Mechatronic Design of a Fast-Non-Contact Measurement System for Inspection of Castings Parts in Production Line

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In

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Monterrey Nuevo León, Mayo 11th, 2018
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• Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
• I have acknowledged all main sources of help.
• Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Darío Fernando Guamán Lozada
Monterrey Nuevo León, May 11th, 2018

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Dedication

To my Dear and Loving parents
Hugo and Adriana.

To my Incredibles brothers
Maria Dolores, Cody, and Dayana.
Acknowledgments

Thank you, God, for giving me everything
To my advisors for guiding me during this period and for their friendship
To Tecnológico de Monterrey that supported me with tuition
To Mexico, who through CONACYT help me with my living expenses
Mechatronic Design of a Fast-Non-Contact Measurement System for Inspection of Castings Parts in Production Line

by

Darío Fernando Guamán Lozada

Abstract

Product recalls for suppliers (Tier 1-2-3) and OEM represents high financial losses and reputation damage. This has motivated manufacturers to inspect 100% of the specifications of 100% parts produced to avoid liability risks.

In general, the manufactured parts are measured in CMM machines, the main problem is that it takes a long time to make the measurement. Therefore, CMM machines cannot be installed in a continuous line process. This problem has led industries to install gauging machines to have full control over their production.

Gauging machines are not flexible, a number of sensors equal to the number of targets to be inspected is needed, complicating the maintenance and increasing the cost. Finally, most gauges are of the go-no go type, which only validates whether the characteristics comply with a standard.

In addition, due to the arrival of the concept of industry 4.0, companies have seen the need to develop fast, reliable and accurate inspection machines capable of sending proper information about themselves or the product to the cloud.

This work presents a new measurement system for an In-Line die-casting process. The main characteristic is the use of a linear motor and non-contact measurement technology for fast and reliable measurements. Also, the machine uses a novel kinematics coupling configuration to allow easy, fast, and accurate positioning of the part in the measurements area. To be compatible with Industry 4.0 the inspection machine is equipped with sensors to send process information to the cloud like operation temperature, vibrations, and dynamic machine behavior.
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Chapter 1: Introduction

In recent years, Toyota’s gas pedal recalls resulted in a fall in Toyota's stock prices equivalent to $35 billion [1]. Products recalls for industries, special for automotive manufacturers that are a Tier-1 supplier for OEM's represent customers and economic losses [2]; even reputation and brand abrasion.

This has motivated industry to inspect 100% of the specifications of parts produced with 100% reliability to avoid the risk of liability. Paying a lot of attention improving each of their processes, especially the quality control [3] over their production.

To know if a production batch meets customer specifications there are well-known quality control methods used by industry based on statistical sampling. Those methods are applied to stochastic processes with a significant sample. But, the main problem is that part measurement takes longer than fabrication, therefore sampling cannot be easily applied in continuous production processes, and where parts sampled are not 100% random [4]. And, on the contrary, these processes are affected by variables such as vibrations, humidity, temperature, operator performance, machine performance, etc.

For mass production, industries have opted for install quick inspection equipment in each line. Those installed equipment in production lines uses gauging techniques for produced
part inspection, giving certain tolerances to the gauges. Advanced inspection machines that use gauging techniques include in the design the use of sensors that show the information of the result in an operator interface.

Some typical problems of inspection equipment that use gauging techniques are the need to use several sensors according to the number of points to be inspected, which increases costs and makes maintenance difficult. It lacks a flexible design, which means that the equipment is planned only for one type-specific workpiece [5]. And, there is no easy access to information that does not allow traceability of the measured part.

The use of inspection equipment at the end of the process lines has led engineers and researchers to face new measurement systems design [6]. The most important challenges are: Reduction of inspection time to be within the available process cycle time; Robustness to increasing the useful life in an industrial environment; Easy maintenance to avoid process breaks; Flexibility to allows easy handling of the coordinates of the measurement targets; Accurate and reliable measurements; And compatibility with the 4.0 industry concept to use machine as information source.

With these considerations, this document details: The methodology design for the development of a fast and accurate In-Line measurement system of workpieces from a die casting process.

1.1 Problem Statement and Context

In the process of die-casting, the aluminum parts are manufactured by molten metal at high pressure in a permanent mold; In the automotive industry, this process is widely used to produce large volumes of engine parts and, in recent years, structural components.

In general, after the die casting process, the pieces produced go to other processes where various operations are carried out in the workpiece. This is to make the workpieces according to customer's specifications. Therefore, it is common that the parts that come
out of the process of die casting are oversized. It is not uncommon for parts produced for automobile engines, to have an oversize about + 1 mm.

At the end of the processes of die casting, gauging inspection machines are used, where with a comparison gauge it is established if a part is within the specifications. Therefore, there is the requirement to replace the low performance of these gauging operations.

**Analysis of state of the art system**

The current process to obtain a die casting part within specification is as follow:

- An industrial robotic arm gets out the workpiece from the die casting machine at high temperature.
- The workpiece is introduced into water to cool it down.
- The workpiece is located in a punching machine to eliminate the material excess.
- Operator to perform different tasks, such as cleaning burrs, placing the piece in the inspection machine and readjusting the piece.
- The operator put the workpiece in the fixing base of the gauging system (G_MACHINE) where is located and fixed (See Figure 1 a).
- 19 LVDT sensors are lifted to touch the workpiece with the help of pneumatic actuators and the inspection is carried out.
- Information is displayed to the operator on a screen (See Figure 1 b).

Available cycle time to perform operation e) to g) is around 15-20 seconds.
The geometrical characteristic validated by the gauging system is flatness. In addition, the number of measuring points is 19, in a workpiece with dimensions around 450x450mm. Figure 2 shows a schematic picture of the die-casting part to be measured, red points represent the targets.

![Figure 2. Die-casting part.](image)

Die-castings parts should have a tolerance of less than ± 0.4 mm. This means that the proposed inspection system should have a repeatability better than 40 µm (1/10 of the tolerance). Table 1 shows the requirements of the measurement system, considering the workpiece and the available cycle time.

<table>
<thead>
<tr>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection area</td>
<td>600 x 600 mm</td>
</tr>
<tr>
<td>Measurement points</td>
<td>18 - 19</td>
</tr>
<tr>
<td>Length between points</td>
<td>50 - 100 mm</td>
</tr>
<tr>
<td>Maximum total cycle time</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Part weight</td>
<td>3.5 kg</td>
</tr>
<tr>
<td>Workpiece tolerance</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>System repeatability</td>
<td>&lt; 40 µm</td>
</tr>
</tbody>
</table>
1.2 Objective

To design, build and test a reliable and high precision In-Line inspection system to measure parts from a die casting process in short time, using a measurement instead gauging system, designed for a robust industrial environmental, and for easy integration to Industry 4.0.

1.3 Design Overview

The solution includes the system design for In-Line parts measurement from a die-casting process. The system meets the following requirements:

- The use of new technology such linear motors and non-contact measurement laser sensor to increase machine speed.
- A flexible measurement system to modify the trajectories for different targets to measure.
- A novel kinematic couplings configuration to accurately locate the workpiece to be measured inside measurement area.
- Ensure precision with an overall measurement system calibration.
- An equipped machine with several sensors to acquire environmental and dynamic information used to introduce the system in the concept of Industry 4.0.
- Design a loading area independent of the measurement area to avoid possible damage due to dust or particles that can affect measurements components.
- Use a Measurement System Analysis method (MSA) to evaluate the system performance.
- Include an operator interface to display the measurements results

1.4 Research Contribution

A novel kinematic couplings configuration was designed and tested to allowing the easy lateral access of the workpiece, ensuring high repeatability.

Non-contact laser measurements technologies were tested and compared. Their capabilities to be used in a die-casting process were resumed.
A new measurement system design was developed, calibrated and tested for an In-Line inspection as fast as a gauging-machine and as high-accurate as a CMM machine for workpieces from a die-casting process.

1.5 Thesis Organization

The presented research is organized into six chapters described below:

Chapter II: This chapter presents the selection and evaluation of a non-contact measurement sensor. Also, show the previous works, the fundamentals, and methods used to design of a fast X-Y high-precision stage to coordinate the movements between each measurement.

Chapter III: This chapter shows the previous work, concepts, and design around the mechanism used to obtain a precise positioning which locates the clamp-plate in the measuring area.

Chapter IV: Presents the proposed system in Industry 4.0. This chapter details the hardware and sensors attached to the machine to monitor the process.

Chapter V: The results of the tests are analyzed and a Measurement System Analysis (MSA) is performed.

Chapter VI: Conclusions and future work is presented.
Chapter 2: Inspection System Design

This chapter shows the design and selection of the two principal components of the inspection area: the non-contact measurement sensor and the high-speed X-Y positioning stage.

The main characteristics of the inspection system considered in the design were: A easy programming of the coordinates to be measured. And, the use of a single measuring sensor to allows reducing the maintenance costs.

1.6 Literature Review

To make quick inspections, an important concept is the use of non-contact measurement sensors. Currently, most industries are adopting this technology [7] due to its advantages compared with measurement machines such as CMM, which use touch trigger probe to capture the coordinates of a specific point. Problems with CMM technology is a low speed needed to ensure accuracy and to avoid possible collisions [8][9].

Laser measurement sensors can obtain high-speed trigger measurements. And, by its design, it allows an easy handling and integration to different systems. Laser sensors have a certain range of measurement, the wider this range, the sensor will have less resolution. Li [7] developed a short-range laser system that optimizes its
resolution by automatically placing the sensor on the Z-axis to measure the contour of the surface.

Measurement laser sensor value is giving by the way on how the measurement is taken. It can be from the average of the measurements of a spot with a specific radius, or from a line. All those parameters are determinates by the laser sensor manufacturer and the technology used to catch the measurement.

Based on that, present section considers the different parameters that constrain the laser displacement sensor selection for the current application.

In addition to allowing flexibility in the measurements, inspection machines design including the use of numeric control (NC) like a CMM. These machines have different types of structures: cylindrical, gantry, spherical and anthropomorphic. The structure is determined by the operation or task performed by the manipulator. For a Cartesian (orthogonal) movements, the use of a gantry structure is more appropriate [10].

Depending on the precision to be achieved, several types of actuator technologies have been used in the design of the X-Y stages. The stepper motors are the most economical solution and combined with the proper transmission as ball screws can achieve high precision values, Yuliza reaches a resolution of 0.018° with the use of a gear set for the development of a system to test tilt sensors [11]. The problems with this type of technology are the loss of step due to the open loop system in its controllers [12]. To solve those types of problems, rotational and linear encoders in stepper and in dc-motors have been widely used [12].

Both linear and rotary encoder can take the position incrementally or absolute, the main difference is that with an absolute encoder the position of the actuator is continuously monitoring even after to shut down the machine [13]. The main advantage of linear encoders is that the measurement obtained by the sensor is taken directly in the position of the axis where the actuator is located and is not inferred as with a rotary encoder.
Optical linear encoders can reach a resolution less than 20nm [14]. The signal from those encoders is used as the feedback signal to the system controller which sends commands to the motor for positioning.

One of the challenges in the design of the positioning stages, and special for this application, is to achieve a fast speed in a short time. Therefore, the main task is related to the selection of the appropriate torque/force of the stage motor to accelerate the load and complete the measurement in the time available.

Cartesian positioning system has components such as linear guides, linear bearing and aluminum profiles that have alignments error. The misalignments could affect indirectly the accuracy of laser sensor measurement. Even when these errors are small, they must be quantified and accounted for.

Several researchers have focused on finding and compensating by software the diverse errors caused in high-precision machines. Schwenke et al. distinguish the “direct” and “indirect” methods to map errors in CNC machines [15].

Direct methods calculate machine errors by comparing the commanded position with the real position using diverse techniques.

Lee [15] uses the direct method to determine five geometric error components of a three-axis of a miniaturized machine tool. Data were obtained from capacitive sensors and use the Least-squares fitting method to represent the analytical models of geometric errors.

Another direct method to compensate machines is the self-calibration algorithm. The self-calibration is realized using a grid plate no higher than test stage. The errors could be determined by measuring the difference between the commanded position of the stage and the measured position in the grid plate. Authors such as Wang et al. [16] use a self-
calibration algorithm to compensate the positioning error of a CMM stage separating the errors of the real measurement.

Miller [16] proposed to capture the measurements in continuous motion instead quasi-static calibration techniques where the machine settle before each measurement. In non-accurate machines, his results show an averaged correlation of 3 micrometers at the quasi-static measurement targets.

In conclusion, the direct compensation method can be performed using different measurement tools to map the error. The accuracy of the compensation is influenced by the accuracy of the measurement tools used to perform the compensation.

For the present application, direct compensation method was applied, the overall moving area of the X-Y stage was mapped with the use of a measurements arm.

2.1 Non-contact Measurement Sensor

For the In-Line Measurement System Design, a laser displacement sensor was placed in an X-Y positioning stage to measure different targets on a workpiece. The constraint features that were considered for the selection of an appropriate laser displacement sensor were:

- Reference distance of 150 mm to avoid physical damage.
- The resolution of the sensor should be approximately one-tenth of the tolerance of the workpiece (400/10 = 40 μm).
- Easy access to data sensor.
- Measurement range ≥ 20 mm.
- Workpiece material: Aluminum

Laser Displacement Sensor Selection

Two sensor brands with different software capacities were chosen to be tested. The specification of each laser sensor is shown in Table 2.
Table 2. Laser sensors specifications.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Sensor_A</th>
<th>Sensor_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement speed rate [Khz]</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>Reference Distance [mm]</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>Range [mm]</td>
<td>±100</td>
<td>±40</td>
</tr>
<tr>
<td>Resolution [μm]</td>
<td>±13</td>
<td>±0,25</td>
</tr>
<tr>
<td>Error by difference of 1 ° C [%]</td>
<td>0,03%</td>
<td>0,01%</td>
</tr>
<tr>
<td>Total Error [μm]</td>
<td>±33</td>
<td>±16</td>
</tr>
<tr>
<td>For applications of [μm]:</td>
<td>±330</td>
<td>±162</td>
</tr>
</tbody>
</table>

2.2 Accurate High-Speed X-Y Stage

Table 3 presents a comparison between different technologies used to generate and transmit the movements to linear actuators, for applications such as measurements processes where the accuracy is the main priority the linear motor combined with linear encoders are the best option.

Table 3. Feed drives used in linear actuators [17][18][19][20][21].

<table>
<thead>
<tr>
<th>Mechanical Drive Technology</th>
<th>Belt</th>
<th>Lead Screw</th>
<th>Ball Screw</th>
<th>Linear Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Up to 200Kg</td>
<td>Up to 100Kg</td>
<td>Up to 200Kg</td>
<td>Up to 30Kg</td>
</tr>
<tr>
<td>Stroke</td>
<td>Up to 10m</td>
<td>Up to 2m</td>
<td>Up to 2m</td>
<td>Up to 10m</td>
</tr>
<tr>
<td>Speed</td>
<td>Up to 5…10m/s</td>
<td>Up to 0,5m/s</td>
<td>Up to 3…5m/s</td>
<td>Up to 5…10m/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>100m/s2</td>
<td>30m/s2</td>
<td>50m/s2</td>
<td>150m/s2</td>
</tr>
<tr>
<td>Precision [μm]</td>
<td>100</td>
<td>50</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Noise</td>
<td>Noisy</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Medium</td>
<td>Very High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Relative cost</td>
<td>1 to 2X</td>
<td>2 to 3X</td>
<td>2 to 3X</td>
<td>3 to 5X</td>
</tr>
</tbody>
</table>

Linear motors have been widely using in recent years due to the advantages such as: decreased backlash, slip, friction, and energy dissipation [22][23]. Chen and Lu evaluated a new motion control using linear motors for a high-precision positioning platform [19]. In addition, linear motor actuators have been widely used for micro and nano-positioning.
due to their precision. Kurisaki et al. developed a new system design using voice coils (linear motors) and can achieve high positioning accuracy using laser interferometers [20].

**Gantry Structure Design**

The minimum dimensions for our system based on the workpiece to be measured are 450 x 450 x 150 mm.

Several system Gantry configurations structures were analyzed allow the movement in an X-Y plane to generate a path that the sensor would follow to acquire the point’s measurement. Figure 3 shows the main configurations were:

- The workpiece to be measured is fixed with respect to the sensor
- In opposite shows, the sensor fixed with respect to the workpiece
- A combination shows the movement of the sensor in an axis and the workpiece in the other.

![Figure 3. X-Y Stage configurations](image)

Based on Table 3 and in Figure 3 a Pugh matrix was generated (See Table 4) where the weight factor is listed in Table 5
Table 4. Pugh analysis - Gantry configuration alternatives.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Movement type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a)</td>
</tr>
<tr>
<td>Linear Motor</td>
<td>Belt drive</td>
</tr>
<tr>
<td>Load</td>
<td>1</td>
</tr>
<tr>
<td>Speed</td>
<td>5</td>
</tr>
<tr>
<td>Acceleration</td>
<td>5</td>
</tr>
<tr>
<td>Precision</td>
<td>5</td>
</tr>
<tr>
<td>Relative cost</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 5. Weight factor table for Gantry configuration alternatives.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Weight factor</th>
<th>Ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movable Load (P)</td>
<td>2</td>
<td>5 kg ≤ P &lt; 20 kg</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>P &lt; 5 kg</td>
</tr>
<tr>
<td>Speed (v)</td>
<td>5</td>
<td>2 m/s ≤ v ≤ 10 m/s</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0,5 m/s ≤ v &lt; 2 m/s</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>v &lt; 0,5 m/s</td>
</tr>
<tr>
<td>Acceleration (a)</td>
<td>5</td>
<td>a ≥ 20 m/s/2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5 m/s² ≤ a &lt; 20 m/s²</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>a &lt; 5 m/s²</td>
</tr>
<tr>
<td>Precision (p)</td>
<td>5</td>
<td>p ≤ 20 µm</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100 µm ≤ p &lt; 20 µm</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>p &gt; 100 µm</td>
</tr>
<tr>
<td>Relative cost (c) USD</td>
<td>3</td>
<td>C ≤ $ 5000</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$ 5000 &lt; C ≤ $10 000</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>C &gt; $10 000</td>
</tr>
</tbody>
</table>

Based on Pugh analysis matrix, it was determined that the Gantry-option a is the most effective configuration for this case.
Linear Actuators: Sizing and selection

Given that speed is the main parameter to be considered in the design of the stage and is restricted by the time available in the process time (around 20s), the measurement time would be about 1/4 of the total time (5s).

The number of points to measure is 19, therefore, it is necessary to calculate the force required in the motor to measure 19 points in 5 seconds. This force is calculated considering a settling time to avoid vibrations in each measurement.

The most common and efficient velocity profile for point-to-point moves is the “1/3-1/3-1/3” trapezoid (Figure 4). This profile breaks the time of the acceleration, traverse, and deceleration into three equal segments. The end result is that the profile provides the optimal move by minimizing the power required to complete the move [24].

![Figure 4. Trapezoidal motion profile.](image)

Then, the main parameters to consider before starting the motor sizing are:

The mass that the actuator carry is given by the coil mass. Commercial linear actuators coils have a mass of 0.1 kg to 6kg, for sizing purpose the coil mass was considered of 0.5Kg and the laser displacement sensor mass of 0.5 Kg, giving as a total of:

\[
m = 1 \text{ kg}
\]

As mentioned before, machine move points to point, the total length to move is of 1.803 m. And, the maximum number of points to be measured are 19, giving an average separation between points of:
\[ e = 94 \text{ mm} \]

The cycle time available to perform the measurement of the workpiece, regardless of the time it takes to load, unload and positioning the workpiece within the measurement system, is approximately 5 seconds. Dividing it by 19 points gives us a trajectory time per point of around:

\[ t = 0.25 \text{ s} \]

The terms used for the calculations are listed in Table 6.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{max})</td>
<td>Max speed considered</td>
</tr>
<tr>
<td>(a_{trap})</td>
<td>Required acceleration to generate a trapezoidal profile</td>
</tr>
<tr>
<td>(a_{sin})</td>
<td>Required acceleration to generate sinusoidal profile</td>
</tr>
<tr>
<td>(F_a)</td>
<td>Required force to accelerate the load</td>
</tr>
<tr>
<td>(F_d)</td>
<td>Required force to deaccelerate the load</td>
</tr>
<tr>
<td>(F_f)</td>
<td>Force due to a Friction</td>
</tr>
<tr>
<td>(F_{rms})</td>
<td>Required average force for the movement</td>
</tr>
<tr>
<td>(t_a)</td>
<td>Time to accelerate</td>
</tr>
<tr>
<td>(t_{on})</td>
<td>Motion time</td>
</tr>
<tr>
<td>(t_{off})</td>
<td>Dwell time</td>
</tr>
</tbody>
</table>

The maximum speed and the required acceleration are calculated as follow:

\[ v_{max} = 1.5 \frac{e}{t} \quad (1) \]

\[ v_{max} = 1.5 \left( \frac{0.094 \text{ m}}{0.25 \text{ s}} \right) \]

\[ v_{max} = 0.56 \frac{\text{m}}{\text{s}} \]
\[ a_{\text{trap}} = 4.5 \frac{e}{t^2} \]  

\[ a_{\text{trap}} = 4.5 \left( \frac{0.094 \text{ m}}{(0.25 \text{ s})^2} \right) \]

\[ a_{\text{trap}} = 6.76 \frac{m}{s^2} \]

\[ a_{\text{sin}} = 1.5\left( a_{\text{trap}} \right) \]  

\[ a_{\text{trap}} = 10.76 \frac{m}{s^2} \]

With those values, the peak and RMS force required are obtained by

\[ F_a = m \ast a + F_f \]  

\[ F_{\text{trav}} = F_f \]  

\[ F_d = m \ast a - F_f \]  

\[ F_{\text{rms}} = \sqrt{\frac{\left( F_a^2 \times t_a \right) + \left( F_f^2 \times t_a \right) + \left( F_a^2 \times t_a \right)}{t_{\text{on}} + t_{\text{off}}}} \]  

Thus, for X-axis:

\[ F_a = m \ast a + F_f \]

\[ F_f = \mu \times m \times g \]

\[ F_a = (1 \times 10.76) + (0.03 \times 1 \times 9.81) \]

\[ F_a = F_{\text{peak}} = 11.05 \text{ N} \]

\[ F_d = (1 \times 10.76) - (0.03 \times 1 \times 9.81) \]

\[ F_d = 10.46 \text{ N} \]
\[ F_{rms} = \sqrt{\frac{(F_a^2 \times t_a) + (F_y^2 \times t_a) + (F_a^2 \times t_a)}{t_{on} + t_{off}}}
\]

\[ F_{rms} = \sqrt{\frac{(11.05^2 \times 0.083) + (0.2352^2 \times 0.083) + (11.05^2 \times 0.083)}{0.250 + 0.01}} \]

\[ F_{rms} = 8.83 \, N \]

And for Y-axis was necessary to consider also the mass of the X-axis, that consist in the Laser sensor (0.5 Kg), the three coils (3*0.5 Kg) and the aluminum structure (around 3 Kg); giving a total mass of:

\[ m = 5 \, kg \]

Applying the Equation (1) to (6) as X-axis for Y-axis the results are:

\[ V_{max} = 0.5 \, \frac{m}{s} \]

\[ a(sinusoidal) = 8.64 \, \frac{m}{s^2} \]

\[ F_{rms} = 20.61 \, N \]

\[ F_{peak} = 26.8 \, N \]

From the previous discussion, the basic dynamic characteristics of the linear positioning system are the following:

- Max speed of 600 m/s
- Max acceleration of 10 m/s²

Several commercial linear motors, linear stages, and sensors were compared from different suppliers. The proposal of H2W Company was chosen due its design, the relatively low cost that includes the X-Y stage controller. The design generated is shown in Figure 5.
Figure 5. Positioning system proposed by H2W a) Motor Coil b) Magnet Track c) Slide rail d) Mounting Plate e) *Laser displacement sensor f) Bearings Blocks g) Aluminum frame (*Not included)

The working area of the x-y stage is 600 x 600 mm and the general dimensions are presented in Figure 6:

Figure 6. X-Y stage dimensions (mm)

And the specifications of the linear motors from the supplier are in Table 7.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Force [N]</td>
<td>27.8</td>
</tr>
<tr>
<td>Continuous Current [Amp]</td>
<td>2.1</td>
</tr>
<tr>
<td>Continuous Power [Watts]</td>
<td>39.3</td>
</tr>
<tr>
<td>Peak Force @ 10% Duty</td>
<td>83.3</td>
</tr>
<tr>
<td>Peak Current @ 10% Duty</td>
<td>6.3</td>
</tr>
<tr>
<td>Peak Power @ 10% Duty</td>
<td>353.7</td>
</tr>
</tbody>
</table>
Those specifications compared with the results for the actuator sizing make this design fit for the application.

2.3 X-Y Stage Errors Mapping

The methodology proposed to compensate machine error was performed with the following steps:

A path was programming in the controller, in which the mounting head moved to cover the measurement plane. The path consists of a grid with 49 targets, each one spaced by 100 millimeters along each axis (Figure 7).

Faro Arm, a portable coordinate measuring device (CMM) shown in Figure 8, was used to measure the 49 coordinates targets respect to a reference Figure 9. This reference system was taken parallel to the aluminum base of the system.
The data obtained was analyzed. The 49 points were graphed. Nine polynomials were used for fitting a surface with the gathered data. Table 8 shows the average error result for 21 testing targets. The “poly22”, a second-order polynomial, has the lowest error: 0.018 mm.

<table>
<thead>
<tr>
<th></th>
<th>poly11</th>
<th>linear</th>
<th>lowess</th>
<th>poly22</th>
<th>poly23</th>
<th>poly32</th>
<th>poly33</th>
<th>poly44</th>
<th>poly55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Error</td>
<td>0.056</td>
<td>0.020</td>
<td>0.019</td>
<td>0.018</td>
<td>0.020</td>
<td>0.020</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Figure 10 shows the surface and the polynomial (poly22) obtained and its coefficients with 95% of confidence bounds.
The polynomial equation was used to compensate the machine in the target coordinates where the measurements are performed. After compensation, the part was measured with both laser Sensor_A and Sensor_B.

FaroArm system specification after its calibration showed an error of 17 µm, this means that the measurements taken in the measurement system after direct calibration method include this error, giving a total error of 35 µm (18 µm + 17 µm).
Chapter 3: Positioning System Design

The need to accurately place workpieces on machines for processing, such as machining or measurement, has led to advanced research to work in the design of mechanisms that allow fast and accurate positioning. This chapter shows the design of different mechanisms that together serve to place the workpiece within the measurement area with high precision.

3.1 Literature Review

Ensure repeatability positioning the workpiece inside the measurement area is one of the main challenges of present work. It is due the needed to perform the measurements in the same coordinate target each time.

To ensure repeatability in positioning, there are well-known mechanisms that use the principle of Exact Restriction Design (ERD). This principle consists in that the number of restriction points must be equal to the number of Degrees Of Freedom (DOF) that will be restricted [25]. In any physical object, there are six DOF. Three linear and three rotational DOF around each axis [26]. If the object is under-constrained, it is free to move. If it is over-constrained, it can cause deformation.
Kinematic coupling designs only come into contact with the number of points equal to the number of DOF that must be constrained and, therefore, make their behavior predictable [25].

Slocum [25] shows a brief review of the uses, advantages, and designs of kinematics coupling, and mention two types of kinematics couplings Three-Groove and Kelvin Clamp. The differences are the way as the load is distributed in each support, for the Three-Groove the forces are equal in all contact point, but in the Kelvin Clamp type, the forces are divided in 3-2-1 contact point respectively for each support.

For high precision applications, it is necessary to evaluate the performance of kinematic couplings [27], T.W. Ng [28] evaluated a mechanism tracking the centroids of an illuminated hole to capture the position of the hole through a camera. The performance of the proposed design is done using linear variable differential transformers (LVDT) due to their high resolution.

A problem with these common kinematic couplings design does not consider the way in which the part is loaded. This section shows the design methodology to develop a new configuration of kinematic couplings that allows easy lateral loading of the workpiece on themselves.

In the literature, the analysis of the kinematic coupling is carried out using the contact principle of Hertz [26][29][30]. Hertz contact theory is a classic theory of contact mechanics useful for engineers and researchers. Although the derivation of the theory is relatively difficult, the final solution is a set of simple analytic equations that relate the properties of the system with the developed stress.

Commonly the Hertz contact equations are useful for applications where the load is significant [25], but due to the high precision required this analysis was considered.
3.2 Workpiece Location Mechanisms

A localization clamp-plate with adequate tolerances was considered allowing to fit with the smallest gap all produces parts. In addition, the clamp-plate must be designed for easy placement of the part by the operator.

Die casting automotive parts has targets (datum’s) on which the part is referenced. In this case, the workpiece is settled in X1, X2 and X3 datum’s. In Figure 11 the location of the support pins is presented. Those datum’s are used to generate a reference plane.

Although the part is seated on a plane generated by the support pins, the part is not completely restricted and can be moved and rotated in the other 3 DOF. Two components were designed, the first (Figure 12a) is used to avoid the movement of the part in the x-y plane, and the second (Figure 12b) to restrict the rotatory movement.

Figure 11. a) Die-casting part b) Supporting pins.
To avoid part movement during the measurement there were included in the design a set of pneumatic clamps, which push the part over the supporting pins and fix it to the plate.

3.3 Automatic Positioning Mechanisms

Positioning the clamp-plate inside the measurement area from loading zone can be performed using commercial linear actuator. But to reach the required precision, there is needed a highly accurate linear actuator. High precision linear actuators can cost thousands of dollars. For example, a linear actuator with a precision of ±80 µm can easily be up to $2000. Therefore, there was a need to find the most cost-effective design to position the piece accurately.
Based on that, in the presented design shown in Figure 14, a non-accurate linear actuator (e) introduces the clamp-plate (c) inside the measurement area. Then, at the end of the actuator stroke, the clamp-plate is mounted on the kinematic couplings.

![Figure 14. Positioning mechanisms assembly a) Kinematic coupling set b) Flexures mechanism c) Clamp-Plate d) Base e) Pneumatic linear actuator](image)

To select the actuator responsible for inserting and removing the clamp-plate from the measurement area, the following consideration was taken:

- It must exert the force necessary to move the clamping plate.
- Is essential that it can be able to control the speed easily.
- The actuator stroke is given by the length of the measurement area and the workpiece size.

Parts of the selected pneumatic actuator are in Figure 15.
The actuator stroke is of 700mm, and the speed is given by the curve shown in speed is given by the air flow in the system and by the load (Figure 16)

![Figure 15. Pneumatic actuator.](image)

![Figure 16. Pneumatic actuator speed vs load [31].](image)

Specifications of the linear pneumatic actuator are listed in Table 9.
Table 9. Pneumatic actuator specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore Size</td>
<td>40</td>
</tr>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Action</td>
<td>Double acting</td>
</tr>
<tr>
<td>Pressure Range</td>
<td>0.1 to 0.8 Mpa</td>
</tr>
<tr>
<td>Fluid temperature</td>
<td>5 to 60 °C</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Non-lube</td>
</tr>
<tr>
<td>Stroke</td>
<td>700</td>
</tr>
<tr>
<td>Stroke length tolerance</td>
<td>0 to 1.8 mm</td>
</tr>
</tbody>
</table>

For the clamp-plate load including workpiece load (around 15kg), the maximum speed based on Figure 16 is 1500mm/s. Currently, the speed is controlled manually with an installed airflow, the speed is set for a smooth movement.

Kinematic couplings configuration design has two “V” supporting blocks that are located parallel one to the other and the third supporting block in “L” shape which is perpendicular to the others two, Figure 17 shows the proposed configuration.

![Kinematic couplings configuration](image)

**Figure 17. Proposed configuration a) V blocks b) L block.**

This configuration allows the easy side access of the clamp-plate to the measurement system area in the direction of the arrow, allowing for accurate positioning of the part.
To mount the clamp-plate over kinematics coupling at the end of the pneumatic actuator stroke, some flexures mechanisms were designed for be manufactured using FFF (Fused Filament Fabrication) technology.

The use of these flexures allows the kinematic coupling to be in contact. Figure 18 shows the working principle. The force F is generated by the pneumatic linear actuator.

![Figure 18. A Schematic function of flexures a) Springs allow contact in each part of the kinematic couplings b) Round pin (part of kinematic coupling) c) V and L blocks (part of kinematic coupling).](image)

Based on the main function of the springs, flexure mechanisms were designed as shown in Figure 19.

![Figure 19. Flexure mechanism 3D design.](image)

The material used was Onyx which is composed of chopped carbon fiber filament in a nylon fiber. Onyx has twice the strength of other 3D printed plastics as PLA or ABS.

The flexure mechanism displacement before the positioning is 3mm in Y-direction and 2mm in Z-direction as a maximum. A simulation was performed (The manufacture does not generate an isotropic piece; therefore, the simulation is only an approximation) to
investigate the applied force on the base-plate and the safety factor. The material properties are shown in Table 10.

Table 10. Onyx mechanical properties [32].

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Standard</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>ASTM D638</td>
<td>36</td>
</tr>
<tr>
<td>Tensile Modulus (GPa)</td>
<td>ASTM D638</td>
<td>1.4</td>
</tr>
<tr>
<td>Tensile Strain at Break (%)</td>
<td>ASTM D638</td>
<td>58</td>
</tr>
<tr>
<td>Flexural Strength (MPa)</td>
<td>ASTM D790*</td>
<td>81</td>
</tr>
<tr>
<td>Flexural Modulus (GPa)</td>
<td>ASTM D790*</td>
<td>2.9</td>
</tr>
<tr>
<td>Heat Deflection Temperature (°C)</td>
<td>ASTM D648</td>
<td>145</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>N/A</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Deformation before the displacement is presented in Figure 20, it shows the displacement in the top part of the flexure due this part is fixed at the clamp-base and the bottom part is to the slide actuator carriage.

Figure 20. Flexure deformation [mm].

The analysis indicates that the safety factor for the design with the considered displacements is more than 2 (See Figure 21)
And the average reaction force in z-axis was of 24N and in y-axis was of 33N. The maximum and minimum forces for both axes are shown in Figure 22 and Figure 23.
Total force in z-axis for 2 flexures is 48N and for y-axis is of 132N, those forces are which maintain the clamp-base in position over the kinematic couplings during the workpiece measurements.

The direction of the force applies is present in Figure 24 a, shows that the configuration is similar to a cantilever beam, where the inner part of the flexure is in traction and the outer is in compression. Parts produced by the process display the largest resistance in the direction collinear to the direction of the deposited fused material. The material was deposited following the contour design as presented in Figure 24 to make better use of the strength of the part.

![Figure 24. a) Force and material direction b) Printer model design.](image)

**Deformation analysis of kinematics couplings**

For the present application, the considered load was 150 N (clamp-plate + workpiece), and the force exerts by the flexures of 48 N in Z-axis and 132 N in Y-axis. An analysis was performed to investigate the maximum deformation of the mechanism to know how it can affect the measurements on workpieces.

The considerations taken for the analysis of the components of the kinematic coupling (“L” and two “V” supporting blocks) are the following:

- The load is uniformly distributed (each block supports the same load)
- The behavior in both “V” supporting blocks is equal

The Hertz contact equations to determine the depth of indentations is giving by:
\[
\delta \approx \left( \frac{2 * F^2}{E^2 * R} \right)^{\frac{1}{3}} \tag{8}
\]

\(F = \text{Load}\)

\(E = \text{young modulus}\)

\(R = \text{Esphere radius}\)

The load for Hertz contact analysis in each support block is:

\# \text{Supports} = 3

\(\text{Load (Z-axis)} = 198 \, N \, (\text{clamp – plate + workpiece + force exerts by flexures})\)

\[
\text{Load per support block} = \frac{198}{3} = 66 \, N
\]

“L” support block

For L support block the force is applied in one contact point (See Figure 25)

![Figure 25. Applied load on L-Block.](image)

Replacing data in (8) with the radius of 10mm for the spheres and a young modulus of 210 for steel

\[
\delta \approx \left( \frac{2 * (66 \, N)^2}{(210 \, Gpa)^2 * (0.01 \, m)} \right)^{\frac{1}{3}}
\]

\[
\delta \approx 2.7 \, \mu m
\]
“V” support block

And for V support blocks the force is applied in two contact point (See Figure 25)

![Figure 26. Applied load on V-Block.](image)

In this case, the load is distributed in the two contact points. The force in each contact is calculated as follow:

\[
F_1 = L \cdot \cos(\emptyset)
\]

\[
F_1 = 66 N \cdot \cos(45)
\]

\[
F_1 = 46.66 N
\]

Then the indentation depth applying (8) is:

\[
\delta \approx \left( \frac{2 \cdot (46.66 N)^2}{(210 \text{ Gpa})^2 \cdot (0.01 m)} \right)^{\frac{1}{3}}
\]

\[
\delta \approx 2.14 \mu m
\]

3.4 Environmental Effects

In industrial workshops there is no controlled environment like in a laboratory, therefore it is necessary to consider the factors that could modify the behavior of the machine. The main factor to consider in the design is the temperature change since the materials used to manufacture the machines tend to modify their dimensions. Due to the temperature
variation in the zone where the industrial plant is located, the considered temperature variation for the present analysis was of 8°C.

A temperature change can modify how the clamp-plate will settle over the kinematics couplings. For the analysis of the mechanism, the following considerations were made:

- The maximum temperature variation to consider is 8°C
- A contact point in the kinematic coupling was fixed (Point 2)
- P3 contact is free to move in the x-y plane
- Due to the position of the V blocks is in the y-axis, the deformation of interest occurs on the x-axis

The location of the mechanism is presented in Figure 27

![Figure 27. Kinematic couplings locations](image)

With a deformation, the kinematic coupling will try to maintain the contact, but because the P3 is free to move, the kinematic coupling will affect the position of P1 or P2 only. The deformation in x-axis between P1 and P3 in the clamp plate is thus analyzed.

\[ \text{Material} = \text{Aluminium} \]

\[ D1 = 50 \]

\[ \Delta T = 8°C \]

\[ \alpha = 2,3 \times 10^{-5} \frac{m}{°C} \]
\[ \Delta d_c = L_0 (\alpha \cdot \Delta T) \]
\[ \Delta d_c = 50 (2.3 \times 10^{-5} \cdot 8) = 9.2 \mu m \]

The aluminum base is statically indeterminate because it is fixed by four screws. The deformation was calculated with the help of finite elements (Figure 28).

![Figure 28. Aluminum base deformation simulation [mm].](image)

The displacements in the x-axis, where the kinematic couplings are in contact are the following:

\[
P1 = -31.5 \mu m \\
P2 = -23.8 \mu m \\
P3 = 32.5 \mu m
\]

The total displacement in distance D1 for the aluminum base is:

\[
\Delta d_b = P1 - P2 \\
\Delta d_b = 7.7 \mu m
\]
By subtracting the maximum deformations between the clamping plate and the aluminum base, it is possible to determine the total displacement when the kinematic coupling is in contact with an increase of 8 °C.

\[ \Delta d = \Delta d_c - \Delta d_b \]
\[ \Delta d = 9.2 \mu m - 7.7 \mu m = 1.5 \mu m \]

The V blocks have an angle of 45° (Figure 29). The displacement in X-axis is the same as in the z-axis, which is perpendicular to the X-Y plane.

\[ \Delta x = \Delta h = 1.5 \mu m \]

### 3.5 Precision Tests

The repeatability of the positioning system was tested as described in the ASME B5.54 standard [33] where at least 10 measurements are needed to determine repeatability, the only difference being that LVDT was used instead of ballbar. The methodology to follow was:

The clamping plate slides several times in and out of the measuring system through the y-axis. For reference to the named axes of the machine, see Figure 30.
Variations of LVDTs sensors on X and Y axis is monitored. At the beginning of this test, both sensors were zeroed. Figure 31 shows both sensors placed in the measurement area.

Measurements were obtained and tabulated for each axis on two different days.

Data registered by LVDTs sensor were plotted in histogram diagrams shown in Figure 32 and Figure 33 for X and Y axis respectively.
Table 11 shows the results of the repeatability test of the positioning system. Maximum range for both axes is less than 25 µm.

Table 11. Positioning system repeatability results.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Average [µm]</th>
<th>Std [µm]</th>
<th>Range [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>9.966</td>
<td>3.467</td>
<td>24.5</td>
</tr>
<tr>
<td>Y</td>
<td>-5.2422</td>
<td>6.536</td>
<td>23.5</td>
</tr>
</tbody>
</table>

The workpiece surface is not completely smooth, as can be seen in Figure 34, a small variation in the positioning of the axes x and y can change the value of the measurement.
therefore, with the achieved values in the positioning tests, is ensured a high-repeatability system.

![Workpiece measurement surface](image)

**Figure 34. Workpiece measurement surface.**

The measurement system assembly is shown in Figure 35. A cover made of polycarbonate was installed over the measuring area to isolate from dust or particles that can damage components such as the linear guides or the laser measurement sensor.

![Proposed measurement system design](image)

**Figure 35. Proposed measurement system design.**
Chapter 4: Digitization for Industry 4.0

For Industry in general, information represents a competitive advantage to take decisions [34]. In manufactures industries, most of this information originates in the shop floor [35]. And, thanks to technological advances, miniaturized sensors can be placed in machines and tools to monitor [36] and establish the machine and processes behavior, which allows to optimize resources, reduce cycle time, increase the useful life, etc.

In Industry 4.0 the term “Big Data” refers to the data which can come from external or internal sources, or be generated by machine-to-machine interaction [37]. All collected data have as objective generate a cyber-physical machine model. This cyber-physical model must consider almost the main information that can affect the system, like environmental conditions such as vibration, temperature, humidity, etc. And machine operation parameters like speed, spindle speed, acceleration, deacceleration, position etc. [38].

The present chapter describes the different sensors that were considered necessary to obtain relevant information and can generate a cyber-physical machine model to monitor and predict possible faults.
4.1 Machine Control and Information Processing

The main advantage in the design of the measurement system is the use of a Beagle Bone Black (BBB) which based on open source hardware. The BBB is a small micro-computer designed for Internet of Things (IoT). This microcomputer has the specification listed in Table 12.

Table 12. Beagle Bone Black specifications.

<table>
<thead>
<tr>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>512MB DDR3 RAM</td>
</tr>
<tr>
<td>4GB 8-bit eMMC on-board flash storage</td>
</tr>
<tr>
<td>3D graphics accelerator</td>
</tr>
<tr>
<td>2x PRU 32-bit microcontrollers</td>
</tr>
</tbody>
</table>

Beaglebone manufacturer releases an industrial BBB version, the Beagle Bone Red which has the same specification as the BBB with the difference that can support temperatures from -20 to +85°C. Beaglebone Red is showing in Figure 36.

Figure 36. Beagle Bone Red.

The Beagle Bone Red (BBR) perform the following functions:

- Interact with the linear motor controller.
- Calculate the distance of each point to the reference plane.
- Send the information gathering from the different sensor to the cloud.
- Display the measurements on the screen for the operator.
The connection diagram is shown in Figure 37.

Sensor information is processing in the BeagleBone Red after to be sent to the cloud. The information is stored in a Google Spreadsheet.

Main information about workpiece measurement is displayed on the screen (Figure 38). QT development pack based on C++ was used to program it. Also, in the main program include libraries to establish communication with the linear motors controller. They send the coordinates to be measured and get the values of the laser measurements. Screen operator is shown indicators that show if the measurement is within specification (green) or is out (red).
4.2 Digitization

To monitor the dynamic behavior of the X-Y positioner, an accelerometer with the ability to measure up to three axes was installed. In theory, the maximum acceleration of the positioner is less than 1G, the accelerometer was set for a range of -1.5G to 1.5G. Figure 39 shows the size of the sensor, the characteristics of the accelerometer can be found in [37].

The information sent by this accelerometer allows us to know the maximum accelerations reached by the positioner in each trajectory in the axes X and Y.
The program that is executed in the controller, which has a subroutine that allows sampling the signal every millisecond. The maximum acceleration value reached in the trajectory is stored and saved for future analysis.

Figure 40 shows information about the dynamic behavior of the machine during the measurement in each point.

![Graph showing average maximum accelerations during measurements.]

Currently, this acceleration information is used to establish the normal operating values of the machine. In case there is an increase or decrease in acceleration values, it could be useful to determine the fault. This type of analysis is not currently installed.

Measurement machine was also equipped with the Bosch XDK platform that has sensors for temperature, humidity, pressure and a three-axis accelerometer (Figure 41).
The platform has the following features:

Table 13. XDK Platform Features.

<table>
<thead>
<tr>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit microcontroller ARM Cortex M3</td>
</tr>
<tr>
<td>Bluetooth LE</td>
</tr>
<tr>
<td>Wi-Fi</td>
</tr>
<tr>
<td>Debug &amp; extension port</td>
</tr>
<tr>
<td>Micro SD</td>
</tr>
<tr>
<td>Push buttons</td>
</tr>
<tr>
<td>Status LEDs</td>
</tr>
<tr>
<td>Li-Ion rechargeable battery</td>
</tr>
</tbody>
</table>

XDK platform is used to measure the physical conditions of the environment of the machine, the sensors are shown in Figure 42:

Figure 42. XDK sensors.
Figure 43 shows the temperature values during the operation of the machine in the industrial plant.

![Temperature Variation](image)

**Figure 43. Machine temperature over time.**

The temperature changes help us to know the possible ranges of uncertainty in the measurements due to the deformation of the materials as the calculations shown in Chapter 3.

The XDK accelerometer is used to get the vibration present during the measurements, the previous analysis shows a maximum amplitude acceleration around 130mG, those vibrations are from external sources like punching machines. In Figure 44 are showing the vibration of the machine before starting the measurements.
One of the important characteristics that could be noticed during the first tests is that the acceleration of the machine between each trajectory increases as the time of use increases, as well as the temperature (See Figure 45).

![Vibration Histogram](image1)

**Figure 44. Machine vibration before measurements.**

![Temperature and acceleration variations](image2)

**Figure 45. Machine accelerations vs temperature.**

This type of information could be used for purposes of monitoring and diagnostics, which could be implemented in a cyber-physical model of the machine.
Chapter 5: Test, Analysis, and Results

5.1 Precision on Reference Pins

Reference pins generate the plane that is used to evaluate each point. It is necessary to guarantee high precision in each measurement of those reference pins. This procedure is called "Calibration procedure" and is performed before starting a series of measurements of workpieces.

To evaluate the repeatability of reference pins, multiple tests were done with the two laser measurements sensor. Each experiment began with the clamp-plate outside of the measurement area. The clamp plate slides inside, and the measurement of each pin is performed (Figure 46). After that, the fixing base slides outside again. Thirty measurements of each pin were registered. The experiment was repeated in different days to account the potential effects of the environmental conditions.
Figure 46. Measurement on reference pin 1 of 3.

Figure 47 shows the box plots from data obtained from the measurement of reference pins, during the calibration procedure with laser Sensor_A.

![Box plots](image)

Figure 47. Laser Sensor_A repeatability on reference pins.

Table 14 shows results of the data analysis of laser Sensor_A. The maximum standard deviation was of 73 μm with an average of 50 μm. The maximum range variation was 175 μm with an average of 137 μm.

Table 14. Laser Sensor_A repeatability results on reference pins [μm].

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>73</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>Range</td>
<td>175</td>
<td>87</td>
<td>137</td>
</tr>
</tbody>
</table>
Figure 48 shows box plot from laser Sensor_B references pins measurements.

![Reference pins variations (Laser sensor_B)](image)

Figure 48. Variation laser Sensor_B repeatability on reference pins.

Table 15 presents the results of data analysis of laser Sensor_B. The maximum standard deviation was of 8.7 μm with an average of 6.02 μm. The maximum range variation was 39 μm with an average of 27 μm.

Table 15. Laser Sensor_B repeatability results on reference pins [μm].

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>8.74</td>
<td>3.68</td>
<td>6.02</td>
</tr>
<tr>
<td>Range</td>
<td>39</td>
<td>17</td>
<td>27</td>
</tr>
</tbody>
</table>

These error measurements in the reference pins will be directly reflected in the results obtained by the distance of the point-to-plane equations (Appendix B).

5.2 Precision on Workpieces

Laser sensor measurements on aluminum workpiece were also performed. For the test, the workpiece is placed in the clamp-plate and is slid inside of the measurement area (See Figure 49). The equation to obtain the distance to a reference plane from each of the measurement targets are described in Appendix B.
Measurements are performed at 18 coordinates points. The clamp-plate is slid out of the measurement area and the operator removes the part from the fixing base.

This procedure was repeated 30 times in two different days to obtain laser measurement and establish system repeatability. Laser Sensor_A and Sensor_B were tested.

Several experiments were done to establish the repeatability of laser sensors. Figure 50 and Figure 51 present the results of the most representative tests for laser Sensor_A and Sensor_B, respectively. Fifteen data of each coordinate points (18 points) were taken on two different days. Box plot graphs were developed to represent the variation of data obtained.

Figure 50 shows that point 16 has the highest variation measured with laser Sensor_A.
Figure 50. Laser Sensor_A repeatability on work part.

Table 16 summarizes the data analysis of total measurement data. The maximum standard deviation was of 25.49 μm with an average of 14.31 μm. The maximum range variation was 75 μm with an average of 43.66 μm.

Table 16. Laser Sensor_A repeatability results on work part [μm].

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>25.49</td>
<td>6.25</td>
<td>14.31</td>
</tr>
<tr>
<td>Range</td>
<td>75</td>
<td>13</td>
<td>43.66</td>
</tr>
</tbody>
</table>

Figure 51 shows variation measured with laser Sensor_B, the highest variation is in point number 1.
Table 17 summarizes the data analysis of total measurement data. The maximum standard deviation was of 9.23 μm with an average of 3.8 μm. The maximum range variation was 33 μm with an average of 15.5 μm.

The previous results indicate that better repeatability was achieved with the laser Sensor_B than with the Sensor_A. The manufacturer of the laser Sensor_B determines an error of 16 μm maximum for this product (Table 2). Therefore, the results of the maximum standard deviation of 9.23 μm are within expected.

### 5.3 Data for Accuracy Tests

Two workpieces were measured in commercial metrology systems to compare and validate the measurements made by the developed measurement system. In addition,
measurements data from the current installed gauging machine in the die-casting process were also compared to know its performance.

The measurement data from commercial metrology system was obtained twice with about eight months apart and compared to validate the reliability of the measurements.

Inspection data from installed gauging system (G-Machine) were compared with the measured data of a CMM machine (Data is available in Appendix A). Analyzed measured data shows that the variation in the provided data is significantly different. Workpiece 1 shows a maximum measurement variation around 340 µm (Figure 52).

![Figure 52. Data comparison of Workpiece 1 (CMM and G-Machine)](image)

Similarly, data from Workpiece 2 show that the maximum variation is around 250 µm (Figure 53).
Figure 53. Data comparison of Workpiece 2 (CMM and G-Machine)

Data from FaroArm was used to guarantee consistent measurements from the presented system. To achieve that, the workpieces were mounted and measured directly over the proposed system, and the measurements were compared with the CMM data. They are shown in Figure 54 and Figure 55 for Workpiece 1 and 2 respectively.

Figure 54. Data comparison of Workpiece 1 (CMM and FARO Arm)
Based on the analysis, it can see that the data measured from Faro Arm of Workpiece 1 are very close to one of the provided measured data (CMM_1) in points 1 to 6. Similarly, with the other provided measured data (CMM_2) in points 7 to 18. In both cases with a variation less than 10 µm.

![Data Comparison Workpiece 2 with Faro Arm](image)

**Figure 55. Data comparison of Workpiece 2 (CMM and FARO Arm)**

For the measured data of Workpiece 2, data behavior is like Workpiece 1. Some data obtained by Faro Arm is so close at some points in the data of CMM_1 and CMM_2 with variation of less than 30 µm.

This comparison suggests that there are two main factors that can affect the consistency in the measurements, especially in the measurements taken on CMM machine. They are:

- The workpiece variation due to temperature changes or release of mechanical stress
- Coordinates were the measurements were done are slightly different

For the next tests, the measurements made with FaroArm were used as a comparison. Because FaroArm measurements are so close to CMM measurements. And, the measurements taken with FaroArm were in situ (in the measurement system).
5.4 Machine Accuracy: Evaluation

After X-Y stage mapping errors and compensation procedure (Section 2.3), the parts were measured several times (30 times) in the compensating system.

Figure 56 is the data obtained from the laser Sensor_A displacement sensor compared with the FaroArm, it shows a variation of 600 μm as the maximum for Workpiece 1.

Figure 56. Data comparison of Workpiece 1 (Laser Sensor_A and FaroArm)

Also, for the Workpiece 2, there is a significant variation of 565 μm (Figure 57).
The results for laser Sensor_B are presented in Figure 58 for Workpiece 1 and in Figure 59 for Workpiece 2. The maximum difference in measurements compared with FaroArm for Workpiece 1 was 72 µm.

For Workpiece 2 the laser Sensor_B show a max variation of 122 µm (Figure 59).
Unlike the laser displacement Sensor_A, laser Sensor_B shows a slight difference of fewer than 72 μm in relation to the measurements of the FaroArm for Workpiece 1.

Table 18 shows a summary of the 10 different parts measurements with the minimum variation achieved by laser Sensor_B compared with the Faro.

Based on this analysis, was determined to use sensor B as the best option for our measurement system.
The lowest error achieved was 52 µm with a standard deviation of 37 µm using Sensor_B compared with the measurements done by FaroArm. This error could be occurred by the following issues:

- The measurement is taken by the laser Sensor_B consist in the average of a line which is projected on the workpiece surface, and the measurements taken with FaroArm was with a probe of the 3mm radius. Then the measurement taken with FaroArm was not 100% exactly at the same position where the laser sensor gets the measurement.

5.5 Workpieces Measurements Compensation

After X-Y stage compensation, there are slight differences between the measurements done by the measurement system and the CMM machine. It also can be for the reason mentioned at the end of section 5.3.

Instead, direct compensation method (Section 2.3), the use of workpieces measurements information to compensate errors is known as indirect compensation. Uekita and Takaya [39] developed a novel on-machine dimension measurement system where the system measures a large part (steam turbine rotor) mounted on a CNC lathe. The system incorporated a set of measurements devices (laser track, a touch-trigger probe, a calibration artifact) to compensate for volumetric errors of the machine tool.

Werner [40] also used an indirect compensation to improve the accuracy of machining components produced on a CNC wire-cut machine. After the initial machining, measurements are done. Based on measurement results, the machining errors are determined, and this information is used to modify the geometric models to correct the machining program.

In the indirect compensation, the information is taken from the measured workpiece, reducing external error sources. Due the present system has a non-contact measurement laser sensor; this compensation method can be implemented easily with the help of the measurements information from the workpieces.
This compensation was done measuring 10 workpieces in a Coordinate Measurement Machine (CMM). This information was subtracted from the measurements taken in the presented system to obtain the average error. Data in tabular form is available in Appendix A.

This average error information was introduced in the algorithm used to compute the normal distance to the reference plane (Appendix B).

In Figure 60, the data measured with the best fit after compensation (Workpiece 6) were plotted and show an average error of 18 μm compared to the measured CMM data.

![Compensated Values (Workpiece 6)](image)

**Figure 60.** Best fit workpiece after compensation.

In Figure 61, the data measured with the worst adjustment after compensation (Workpiece 10) was plotted and shows an average error of 22 μm compared to the measured CMM data.
Figure 61. Worst fit workpiece after compensation.

Table 19. Indirect method calibration results [µm]

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMM – Laser Sensor_B</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

The mean of the variation of the 10 workpieces after compensation compared with the measurements performed on CMM machine shown the average error of 9 µm with a standard deviation of 10 µm.

Castings tend to change in dimensions over time. And cannot be used as patterns. As consequence, a robust calibration additament must be built.

5.6 Measure System Analysis (MSA)

Ensuring the reliability in inspection machines is a great challenge in industries that have adopted the concept of Six Sigma, where the goal is to achieve control over all parts produced with a maximum of 3.4 defective parts per million [41].
In addition, for today manufacturing industry quantitative data analysis plays an important role due to the need to reduce uncertainty for optimizing processes for a competitive global marketplace [42].

A very important key to achieving the concept of Six Sigma is the analysis of measurement systems (MSA) [43]. MSA refers to diverse methods for the analysis of measurement systems performance [44]. The main goals of the MSA are the quantification of measurement uncertainty, accuracy, precision (repeatability and reproducibility), the stability and linearity over time and across the intended range of use of the measurement process [45]. MSA is a powerful instrument for the development of improvement plans and it can help to make decisions about whether a measurement process is adequate for a specific engineering or manufacturing application [46].

**Calculated Error**
The maximum expected calculated variation caused by indentation (2.14 μm), by deformation due to temperature change (1.5 μm) and by the uncertainty of laser sensor (16 μm) is of:

\[
espected\ error = \sqrt{2.14^2 + 1.5^2 + 16^2} = 16.21\ \mu m
\]

**Measured Error**
The precision tests in Table 15 show a standard deviation of 8.74 μm and 9.23 μm in Table 17 for results obtained with laser Sensor_B lower than the values achieved by laser sensor A (Table 14 and Table 16)

As mentioned above, the tolerance required for the work piece is ± 400 μm, and according to the 10:1 metrology rule, this means that the system must have an uncertainty of less than ± 40 μm. The values of the calculated error and the measured error are lower than the required error (± 40 μm), therefore, the measurement system with laser Sensor_B meets the requirements of the application.
R&R (ANOVA) Study

The variations of any manufacturing part can be divided into part variation and measurement variation. Measurement variation also can be broken down into repeatability and reproducibility.

Repeatability means the variation in the measurements conducted different times in a part with the same measurement system and Reproducibility refers to the average variation produced by different measurements conducted by the same evaluator for a part in the same measurement system [45]. A tool commonly used to evaluate the Repeatability and Reproducibility is the “R&R”, which has been used as the main tool [47] for MSA. For instance, Saikaew [48] evaluates a measurement system using R&R study in three randomly mini CNC lathe machines.

An R&R study was designed for the machine, 10 die-castings parts were measured by three different operators three times each one. The proposed measured system was calibrated once at the beginning of the test.

The software Minitab was used to get R&R test result with the ANOVA method. The result of the R&R test of each measured point with a workpiece tolerance of ± 0.4mm is shown in Table 20.

<table>
<thead>
<tr>
<th>Point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;R %</td>
<td>6.3</td>
<td>3.5</td>
<td>3.1</td>
<td>3.4</td>
<td>3.6</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
<td>2.5</td>
<td>2.1</td>
<td>2.8</td>
<td>3.0</td>
<td>3.3</td>
<td>4.2</td>
<td>3.7</td>
<td>3.1</td>
<td>3.6</td>
<td>4.2</td>
<td>3.7</td>
</tr>
</tbody>
</table>

According to Automotive Industry Action Group (AIAG) [49], a general rule of thumb for measurements system is:

- Under 10% error is acceptable
- Ten to 30% error suggests that the system is acceptable depending on the importance of the application, cost of the measuring device, cost of repair, and other factors.
• Over 30% error is considered unacceptable; the measurement system should be improved

The maximum value in our test was of 6.3%. Therefore, the measurement system is considered acceptable for the application. This is consistent with the Error Analysis of the previous section. Also, R&R (ANOVA) study ensure the six-sigma concept.
Chapter 6: Conclusions and future work

6.1 Conclusions

A new measurements system design was developed for a fast and accurate inspection machine for an online measurement process. The design uses laser measurement sensors mounted on a gantry system with linear motors. The inspection machine was able to measure 19 targets on the workpiece in less than 10 seconds. The measurement characteristic was flatness.

The precision of the machine was ensured by testing each of the main parts that make it up, such as the positioning system and the measurement system. Achieving a repeatability of 9.23 μm in total (Section 5.6), being a value lower than estimated by simulations.

The calibration of the machine was made to compensate for the errors caused by geometric mismatches in the machine parts. An indirect calibration technique was used, obtaining, as a result, an accuracy of 9 μm with a standard deviation of 10 μm. This value is lower than the value reached by the current measuring system of 34 μm with a standard deviation of 29 μm. With these results, the machine can easily achieve a measurement of workpieces with the required tolerance of ± 0.4 mm.
The reliability of the machine was measured by an R & R study, the results of this study show values lower than 7%. The value that is within the Automotive Industry Action Group [42] general rule that determines that our machine is acceptable for the present application.

6.2 Future Work

Others kinematics coupling configuration can be tested. The proposed geometric location of kinematic coupling is restricted to avoid the collision with other parts of the machine, then this configuration is sensible to change the position due to external forces.

To increase machine speed, there are motion profiles used to reduce the jerk which is the rate of acceleration change. Applying those motion profiles instead trapezoidal profile, the machine can achieve the smoothest movement. Also, measurements can be done in continuous motion instead point to point.

To reduce the cycle time, the following changes could be performed in the measurement system: Insert workpiece directly on the measurement area, isolating the measurement area using protective bellows convertors for linear motors.

Finally, the data collection of the sensors should be used as part of a cyber-physical model of the machine. With the cyber-physical model, it could be easy to analyze the behavior of the machine in real time and during its useful life. In addition, use the data from the workpiece measurements to analyze the performance of the process. All this to improve decision making.
# Appendix A: Accuracy system validation

## Data comparison of Workpiece 1 (CMM and G Machine) [mm]

<table>
<thead>
<tr>
<th></th>
<th>CMM₁</th>
<th>CMM₂</th>
<th>G_Machine₁</th>
<th>G_Machine₂</th>
<th>Range</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.006</td>
<td>0.037</td>
<td>0.086</td>
<td>0.026</td>
<td>0.080</td>
<td>0.039</td>
<td>0.034</td>
</tr>
<tr>
<td>P2</td>
<td>0.520</td>
<td>0.602</td>
<td>0.553</td>
<td>0.442</td>
<td>0.160</td>
<td>0.529</td>
<td>0.067</td>
</tr>
<tr>
<td>P3</td>
<td>0.217</td>
<td>0.414</td>
<td>0.345</td>
<td>0.377</td>
<td>0.197</td>
<td>0.338</td>
<td>0.085</td>
</tr>
<tr>
<td>P4</td>
<td>-0.045</td>
<td>0.218</td>
<td>-0.096</td>
<td>0.122</td>
<td>0.314</td>
<td>0.050</td>
<td>0.146</td>
</tr>
<tr>
<td>P5</td>
<td>-0.156</td>
<td>0.177</td>
<td>-0.144</td>
<td>0.122</td>
<td>0.333</td>
<td>0.000</td>
<td>0.174</td>
</tr>
<tr>
<td>P6</td>
<td>-0.209</td>
<td>-0.024</td>
<td>-0.171</td>
<td>-0.126</td>
<td>0.185</td>
<td>-0.133</td>
<td>0.080</td>
</tr>
<tr>
<td>P7</td>
<td>0.126</td>
<td>0.345</td>
<td>0.136</td>
<td>0.287</td>
<td>0.219</td>
<td>0.223</td>
<td>0.109</td>
</tr>
<tr>
<td>P8</td>
<td>0.159</td>
<td>0.274</td>
<td>0.177</td>
<td>0.213</td>
<td>0.115</td>
<td>0.206</td>
<td>0.051</td>
</tr>
<tr>
<td>P9</td>
<td>0.169</td>
<td>0.280</td>
<td>0.187</td>
<td>0.185</td>
<td>0.111</td>
<td>0.205</td>
<td>0.050</td>
</tr>
<tr>
<td>P10</td>
<td>0.163</td>
<td>0.230</td>
<td>0.122</td>
<td>0.169</td>
<td>0.108</td>
<td>0.171</td>
<td>0.044</td>
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<tr>
<td>P11</td>
<td>0.265</td>
<td>0.220</td>
<td>0.241</td>
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<td>0.111</td>
<td>0.220</td>
<td>0.048</td>
</tr>
<tr>
<td>P12</td>
<td>0.144</td>
<td>0.156</td>
<td>0.127</td>
<td>0.069</td>
<td>0.087</td>
<td>0.124</td>
<td>0.039</td>
</tr>
<tr>
<td>P13</td>
<td>0.167</td>
<td>0.050</td>
<td>0.194</td>
<td>-0.056</td>
<td>0.250</td>
<td>0.089</td>
<td>0.115</td>
</tr>
<tr>
<td>P14</td>
<td>0.036</td>
<td>-0.160</td>
<td>0.019</td>
<td>-0.205</td>
<td>0.241</td>
<td>-0.078</td>
<td>0.123</td>
</tr>
<tr>
<td>P15</td>
<td>0.268</td>
<td>0.202</td>
<td>0.236</td>
<td>0.003</td>
<td>0.265</td>
<td>0.177</td>
<td>0.119</td>
</tr>
<tr>
<td>P16</td>
<td>-0.014</td>
<td>0.053</td>
<td>0.005</td>
<td>-0.045</td>
<td>0.098</td>
<td>0.000</td>
<td>0.041</td>
</tr>
<tr>
<td>P17</td>
<td>0.049</td>
<td>0.127</td>
<td>0.061</td>
<td>-0.025</td>
<td>0.152</td>
<td>0.053</td>
<td>0.062</td>
</tr>
<tr>
<td>P18</td>
<td>-0.017</td>
<td>0.015</td>
<td>-0.051</td>
<td>-0.016</td>
<td>0.066</td>
<td>-0.017</td>
<td>0.027</td>
</tr>
</tbody>
</table>

## Data comparison of Workpiece 2 (CMM and G Machine) [mm]

<table>
<thead>
<tr>
<th></th>
<th>CMM₁</th>
<th>CMM₂</th>
<th>G_Machine₁</th>
<th>G_Machine₂</th>
<th>Range</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.006</td>
<td>0.037</td>
<td>0.086</td>
<td>0.026</td>
<td>0.080</td>
<td>0.039</td>
<td>0.034</td>
</tr>
<tr>
<td>P2</td>
<td>0.520</td>
<td>0.602</td>
<td>0.553</td>
<td>0.442</td>
<td>0.160</td>
<td>0.529</td>
<td>0.067</td>
</tr>
<tr>
<td>P3</td>
<td>0.217</td>
<td>0.414</td>
<td>0.345</td>
<td>0.377</td>
<td>0.197</td>
<td>0.338</td>
<td>0.085</td>
</tr>
<tr>
<td>P4</td>
<td>-0.045</td>
<td>0.218</td>
<td>-0.096</td>
<td>0.122</td>
<td>0.314</td>
<td>0.050</td>
<td>0.146</td>
</tr>
<tr>
<td>P5</td>
<td>-0.156</td>
<td>0.177</td>
<td>-0.144</td>
<td>0.122</td>
<td>0.333</td>
<td>0.000</td>
<td>0.174</td>
</tr>
<tr>
<td>P6</td>
<td>-0.209</td>
<td>-0.024</td>
<td>-0.171</td>
<td>-0.126</td>
<td>0.185</td>
<td>-0.133</td>
<td>0.080</td>
</tr>
<tr>
<td>P7</td>
<td>0.126</td>
<td>0.345</td>
<td>0.136</td>
<td>0.287</td>
<td>0.219</td>
<td>0.223</td>
<td>0.109</td>
</tr>
<tr>
<td>P8</td>
<td>0.159</td>
<td>0.274</td>
<td>0.177</td>
<td>0.213</td>
<td>0.115</td>
<td>0.206</td>
<td>0.051</td>
</tr>
<tr>
<td>P9</td>
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<td>P16</td>
<td>-0.007</td>
<td>0.095</td>
<td>0.102</td>
</tr>
<tr>
<td>P17</td>
<td>0.056</td>
<td>0.157</td>
<td>0.101</td>
</tr>
<tr>
<td>P18</td>
<td>-0.091</td>
<td>-0.013</td>
<td>0.078</td>
</tr>
<tr>
<td></td>
<td><strong>Error Average</strong></td>
<td></td>
<td><strong>0.051</strong></td>
</tr>
</tbody>
</table>
Appendix B: Mathematical model for definition of the plane from measured data

There are three main steps to get the normal distance of the 18 points to a plane:

The general equation of a reference plane

Based on datum’s reference $(X_1,X_2,X_3)$, the three pins $(K_1, K_2, K_3)$ are measured by the laser sensor. See Figure 62. The coordinates point of $(K_1, K_2, K_3)$ are $(x_1, y_1, z_1)$, $(x_2, y_2, z_2)$ and $(x_3, y_3, z_3)$, respectively.

Figure 62. Reference pins

It is important to notice that in the workpiece the datum $X_2$ lies above the other two by one millimeter (Figure 63). This must be compensated for the calculations.
The coefficients A, B, C and D of a plane general equation that crosses the three points (Figure 64) are calculated with the determinant of the following matrix:

\[
\begin{vmatrix}
 x - x_1 & y - y_1 & z - z_1 \\
 x_2 - x_1 & y_2 - y_1 & (z_2 - 1) - z_1 \\
 x_3 - x_1 & x_3 - x_1 & z_3 - z_1 \\
\end{vmatrix} = 0
\]  \hspace{1cm} (9)

\[
Ax + By + Cz + D = 0
\]  \hspace{1cm} (10)

Displace the plane equation by 13mm

Due to the workpiece’s thickness, the reference plane equation is not where the points to be measured lie. The plane must be displaced by 13mm to calculate the deviations with an ideal plane of the part. The vectorial equation of a normal line (Equation 12) and
Pythagoras Theorem (Equation 13) was used to displace a plane in the normal of the main plane:

\[
(x_2, y_2, z_2) = (x_1, y_1, z_1) + \beta (A, B, C) \tag{11}
\]

\[
x_2 = x_1 + \beta \times A \\
y_2 = y_1 + \beta \times B \\
z_2 = z_1 + \beta \times C
\]

\[
(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 = d^2 \tag{12}
\]

Replacing 12 in 13

\[
(x_1 + \beta \times A - x_1)^2 + (y_1 + \beta \times B - y_1)^2 + (z_1 + \beta \times C - z_1)^2 = d^2
\]

\[
\beta = \frac{d}{\sqrt{A^2 + B^2 + C^2}} \tag{13}
\]

\(d\) is the distance to move the plane \((d=13 \text{ mm})\)

\(A, B,\) and \(C\) are the coefficients of the general plane equation.

\(\beta\) is the factor to move the plane

The \(\beta\) factor is replaced in 8 and a new point displaced 13 mm in the normal of the plane is found

\[
(x_2, y_2, z_2) = (x_1, y_1, z_1) + \beta (A, B, C)
\]

Finally, a new \(D\) coefficient for the general plane equation is calculated:

\[
D_m = (A, B, C) \times (x_2, y_2, z_2)
\]

\(D_m = \text{coefficient of the displaced plane equation}\)

And \(Ax + By + Cz + D_m = 0\) is the plane equation used to evaluate each of the 18 points
Compute the Normal Distance

The distance of a point \( P \) to a plane \( \gamma \) is the smallest distance from the point to the plane. This distance corresponds to the perpendicular drawn from the point to the plane. The normal distance is calculated for 18 points (\( P_1, P_2... P_{18} \)) shown in Figure 66.

The normal distance of a point \( P(x_0, y_0, z_0) \) to a plane \( \gamma = Ax + By + Cz + D_m = 0 \) is calculated with the following equation:

\[
d(P, \gamma) = \frac{Ax_0 + By_0 + Cz_0 + D}{\sqrt{A^2 + B^2 + C^2}}
\]  

(14)
Appendix C: Target coordinates
Bibliography


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Curriculum Vitae

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SUMMARY
Mechatronic engineer with experience in mechanical-electronic design (CAD / CAM / CAE), industrial automation, and quality control. Also, knowledge of control motion. I am actively seeking to expand my knowledge in the management, design, and simulation of production lines.

EDUCATION

Student - Master of Science in Manufacturing Systems
Instituto Tecnológico de Monterrey (ITESM), Monterrey, México.
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EXPERIENCE

Senior Project Engineer
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- Design, redesign, and implementation of mechatronics projects to produce fiber cement sheet.
- Plan predictive, preventive and corrective maintenance activities to be done in the industrial plant.
- Mechanical design and settle of new manufacturing lines, such as a water jet cutting line.

Designer of machines and products
CNC Innovation (Ecuador)
- Mechanical-electronic design, redesign, and manufacturing of CNC laser cut machine
- Design and computer-aided manufacturing for new products for laser cutting.