DEVELOPMENT OF A SMART METROLOGY MACHINE

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by

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ABSTRACT

In today's landscape of modern manufacturing, stringent measures for upholding standards of quality are very important to ensure product longevity and customer satisfaction. Precision engineering demands cutting edge technologies to deliver on this requirement for industries reliant on heavily meticulous measurements. This thesis delves into the design, fabrication, calibration and successive testing of a coordinate measuring machine (CMM) capable of maintaining an accuracy of less than 10 microns that is in line with recent technological advancements.

The envisioned CMM seeks to redefine precision engineering in the local industry across different sectors. The project is aimed at enhancing quality control processes thereby increasing efficiency & cost effectiveness in manufacturing operations. The construction boasts affordability and ease of assembly with parts available easily. Through design optimization and meticulous research, this thesis lays the groundwork for the development of a versatile and high precision CMM.

The potential impact of a locally produced, high accuracy CMM goes beyond the promise of technological advancement: it can serve as the driving force for stimulating domestic manufacturing and paving the path to economic prosperity.

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ORIGINALITY REPORT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
RMS	Root Mean Square

RPM	Revolutions per minute
DAQ	Data Acquisition Software
GCS	Global Coordinate System
DRO	Digital Readout
CR	Critical RPM

CHAPTER 1: INTRODUCTION

Over time, the manufacturing industry has seen a significant shift from traditional measurement methods (handheld or using optical comparators) to more advanced means of measurement. A coordinate measurement machine (CMM) is one such example used to ensure precise dimensional accuracy of parts. Traditional measurement methods relied a lot on the operator's skill, had many limitations and potential for errors. Introducing errors in quality assurance guarantees that defective parts would go unnoticed. This presents a huge problem in industries that manufacture parts that need to pass high precision standards (aerospace & defense, automotive, heavy machinery, medical, electronics, and energy & power.).

In this thesis, we present the design, fabrication, calibration and testing of a bridge type CMM. The final product aims at measuring tolerances to within 10 micrometers to pass stringent quality standards (in line with the rigorous standards practiced around the world) and allow for durable, high-quality components with good export potential.

Problem Statement

The local manufacturing industry faces multifaceted challenges that include material wastage, diminishing exports, and sluggish quality assurance processes. Traditional methods of checking quality are still very prevalent and are the biggest reasons why locally manufactured parts do not meet export standards. Although in some cases, automated and modern precision measurement tools have been employed, this comes at great cost.

Moreover, this shift to better precision measurement tools is contained in a bubble with only selective (financially able) companies buying and actively using CMMs.

The problem at hand is the lack of availability of domestically produced affordable CMMs. For companies that do have them, they import them from a handful of international manufacturers of the machine. The total cost encumbered is the sum of the product cost, shipping, customs and various other taxes. The grand total exceeds a couple hundred thousand USD for a good-sized machine.

Globally, the advent and successive optimization of CMMs has led to an economic boom and that should not be any different for Pakistan. The key to revolutionizing the manufacturing industry lies in enforcing stringent quality standards which can only be achieved through increased use and availability of CMMs (which would lead to increased exports and decreased process times).

Motivation

The motivation behind this project is to design, fabricate and deliver a working CMM that can measure dimensions up to 10 micrometers thereby addressing the challenges faced by the local manufacturing industry. By incorporating a manual handling system, high precision probes, micro stepping, and intensive calibration, we aim to deliver a CMM that will not only be highly precise, but it will be available at a discounted price (compared to the international market). The possibility of parts being manufactured to tighter tolerances would lead to increased durability which indirectly relates to less material wastage and need for replacement of parts. Additionally, if domestically produced parts clear the stringent quality standards set by authorities around the globe, Pakistan could potentially decrease its reliance on imports while simultaneously boosting exports of mechanical parts and devices.

Objectives

The first objective of the project is to design and deliver a bridge type CMM that has a workspace of 2 by 2 by 2 ft. This should allow dimensional measurement of parts that fall under this scope.

The second objective is to make the CMM using cost-effective parts. Our goal is to source parts locally or from China and cut back on import and shipping costs as much as possible.

The third objective is to calibrate the fabricated machine, so it delivers the required accuracy of 10 micrometers or less. Perhaps the most important deliverable for this project is ensuring the final product can repeat measurements within a 10 micrometers tolerance. This will define if our machine can uphold rigorous quality standards.

Overall, all objectives are aligned towards delivering a fully complete product that can measure a dimensional value to 10^{-6} meters. We will provide basic software (LabView) integration to go with the machine and the end product will cost less than what is available on the international market. Through this we hope to tackle the many problems encountered by the manufacturing industry of Pakistan with the aim of improving prospects through improved product quality and enhanced competitiveness.

CHAPTER 2: LITERATURE REVIEW

Coordinate Measuring Machine:

CMMs are mechanical systems which involve movement of a measuring probe to determine coordinates of points on the workpiece surface. They are primarily composed of four components: ***main structure, probing system, control/computing system, and***

measuring software. CMMs play a vital role in diverse industries, including Aerospace, Automotive, Medical Devices, Electronics. [1]

Purpose and Method:

Measurement of an object's actual form and dimensions and comparison with desired shapes and sizes are the focus of coordinate metrology. It entails assessing the part or object's location, orientation, dimensions, and geometry. makes measurements according to Cartesian coordinates. With computer control, the head is automatically guided, and the point is automatically taken when it contacts the part. Dimensional measurements are made by creating geometries with the obtained points. Measurements can be made with or without CAD data. When a measurement with CAD data is planned, this plan can be repeated automatically. CMM machines have high precision between dimensional measurements. Measurements can be made with a precision of 1 micron or even less. [2]

Types of CMM and their Applications:

CMMs are available in different types: Bridge type, gantry type, L-shaped, Cantilever, etc. Each type of CMM is manufactured and designed according to their applications. Bridge type and gantry type CMMs have highest precision due to higher stability. Gantry type CMMs are used for large working spaces, compared to Bridge type. Gantry type CMMs are most difficult to relocate, thus higher immobility compared to bridge type and L type

CMMs [3]. CMMs can be used for measurements ranging from the most basic, like measuring a diameter and length, to the most intricate, like measuring a free form part [1], an automotive engine, the center of a cooling hole on a jet propulsion aero foil, a gear, a metal die casting, or the turbine of a jet propulsion engine [4], [5].

Research And Advancements:

There has been an interest on the part of researchers, going back at least to the early **1990s** [6], in methods to derive task-specific measurement uncertainties from more general CMM performance evaluations, and this effort has since been carried forward by workers in several countries. CMMs were first introduced as manual measuring devices in the early **1960's** and were based on three-axes machining tools where the tool was simply replaced by a sensing device. The sensors employed at this time were hard probes which contacted the part surface. The center coordinates of the hard probe were shown on a display and recorded. These measurements were very time-consuming, with limited accuracy and repeatability and with the chance of user errors. In 1972, the first CMM which satisfies today's definition of a CMM by observation of the principle of coordinate measuring technique, was built by the manufacturer ***C. Zeiss in Germany***. After this breakthrough the CMM evolution accelerated, especially in the field of development of new probing systems. 1 2 Touch trigger contact probes were developed first which overcame the disadvantages of hard probes and made it possible to automate the process of making contact. In 1973, measurement accuracy reached a new level clue to the introduction of a three-dimensional measuring probe system. Today non-contact probe systems, like laser devices or electronic cameras are present, which enlarge the spectrum of probe systems from which the user can choose. [7]

Mathematical Methods and Performance Indices:

The calculation of geometric elements like circle, rectangle, sphere, etc, is based only on the touched points. To calculate a geometric element a mathematical minimum number of points is required. When more points are taken, a better fitting element can be calculated by a mathematical approximation method. The four approximation techniques listed below are commonly used in the coordinate measuring technique: ***Least Squared Sums (Gauss Criterion), Tschebyscheff Minimum Criterion, Maximum Contact Element, Minimum Contact Element*** [7]. Generic CMM performance indices have been available for some time, the most prominent being those promulgated by the International Organization for Standards (ISO) [8] and by the American National Standards Institute (ANSI) [9].

Twin Based CMM:

The results obtained by the article [10] give the possibilities to enlarge the CMM capacity and the automation of processes to obtain more potential with the approach which is the digital measuring with twin based CMM [11]. Starting from this idea the concept was developed to give 2 types of results, one as the result are required from drawing specification, and the other as CNC program need to be corrected at all rotation and clamping estate. With the proper CNC correction report given by CMM, the machine setup technician doesn't need to elaborate a strategy to correct the program and all results are presented to him. Furthermore, the CNC program parameter can be developed to receive the data and to input automatically into the variable program, and the values to be received via intranet to the CNC or by copying the correction parameters setup program given by CMM. To increase the measurement precision, we can conduct another development of this article based on analysis and integration of geometric errors given by the practical fact that for CNC there are 3 linear guideways with 6 motion errors influenced by accelerations and braking, including 3 translation and 3 angle errors.

Deviation and Tolerance Control:

Flatness deviation measurement or tolerance control is a common task in coordinate metrology. The different aspects of flatness measurement strategy were widely investigated. Raghunandan and Rao [12] investigated the influence of surface roughness on accuracy of flatness inspection and concluded that roughness can be parameter for definition of sample size. The same authors in [13] presented a method to determine an optimum sample size for industrial flatness measurements. In paper [14], studies related the measurement errors determination in case of inclined surfaces measurement on Coordinate Measurement Machines.

Intelligent CMMs & Offline Programming:

According to Zhang et al. [15], intelligent CMMs would most likely be successors of currently available CMMs. In their paper, they identified that intelligent CMM would be able to perform all functions automatically such as extraction of geometric and measuring information from its CAD file, selection of probe type, determination of measuring features, generation of number and coordinates of measuring points, etc. Intelligent planning environment for generating automated CMM inspection should be able to interpret and extract necessary design information available in CAD model, generate data structure for inspection plan and identify efficient inspection sequence [16].

Generally, offline programming is a research area that is rapidly developing simultaneously with other applications of offline programming like robotics and CNC machining. In an integrated virtual environment, the user can plan an inspection strategy for a given task and evaluate the uncertainty associated with the measurement results, all without the need of using a physical machine. [17]

Many researchers are using CAD systems for the offline programming of CMM machines. Computer graphics simulation of the machine and its work cell can be realized with different models such as wireframe and solid models [18]. Pan and Zhang in [19] are using CAD/CAM software modules for offline programming and they recognize that it is the only way to generate programs effectively. Yau and Menq [20], [21] implemented an automated inspection planning system based upon the commercial CAD system CATIA and a knowledge based expert system shell with five steps in inspection planning. From Medeiros et al. A position-sensing device, six degrees of freedom, is used for the detection of measurement points in a real part and thus creates a CMM program. The experimental results show that the position-sensing device, though not precise enough for the inspection of the piece, has sufficient accuracy for a programming machine. These results are verified by writing and performing a CMM program [22].

Microsystem Components

Brand et al. [23] developed CMM for measuring microsystem components with uncertainty less than 0.1 µm and measuring range of 25 mm × 40 mm × 25 mm. It was a special kind of CMM with an optical measurement system and two tactile 3D-micro-sensing systems. One of the sensors made use of very small probing balls with diameters 25 µm and probing forces as low as 1 µN while other sensor was based on silicon boss-membrane with piezo resistive transducers. Moreover, opto-tactile 3D-sensor with optical fiber was used for the probe pin. This machine improved the capabilities of CMM using **high-resolution scales** and **optimized air bearings.**

Air Bearings:

Air Bearings have been employed in Coordinate Measurement Machines (CMM) to achieve ultra-precision and high accuracy. Unlike conventional ball or roller bearings, there is zero friction between the bearing surfaces. The engineers, therefore, can minimize the control effort required to achieve high accuracy and precision. Air bearings have obvious advantages over contact-type bearings. However, because of their low viscosity and nature of flow, they have some limitations. They may exhibit self-excited vibrations, called pneumatic hammer, if not designed properly. The damping of the air bearing is also not as good as that of the oil bearing. The load capacity and stiffness are also relatively poor. Nevertheless, the advantages of using air bearings always excited the researchers and obliged them to look for new designs [24]. Fourka and Bonis [25] have developed a simulation program to investigate the influence of feeding system type on the performance of externally pressurized gas bearings. They used different kinds of multiple inlets specifically designed with orifices or porous compensation. Roblee and Mote [26] presented a design method for flat, circular thrust bearings.

Area under Research - Uncertainties:

Widespread application of CMMs in industrial dimensional metrology can be attributed to their ability to measure variety of characteristics on a range of products. However, CMM measurements are accompanied with unlimited sources of variability such as workpiece position and orientation, sensor type and configuration, environment conditions, sampling strategy, computational strategy, etc. [27] So, because of increased demands for better accuracy and precision, efforts to determine potential sources of measurement uncertainties have also been increasing. For instance, the work of Weckenmann et al. [28], where contributions of different uncertainties have been identified on CMM.

Butler [29] identified the measuring probe as one of the most important sources of error in CMM measurement results. According to the author, measuring probes constitute about 60% of errors in measurements performed on CMM. It is very important for CMM users to verify probing accuracy once it has been used over a period. A fuzzy knowledge-based models to determine 3D probing accuracy for one- and two-stage touch trigger probes has been proposed by Achiche and Wozniak [30]

Conclusion:

Conclusively, in the development of the Coordinate Measuring Machine, different researchers in different countries are contributing to enhancing certainties and precision in

CMMs, for micro and nano measurements in diversified fields of applications. However, in an underdeveloped country like Pakistan, industries like automotive still demand a cost effective and precise inspection machine (precision under 10 microns) to ensure quality check, consequently exporting their manufactured products. The need of this project is to study the progress made in the metrology world and try to see how Pakistan can not only replicate but improve on it (and subsequently capitalize on it).

CHAPTER 3: METHODOLOGY

We employed a systematic approach towards designing and fabricating a Coordinate Measuring Machine (CMM) with a specified accuracy of near 10 microns. The initial phase involved an extensive literature review, exploring relevant research papers to identify a gap in the local market for our CMM. The design process encompassed multiple iterations, starting from a basic design, and iteratively refining it through analysis, consultations, and continual adjustments. This iterative methodology enabled us to arrive at an optimal design aligned with our project requirements.

Choosing the Design

In lieu of the literature review, two types of designs were considered for the CMM, namely:

- Gantry type
- Bridge type

Gantry Type

This design facilitates efficient measurements across extended surfaces, ensuring the comprehensive examination of sizable workpieces. The inherent stability and horizontal mobility of the gantry type CMM contribute to its versatility, making it a preferred choice for applications requiring precision metrology on a larger scale.

Bridge Type

The bridge type Coordinate Measuring Machine (CMM) features a horizontal bridge structure supporting the measuring probe, which moves vertically along precision rails. This design offers a stable and compact configuration, making it suitable for applications requiring high precision in a relatively smaller workspace. The inherent rigidity of the bridge structure enhances measurement stability, while the vertical movement allows for precise three-dimensional assessments.

After comprehensive research, the bridge type CMM as the better option due to the following reasons:

- Enhanced Stability
- Optimum Measuring Volume
- Improved Accessibility to Workspace
- Reduced Footprint

Final Design

In accordance with choosing the bridge type system as our finalized design, we considered simplicity, cost, ease of access, availability of required materials and longevity of parts in finalizing our design.

Base Plate:

A CMM requires a base plate that should bear the machine's weight and provide stability and support to the part being measured (movements/ deformations would cause errors in the dimensional measurements collected). One important parameter that required consideration was the RMS value of the base plate used. Granite was considered because of its extremely smooth surface but was rejected in favor of powder coated mild steel. Cost and availability were the driving factors in this decision. Our final design had a 3 by 3 ft Mild Steel plate that was powdered coated for improved longevity.

Ball Screw and Motor Selection:

To drive the bridge system, we chose that ball screw, coupled with a stepper motor, would provide sufficient results in terms of speed, reliability, and mobility.

To select the right ball screws for our application, a series of calculations were carried out according to the catalog provided by the manufacturer. These calculations involved performing *Max Force Test, Avg Force Test, Critical Speed Test, Buckling Test* to ensure that the ball screws would be able to withstand the operations of the CMM while maintaining a minimum safety factor of 2. All these tests were done according to the final masses of our axes.

The breakaway torques of ball screws on all the axes were calculated to select the appropriate motors. Servo motors were considered because of their high holding torque and closed loop operation. But they were disregarded because of added complexity and the fact that we did not have high RPM requirements.

To drive the bridge, the following components were used:

- NEMA 23 Stepper Motors (X, Y & Z axes)
- TB6600 Stepper Drivers
- Associated Stepper Signal Generators
- SFU 1605 Ball Screws (16 mm diameter & 5 mm lead)
- BK-12 and BF-12 Ball Screw Supports
- Flexible Couplings

All these components are mounted on the existing setup using nuts and bolts.

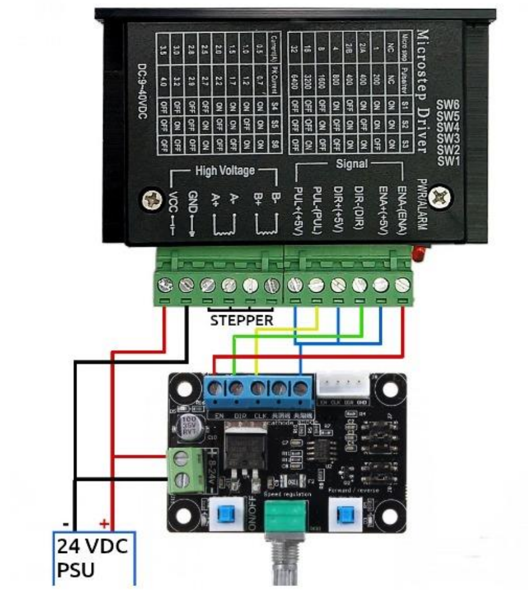

Figure 1 Motor Circuit

Linear Guideways Selection:

For linear bearings, we had a choice between air bearings and linear guideways. Air bearings provided a much more efficient, precise, and friction-free operation as compared to linear guideways. However linear guideways provided a much simpler, low maintenance solution at a fraction of the price of air bearings. So, considering the cost and availability concerns, we decided to go with linear guideways instead of air bearings. Linear guideways were selected after going through the manufacturer's catalog and finding the right fit for our needs. The final product is listed below:

- WERB HGW20HC Linear Guideways

Where HG is the model series with the ball type roller bearings. The third letter in the model number (W) specifies the type of guideway block: flange. 20 represents the rail size for the selected model. The letter after the rail size (HC) represents the load type of the model: heavy load type. The final letter (A) represents the mounting type of the linear rails: from the top.

Linear Encoders

Linear encoders, integral to Coordinate Measuring Machines (CMMs), convert linear displacement into electrical signals using optical or magnetic principles. These devices provide real-time positional data for precise coordinate measurements, contributing significantly to the accuracy of CMMs.

Selection Criteria

Resolution: We require an accuracy of 10 micrometers in our final reading.

Accuracy: High accuracy is also crucial for accurate reading.

Signal output frequency: The Linear encoder output must be compatible with the chosen DRO.

Selected Apparatus Specifications:

Based on above mentioned criteria we selected Shenzhen Hengxingxing Precision Apparatus Co. Limited’s glass scale linear encoder with the following specifications

- Accuracy: It can measure with an accuracy of 1 micrometer.
- Output Signal: It outputs a digital signal (TTL square wave) via RS232 cable.
- Output Signal Frequency: Less than 5 MHz
- Length: 900 mm

Digital Readout (DRO)

The Digital Readout (DRO) is a technological component that plays a pivotal role in coordinate measuring machines (CMMs). It links the data transferred from linear encoders to the computer, allowing us to handle the data in the program.

DRO Selection Criteria

Selecting a Digital Readout (DRO) system for a coordinate measuring machine (CMM) involves considering specific criteria tailored to the project's requirements:

- The DRO should be able to handle accurate reading measuring in microns, as per the strongest accuracy requirements of our project.

- Considering the three-dimensional nature of Coordinate Measuring Machines, it was imperative that the selected DRO system could accommodate inputs from all three axes (X, Y, and Z).
- The input signal is a TTL square wave that has a frequency of less than 5 MHz
- To ensure integration with LabVIEW we required serial communication capability.

The mentioned criteria led to the selection of the product made by HYMSEANN, SNS-3V with RS-232 port.

The SNS-3V employed in our Coordinate Measuring Machine (CMM) features a sophisticated architecture designed to facilitate accurate and real-time measurements across multiple axes. The DRO also contains an LCD to display all 3 axes coordinates in real time. Data is fed to LabVIEW in real time using a DB9 RS232 to USB converter.

Y Axis

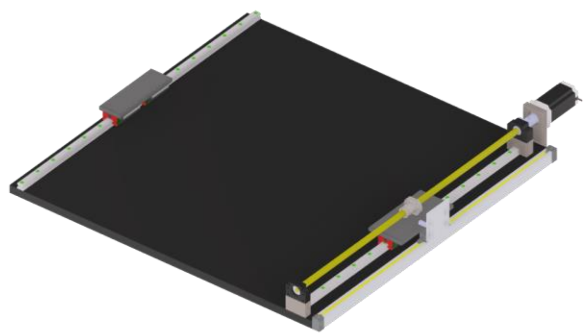

Figure 2 Y axis movement assembly

The y axis is represented by the base plate and guide rails on both sides. Only 1 stepper motor (NEMA 23) powers 1 ball screw (passes through the I beam & no slave axis as the use of 2 motors would have made calibration very difficult). The assembly is hooked onto the plate using screws. BK-12 and BF-12 hold the ball screw in place where BK allows for thrust loads (worse case contingency planning) and BF does not. Guideway blocks are mounted onto the guide rail and carry the weight of the bridge structure (divided between the 2 rails). A linear encoder is mounted using screws from the sides and is connected to the I-beam (x-axis structure) using an out of the box variable L-shaped bracket. Considering the dimensions of the ball screw, the BK and BF supports needed to be raised to allow for free rotation of the screw and to make the design more compact (as opposed to side by side formation).

Initially, side by side configurations for the encoder, screw and rails were tried but rejected in favor of saving space and allowed for a much neater design.

X axis

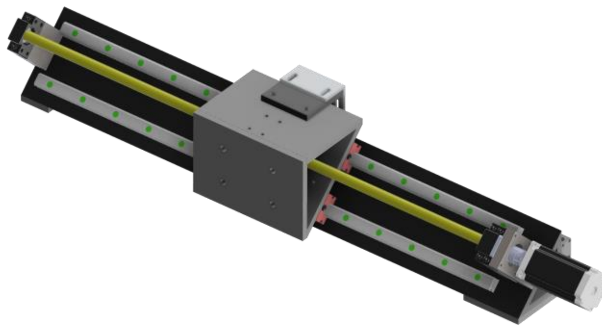

Figure 3 X axis movement assembly isometric view

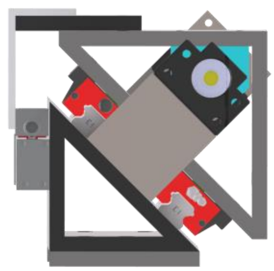

Figure 4 X axis movement assembly side view

The parts were particularly assembled in this way to counter the bending moments and torque effects associated with the z axis. In a previous iteration of the design, we had used a vertical plate which yielded significant torsional effects. Aluminum extrusions were also used but had severe torsion effects. This latest triangular formation allows for better load distribution and a higher safety factor for the y axis.

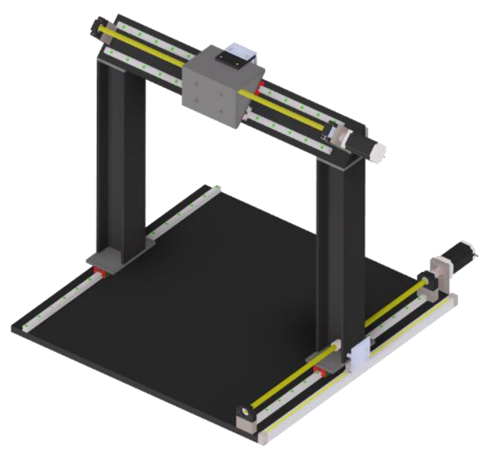

Figure 5 Bridge Structure isometric view

The bridge structure is erected using 2 I-Beams on the sides. The choice of using beams was not initially considered. We used plates which made mounting very difficult, were less sturdy, prone to failure, and took up a lot of space which increased our material requirements and subsequently cost. I-beams solved all these problems, were locally available and made for a compact & efficient design.

One stepper motor (NEMA 23) powers the only ball screw which passes through the triangular frame and has a nut housing attached to it. Rotation of the motor moves the triangular frame linearly in the x axis which moves the z axis attached to it. Like the y axis, the weight is carried by the guide rails (in this case, at an angle). The use of 2 rails and 4 guide blocks is justified in favor of better balancing, less rotational moments, and more stable motion. As with the y axis, the BK and BF supports are lifted to allow for a more compact assembly and no restrictions in motion. A linear encoder is mounted using screws from the sides and is connected to the moving assembly using an out of the box variable L-shaped bracket. The triangular beam is welded using plates which is bolted to the I-beam with additional plates in between. Screws are used to mount the rails. Blocks contain ball-bearings internally and slide on the rail (mounted from the side).

Z axis:

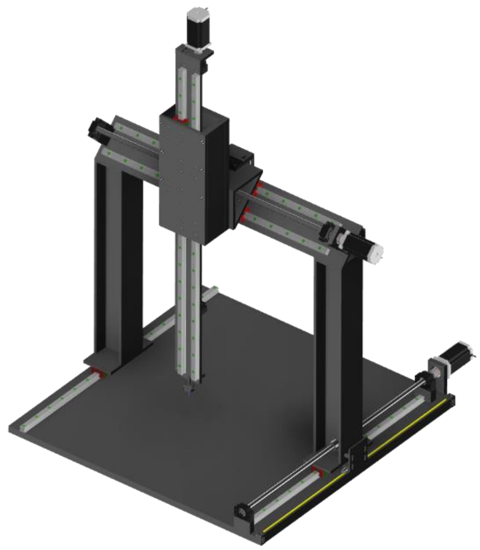

Figure 6 Complete assembly isometric view (z axis attached)

The Z axis was mounted to the bridge using screws (the rectangular structure consisted of 20- and 10-mm plates bolted together and remain stationary; the front plate is 10 mm). An Aluminum plate goes through the rectangular assembly onto which rails (towards the front face), probe, BK and BF are mounted (towards the rear face). One NEMA 23 motor powers the z axis. A linear encoder is mounted using screws from the sides and is connected to the moving assembly using screws.

In previously rejected iterations, the configurations took a lot of space and made the plate to be very thick. This increased the weight of the z axis and bending moment on the x axis. Two rails use 4 guide blocks and are overlapped to reduce the space and material being used.

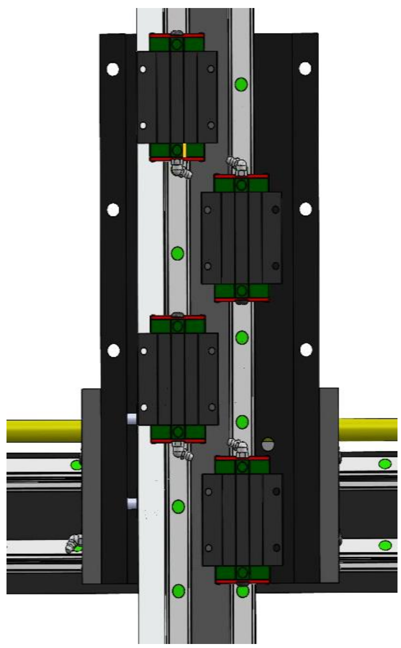

Figure 7 Block arrangement on z axis

Probe

Probe is one of the most critical parts of a CMM. They employ transducers that convert physical measurements into electrical signals. Various types of probes exist e.g., touch trigger, no contact etc and each type uses a unique system to register contact and relay that information to the CMM software. Non-touch probes allow for fast surface traversing and scanning. Since our project scope was majorly focused on checking geometric properties of objects (circularity, perpendicularity, parallelism etc) which required discrete data collection, we decided that a touch probe would be the best choice. Wired transmission was opted because of low cost and fast transmission of touch registering signal. Since our structure is straightforward, there was no inherent risk of wires coming in the way (Cable drags were used as covers). Probe selected:

- SilverCNC's SLP 25 (unidirectional repeatability of 1 µm, sufficient overtravel allowance (to prevent damage) and sensitive trigger force, smart switch, convenient mounting)

Staying true to our objective of cutting down cost as much as possible, another cheaper probe was tested: V6/TP06. This offered an economic solution with almost the same features.

The circuitry of the probe involved power cables (Black & Red), a digital output cable (yellow). When the probe contacts a surface a 0 is registered (In normal operation the probe gives a constant signal of 1). This signal (0 when triggered) would convey to the LabVIEW to take a live reading from the linear encoders to give us position data.

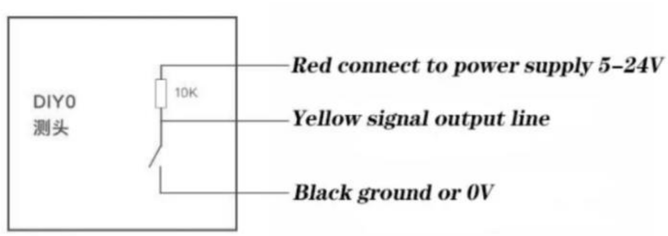

Figure 8 Probe Wiring Schematic

LabView Integration

A simple VI on LabView that serves as a controller between the user and the machine was made. The user will input what geometric feature needs measuring (and the nominal dimensions of the region being measured) and would then manually move the machine to get the input data points required. After that is achieved, the VI would compare actual readings to nominal ones and give the deflection. The features that the program allows the user to measure are:

- Diameter
- Flatness
- Angle
- Angularity
- Point to point distance
- Height, Width, & Length

- Circle to Circle distance

More features could be easily integrated (such is the nature of our code). The biggest hurdle that we faced during software development was the fact that the data coming in from the DRO (serial communication port) was not as clean as one would expect. Additionally, the probe input was flickering too much (problem with interfacing Arduino with LabVIEW). There was a lot of ‘garbage’ coming in (for reference, every 1 right value we got, we got 400 garbage ones alongside). To fix this problem, multiple filter mechanisms were incorporated which although cleaned the code, slowed it down as well (even though we played with the delays a lot). Hence, most of our efforts were aimed at improving data quality. We tried doing this by switching to Arduino and pairing it directly with LabVIEW using the hobbyist toolkit. This solved the flickering problem with the probe. The garbage from DRO would be solved through a similar approach.

For the operator, the machine would come with a manual that would state how many points are necessary to measure each feature (reference and data points included because certain features require reference planes to be made and then data points be either projected on them or be referenced to them).

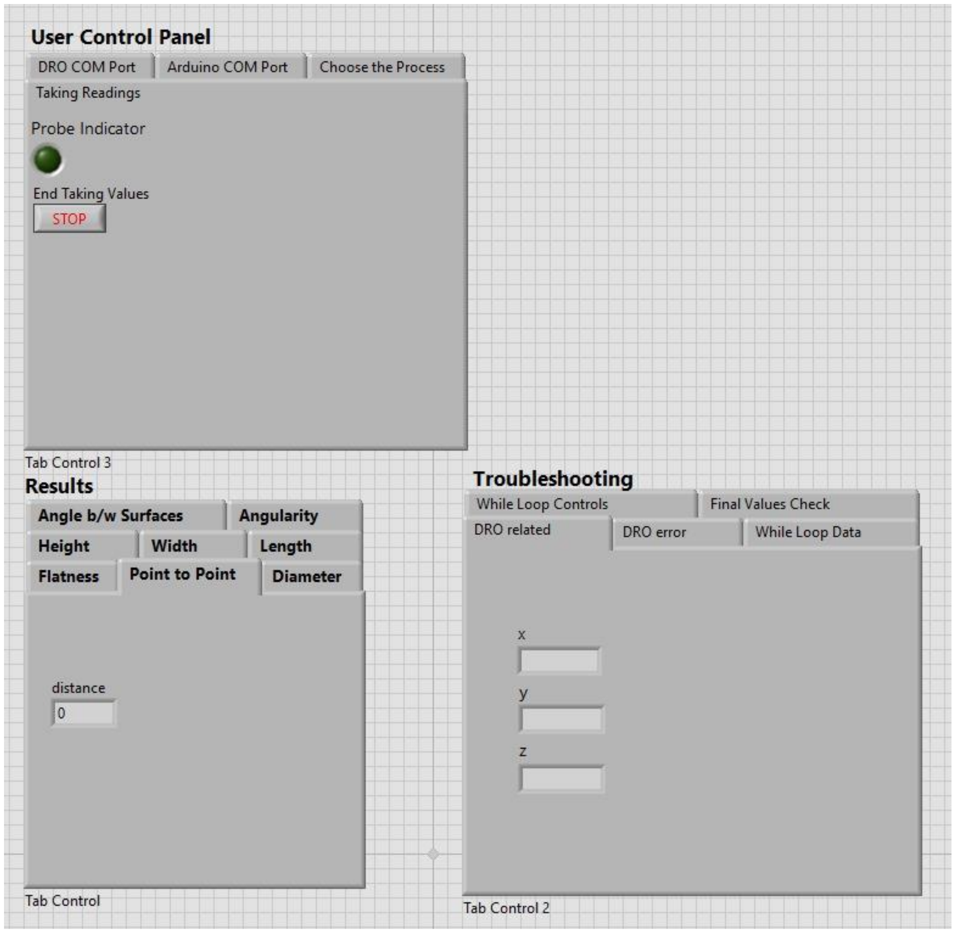

Figure 9 Front Panel Draft (Code)

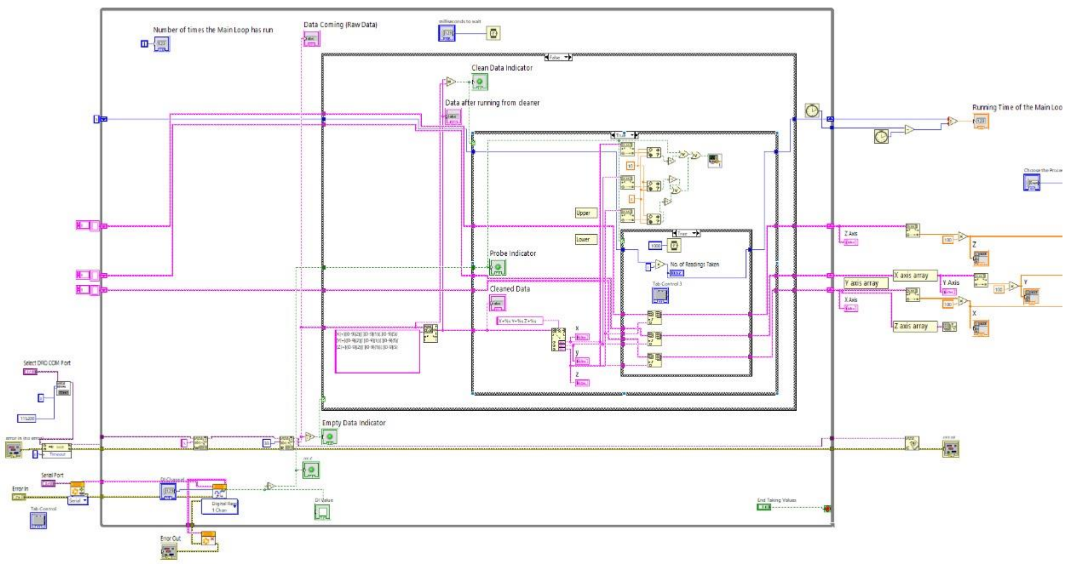

Figure 10 Filtering Mechanisms & Data Capturing

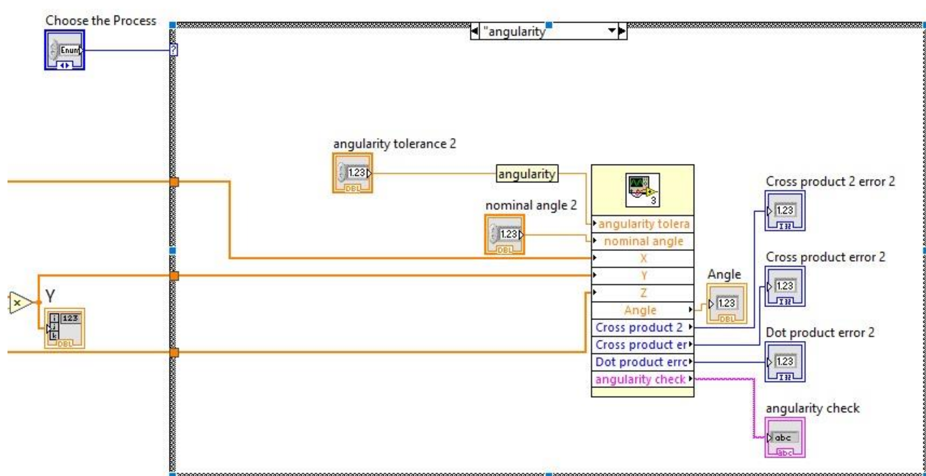

Figure 11 Choosing what the operator wants to measure

Oiling Mechanism

The oiling mechanism was chosen according to the guidelines highlighted in the installation guidelines for linear guiderails by HIWIN. According to the catalogue, our rails (HG20) required 3 cm^3 of grease that was to be administered through a grease nipple on the side of our guide blocks through a grease gun. Greasing was done for each rail (keeping in mind that the next time would be after approx. 6 months of use).

CHAPTER 4: RESULTS AND DISCUSSIONS

The Results and Discussion section marks a critical juncture in our investigation, where we first delve into the detailed examination of ANSYS results pertaining to the components comprising our designed Coordinate Measuring Machine (CMM). The primary objective of this phase was to scrutinize and ensure the structural stability and integrity of the CMM, an important consideration for achieving precise measurements within the targeted accuracy range of 10 microns or less. Leveraging the power of ANSYS simulations, we subjected each component to rigorous analyses under varying loading conditions. This comprehensive approach aimed to unveil potential stress concentrations, deformations, and weaknesses within the structure. Through an intricate exploration of these ANSYS results, we sought to identify areas of improvement and validation of our design choices. The forthcoming discussion will dissect these results, providing in-depth insights, addressing any challenges encountered during the simulation process, and offering a thorough understanding of the structural performance of our meticulously designed CMM.

Constraints & Loadings

- The holes of the bottom plates were used as fixed supports.
- An equivalent material to MS Steel was assigned to geometry (Z axis being aluminum) and Standard Earth Gravity was turned on to account for the structure's mass and its effects on its various components.

- A vertical load of 700N pointing downwards was applied on the triangular beam (exaggerated) to simulate the downward force generated by the mass of Z-axis (Z-axis itself was not included in the simulation for simplification).
- A moment of 90 Nm was applied to the triangular beam to simulate the moment caused by the Z-axis.

All directional deformations are defined in terms of ANSYS GCS

Bridge Structure

Static Structural analysis was run on the bridge structure using ANSYS Mechanical to ensure a stable and rigid structure.

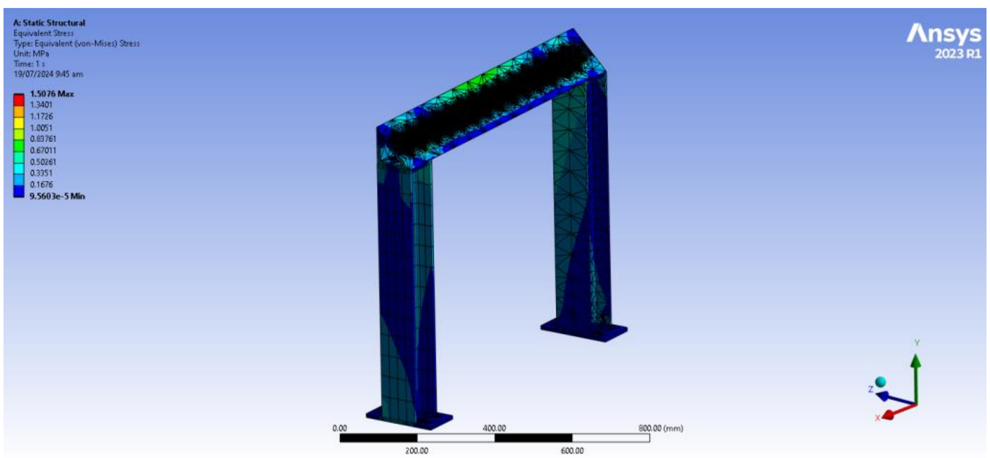

Figure 12 Stress analysis of bridge

The maximum equivalent structure experienced by the bridge structure is 1.5076 MPa which when compared to the yield strength of MS steel yielded a safety factor of 15 (largest value that ANSYS can register) that ensures our design is structurally integral.

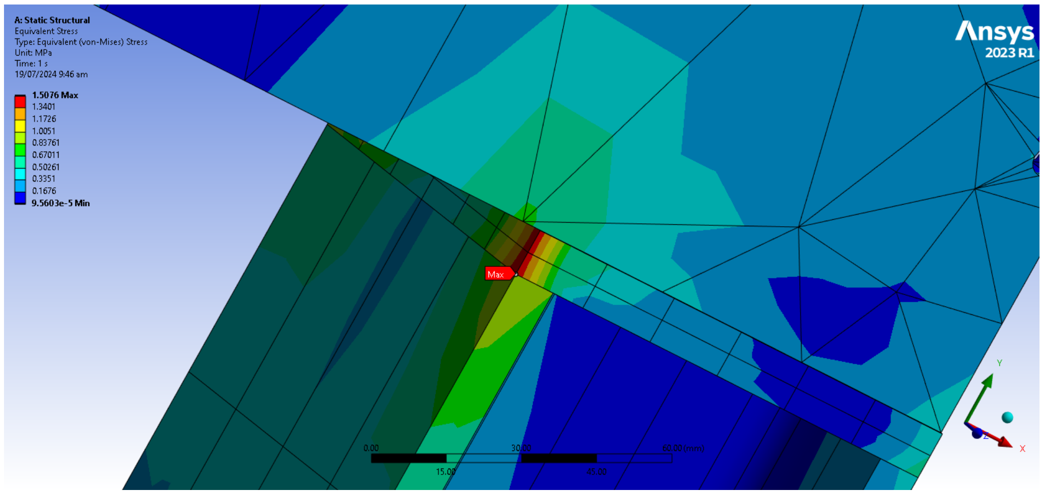

Figure 13 Maximum stress probe location

Maximum stress occurs at the edge of the plate that connect the I-beam to the triangular beam.

I-Beams

To ensure no buckling in the I-beams, directional deformation was checked for each beam under the stated loading conditions.

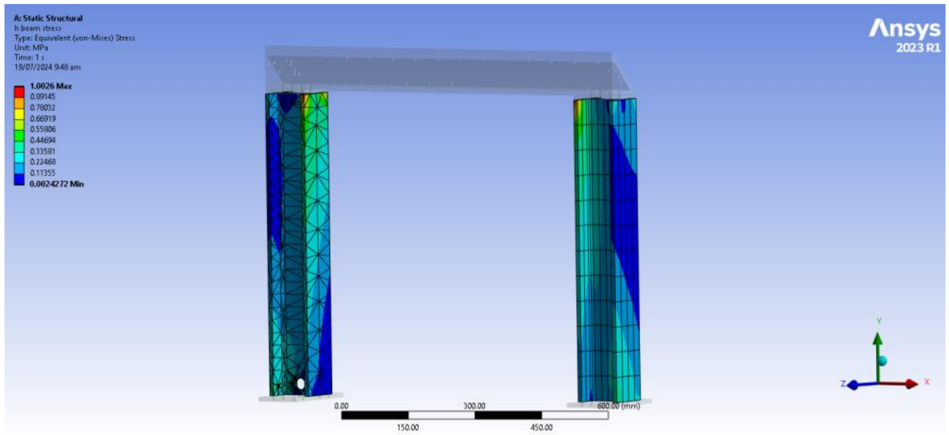

Figure 14 I Beam analysis (driving axis)

The deformation in the Z-axis was checked.

Table 1 ANSYS I Beam Simulation Results

Beam	**Directional Deformation (mm)**	**Maximum Stress (MPa)**	**Safety factor**
100 x 100 (mm)	0.0023	1.0026	15*

Initially, we tested 100 x 50 beam on the slave axis but from our simulations, we decided that swapping it out for the 100 x 100 beam would be a safer option in terms of stability.

Triangular Beam:

For the triangular beam, the deformation in Y-axis and Z-axis was checked as it was the conservative way to approach this problem owing to our loading conditions.

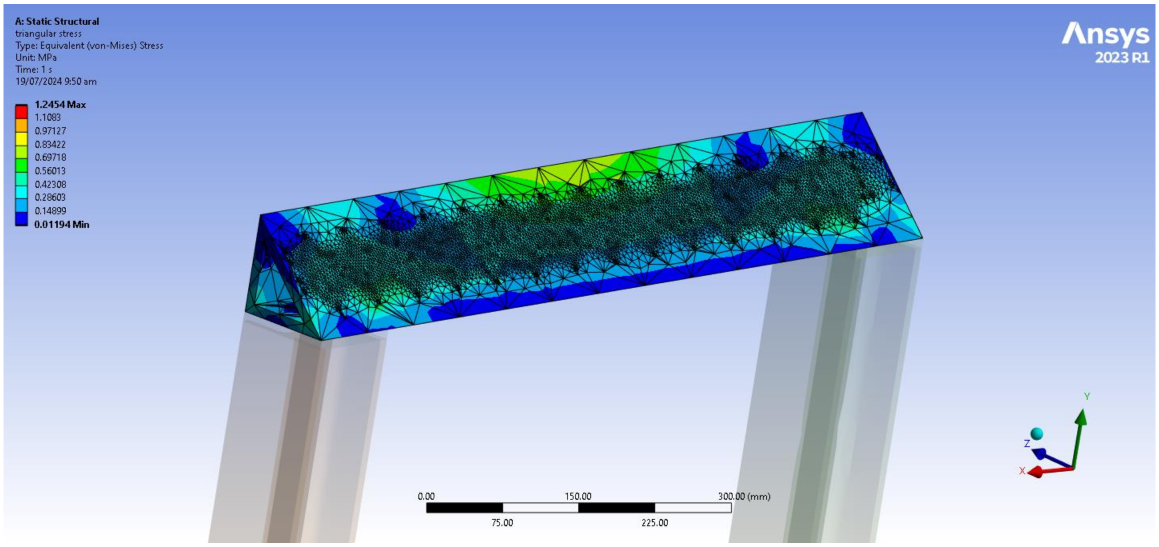

Figure 15 Triangular Beam analysis

Table 2 ANSYS Triangular Beam Simulation Results

Triangular Beam	Directional Deformation Y-axis (mm)	Directional Deformation Z-axis (mm)	Maximum Stress (MPa)	Safety factor
100 x 100 (mm)	0.0045	-0.005	1.245	15*

These maximum stress values in all the ANSYS simulations provide a safety factor much higher than that calculated by ANSYS. Literature review indicated that the highest value of stress factor registered by ANSYS is 15. This unusually high value of safety factor can be attributed to very low loads as our main loads come only from the weight of the structure and there are no additional loads present in the assembly. As we are designing a CMM, our main concern is accuracy, which calls for a more and more rigid structure to minimize the deflection in the structure. This also translates to vigorous vibrational control for the structure.

Ball Screw

Ball screw selection was an iterative process and numerical analysis showed that our final choice of SFU 1605 met the requirements of the design. The test results for the selected ball screw are given in the table below.

Table 3 Ball Screw Failure Testing Results

TEST	**Parameter**	**x axis**	**y axis**	**z axis**	**Status**
Max Force Test	Max Thrust max (N)	42.955	95.4	477.580	OK
	Permissible axial Load (N)	19960.08	19960.08	19960.08	
Avg Force Test	Avg Force	69.789	113.488	430.332	OK

	Permissible Avg Axial Load	9025.2	9025.2	9025.2	
Critical Speed Test	Max RPM	1800	1800	1800	OK
	Critical RPM	2316.124	2316.124	2316.124	
	Max Permissible RPM[1]	1852.9	1852.9	1852.9	
	Permissible RPM by DN value	3125	3125	3125	
Buckling test	Buckling Load	330.033	330.033	330.033	OK
	Permissible Compressive and Tensile Load	1940.871	1940.871	1940.871	

[1] (80%of CR)

Motors:

The motor selection involved calculation of effective masses on each axis. These results are summarized below:

Table 4 Effective Masses on each axis

Axis	X	Y	Z
Effective Mass on each (kg)	35.4204	101.87	12.485

An online motor sizing calculator was used to determine the right motors for our project. After the ball screws were finalized, their dimensions and effective masses of each axis were used to select the stepper motors.

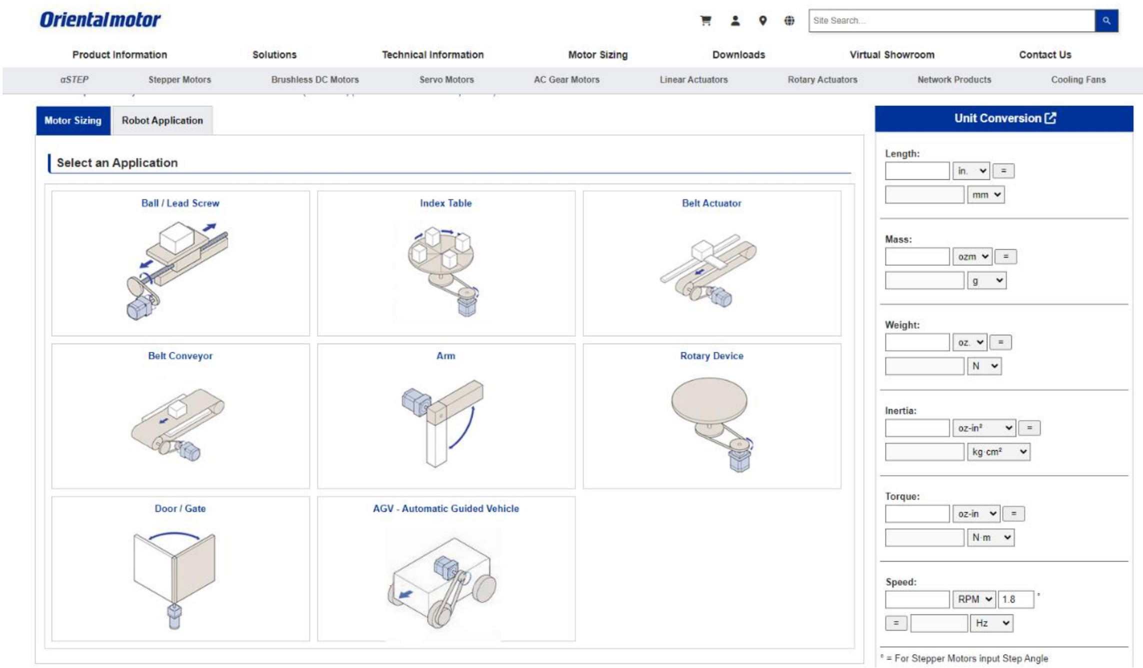

Figure 16 Online Motor Sizing Calculator

Testing:

Two types of tests were performed to assess the stability of our structure and accuracy of measurements.

1. Firstly, we moved each axis individually and recorded the deflection in other directions. The linear encoders assembly proved to be sturdy and no deflection higher than 1 micron was observed.
2. We selected an item (a 9V Toshiba Battery) and took its dimensions using a digital multimeter, with accuracy up to 10 microns, to have an initial assessment of the accuracy of our readings. The results of this test are presented below.

The same process was carried out for both items. Firstly, we measured their length using a digital vernier caliper and then we took multiple readings to confirm the accuracy of our equipment. The results are tabulated below.

Table 5 Vernier vs CMM (Data Comparison)

Readings	**Vernier Caliper**	**CMM**		**Deviation after adjustment (mm)**	**Target Deviation**
		Iterations (mm)	**Deviation (mm)**		
1	25.96	27.538	1.578	0.078	< 0.010
2	25.96	27.416	1.456	-0.044	
3	25.96	27.359	1.399	-0.101	
4	25.96	27.411	1.451	-0.049	
Deviation Range (mm)	0.044 - 0.101				

The results are not very accurate as expected at this stage of the process. We are receiving an error at its best at 44 microns. Nevertheless, these results can be greatly improved by calibration and testing of equipment, which is crucial to the finalization of a working CMMs. Perhaps one of the biggest sources of errors is the probe's post travel which allows the axes to keep moving even after the probe triggers (the axial inertia comes into play that adds a couple tens of microns).

CHAPTER 5: CONCLUSION AND RECOMMENDATION

In conclusion, the structure designed for the CMM has proved stable during the limited testing period. However, there are still various factors that are affecting the accuracy of the machine.

One factor slowing down the measurement processes is the inconsistency in the data transmission between the DRO and LabView. The data we receive is composed of good data and garbage. The ratio of garbage to good data readings is 4:1. This is a hurdle in achieving the required accuracy as it stops our program capturing the exact value of linear encoders, i.e. coordinate values. This limitation is due to the improper integration of hardware and software, which can be due to multiple reasons, one being the wire we used, and importantly, the time our code takes to run. This causes improper coordinates to be recorded and systematic errors can be seen in the test values. Resolving this issue (refining the code and using inbuilt toolkits such as the hobbyist toolkit in LabVIEW etc.) will allow the reading stream to be much smoother real-time values are spontaneously reflected in the software, thereby increasing accuracy.

The machine's accuracy can also be increased by calibrating it by in-depth testing. The factors that affect the accuracy are the parallelism of linear encoders with the base plate, vibrations caused due to the rotary motion of motors and transmission of motion, poor surface finish of the base plate, improper alignment of measured object and dynamic instability.

Recommendations for improving the machine include doing a vibration analysis on the structure and calibrating the structure using precise instruments. We recommend that sufficient time be spent on studying how dampers could be integrated into the setup especially in two of the most affected areas:

- Beneath the MS Base plate to isolate the machine from external vibrations.
- Damping the beam structure to counter for internal vibrations (vibrations transmitted from the driving axis to the slave axis)

It is recommended to reduce internal vibrations (this study should be done keeping the maximum speed of the driving axes in mind) to a minimum and use the machine in an environment less prone to external vibrations. Additionally, a check on motor start and stop should be incorporated that prevents sudden jerking motions even if the operator goes from maximum speed to zero or vice versa. Limiting switches at the end of the traversed lengths on all axes would further increase the machine's safety making it less prone to damage.

Another recommendation is integrating the motor control within the LabVIEW environment instead of using signal generators. This is to increase the ease of use for the operator. Nevertheless, a joystick-based approach still works adequately.

Another major concern in this machine is the pretravel and post travel of the probe stylus and accounting for this error would go a long way in reducing the inaccuracy of the measurements taken by the machine. It is suggested to study probe behavior by simulating hundreds of trigger scenarios. If we can map how much force deflects the probe by how much, a model can be made to correct the actual readings by that amount. For improved versatility and enabling the machine to work with slanted surfaces, a study on lobing errors and how to decrease them is also suggested.

Lastly, alignment aids and guide blocks should be used to align work pieces before measurement starts. We used basic clamps to prevent the workpieces from moving and although they served their purpose, a better solution could be sought for.

To conclude, this project which includes the fabrication of the structure and basic software plus electronics integrability serves as a halfway point to delivering a market ready machine (with an accuracy of 10 microns). Further work on vibrational damping, calibration and refinement would ensure that the machine measures values within the 10 microns range consistently over multiple readings.

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