of the component placement in the 3D printed part. For this reason the “PatMax Pattern” testing had to be selected. This method was more efficient because it identifies numbering and lettering on the components tested as shown in Figure 16.

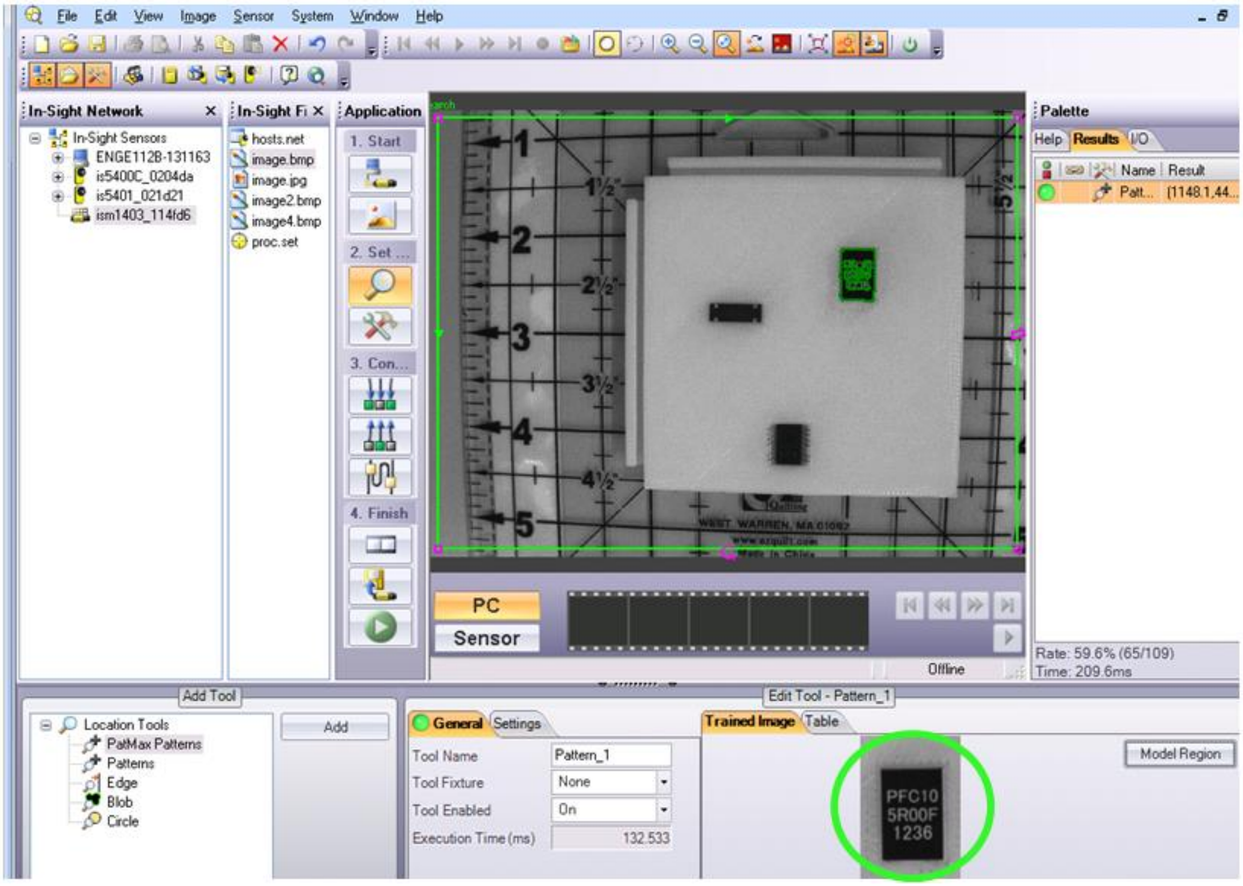

Figure 16 Machine Vizion System PatMax Pattern Testing Area

From Figure 16 is possible to see the evaluated area in green color, but also on the bottom right side it is possible to see the model region that is conformed of the electronic component with numbering on it.

After removing the electronic component that have been identified as the model region it is possible to observe that the In-Sight system will mark it as a defect (Figure 17) and the selected are will change the color from green to red.

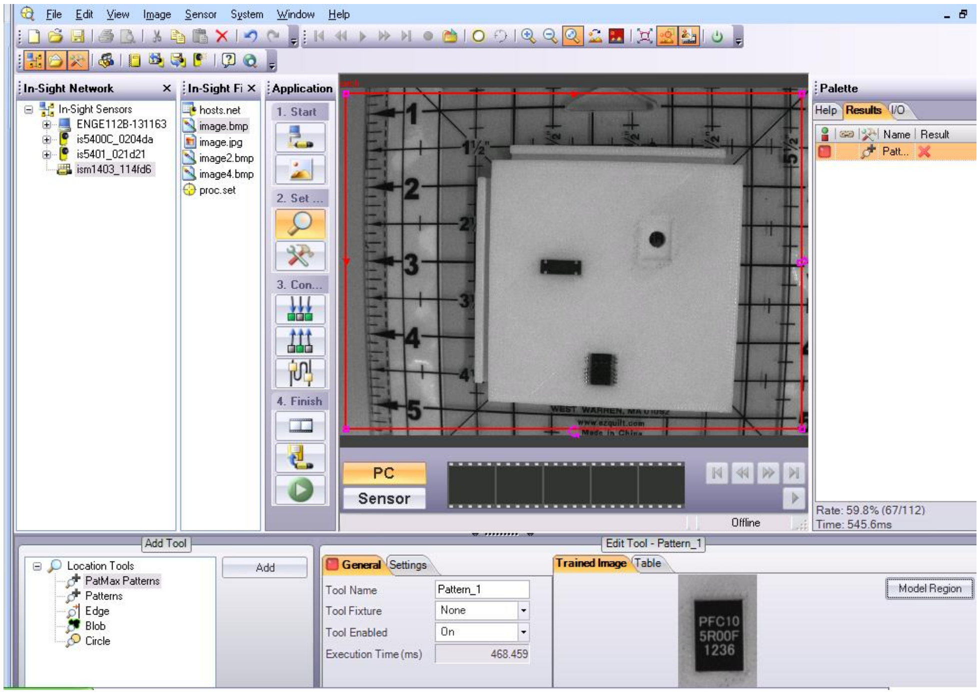

Figure 17 Machine Vizion System Defective Platform using PatMax Pattern

On the other hand if the electronic components that are not selected as model region are removed the In-Sight system will mark it as a non-defective part (Figure 18) and will change the evaluated area to green.

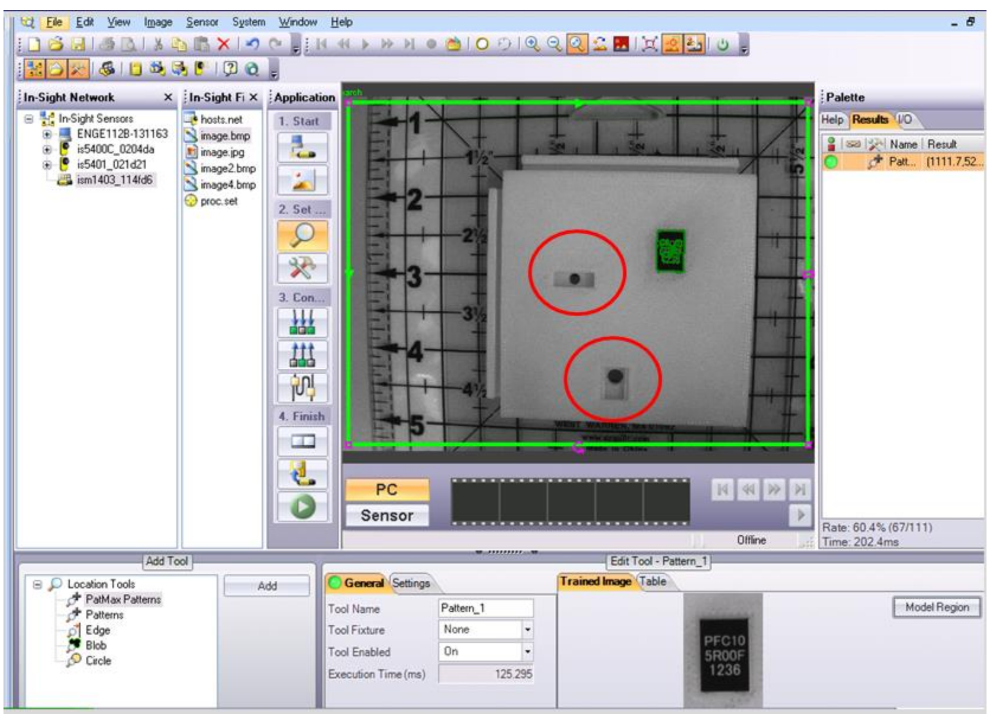

Figure 18 Machine Vizion System Non-defective Platform using PatMax Pattern

As seen in the previous images one of the challenges of PatMax Pattern is that if any electronic component does not have lettering or numbering it is not possible to identify it as the model region and thus placement errors can be made. In order to prevent placement errors a FDM machine was used to create a new assembly base (Figure 19) with assembly components (Figure 21) to test the PatMax Pattern. Figure 20 shows the new assembly base with the components placed on the specific slots.

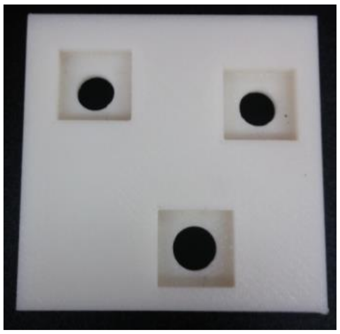

Figure 19 3D Printed New Assembly Base

Figure 20 New Assembly Base with Components

Figure 21 3D Printed New Assembly Components

The lettering shown in Figure 22 was selected in order to avoid any similarity from one letter to another for example B and E or E and F. Figure 22 shows the homepage of the In-Sight system with the new assembly base and its components in place.

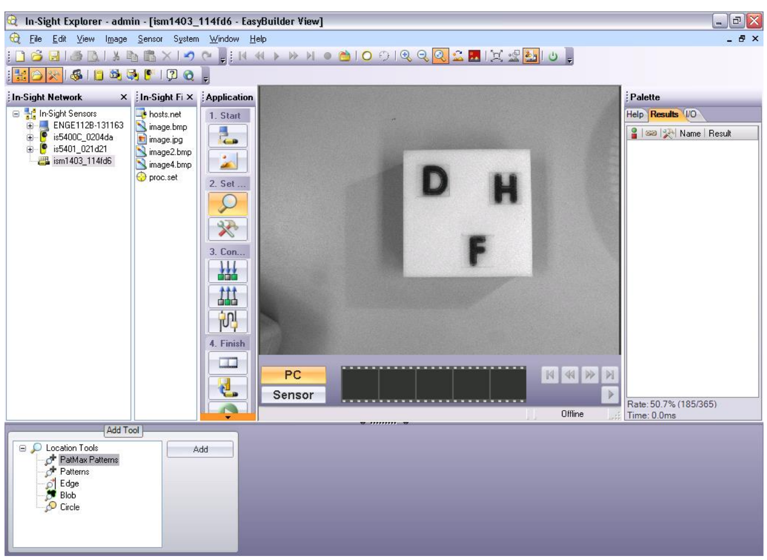

Figure 20 Machine Vizion System with New Assembly Base Homepage

After creating the new assembly base it is possible to conduct another experiment utilizing the PatMax Pattern. The following images show the new assembly base been tested with the PatMax Pattern, lets observe that the model region it is consisted of the components “D, H, F”.

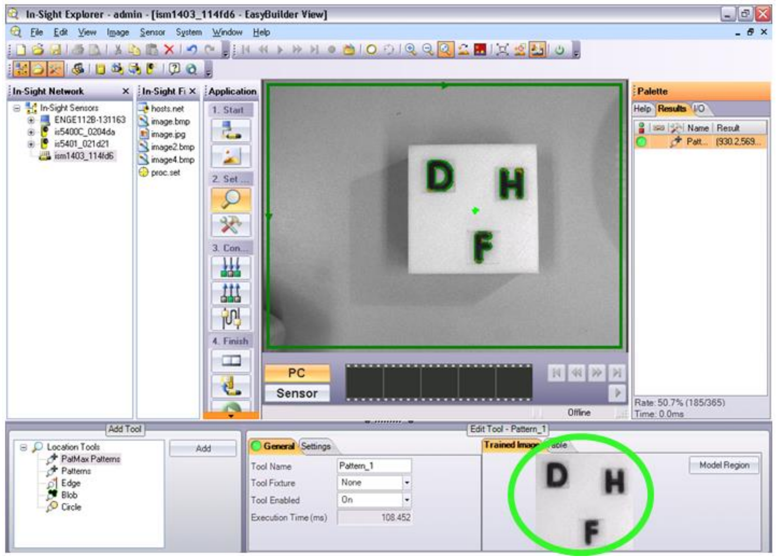

Figure 21 Machine Vizion System PatMax Pattern Testing Area New Assembly Base

As mention before the chosen letters D, H, F were selected to avoid similarity because these letters do not share shape. After removing some components as seen in Figures 24 and 25 it is possible to see that the In-Sight system detects a defect and marks the part as defective, this occurs because the system identifies that there are missing components comparing it with the model region.

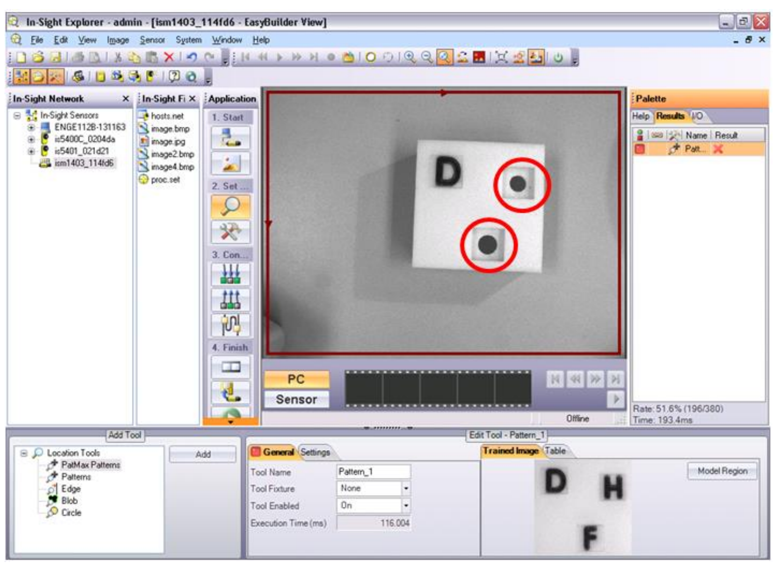

Figure 22 Machine Vizion System Defective New Assembly Base using PatMax Pattern (Missing 2 Components)

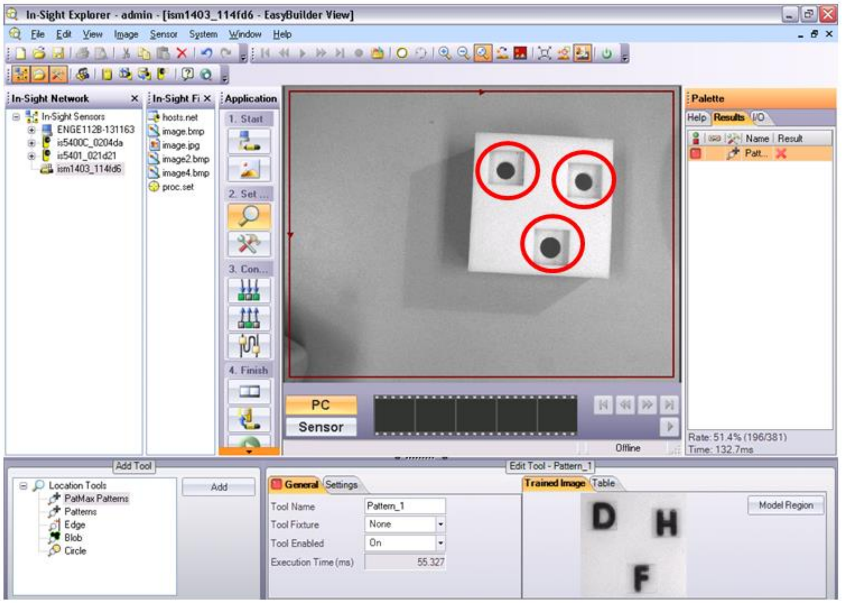

Figure 23 Machine Vizion System Defective New Assembly Base using PatMax Pattern (Missing All Components)

Figure 26 shows the components been rotated clockwise and the In-Sight system detecting an anomaly in the component arrangement and marking it as a defect. This happens because the arrangement it is not the same as the model region.

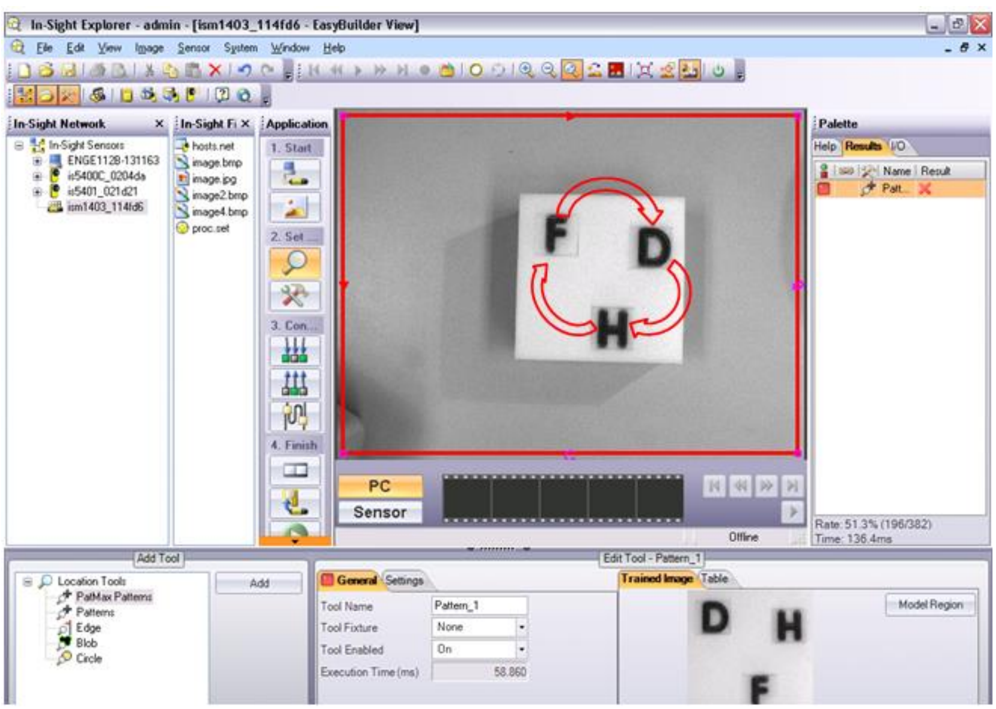

Figure 24 Machine Vizion System Defective New Assembly Base using PatMax Pattern (Clockwise Component Rotation)

Finally, after all the testing was conducted the components were placed in their original position and the In-Sight system marked the assembly base as a good part without any defect.

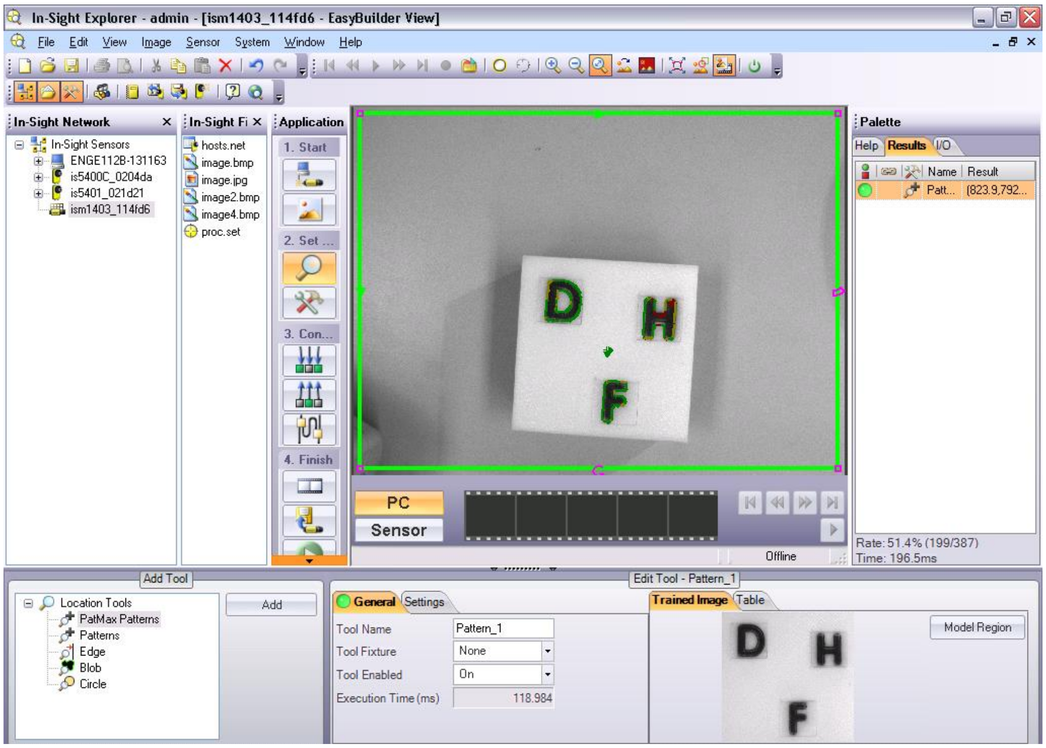

Figure 25 Machine Vizion System Non-defective New Assembly Base using PatMax Pattern

In conclusion, the PatMax Patter is the best option to check for quality in the assembly base, even though it has some constrains like if the components been verified do not have any lettering or numbering. For this research, the PatMax Pattern will be used to analyze accuracy of component placement. In order to achieve a high quality of component placement it is needed to have a high precision placement robotic arm. Section 3.5 describes a precision test created to measure the precision of the Yamaha SCARA YK180X robot.

Chapter 4: Computational Results

4.1 Precision Test

It is well known that robots main task is to pick and place components or parts. Therefore, in order to achieve a high quality pick and place, the robot has to be accurate and precise. Before practicing any experimentation on placing the electronics components on to the additive manufactured part, a precision test was done to corroborate that the Yamaha SCARA YK180X is accurate and precise. The precision test consisted in programing the robotic arm to move to 7 different landing areas that were chosen randomly and mark a hole with a push pin on each area to complete a cycle. Figure 28 shows the 7 different landing areas, these areas were selected in order to cover every possible motion of the robotic arm.

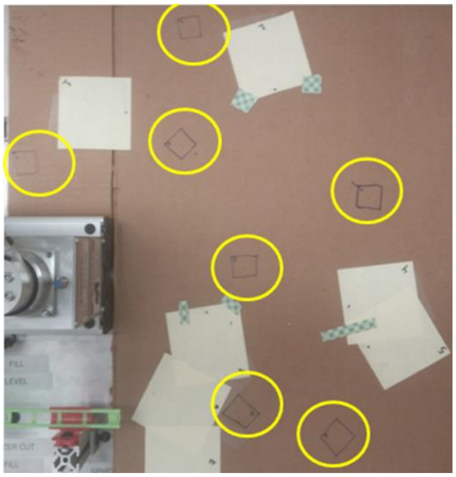

Figure 26 Precision Test Landing Area Top View

In order to attach the push pin to the robotic arm, a new robotic head was created using Solidworks and manufactured using a Fuse Deposition Modeling (FDM) machine (Figure 29).

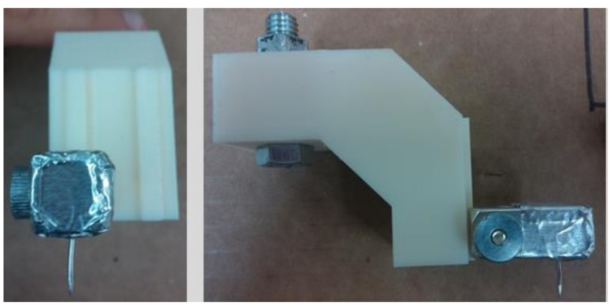

Figure 27 Precision Test Pin Head Attachment Front View (Left), Side View (Right)

The test was ran at 5 different velocities, 1%, 5%, 20%, 50% and 95% of the maximum velocity of the robotic arm and for each velocity a total of 4 cycles (one cycle consist of the arm reaching every one of the 7 designated points) were performed. The robotic arm also performed 300 cycles at 95% and 450 cycles at 20%. After analyzing data, it was concluded that the precision test was not able to provide enough information to accurately measure the robot's precision. The issues with the accuracy of this test were due to the fact that the measurements from one cycle to the next cycle were done manually with a caliper and therefore can be affected by the human error. Figure 30 shows the defects to some of the push pin holes on their contour. For this reasons a second precision test had to be designed to eliminate human error.

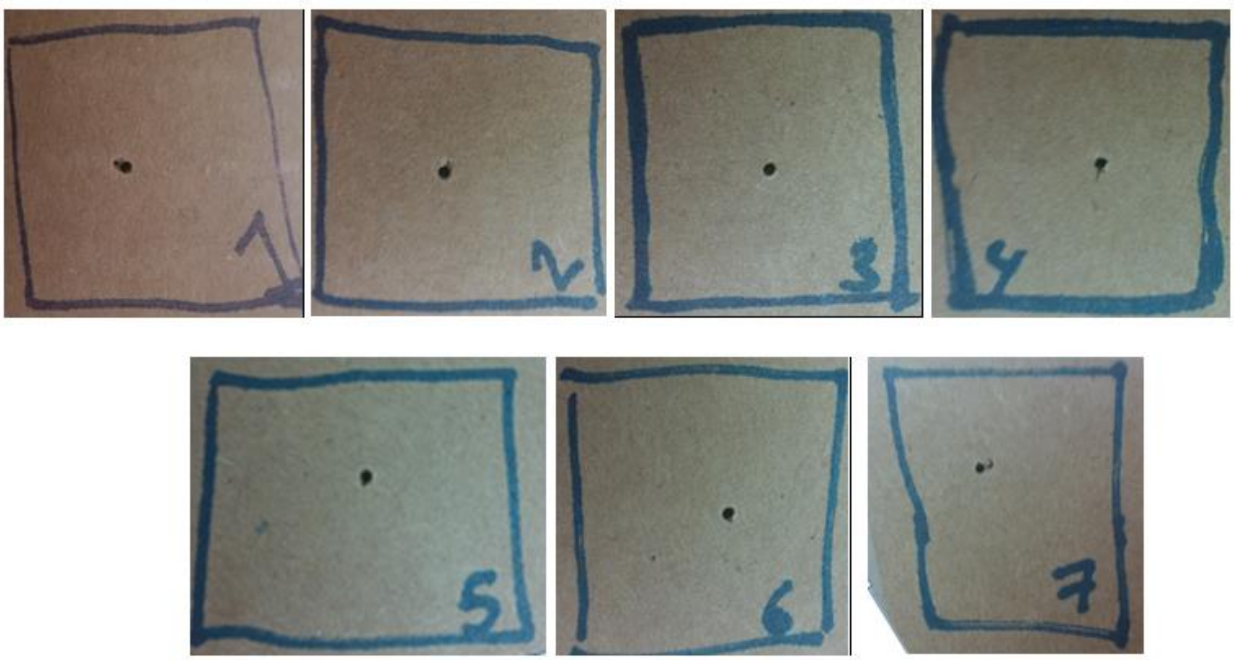

Figure 28 Defective Accuracy Test Landing Areas

In the second test, a platform was created to fit the robotic station floor and locking in place with 2 bolts to prevent misaligning the boards from one cycle to another cycle. This platform was created to hold four pieces of wood where all the perforations were pre-made. Figure 31 and 32 shows the implemented precision platform. The main purpose of creating this platform was to be able to place the

boards on the same area every time they were removed for measurement and prevent any human error misplacement.

Figure 30 Implemented Precision Platform with Bolts

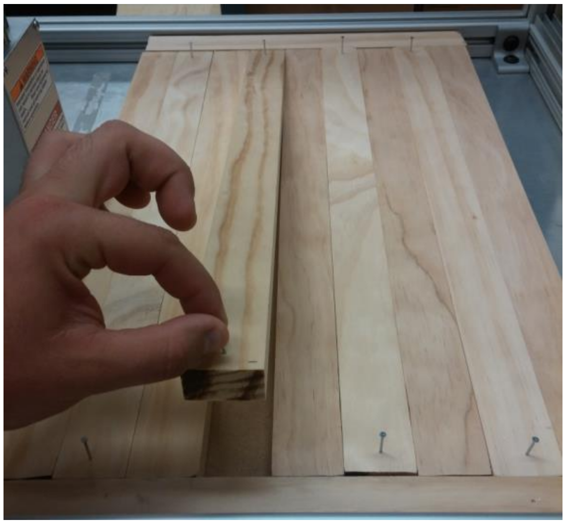

Figure 29 Implemented Precision Platform with Testing Boards

The platform consisted of 4 boards that were perforated with a total of 10 holes to practice the push pin puncture. The robotic arm was utilized to select the perforation areas, some of the holes were selected by extending the robotic arm to his maximum aperture on the X and Y axis (perforations 2, 3, 5, 6, 8, and 9). Also, perforations 4, 7, 10 and 1 were selected by finding the middle point between the already existing points. The following figure shows the 10 areas used for the precision test.

Figure 31 Precision Test Landing Areas

During the first precision test a couple of challenges were presented, for example, the material used to do the perforations on was cardboard which is stiff. In order to prevent this issue from happening again, clay was chosen because it is soft and can hold its shape for long period of time. Three different colors were selected to identify the sections of the platform (Red, Blue, and Green). This clay was used by filling the premade perforations where the push pin will land. Figure 34 show the board perforation without clay, with clay and with a push pin perforation.

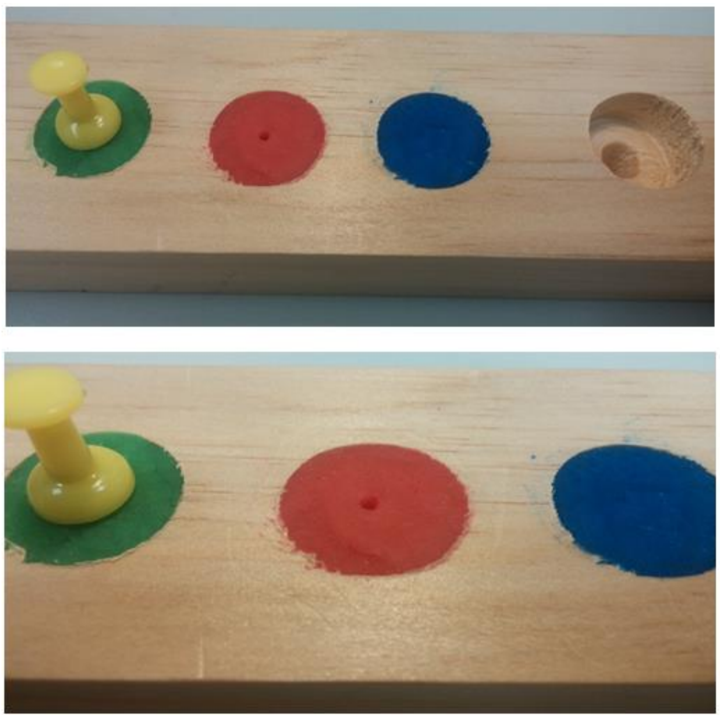

Figure 32 Board Perforations with and without clay.

4.2 Randomized Factorial Design

For this experiment, a randomized factorial design was utilized; to obtain randomized and independent values in other word it was created to eliminate any consistency. The test was ran at 4 different velocities; 1%, 10%, 25%, and 50%. These velocities were selected to be lower than 50% because all the components need to be handle with care and exceeding these velocities might cause any damage to the components. Each cycle consisted of reaching the 10 points and back to the starting point. Also, for this test 3 extra weights of 10 grams, 25 grams, and 50 grams were utilized to verify that the weight of the part been pick and placed do not affect the accuracy of the robotic arm. These weights

were selected to not exceed a 5% of the maximum payload of the robotic arm. According to the manufacturer the maximum payload is 1000 grams. Minitab software was utilized to create the randomized factorial design sequence. Table 1 show the variables weight, speed and replication with their respective values to create the randomized factorial design.

Table 1 Randomized Variables

Weight	0 Grams	10 Grams	25 Grams	50 Grams
Speed	10%	25%	50%	
Replications	10			

Table 2 shows the randomized factorial design sequence (The full table can be find in the appendix). Table 2 is consisted of three columns. The first column is tittle RunOrder, the run order is the order that the cycles were performed. The next column will show the velocity used for the run order and the final column is the weight utilized for each run order.

Table 2 Randomized Factorial Design Sequence

Randomized Factorial Design		
RunOrder	Velocity	Weight
1	25	25
2	10	50
3	50	10
4	50	50
5	25	10
6	25	25
7	25	10
8	10	25
9	50	50
10	50	0
11	10	50
12	25	0
13	25	50
14	50	10
15	50	25
16	50	10
17	50	25
18	50	0

Once the randomized factorial design sequence was completed the accuracy test was conducted. The randomized factorial design sequence was followed to ensure that all the samples were random and independent. Figure 35 shows the platform with clay ready to use. First, all the landing points had to be programmed to the robot. Second, the landing perforations had to be filled with clay and even out to prevent any discrepancy.

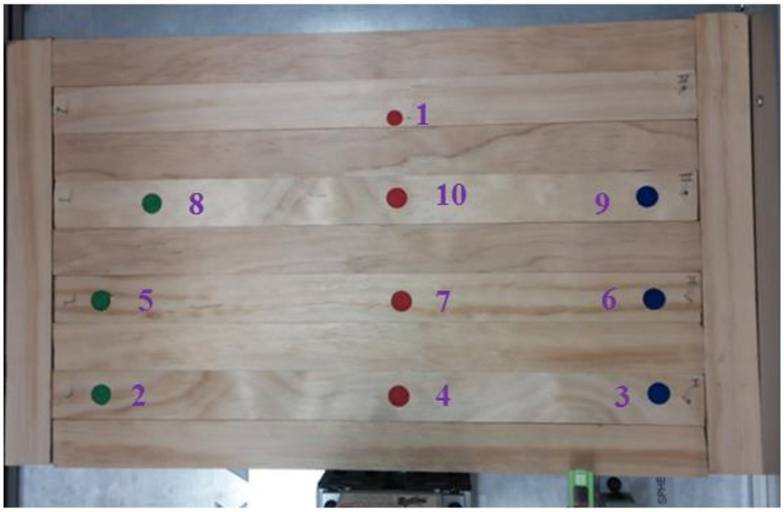

Figure 35 Top View Landing Areas with Clay

Figure 36 shows the extra weight used for this test. The desired cycle can be performed by modifying the velocity or adding or removing the extra weight. The three different extra weights were 10, 25, and 50 grams. These weights were made out of clay because the clay can conform to any surface.

Figure 36 Extra weights, Blue (50 Grams), Red (25 Grams) and Green (10 Grams)

Figure 37, 38, and 39 shows the push pin head with their respective extra weight in place. The image on the left side is the side view of the push pin head and the image on the right side would be the front view of the push pin head with extra weight.

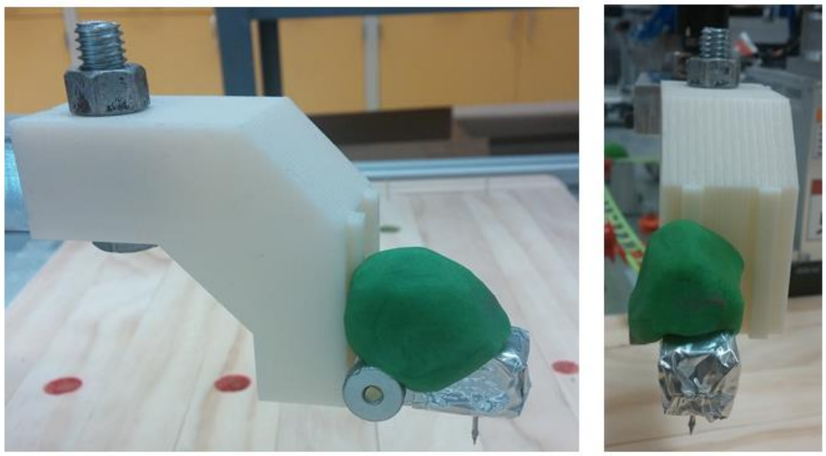

Figure 37 Robotic Arm with 10 Grams extra weight

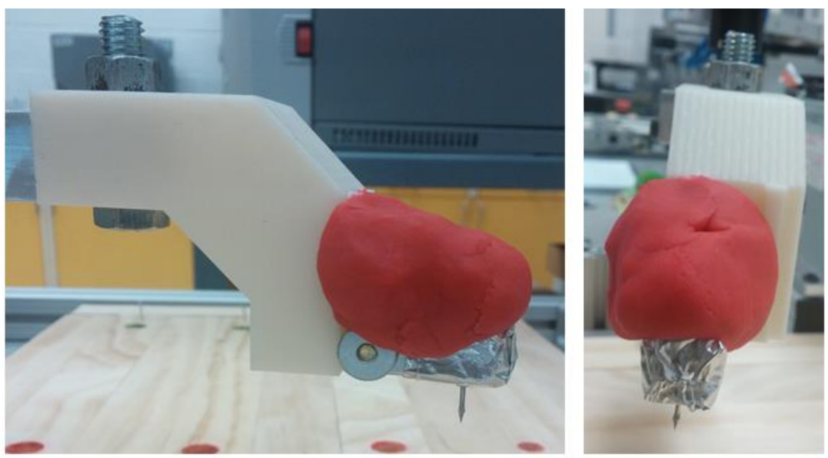

Figure 38 Robotic Arm with 25 Grams extra weight

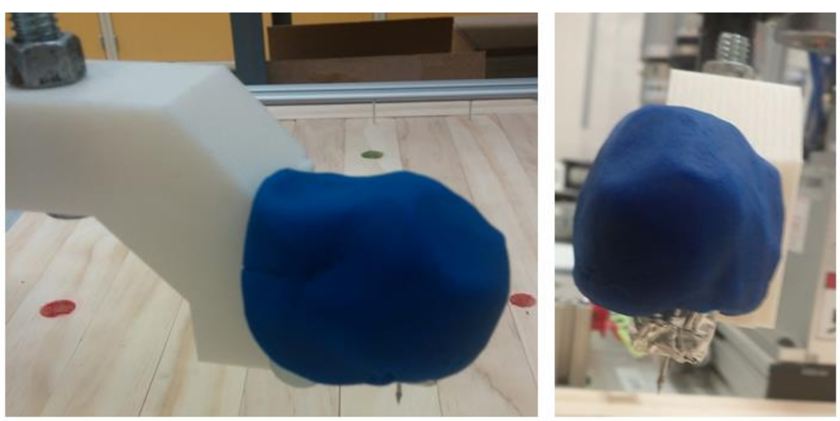

Figure 39 Robotic Arm with 50 Grams extra weight

Once the desired velocity and desired weight are selected it is possible to run the test. As mention before, the sequence followed for the cycle is shown in the randomized factorial design sequence. A total of four cycles were run for each individual combination (RunOrder) and after the four cycles are finished the measurements can be performed. Figure 40 shows the robotic arm in operation.

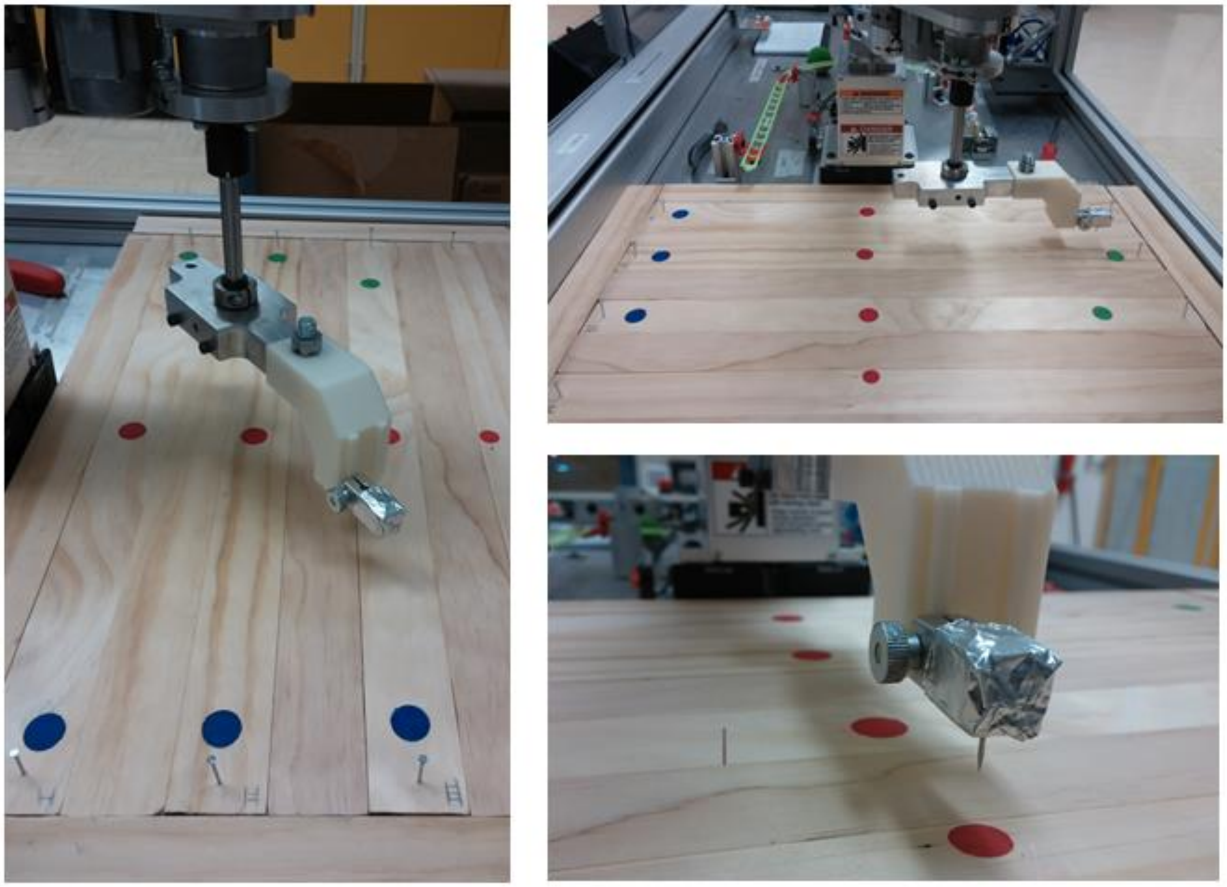

Figure 40 Precision Test in Action

4.3 Measurement Station

As soon as the fourth cycle is completed, the measurements can be taken in the measurement station. This measurement station was created to standarized all the measurements. The station consisted of a Cognex camara, holding boards, ruler, and a fluorescent light (Figure 41). All the equipment used for the measurements stayed on the same position for the duration of the precision test. The Cognex camera can be manipulated utilizing the In-Sight Vizion System software. Once the cycle is finished the wooden boards with the perforations are placed in the measurement station as seen in Figure 41 and a screen shot is taken of the In-Sight Vizion System (Figure 42). In figure 42 (same as the previous) it is

possible to see the ruler located next tho the push pin hole. The main purpose of the ruler is for dimensions reference. All the measurements taken from the In-Sight Viziozn System were in pixels, this unit cannot be used as a point of comparison because it depends of light, movement and camara resolution. In order to convert pixels into millimiters another software is used called “GRiP” that can be found at [www.grelf.net.](http://www.grelf.net)

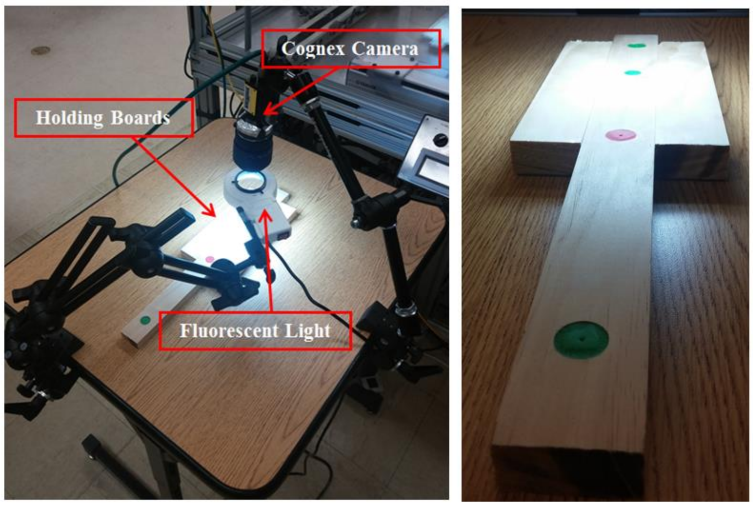

Figure 41 Measurement Station Components (Left), Holding Board with Precision Board (Right)

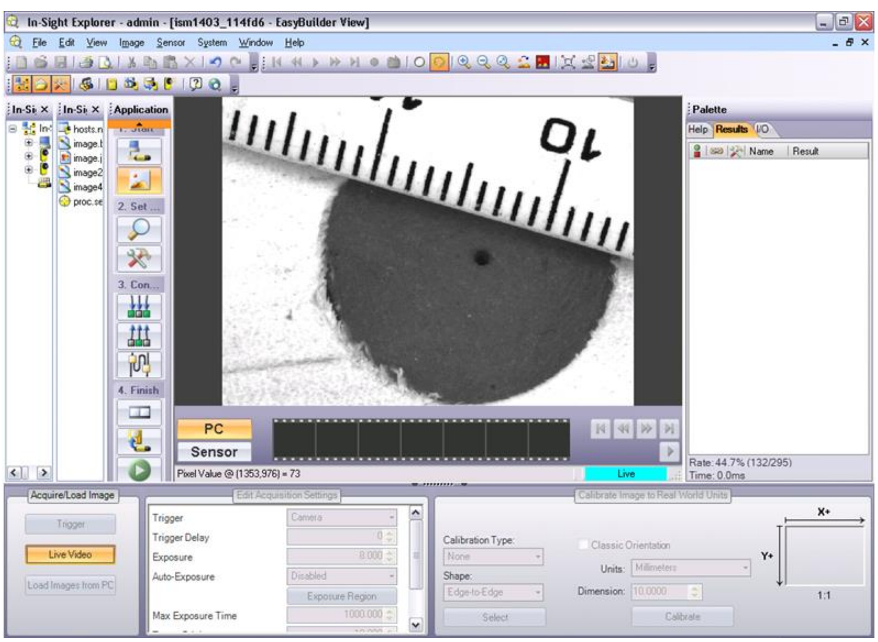

Figure 42 In-Sight Vizion System Screen Shot of Perforation Area

4.4 GRIP

"GRiP was originally designed to stack together astronomical photos taken with a digital camera on a fixed tripod from a light-polluted urban site so that as much faint detail as possible cold be seen."[21]. GRiP software is utilized to edit images, but also it can be used to measure pixels. For this research this software was utilized to convert pixel units into millimeters in order to measure a diameter and therefore quality. Figure 43 shows the home page of the software that has been downloaded.

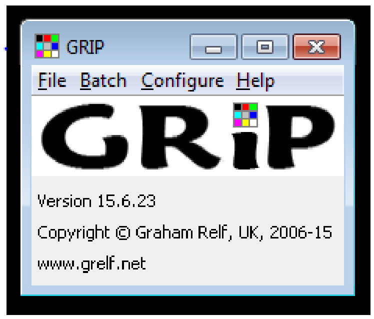

Figure 43 Grip Homepage

After taking all the pictures of every point for every cycle, the conversion of pixels in to millimeters can start. First, all the pictures have to be saved as "JPG" format. Next, it is necessary to open every image with the software. In order to open a new image it is necessary to click the file button in the home page and click the open image button (Figure 44).

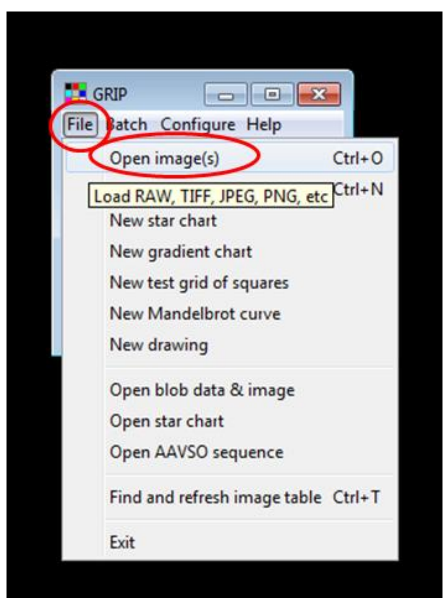

Figure 44 Open Image steps

After selecting the open image button a browser will appear and from here the image can be selected (Figure 45). Figure 46 shows the image opened.

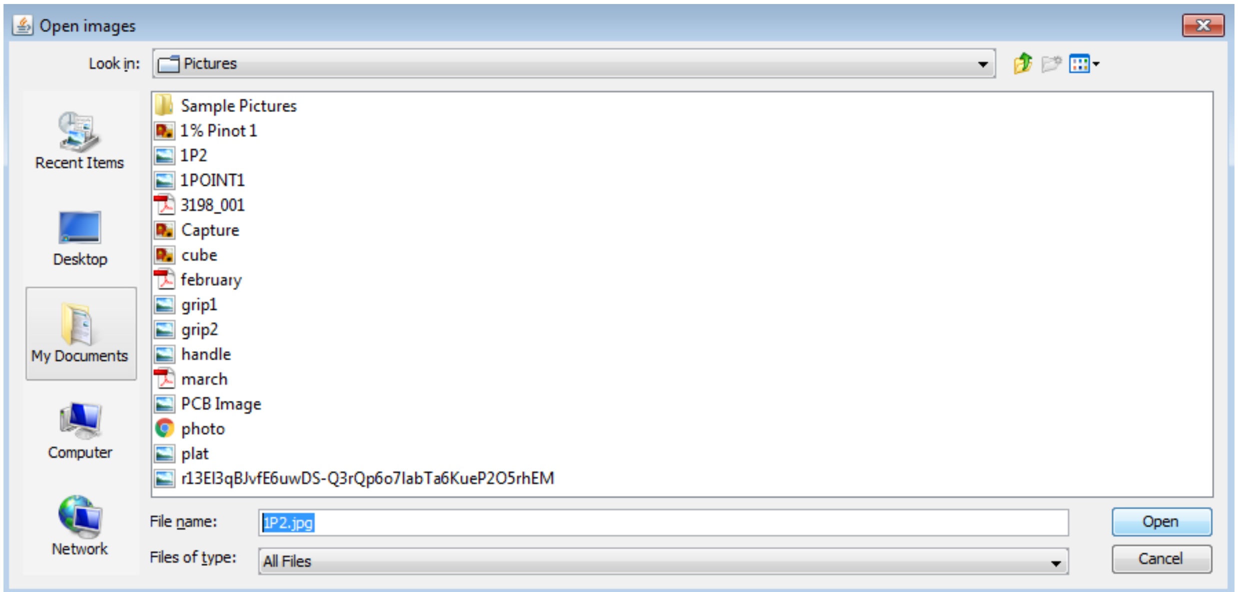

Figure 45 GRiP Open Image Browser

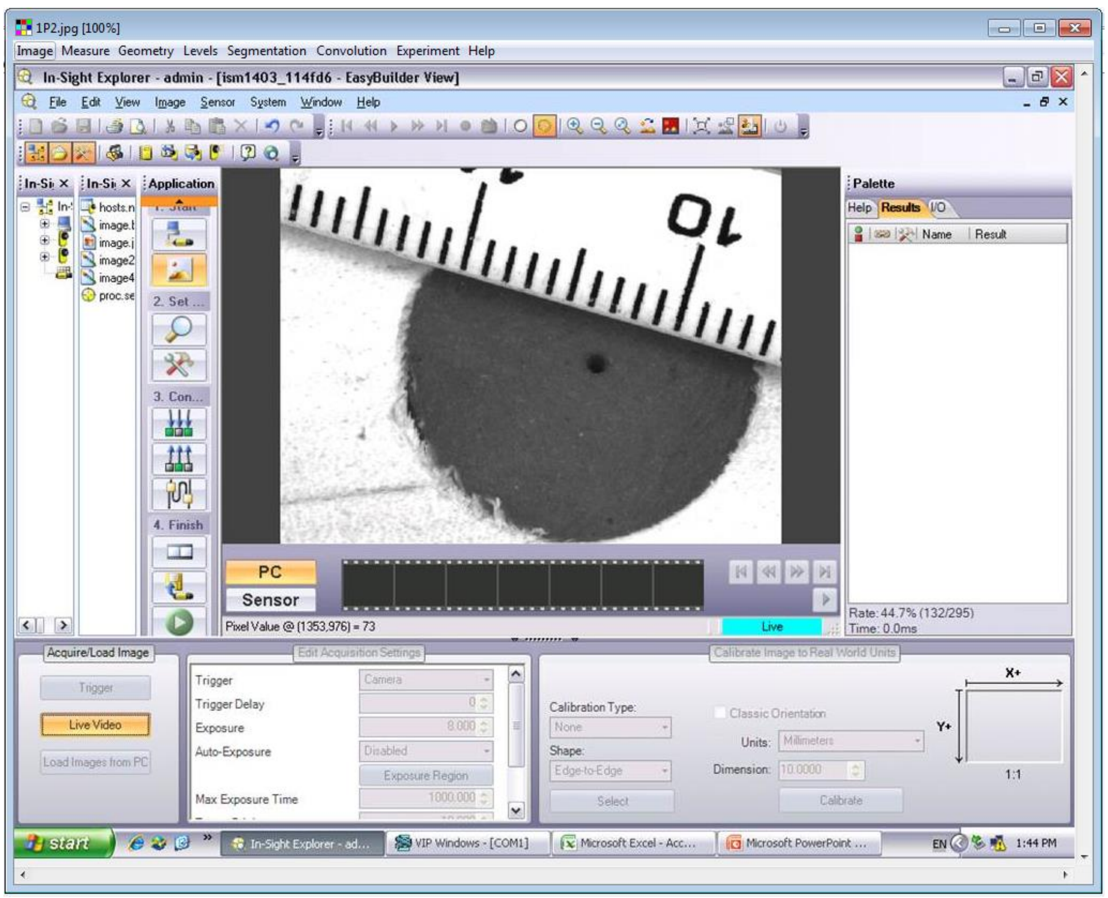

Figure 46 Selected Image Opened with GRiP

Next, the image can be sized by cropping it; by clicking in the button geometry it is possible to crop the image. Figure 47 shows the image after been cropped from Figure 46.

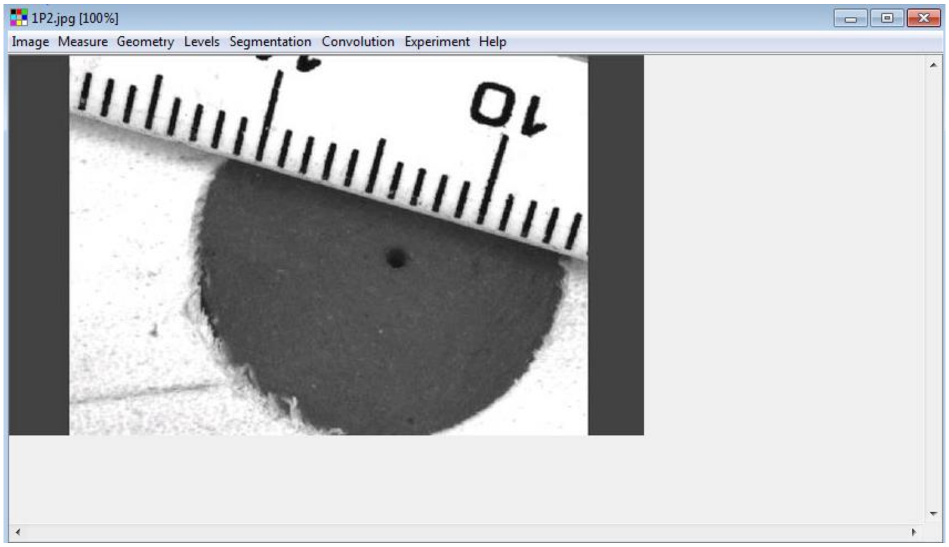

Figure 47 Cropped Image with GRiP

Once the desired imaged is open, the measurements can be taken. First it is necessary to calibrate the pixels to millimeters by using the ruler on the picture. For this research, all the measurements were done in millimeters, but the GRiP software can be calibrated using any required unit. By clicking on the measure button and then on the calibrate distance it is possible to calibrate the image (Figure 48).

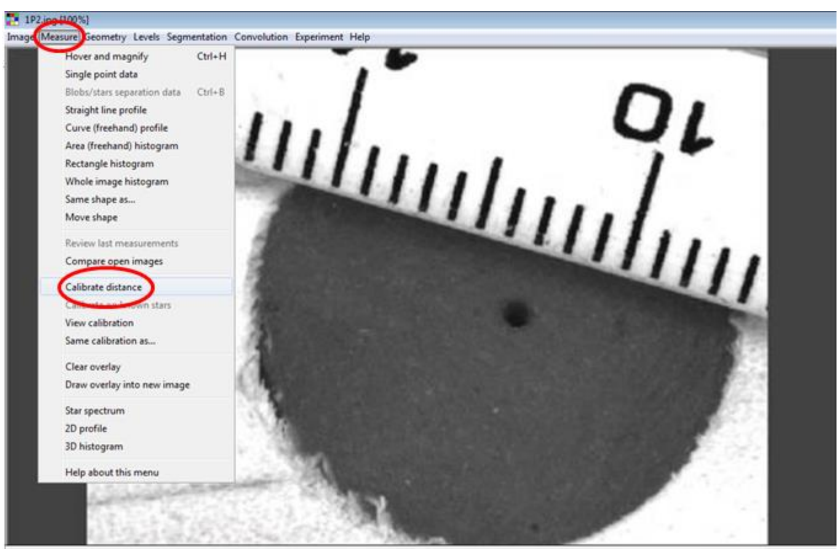

Figure 48 Calibrating Steps GRiP

The following image will show the next step to calibrate the image (Figure 49). In here it is possible to define the units and from what point to what point is the corresponding distance.

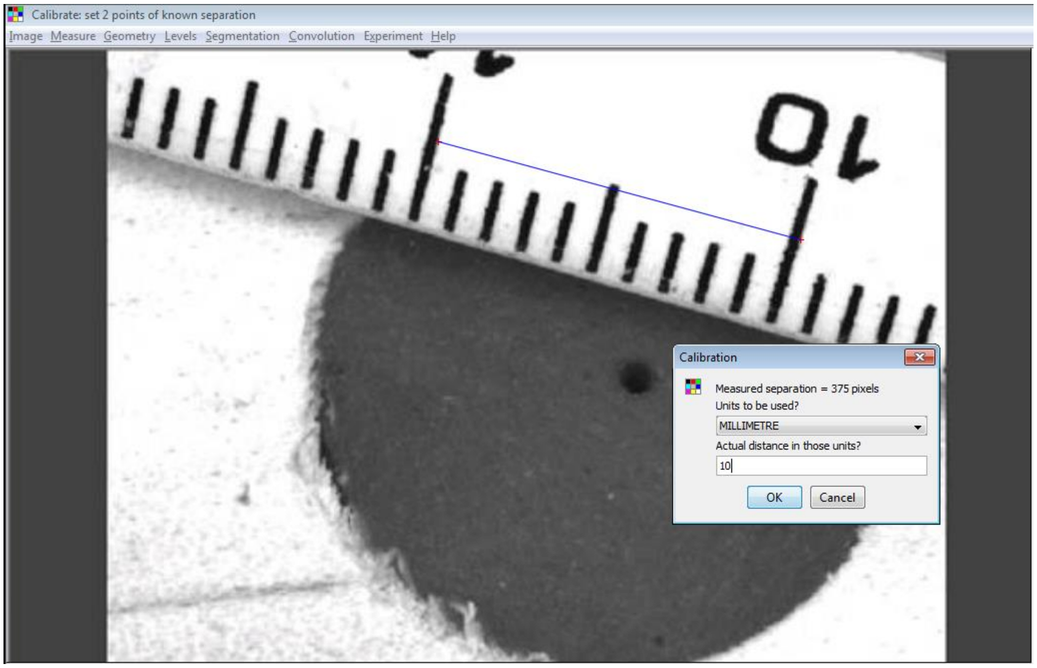

Figure 49 Ruler Calibration Distance

Figure 50 shows the results of converting the pixels in to millimeters. For this image a total of 37.7881 pixels per millimeter can be found.

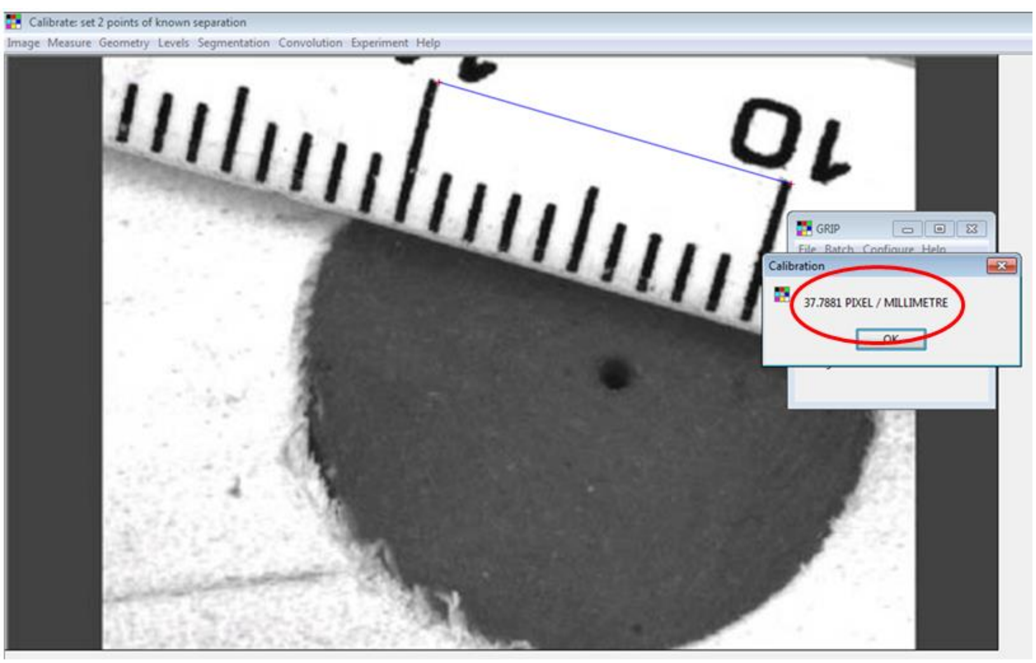

Figure 50 Calibration from Pixel to Millimeter

After the calibration is finished the measurements can be taken. First, it is needed to click the top button called Measure, and then the straight line profile option. The program will measure the diameter of the circle and convert the pixels into millimeters (Figure 51 and Figure 52).

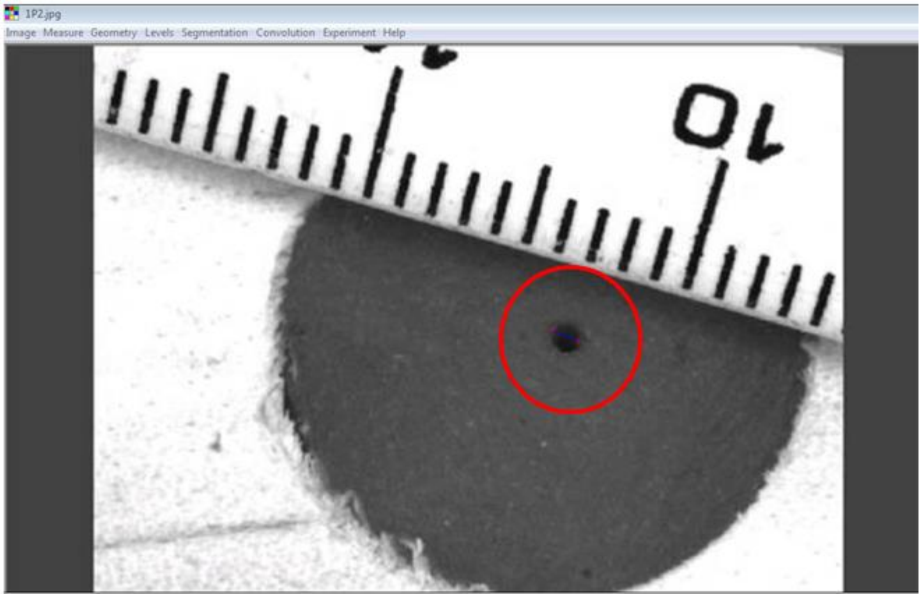

Figure 51 Push Pin Diameter Measurement

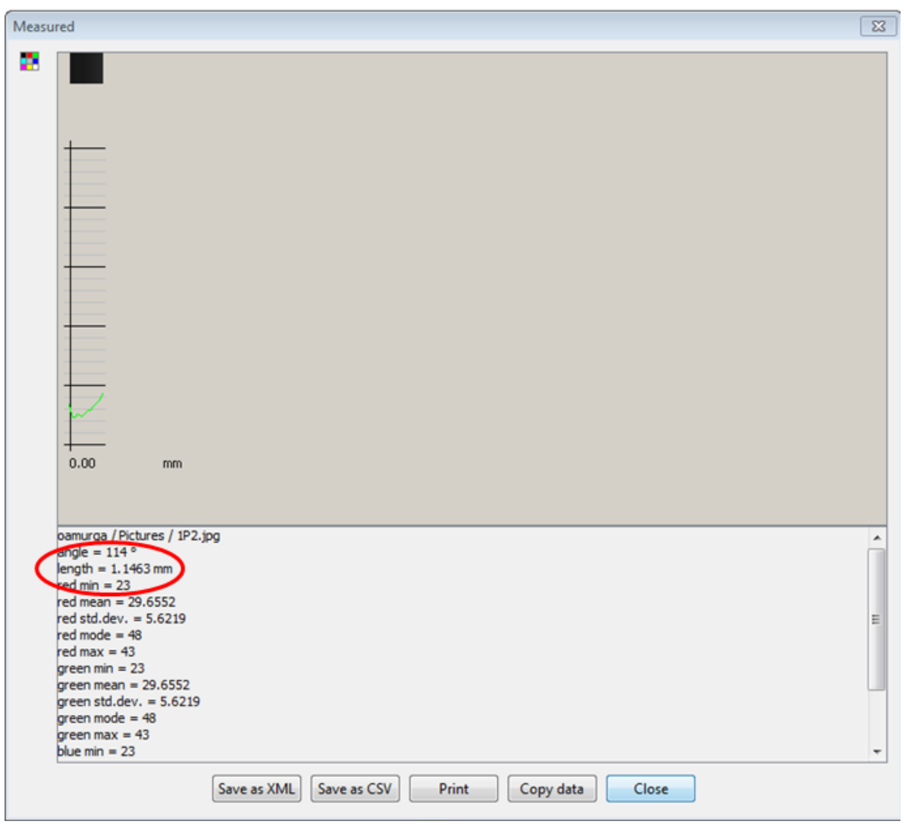

Figure 52 Push Pin Diameter Measurement Results

Finally, this process was followed for all the images taken at 1%, 10%, 25%, and 50% with the combination of the no extra weight (NEW), 10 grams, 25 grams, and 50 grams. The following tables will show all the measurements taken from the pictures.

4.5 Precision Test Hole Measurements

Table 3, 4 and 5 show all the measurements taken for all 10 points at different velocities with no weight or with extra weight. The 1% column can be defined as the target for it is the slowest velocity that the robot can run and will be more precise. Also, no extra weight was added for the 1% velocity measurements.

Table 3 Push Pin Measurements at 10% Velocity

	Velocity				
	1%	10%			
Point	NEW	NEW	10 Grams	25 Grams	50 Grams
1	1.1461	1.1462	1.1460	1.1462	1.1461
2	1.1463	1.1461	1.1461	1.1460	1.1463
3	1.1454	1.1452	1.1455	1.1454	1.1452
4	1.1471	1.1470	1.1469	1.1471	1.1470
5	1.1452	1.1451	1.1453	1.1451	1.1451
6	1.1449	1.1450	1.1450	1.1449	1.1451
7	1.1462	1.1464	1.1460	1.1462	1.1461
8	1.1446	1.1447	1.1448	1.1443	1.1446
9	1.1452	1.1452	1.1453	1.1451	1.1450
10	1.1469	1.1468	1.1469	1.1470	1.1468

Table 4 Push Pin Measurements at 25% Velocity

	Velocity				
	1%	25%			
Point	NEW	NEW	10 Grams	25 Grams	50 Grams
1	1.1461	1.1461	1.1460	1.1462	1.1460
2	1.1463	1.1461	1.1462	1.1461	1.1463
3	1.1454	1.1453	1.1452	1.1452	1.1454
4	1.1471	1.1470	1.1471	1.1470	1.1469
5	1.1452	1.1451	1.1451	1.1451	1.1453
6	1.1449	1.1449	1.1451	1.1449	1.1450
7	1.1462	1.1462	1.1461	1.1462	1.1460
8	1.1446	1.1445	1.1446	1.1446	1.1445
9	1.1452	1.1452	1.1450	1.1452	1.1452
10	1.1469	1.1471	1.1468	1.1470	1.1469

Table 3 Push Pin Measurements at 50% Velocity

	Velocity				
	1%	50%			
Point	NEW	NEW	10 Grams	25 Grams	50 Grams
1	1.1461	1.1460	1.1462	1.1460	1.1461
2	1.1463	1.1462	1.1461	1.1462	1.1460
3	1.1454	1.1455	1.1454	1.1455	1.1455
4	1.1471	1.1470	1.1472	1.1470	1.1471
5	1.1452	1.1452	1.1451	1.1453	1.1451
6	1.1449	1.1451	1.1451	1.1450	1.1450
7	1.1462	1.1464	1.1464	1.1461	1.1462
8	1.1446	1.1446	1.1447	1.1446	1.1443
9	1.1452	1.1450	1.1452	1.1452	1.1453
10	1.1469	1.1469	1.1468	1.1469	1.1467

4.6 Design of Experiments

The main objective of this research is to create a design of experiments to evaluate the accuracy or a robotic station. In order to evaluate all the measurements a general linear model experiment was created utilizing Minitab to analyze the interaction of speed and weight previously mention. The following table shows the results of the experiment.

Table 4 Design of Experiment Results

General Linear Model: Size versus Speed, Weight

Factor	Type	Levels	Values
Speed	fixed	3	10, 25, 50
Weight	fixed	4	0, 10, 25, 50

Analysis of variance for Size, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	0.0000000	0.0000000	0.0000000	0.02	0.979
Weight	3	0.0000000	0.0000000	0.0000000	0.01	0.998
Speed*Weight	6	0.0000000	0.0000000	0.0000000	0.01	1.000
Error	108	0.0000754	0.0000754	0.0000007		
Total	119	0.0000755				

After analyzing the P-Values of speed, weight and speed*weight it is possible to conclude that this values are not significant, in other words the size of the hole created by the push pin is not affected by the speed or weight. Also, it is important to mention that the maximum payload of the robotic arm is 1000 grams according to the manufacturer. The details of the Yamaha SCARA YK180X can be found in the appendix II.

4.6.1 Process Capability Index (Cpk)

After the general linear model has been conducted, and after concluding that the interaction between weight and speed is not significant for this research, it is possible to conduct a process capability index to verify that all the measurements are within the specification limits. Figure 53 shows the set up used for the Cpk and the boundaries specifications.

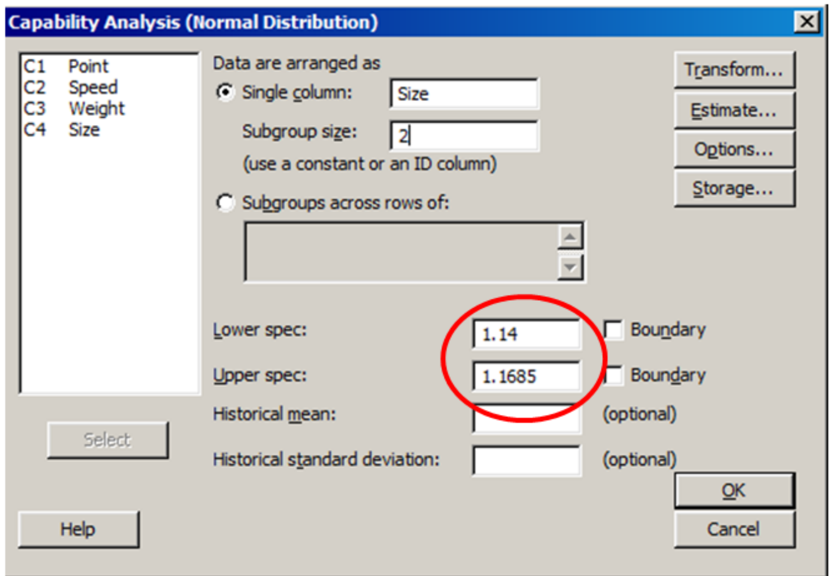

Figure 53 Capability Analysis Set up

The lower specification limit was set up to 1.14 millimeters because the diameter of the push pin is 1.14 millimeters at point of measurement and it is not feasible to measure less than the diameter of the push pin as seen in Figure 54.

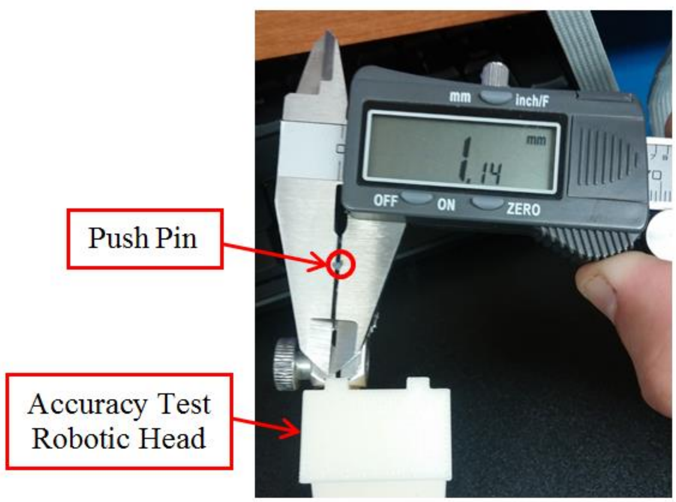

Figure 5433 Push Pin Measurement

The upper specification limit is 1.1685 which was calculated as shown in the following equation.

Equation 1 Upper Specification Limit Calculation

$$\left[\frac{1.14 * \propto}{2}\right] + 1.14 = 1.1685$$

$$\propto = Significance\ Level = 5\%$$

$$\left[\frac{1.14 * 0.05}{2}\right] + 1.14 = 1.1685$$

After, specifying the upper and lower specification limits the Cpk is calculated to be 2.07 as seen in Figure 55.

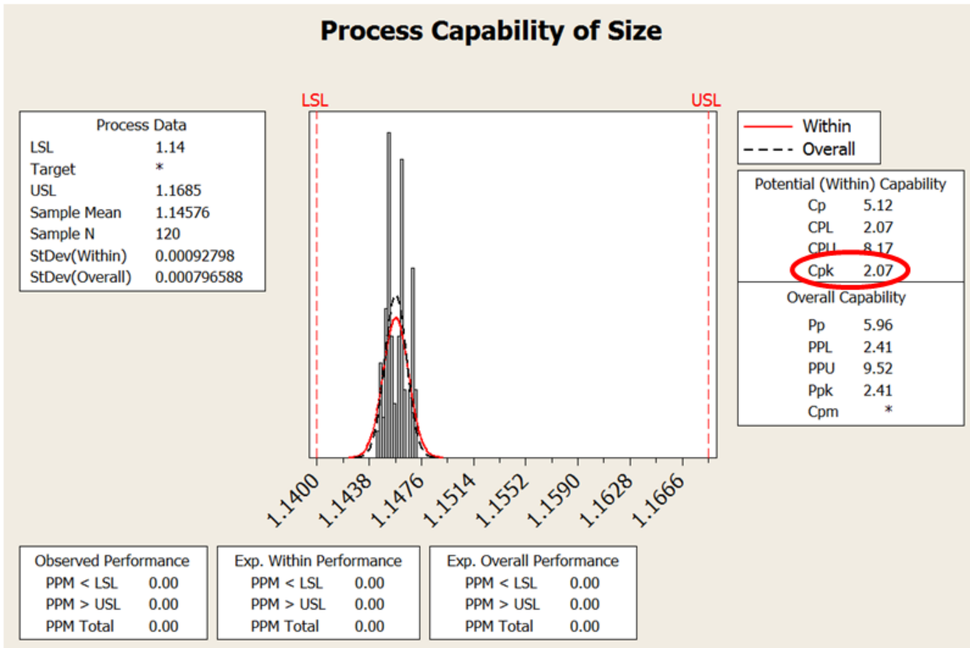

Figure 55 Process Capability of Size

In conclusion, the Cpk calculated of 2.07 it is an acceptable value, for it means that there will be a rate of around 3.4 defects per million.

Chapter 5: Conclusions and Future Work

Reducing cost, creating a safe environment for human workers and improving product quality are the main objectives to automate a manufacturing process. In this research a series of accuracy tests were run to measure accuracy of an automation station in order to achieve a high product quality. The first accuracy test created to measure accuracy was not the most effective due to a high rate of human error. A second accuracy test was created to eliminate any human error, but had some challenges. The main challenge of the second accuracy test was to convert all images from pixels to millimeters. After all the conversion was completed a design of experiment was conducted using a general linear model. The results of this design of experiments show that the interaction of weight and speed do not affect the accuracy of the robotic arm. Finally, from the second accuracy test it is possible to conclude that the Yamaha SCARA YK180X located at The University of Texas at El Paso is accurate even if a cycle is run at different velocities and different weights.

5.1 Future Work

From the previous accuracy results it is possible to create a new accuracy assembly test with electronic components. For this test a Design of Experiments will be used to conduct the runs. A factorial design will be used of 5 levels to ensure that any of the levels affect the accuracy of the robot. The following table shows the levels that will be used to conduct the experiment.

Table 5 2^k Factorial Design Factors

	Min	Max
Velocity	1%	50%
Weight	0 Grms	50 Grms
Distance	19 cm	42.75 cm
Chip Number	1	4
Chip Layout	Linear	Nonlinear

The Following tables will show the Full Factorial Design that will be used to conduct the future experiment.

Table 6 Full Factorial Design

Full Factorial Design			
Factors	5	Base Design	5, 32
Runs	32	Replicates	1
Blocks	1	Center Points	0

Table 7 Full Factorial Design Runs

StdOrder	RunOrder	Velocity	Weight	Distance	Chip Number	Chip Layout
1	1	1	0	19	1	Linear
2	2	50	0	19	1	Linear
3	3	1	50	19	1	Linear
4	4	50	50	19	1	Linear
5	5	1	0	42	1	Linear
6	6	50	0	42	1	Linear
7	7	1	50	42	1	Linear
8	8	50	50	42	1	Linear
9	9	1	0	19	4	Linear
10	10	50	0	19	4	Linear
11	11	1	50	19	4	Linear
12	12	50	50	19	4	Linear
13	13	1	0	42	4	Linear
14	14	50	0	42	4	Linear
15	15	1	50	42	4	Linear
16	16	50	50	42	4	Linear
17	17	1	0	19	1	Nonlinear
18	18	50	0	19	1	Nonlinear
19	19	1	50	19	1	Nonlinear
20	20	50	50	19	1	Nonlinear
21	21	1	0	42	1	Nonlinear
22	22	50	0	42	1	Nonlinear
23	23	1	50	42	1	Nonlinear
24	24	50	50	42	1	Nonlinear
25	25	1	0	19	4	Nonlinear
26	26	50	0	19	4	Nonlinear
27	27	1	50	19	4	Nonlinear
28	28	50	50	19	4	Nonlinear
29	29	1	0	42	4	Nonlinear
30	30	50	0	42	4	Nonlinear
31	31	1	50	42	4	Nonlinear
32	32	50	50	42	4	Nonlinear

Finally, before accurately assembly the electronic components the test will be done using AM parts. Figure 56 shows the assembly base that will be used and Figure 57 shows the components that will be used to pick and place. From this test it is expected to increase the confidence of accurately placing electronic components to 3D manufacture parts.

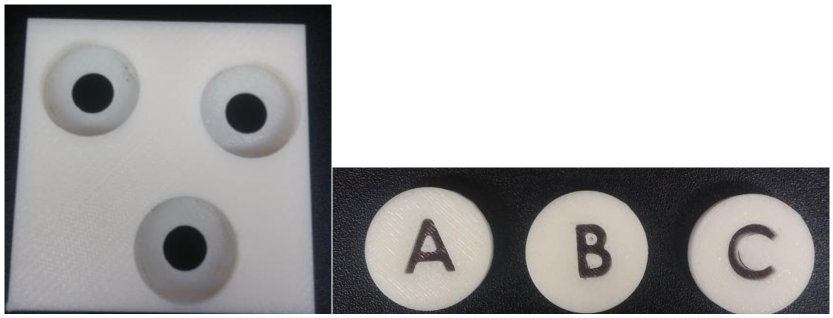

Figure 56 Circular Assembly Base without Components (Left). Circular Components (Right)

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Appendix I – Randomized Factorial Design Run Order

Randomized Factorial Design			
StdOrder	RunOrder	Velocity	Weight
7	1	25	25
16	2	10	50
70	3	50	10
72	4	50	50
54	5	25	10
115	6	25	25
66	7	25	10
51	8	10	25
96	9	50	50
33	10	50	0
4	11	10	50
41	12	25	0
116	13	25	50
58	14	50	10
59	15	50	25
94	16	50	10
95	17	50	25
57	18	50	0
81	19	50	0
74	20	10	10
80	21	25	50
6	22	25	10
71	23	50	25
3	24	10	25
50	25	10	10
104	26	25	50
12	27	50	50
21	28	50	0
82	29	50	10
24	30	50	50
32	31	25	50
13	32	10	0
29	33	25	0
118	34	50	10
40	35	10	50
111	36	10	25
26	37	10	10
53	38	25	0
5	39	25	0

37	40	10	0
107	41	50	25
39	42	10	25
99	43	10	25
92	44	25	50
27	45	10	25
110	46	10	10
46	47	50	10
17	48	25	0
69	49	50	0
22	50	50	10
2	51	10	10
8	52	25	50
93	53	50	0
43	54	25	25
73	55	10	0
19	56	25	25
84	57	50	50
47	58	50	25
106	59	50	10
42	60	25	10
89	61	25	0
117	62	50	0
31	63	25	25
67	64	25	25
34	65	50	10
88	66	10	50
61	67	10	0
87	68	10	25
68	69	25	50
119	70	50	25
113	71	25	0
120	72	50	50
90	73	25	10
36	74	50	50
30	75	25	10
25	76	10	0
48	77	50	50
62	78	10	10
11	79	50	25
20	80	25	50
108	81	50	50
38	82	10	10

103	83	25	25
9	84	50	0
60	85	50	50
44	86	25	50
97	87	10	0
112	88	10	50
100	89	10	50
77	90	25	0
1	91	10	0
64	92	10	50
56	93	25	50
75	94	10	25
45	95	50	0
86	96	10	10
91	97	25	25
52	98	10	50
79	99	25	25
102	100	25	10
114	101	25	10
49	102	10	0
78	103	25	10
83	104	50	25
76	105	10	50
28	106	10	50
101	107	25	0
15	108	10	25
105	109	50	0
109	110	10	0
98	111	10	10
55	112	25	25
10	113	50	10
63	114	10	25
23	115	50	25
65	116	25	0
35	117	50	25
14	118	10	10
85	119	10	0
18	120	25	10

Appendix II – 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	Cable	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
YK180X	100: 100mm	3L: 3.5m 5L: 5m 10L: 10m	RCX340-4							

Specify various controller setting items. RCX340 ▶ P.494

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

Controller	CE Marking	Expansion I/O	Network option	iVY System	Gripper	Battery
RCX240S						BB

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/

Figure 57 Yamaha SCARA YK180X Specifications

YK180X

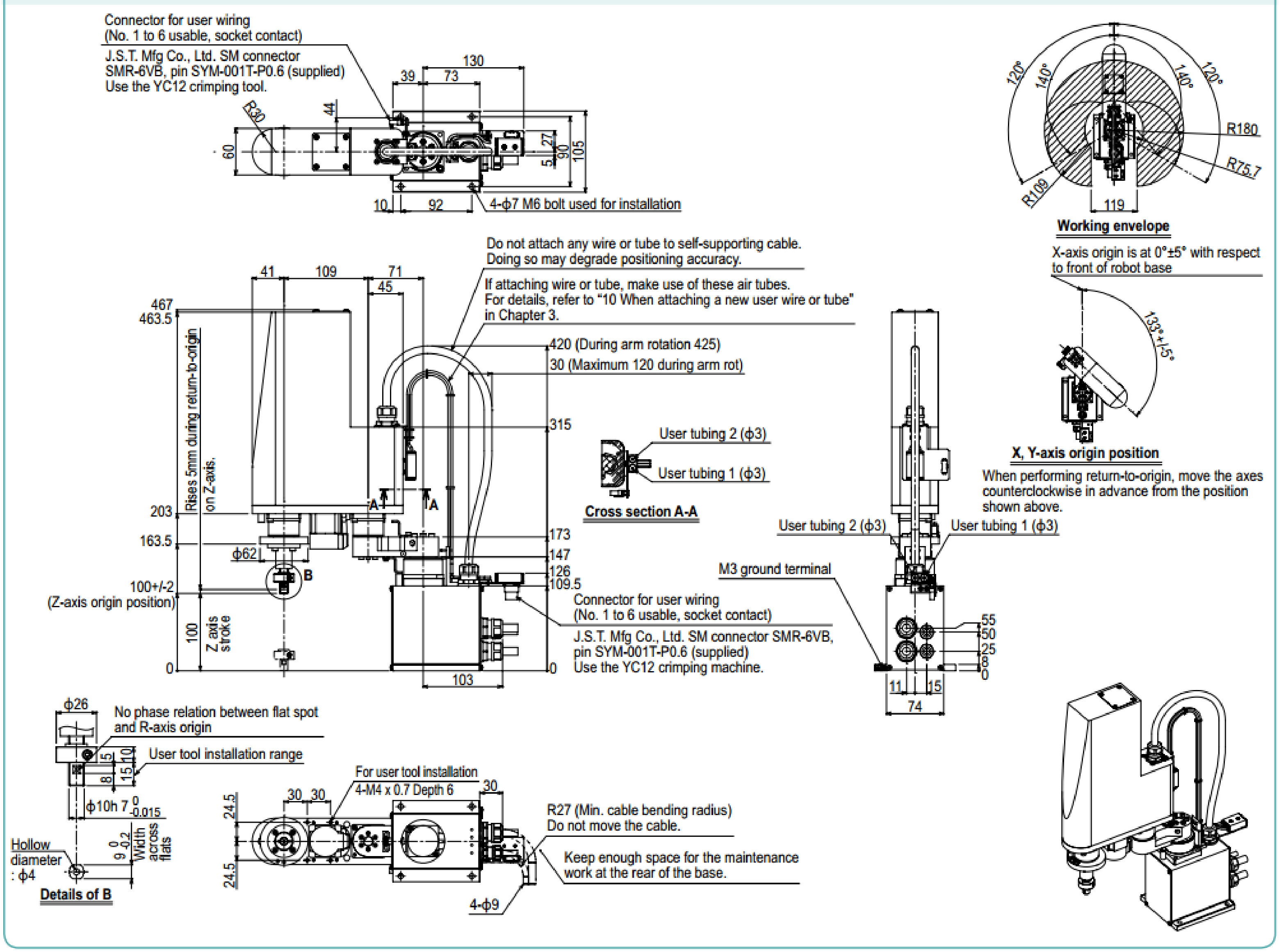

Figure 58 Yamaha SCARA YK180X Specifications

Vita

Oscar A Murga is originally from Chihuahua Chihuahua, México. I move to El Paso Texas on Spring 2010 and did my undergraduate at the University of Texas at El Paso (UTEP) and graduated in Fall 2013 with a B.S. in Mechanical Engineering. While attending to school I work at the Student Recreation Center as a Student Supervisor for the area of Outdoor Adventure Program where I developed good communication skills and leadership skills. During this time I was part of the American Society of Mechanical Engineers (ASME) and I volunteered for the Mini Baja hosted at UTEP.

I will graduate from UTEP with a M.S. in Manufacturing Engineer on fall 2015. During this time I worked with Dr. Bill Tseng at the Industrial, Manufacturing and Systems Engineering Lab. Since spring 2015 I started working as a Manufacturing Supervisor at Dish Network where I have put in practice all my knowledge gain from school and previous work.

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