



ING. MECATRÓNICA

**Thesis submitted prior to obtaining the degree of
Mechatronics Engineer.**

Author: Juan Pablo Jervis Carrera

Tutor: Guillermo Alfredo Mosquera Canchingre

Diseño para la Conversión de una Fresadora Manual a un Sistema CNC

Design for Retrofitting a Manual Milling Machine into a CNC System.

Quito-2026

Aprobación del Tutor del Trabajo de Integración Curricular

Yo Guillermo Alfredo Mosquera Canchingre, en calidad de tutor del Trabajo de Integración Curricular denominado: *Diseño para la Conversión de una Fresadora Manual a un Sistema CNC*, realizado por Juan Pablo Jervis Carrera, ha sido orientado y revisado en todas sus partes y considero que cumple los requisitos establecidos por la institución. En virtud de ello doy mi aprobación a fin de continuar con el proceso académico correspondiente.



Guillermo Alfredo Mosquera Canchingre

Tutor del Trabajo de Integración Curricular

Declaración de autoría y cesión de derechos

Yo, Juan Pablo Jervis Carrera, declaro bajo juramento que el trabajo aquí descrito es de mi autoría; que no ha sido presentado anteriormente para ningún grado o calificación profesional y que se ha consultado la bibliografía detallada.

Cedo mis derechos de propiedad intelectual a la Universidad Internacional del Ecuador, para que sea publicado y divulgado en internet, según lo establecido en la Ley de Propiedad Intelectual, Reglamento y Leyes.



Autor: Juan Pablo Jervis Carrera

C.I.: 1720880804

Dedicatoria

Dedico este trabajo a mi esposa, Isabel, quien llegó a mi vida en uno de los momentos más difíciles que he enfrentado. Fuiste quien me ayudó a encontrar nuevamente el rumbo cuando no sabía qué hacer con mi futuro y quien me motivó a regresar a mis estudios. Desde entonces, he decidido dedicarte el resto de mi vida. Alcanzar este momento ha sido uno de los mayores desafíos que he enfrentado, y no puedo imaginar haber recorrido este camino sin ti. Gracias por acompañarme con amor, paciencia y fortaleza en cada paso, por creer en mí incluso cuando yo dudaba de mí mismo y por ser mi apoyo incondicional.

Agradecimiento

Primeramente, agradezco a Dios por haberme concedido la fortaleza, la sabiduría y las oportunidades necesarias para culminar esta importante etapa de mi vida. Cada una de las personas y circunstancias que hicieron posible la realización de este trabajo han sido una bendición, y reconozco que, sin ellas, no habría sido posible alcanzar esta meta. Expreso mi más profundo agradecimiento a mi familia por su amor, apoyo y confianza incondicionales. En especial, a mi esposa, Isabel, quien fue mi motivación para retomar los estudios y continúa siendo mi inspiración para enfrentar cada nuevo desafío. Su paciencia, comprensión y constante apoyo fueron fundamentales durante todo este proceso. A mis padres, Carolina y Pablo, por brindarme la invaluable oportunidad de formarme profesionalmente y por acompañarme en cada etapa de mi vida, tanto en los momentos de éxito como en los de dificultad. Su esfuerzo, sacrificio y ejemplo han sido el pilar sobre el cual he construido este logro. A mi hermano Thomas, quien siempre ha estado presente en cada etapa de mi vida y cuyo apoyo sé que siempre podré encontrar. A pesar de ser mi hermano menor, es una de las personas que más admiro. Su responsabilidad, integridad y madurez son cualidades que me inspiran y que espero poder igualar cada día. Finalmente, expreso mi sincero agradecimiento a mis profesores, tutores y mentores de la carrera por compartir sus conocimientos y contribuir a mi formación académica. De manera muy especial, agradezco al Ing. Guillermo Mosquera, director de esta investigación, por su orientación, paciencia, confianza y valiosos consejos durante el desarrollo de este trabajo. Su experiencia y dedicación fueron fundamentales para la culminación de esta tesis.

Table of Contents

Title Page	I
Approval of the Curricular Integration Work Supervisor	II
Declaration of Authorship and Assignment of Rights	III
Dedication	IV
Acknowledgments	V
Table of Contents	VI
List of Tables	IX
List of Figures	X
Abstract	1
ABET Criteria	2
Introduction	4
Chapter I	5
Introduction	5
1.1 Problem Description	5
1.2 Objectives	6
1.3 State of the Art	7
Chapter II	9
Methodology	9
2.1 Requirements Definition	9
2.1.1 Functional Requirements	9
2.1.2 Non-Functional Requirements	9
2.1.3 System Constraints	10
2.2 Conceptual Design	10
2.2.1 Motion Control Architecture	10
2.2.2 Actuator Selection Concept	10
2.2.3 Conceptual Design Selection Matrix	11
2.3 Risk Factors & Mitigation	11
2.3.1 Risk 1: Insufficient Motor Torque	11

2.3.2	Risk 2: PID Controller Instability	11
2.3.3	Risk 3: Positioning Inaccuracy	12
2.4	Specific Design	12
2.4.1	Existing Milling Machine	12
2.5	Servo Motor Sizing	12
2.5.1	Inertial Force	13
2.5.2	Friction Force	13
2.5.3	Gravitational Force	14
2.5.4	Cutting Forces	14
2.5.5	Required Motor Speed	16
2.5.6	Feed Rate	16
2.5.7	Total Forces	16
2.5.8	Required Torque	17
2.5.9	Safety Factor	17
2.5.10	Motor Selection	18
2.5.11	Cost Analysis	19
2.6	Mechanical Integration	20
2.6.1	Design Requirements	20
2.6.2	Conceptual Design Alternatives	21
2.6.2.1	Belt and Pulley Transmission	21
2.6.2.2	Direct Ball Screw Drive	21
2.6.3	Selection of the Mechanical Integration Concept	22
2.6.4	Motor Placement and Alignment	23
2.6.5	Final Motor Mounting Assembly	24
2.6.5.1	Structural Support Strategy	24
2.6.5.2	Interface with the Milling Machine Structure	24
2.6.5.3	Motor Bracket and Coupling Interface	25
2.6.5.4	Axis-Specific Implementation	25
2.6.5.5	Assembly Verification	26
2.7	Digital Model Development and Assembly Preparation	26
2.7.1	Digital Model Integration in MATLAB Simulink	28
2.7.2	Joint Configuration and Axis Motion Mapping	28

2.7.2.1	Lead Screw Kinematic Relationship	28
2.7.2.2	Closed-Loop PID Controller Implementation	29
2.7.3	Performance Evaluation	30
2.7.4	PID Gain Sensitivity Analysis Using a Full Factorial Design	31
2.7.5	Effect of Feed Rate on Tracking Accuracy and Actuator Demand	34
2.7.6	Effect of Gear Geometry Complexity on CNC Tracking Performance.....	35
Chapter III		36
Results & Discussion		36
3.1	Obtained Results	36
3.1.1	Overall RSM Analysis	36
3.1.2	Overall Max Error Analysis	37
3.1.3	Feed Rate influence Analysis	39
3.1.4	Gear Geometry Complexity Analysis	39
3.2	Discusion	43
3.2.1	Motor Selection and Actuator Performance Validation	43
3.2.2	Economic Feasibility	43
3.2.3	Simulation Limitations and Design Considerations	44
Conclusions		45
Recommendations		47
References		48
Annexes		50

List of Tables

Table I	ABET Criterion Outcomes and Target Mastery Levels	2
Table II	Summary of Conceptual Design Choices	11
Table III	Specific cutting force (K_c) for different workpiece materials [1].	15
Table IV	Comparison of candidate servo motors for the X and Z axes.	18
Table V	Comparison of candidate servo motors for the Y-axis.	19
Table VI	Estimated acquisition cost of the selected servo motors and servo drives. .	20
Table VII	Comparison of the mechanical integration concepts considered for the CNC retrofit.	22
Table VII	Gain sensitivity data results for the X-axis.	32
Table IX	Gain sensitivity data results for the Y-axis.	32
Table X	Gain sensitivity data results for the Z-axis.	33
Table XI	Overall RMS tracking error from X, Y, and Z-axis.	34
Table XII	Effect of feed rate on the overall tracking error and peak actuator torque. ..	34
Table XII	Experimental conditions used to evaluate the influence of gear complexity on controller performance.	35
Table XIV	Influence of gear complexity on tracking accuracy and peak actuator torque.	35

List of Figures

Fig. I Bridgeport-type CAD model used as the reference for the retrofit design.	27
Fig. II Block diagram of the simulation and control logic.....	30
Fig. III Influence of K_p, K_i, K_d over RMS error.	36
Fig. IV Overall Error influenced by control configurations.	37
Fig. V Comparison between influence of PID Parameters.	37
Fig. VI Comparison of X-Axis Position Tracking Performance Between the Best and Worst PID Configurations.	38
Fig. VII Effect of Feed Rate on Accuracy and Torque Demand.	39
Fig. VIII Effect of Feed Rate on Accuracy and Torque Demand.	40
Fig. IX Maximum Position Error for Different Gear Geometries.	41
Fig. X Position Tracking: Lowest vs Highest Geometry Complexity.	42
Fig. XIX Axis support frames.....	50
Fig. XII Z-Axis support frames.....	51
Fig. XIII Y-Axis 7.11 cm support frames.....	52
Fig. XIV X-Axis 17.8 cm support frames.....	53

Abstract

Retrofitting conventional milling machines with Computer Numerical Control (CNC) systems offers a cost-effective alternative to purchasing new equipment while extending the operational life of existing machines. This thesis presents the complete mechatronic design and virtual validation of a three-axis CNC retrofit for a conventional vertical milling machine. A three-dimensional CAD model was developed in SOLIDWORKS to determine the mechanical characteristics of the system and support servo motor selection. The design was subsequently implemented in MATLAB/Simulink and Simscape Multibody, where independent PID controllers were developed for each linear axis. The proposed control system was evaluated through simulation using a series of performance tests, including PID gain sensitivity analysis, feed rate variation, and machining geometry complexity. System performance was assessed using RMS tracking error, maximum position error, and peak motor torque. The results demonstrated stable closed-loop operation with sub-millimeter positioning accuracy under nominal operating conditions, while increases in feed rate and trajectory complexity produced predictable increases in tracking error and actuator demand without compromising system stability. The proposed methodology demonstrates that virtual prototyping provides an effective framework for validating CNC retrofit designs prior to physical implementation, reducing development time and supporting informed mechanical and control system design decisions.

Keywords: CNC Retrofit, PID Control, MATLAB/Simulink Simulation.

ABET Criteria/ Final Report Cross Reference Table

TABLE I
ABET Criterion Outcomes and Target Mastery Levels

ABET Criterion Outcome	Target Level of Mastery	Best Examples with Section Numbers
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Analysis, Comprehension	Sections 2, 3.2–3.8, 4.1–4.3
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Analysis, Evaluate	Sections 1.2, 3.1–3.8, 4.3, 5
3. An ability to communicate effectively with a range of audiences.	Analysis	Entire report (Sections 1–5)
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Analysis	Sections 1.2, 3.6, 4.3, 5
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Analysis	Sections 1, 5
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Analysis, Evaluate	Sections 3.8, 4.1–4.3, 5

Introduction

Computerized Numerical Control (CNC) machine tools have become essential to manufacturing processes as they are capable of creating highly precise, repeatable, and productive parts. The increasing need for automated manufacturing along with the introduction of Industry 4.0-type technologies have made CNC tooling more widely used within the many different manufacturing industries. However, the purchase of new CNC machining centers comes with a large cost, which is often too much for small and mid-sized enterprises (SMEs) to afford. Retrofitting existing manual milling systems has therefore become a popular choice to extend the economic lifespan of older equipment.

This research addresses the design and virtual validation of a CNC retrofit for a conventional Supermax YC-1.5VA turret milling machine. Rather than focusing on the physical implementation of the retrofit, the project develops a complete digital prototype capable of evaluating the feasibility of the proposed mechanical and control system before hardware acquisition. The retrofit incorporates servo-driven linear axes and a closed-loop PID control system implemented within the MATLAB/Simulink environment. By integrating multibody dynamics with motion control, the proposed simulation framework allows the dynamic behavior of the retrofitted machine to be evaluated under realistic machining trajectories while providing valuable information for actuator selection, controller tuning, and overall system performance.

The project goals were achieved through the integration of mechanical design, computer-aided engineering, and control systems development. A CAD model of a Bridgeport-type milling machine that was geometrically representative of the original Supermax machine was adapted to closely match its features, and then simplified for dynamic simulation. The assembly was then exported to Simscape Multibody, where the mechanical structure was combined with servo motor models, lead screw transmissions, and PID controllers for each machine axis. Custom machining trajectories were developed in MATLAB to simulate CNC operations and to perform quantitative evaluations of positioning accuracy, actuator torque requirements and controller performance under various operating conditions.

Several practical constraints influenced the development of the proposed system. Since no publicly available CAD model of the original Supermax YC-1.5VA milling machine was available, a similar Bridgeport-type model obtained from the GrabCAD repository was modified and

adapted for this work. Additionally, the scope of the project was limited to virtual implementation and validation; therefore, physical phenomena such as cutting forces, structural deflection, backlash, bearing friction, and thermal effects were not included in the simulation model. Nevertheless, the resulting digital representation provides a realistic approximation of the machine dynamics and serves as an effective platform for evaluating the feasibility of the proposed retrofit prior to physical implementation.

To ensure a systematic development process, the project follows a systems engineering methodology that progresses from mechanical modelling and actuator selection to control system implementation and performance evaluation. Analytical calculations were initially performed to size the servo motors and transmission components, after which a multibody simulation model was developed to validate the proposed design. Finally, a series of simulation-based experiments were conducted to evaluate the influence of PID controller tuning, machining feed rate, and gear geometry complexity on positioning accuracy and actuator torque demand, thereby providing quantitative evidence of the proposed retrofit's performance.

The remainder of this document is organized as follows. Chapter 1 presents the problem statement, objectives, and state of the art related to CNC retrofitting, digital manufacturing, and servo control systems. Chapter 2 describes the proposed design methodology, including the mechanical calculations, actuator selection, CAD model preparation, control system development, and simulation environment. Chapter 3 presents the experimental methodology together with the simulation results and performance analysis. Finally, Chapter 4 discusses the principal findings of the study, evaluates the economic feasibility of the proposed retrofit, outlines the limitations of the simulation model, and presents the conclusions and recommendations for future work.

In conclusion, this study has shown that virtual prototypes are a practical way to lessen the uncertainty of CNC conversion projects as they allow for the testing of important design decisions before making physical prototypes. The proposed method also offers an accessible, low-cost alternative to evaluate the feasibility of converting equipment to CNC by helping to select actuators, optimize controllers, and predict performance. Thus, this research supports the modernization of traditional machine tools, and provides a useful tool for SME manufacturers that want to use CNC technology without spending a large amount of money on new equipment.

Chapter I

Introduction

Problem Description

Computer Numerical Control (CNC) technology has become a fundamental component of modern manufacturing. This is accredited to its ability to produce components with high precision and efficiency. Unlike conventional machine tools, CNC systems automate machining operations, reducing operator dependency and improving product quality. As industries continue to demand tighter tolerances and increased productivity, CNC machines have become essential for automotive manufacturing, industrial equipment production, and aerospace industries.

Despite these advantages, many SMEs continue to rely on conventional manual milling machines. In many cases, pre-existing manual machines remain mechanically functional and structurally robust, making SMEs reluctant to justify costly CNC replacements. Consequently, machine retrofitting has emerged as an attractive alternative, allowing organizations to extend the useful life of their equipment while integrating modern automation practices, at a significantly lower cost.

The process of retrofitting a manual milling machine into a CNC system involves more than simply replacing manual controls with electric actuators. Successful implementation requires the integration of suitable drive systems, motion controllers, and software interfaces. These allow the machine to achieve the positioning accuracy, repeatability, and reliability expected from CNC operation.

Prior to physical implementation, simulation and virtual prototyping provide valuable tools for evaluating retrofit feasibility and reducing development risks. Through the use of computer-aided design (CAD) and dynamic simulation software, engineers can assess mechanical integration, analyze motion behavior, validate control strategies, and estimate system performance. All without incurring the high manufacturing and testing costs associated with physical prototypes.

This research presents the design of a CNC retrofit for a conventional manual milling machine used by ROBIN GEAR'S. Since no digital representation of the Supermax YC-1.5VA milling machine was available, a geometrically similar model was sourced from the GrabCAD

online repository to serve as the foundation for the mechanical design. Afterwards suitable actuators, controllers, and CNC control elements were then selected according to the machine's operational requirements.

To evaluate the proposed retrofit, the complete assembly was exported to a simulation environment where a virtual model of the machine was developed. A closed-loop PID control was implemented to execute refined 3-degree machining trajectories. The simulation framework enabled analysis of positioning accuracy, motion control behavior, and operational efficiency. Additionally, an economic assessment was conducted to compare the proposed retrofit approach with the acquisition of a new CNC machine.

The scope of this study is limited to the design, modeling, simulation, and evaluation of the proposed retrofit system. Physical implementation and experimental validation are beyond the scope of the project. Nevertheless, the developed methodology provides a practical framework for assessing the technical and economic viability of CNC retrofitting projects.

Objectives

To design and evaluate, through digital modelling and simulation, a CNC retrofitting solution for a conventional manual milling machine that enhances precision, automation, and productivity, while remaining economically and technologically accessible for SMEs manufacturing environments.

To develop a complete digital three-dimensional model of a conventional vertical turret milling machine by sourcing and adapting a geometrically representative CAD model, enabling accurate mechanical and functional representation of the retrofit system within a simulation environment.

To determine the servo motor and drive specifications required for the proposed CNC retrofit through analytical calculation of the mechanical loads acting on each machine axis, and to select commercially available actuator solutions suitable for replication across similar manual machines used in small industrial contexts.

To implement and validate a closed-loop PID motion control system within the MATLAB Simulink and Simscape Multibody simulation environment, and to evaluate the mechanical, control, and motion performance of the proposed retrofit through systematic simulation experiments, ensuring positional accuracy and operational reliability across a range of machining conditions.

To analyze the economic feasibility of the proposed CNC retrofit by estimating the in-

vestment required for the primary actuation components and comparing this cost against the acquisition of new CNC equipment, establishing the retrofit approach as a scalable and cost-effective alternative for SMEs.

State of the Art

The manufacturing industry is evolving to include more automation and using modern digital technologies for production processes. Modern Computer Numerical Control (CNC) machine tools produce high quality parts quickly and with a high level of accuracy [2]. However, the cost of converting from manual to CNC production equipment is a significant barrier to entry for many SMEs [3–5]. Retrofitting conventional milling machines has many advantages; retrofitting allows manufacturers to utilize existing equipment, thereby extending the life of that asset, and adding new technology such as modern motion and control systems, and enhancing the performance of the milling process [6–9].

Many researchers have developed multiple strategies for retrofitting existing manual milling machines to CNC systems using integration of different types of motors (servo and stepper), ball screw mechanisms (used to convert rotary motion into linear motion), electronic motion control systems, and computer-based supervisory control systems. Retrofitting can improve accuracy, repeatability, and efficiency of production significantly and requires only a small fraction of the investment as compared to purchasing new CNC equipment [10, 11]. With many commercially available servo systems and open-architecture control platforms, retrofitting has become much easier to implement into educational laboratories, research institutions, and industrial operations [12, 13].

In addition to the mechanical conversions themselves, there has also been increasing attention given to the use of digital engineering tools to aid in the retrofit process. Examples of digital engineering tools include three-dimensional (3D) computer-aided design (CAD) models, multibody dynamic simulations, and virtual commissioning techniques [14, 15]. These tools can be used to evaluate the design of proposed modifications prior to their physical implementation. The benefit of this type of evaluation is that it reduces the number of design iterations needed, overall development time, and implementation costs. Simulation environments such as SOLIDWORKS Motion and MATLAB Simscape Multibody can be used by engineers to accurately determine machine kinematics, estimate actuator loads, analyse structural motion, and evaluate controller performance under realistic operating conditions.

The integration of simulation with the development of the control system is particularly

valuable in the design of CNC machines. Rather than being limited exclusively to experimental testing, the use of virtual models allows for the evaluation of all aspects of servo motors, drive systems, and PID controllers by simulating their behaviour during the use of representative machining trajectories. In simulated environments, industry-standard methods are used to optimize the PID controller gains while assessing key performance indicators, including tracking accuracy, actuator torque requirements, positioning errors, and overall system stability. This method of model-based design reduces commissioned time and provides a method for validating design decisions before purchasing hardware for implementation.

While digital technologies and industry 4.0 are becoming more prevalent in modern manufacturing, many retrofitting studies still consider CNC systems in mechanical terms only. Digital Shadows and Digital Twins use real-time data collection to allow for ongoing association of the virtual and physical versions of the component of the machine [16, 17]; the data allows for predictive maintenance, optimization of production processes, and remote monitoring. Before these types of higher-level technologies can be put into place successfully, a suitable digital model that can accurately simulate all dynamic aspects of the machine must first be created.

As a result of this, more researchers are being made to consider how they can create high fidelity virtual prototypes of machines by using these digital representations of the physical machine. This type of digital model will help validate the mechanical design as well as provide the information needed to develop the control system and select the appropriate servomotor, and allow for performance assessment under different machining conditions [18, 19]. Therefore, by combining tools offered by computer-aided design, multibody simulation, and control engineering into a single unified environment researcher can evaluate the retrofit options available to them, reduce their technical risks associated with the actual retrofitted machine, and minimize their total cost of developing and implementing a retrofitted machine.

The present work follows this model-based design philosophy by developing a complete virtual prototype of a turret-type milling machine using SOLIDWORKS and MATLAB Simscape Multibody. Rather than focusing solely on the mechanical conversion, the proposed methodology integrates mechanical modelling, servo motor selection, PID controller implementation, and simulation-based performance evaluation [20–22]. The developed digital model is subsequently used to investigate controller tuning, machining feed rates, and workpiece geometry complexity, demonstrating the feasibility of the proposed CNC retrofit prior to physical implementation.

Chapter II

Methodology

To keep the development process organized, this project followed the Systems Engineering V-Model. The framework guided the design and implementation of the CAD model and simulation environment, ensuring that each design decision supported the intended virtual behavior of the CNC machine.

Requirements Definition

The first phase of the V-Model established the core constraints and objectives of the system. The scanning process, including mounting and data output, needed to be highly efficient to be viable in a real-life scenario. Furthermore, the system required a lightweight architecture to allow single-handed operation and prevent the motor from stalling under heavy moving loads. Finally, the project prioritized a strict budget, necessitating the use of readily available and cost-effective components such as standard stepper motors, lead screws, and standard aluminum extrusion profiles.

To formalize the engineering design process, the system parameters were strictly categorized into functional requirements, non-functional requirements, and physical constraints.

Functional Requirements

- The system shall convert the manual X, Y, and Z axis movements of the milling machine into motor-driven motion.
- The system shall execute predefined machining trajectories generated from CNC commands.
- The system shall incorporate closed-loop control for axis position regulation.
- The system shall provide a virtual representation of the milling machine and retrofit components.
- The system shall evaluate machining trajectory execution accuracy.
- The system shall support economic comparison between retrofitting and purchasing a new CNC machine.

Non-Functional Requirements

- The simulated system shall achieve positioning errors within acceptable limits for milling operations.

- The PID controller shall minimize overshoot during positioning operations.
- The virtual model shall accurately represent the kinematic and dynamic behavior of the machine based on available mechanical data.

System Constraints

- The project is limited to design and simulation and shall not include physical implementation.
- The retrofit shall be limited to X, Y, and Z axis automation.
- The control system shall utilize PID-based position control.

Conceptual Design

With the system requirements established, the operating concept and simulation architecture were defined. The primary measurement was established as the position control of the 3-movement axis with the use of PID controlled motors. To translate this idea into a functional mechatronic system, several design alternatives were evaluated to determine the most efficient and reliable approach.

Motion Control Architecture

One of the first conceptual impasses regarded determining the best architecture for the desired system. The reason being, while an open-loop control is typically lower in cost and easier to maintain, it does not utilize any type of feedback; therefore, an open-loop control system cannot "see" when something is not in position or adjust for any type of disturbance. If the open-loop control system does lose step, then the accuracy for machining would be compromised. On the other hand, a closed-loop PID controller has the advantage of using encoder feedback to continually compare the actual position to that of the desired position. Due to this constant comparison, it is better for tracking and error correction. However, PID control does require controller tuning as well as higher level hardware. Nevertheless, the precision, stability, and reliability characteristics of the closed-loop PID controller are what led to the decision of using a closed-loop PID control system over an open-loop control system.

Actuator Selection Concept

There were two different options when referring to which type of motor would be used in the design, stepper or servo. Steppers are a very common choice in CNC applications because they typically have a low cost, are relatively easy to control and provide very precise movement in moderate force applications. However, stepper motors are subject to both positional and machining errors thanks to their generally open-loop configuration. In contrast, servo motors

utilize encoder feedback to allow continuous closed-loop position control, resulting in much greater accuracy, reliability and dynamic performance. Therefore, although servo motors tend to be more expensive than steppers, they were selected for this application.

Conceptual Design Selection Matrix

Table II Summarizes the main design alternatives considered during this phase and the final decisions that defined the prototype's architecture.

TABLE II
Summary of Conceptual Design Choices

Design Theme	Evaluated Options	Selected Option & Justification
Motion Control Architecture	1. Open-loop control 2. Closed-loop PID control	Closed-loop PID control: Allows for control and real-time feedback.
Actuator Selection Concept	1. AC Servo Motor 2. Stepper Motor	AC Servo Motors: Built-in encoder allows for closed-loop control without the need for additional hardware.

Risk Factors & Mitigation

The development and validation of a virtual CNC retrofit system introduces mechanical, control, and simulation-related uncertainties which may hinder the accuracy of the design. To ensure reliable simulation results and realistic machine behavior a series of risk factors and mitigation strategies were identified.

Risk 1: Insufficient Motor Torque

The selected servo motors may not provide sufficient torque to move the machine axes under maximum loading conditions, leading to positioning errors or motor stalling.

Mitigation Strategy: Perform torque calculations based on the mass, lead screw characteristics, friction, and expected cutting loads to ensure the selected motors provide an adequate safety factor.

Risk 2: PID Controller Instability

Poorly tuned PID gains may result in excessive overshoot, oscillations, or unstable axis motion.

Mitigation Strategy: Tune the PID controller through simulation and evaluate system response using multiple test trajectories to achieve stable and accurate motion.

Risk 3: Positioning Inaccuracy

Mechanical backlash or insufficient controller performance may reduce positioning accuracy during machining operations.

Mitigation Strategy: Implement closed-loop position control using feedback and evaluate tracking error throughout the simulation process.

Specific Design

Existing Milling Machine

The retrofit was developed using a conventional vertical turret milling machine as the baseline platform, the Supermax YC-1.5VA. SME manufacturing facilities widely use this type of machine because of their robust builds and versatility in carrying out many machining processes. They are reliable machines, however the original machine used only manual hand-wheel movement in positioning in three linear axes restricting productivity, repeatability, and machining precision. Since the machine retains a structurally sound frame and motion transmission system, it represents a suitable candidate for CNC conversion through the integration of motorized actuation and automated control while preserving the original mechanical architecture.

A challenge encountered during the design process was the absence of a publicly available one-to-one CAD model of the Supermax YC-1.5VA milling machine. To overcome this limitation, a commercially available CAD model of a geometrically similar vertical turret milling machine was selected as the baseline reference. The model was reviewed and modified where necessary to approximate the dimensions and kinematic characteristics of the Supermax machine, providing a suitable digital platform for the design and integration of the retrofit components. This approach enabled the development and validation of the proposed CNC conversion while maintaining consistency with the physical characteristics of the target machine.

Servo Motor Sizing

The first item to be determined is the mass each axis needs to move. On our X axis 57.08 kg corresponds to its own, with an addition of the material we are going to machine. An approximate estimate of steel gears in automotive design is between 2.25 - 3.5 kg, we will be using the upper limit of 3.5 for our analysis. Giving us a final mass of 60.58 kg for our X axis.

$$m_x = m_{axis} + m_{payload} \quad (2.1)$$

The mass of our Z axis is 22.69 kg, however since all of the X axis components rest on top of the Z axis we must add that mass to give us a final mass of 83.27 kg.

$$m_z = m_{axis} + m_x \quad (2.2)$$

Finally the Y axis lies below the others and moves the entire worktable. Having its own mass being 175.3 kg and considering that of the two others we get a total mass of 258.57 kg.

$$m_y = m_{axis} + m_x + m_z \quad (2.3)$$

The mass of the servo motors was neglected during the preliminary sizing calculations because it represents a small fraction of the moving mass (<5% for all axes) and does not significantly affect the required actuator torque. Once the final motors were selected, their mass would be incorporated into the CAD assembly and dynamic simulation.

The second items to be determined are the Forces acting upon each axis. We will be considering the inertial forces, the friction forces, the cutting forces and the force of gravity upon each of the axis respectively.

Inertial Force

A moderate acceleration of 0.2 m/s² was assumed for the sizing calculations, as it is representative of a controlled and continuous machining operation.

$$F_i = ma \quad (2.4)$$

$$F_{i,X} = 12.11 \text{ N}$$

$$F_{i,Y} = 51.71 \text{ N}$$

$$F_{i,Z} = 16.65 \text{ N}$$

Friction Force

Given that cast iron on cast iron has a friction coefficient of 0.07 – 0.15 (greased vs non-greased) an average coefficient of 0.12 was selected for the static friction.

$$F_f = \mu mg \quad (2.5)$$

$$F_{f,X} = 71.31 \text{ N}$$

$$F_{f,Y} = 304.39 \text{ N}$$

$$F_{f,Z} = 98.02 \text{ N}$$

Gravitational Force

Only our Y axis is constantly suffering from the force of gravity since it is our vertical axis.

$$F_g = m g \quad (2.6)$$

$$F_{g,y} = 2.54 \text{ kN}$$

Cutting Forces

To more accurately determine the cutting force, a test scenario was defined with an axial depth of cut (a_p) of 2 mm and a feed per tooth (f_z) of 0.05 mm/tooth. These parameters were then used to determine the chip cross-sectional area (A).

$$A = a_p f_z \quad (2.7)$$

$$A = 0.1 \text{ mm}^2$$

Next we found the teeth per revolution, assuming number of flutes (Z) is 4, Cutting speed (V_c) is 80 [m/min], Tool diameter (D) is 12 [mm], and Lead screw lead is 5 [mm/rev]; in order to determine the specific cutting force (K_c) found in Figure ??.

$$f_{\text{rev}} = z f_z \quad (2.8)$$

$$f_{\text{rev}} = 0.2 \text{ mm/rev}$$

TABLE III
Specific cutting force (K_c) for different workpiece materials [1].

Work Material	0.1 (mm/rev)	0.2 (mm/rev)	0.3 (mm/rev)	0.4 (mm/rev)	0.6 (mm/rev)
Mild Steel	3610	3100	2720	2500	2280
Medium Steel	3080	2700	2570	2450	2300
Hard Steel	4050	3600	3250	2950	2640
Tool Steel	3040	2800	2630	2500	2400
Tool Steel	3150	2850	2620	2450	2340
Chrome Manganese Steel	3830	3250	2900	2650	2400
Chrome Manganese Steel	4510	3900	3240	2900	2630
Chrome Molybdenum Steel	4500	3900	3400	3150	2850
Chrome Molybdenum Steel	3610	3200	2880	2700	2500
Nickel Chrome Molybdenum Steel	3070	2650	2350	2200	1980
Nickel Chrome Molybdenum Steel	3310	2900	2580	2400	2200
Hard Cast Iron	3190	2800	2600	2450	2270
Meehanite Cast Iron	2300	1930	1730	1600	1450
Grey Cast Iron	2110	1800	1600	1400	1330

This allows us to determine the specific cutting force, $K_c = 3600$ MPa. finally we may calculate our Cutting Force.

$$F_c = A K_c \quad (2.9)$$

$$F_c = 360 \text{ N}$$

Required Motor Speed

$$n = \frac{1000 V_c}{\pi D} \quad (2.10)$$

$$n \approx 2122 \text{ rev/min}$$

Feed Rate

$$V_f = n f_{\text{rev}} \quad (2.11)$$

$$V_f = 424.41 \text{ mm/min}$$

Total Forces

X-axis

$$F_x = F_i + F_f + F_c \quad (2.12)$$

$$F_x = 12.11 \text{ N} + 71.31 \text{ N} + 360 \text{ N}$$

$$F_x = 443.42 \text{ N}$$

Y-axis

$$F_y = F_i + F_f + F_c + F_g \quad (2.13)$$

$$F_y = 51.71 \text{ N} + 304.39 \text{ N} + 360 \text{ N} + 2.54 \text{ kN}$$

$$F_y = 3.25 \text{ kN}$$

Z-axis

$$F_z = F_i + F_f + F_c \quad (2.14)$$

$$F_z = 16.65 \text{ N} + 98.02 \text{ N} + 360 \text{ N}$$

$$F_z = 474.67 \text{ N}$$

Required Torque

In order to calculate the torque, we must establish that the lead used for our Lead screws (L) is 5 [mm/rev], that the efficiency of our ball screw (η) is 0.90, and that each torque will be dependent on the total force (F) applied to each axis.

$$T = \frac{F L}{2000 \pi \eta} \quad (2.15)$$

$$T_x = 0.39 \text{ N m}$$

$$T_y = 2.87 \text{ N m}$$

$$T_z = 0.42 \text{ N m}$$

Safety Factor

A factor of safety of 2.0 was applied to the calculated torque requirements to account for uncertainties in the estimated cutting forces, friction, transient acceleration, and future wear of mechanical components. This value is commonly adopted in servo motor sizing for industrial automation systems, providing adequate design margin without leading to excessive motor oversizing.

$$T_{SF} = 2 * T \quad (2.16)$$

$$T_x = 0.78 \text{ N m}$$

$$T_y = 5.74 \text{ N m}$$

$$T_z = 0.84 \text{ N m}$$

Motor Selection

TABLE IV
Comparison of candidate servo motors for the X and Z axes.

Motor	Torque [Nm]	Speed [RPM]	Encoder	Driver	Price
ELM2H-0750LA80E	2.39	3000	23-bit optical	EL6/EL7/EL8	\$279–353
MHMF082L1U2M	2.39	3000	23-bit lead wire	MINAS A6	\$354–522
ECMA-C20807RS	2.39	3000	17-bit incremental	ASDA-B2/A2	\$433–788

The calculated torque requirements for the X and Z axes were 0.78 N·m and 0.84 N·m, respectively. Since all three candidate motors provide a rated torque of 2.39 N·m at a rated speed of 3000 rpm, each motor satisfies the mechanical requirements of the proposed retrofit with a significant design margin. Consequently, the selection criteria focused on secondary characteristics, including encoder resolution, drive compatibility, and overall cost.

Among the evaluated alternatives, both the Leadshine ELM2H-0750LA80E and the Panasonic MINAS A6 MHMF082L1U2M feature high-resolution 23-bit encoders, providing superior positioning accuracy compared to the 17-bit encoder used by the Delta ECMA-C20807RS. Although all three motors are capable of meeting the positioning requirements of the retrofit, the higher encoder resolution offers improved feedback accuracy and smoother closed-loop control, making the Leadshine and Panasonic motors more suitable for precision CNC applications.

From an economic perspective, the Leadshine ELM2H-0750LA80E represents the most cost-effective solution, with an estimated price between \$279.14 and \$353.31, compared to \$353.60 and \$522.00 for the Panasonic motor and \$433.39 to \$787.50 for the Delta alternative. Since all three motors provide identical rated torque and speed, the additional cost of the Panasonic and Delta models does not translate into a significant performance advantage for the intended application. Therefore, the Leadshine ELM2H-0750LA80E was selected for both the X and Z axes because it satisfies all mechanical and control requirements while minimizing the overall retrofit cost.

TABLE V
Comparison of candidate servo motors for the Y-axis.

Motor	Torque [Nm]	Speed [RPM]	Encoder	Driver	Price
ELM2L-2000LA100ET-H MS10A	6.37	3000	23-bit optical	EL7	\$649–677
MHMF152L1H6	7.16	2000	23-bit absolute	MDDL T55SF/N55S	\$265–1,371
ECMA-C21020RS	6.37	3000	17-bit absolute	ASD-A2-2023-M	\$436–1,143

The vertical Y-axis is responsible for supporting and moving the entire spindle assembly and therefore requires a substantially higher rated torque of 5.74 N·m. All three candidate motors exceed this minimum requirement, with rated torques ranging from 6.37 N·m to 7.16 N·m, ensuring sufficient continuous torque for safe operation while providing additional capacity for transient loading during acceleration and machining.

The Leadshine ELM2L-2000LA100ET-H MS10A and the Panasonic MINAS A6 MHMF1-52L1H6 both incorporate 23-bit encoders, whereas the Delta ECMA-C21020RS utilizes a 17-bit encoder. While the Panasonic motor offers the highest rated torque, its lower rated speed of 2000 rpm provides no practical advantage for this application, as the retrofit design does not require torque beyond the calculated design value. Furthermore, the Panasonic motor exhibits the largest price variation among the evaluated alternatives, ranging from \$264.85 to \$1,370.59, making its procurement cost less predictable.

The Leadshine ELM2L-2000LA100ET-H MS10A provides an optimal balance between performance and cost. With a rated torque of 6.37 N·m, a rated speed of 3000 rpm, a 23-bit optical encoder, and compatibility with the EL7 servo drive family, it fully satisfies the design requirements while maintaining a competitive purchase price between \$649.27 and \$677.22. Consequently, the Leadshine motor was selected for the Y-axis because it offers sufficient torque capacity, high-resolution feedback for accurate closed-loop positioning, and the lowest cost among the consistently available industrial alternatives.

Cost Analysis

A preliminary cost analysis was conducted to evaluate the economic feasibility of the proposed retrofit by considering the primary actuation components required for CNC conver-

sion, namely the servo motors and their corresponding servo drives. At this stage of the project, other retrofit components such as motor mounting brackets, couplings, bearings, electrical enclosures, wiring, and control hardware have not yet been finalized; therefore, they are excluded from the present analysis. This section serves as an initial estimate of the investment required for the motion control system and will be expanded during the final stages of the project.

The selected Leadshine servo motors were chosen not only because they satisfy the calculated torque and speed requirements but also because they provide the lowest overall cost among the evaluated alternatives while maintaining high-performance specifications, including 23-bit optical encoders and compatibility with the EL7 family of servo drives. The associated servo drives were selected to ensure full compatibility with the chosen motors and to provide closed-loop position, velocity, and torque control suitable for CNC machining applications.

Table below summarizes the estimated acquisition costs of the selected servo motors and servo drives. Prices correspond to publicly available distributor quotations obtained during the course of this investigation and are presented as approximate values. Actual procurement costs may vary depending on supplier, regional availability, shipping costs, taxes, and quantity discounts.

TABLE VI
Estimated acquisition cost of the selected servo motors and servo drives.

Servo Motor	Qty	Unit Price	Driver	Qty	Unit Price	Total
ELM2H-0750LA80E	1	\$279.14	EL7-EC750F	1	\$400.95	\$680.09
ELM2L-2000LA100ET-H MS10A	1	\$649.27	ASD-A2-2023-M	1	\$573.98	\$1,223.25
Total Investment						\$1,903.34

Mechanical Integration

The retrofit required a method of mechanically coupling the servo motors to the existing feed mechanisms of the manual milling machine. The selected solution needed to transmit sufficient torque for CNC operation while minimizing modifications to the original machine, maintaining serviceability, and preserving structural rigidity.

Design Requirements

Before selecting a mechanical integration strategy, a set of design requirements was established based on the objectives of the retrofit project. Since the goal was to convert an

existing manual milling machine into a CNC system while preserving as much of the original structure as possible, the selected solution was required to:

- Transmit sufficient torque to drive each machine axis under expected machining loads.
- Maintain high positioning accuracy and repeatability for precision machining.
- Reuse the original machine components whenever possible.
- Require minimal permanent modifications to the milling machine.
- Minimize maintenance requirements throughout the machine's service life.
- Fit within the available installation space around each machine axis.

These requirements served as the evaluation criteria for comparing the alternative mechanical integration concepts.

Conceptual Design Alternatives

Two very distinct methods were evaluated for transmitting motion from the servo motors to the axes of the milling machine. The first was a timing belt & pulley transmission between each of the motors and the ball screw of the machine, while the other connected each servo directly to the existing ball screw using a flexible shaft coupler. Both are typical methods for transferring motion in CNC machinery; however, they differ substantially in their accuracy, maintenance, mechanical complexity, and ease of manufacture.

Belt and Pulley Transmission. The first concept consisted of mounting the servo motors remotely and transmitting motion through a timing belt and pulley system. By selecting different pulley diameters, the transmission ratio can be adjusted to reduce motor speed while proportionally increasing the torque delivered to the ball screw. This arrangement also provides great flexibility when presented limited installation space.

Nonetheless, belt-drive systems consist of a number of additional mechanical components including idlers, drive shafts, ball bearing supports and an adjustable tensioning mechanism. Belt stretching due to elastic deformation will necessitate regular readjustment of tension and can develop a degree of flexibility in the transmission system which can affect the accuracy and repeatability of position acquisition, and drastically when there are rapid directional changes in machining, where belt backlash, along with other sources of deflection in the belt, will be accentuated.

Direct Ball Screw Drive. The second concept directly couples each servo motor to the existing precision ball screw through a flexible shaft coupling. Rather than introducing an intermediate transmission, the motor drives the machine's original ball screw directly while replacing only the

manual actuation mechanism. This configuration preserves the original machine kinematics and minimizes the number of additional mechanical components.

One major disadvantage of direct coupling is not providing any form of mechanical gear reduction. Therefore, the servo motors that are applied must be able to provide the amount of torque required to achieve the intended output without any assistance from a transmission ratio. Additionally, there are specific methods to align the motor shaft with respect to the ball screw to prevent excessive loads on the bearings and allow for smooth operation.

TABLE VII

Comparison of the mechanical integration concepts considered for the CNC retrofit.

Evaluation Criterion	Belt and Pulley Transmission	Direct Ball Screw Drive
Speed Reduction	Adjustable through pulley ratios	None (1:1 transmission)
Torque Capacity	Torque multiplication possible through gear reduction	Limited to motor torque capability
Positioning Accuracy	Reduced by belt compliance and elasticity	High due to direct mechanical transmission
Backlash	Possible due to belt stretch and tension variation	Minimal when combined with preloaded ball screws
Mechanical Stiffness	Moderate	High
Maintenance	Requires periodic belt inspection and tension adjustment	Minimal maintenance
Mechanical Complexity	Higher number of pulleys, shafts, bearings and tensioners	Simple assembly with fewer components
Installation Footprint	Larger due to transmission components	Compact motor-to-screw arrangement
Manufacturing Requirements	Several custom transmission components	Primarily motor brackets and flexible couplings
Reuse of Existing Machine	Partial reuse	Maximum reuse of original ball screw mechanism

Selection of the Mechanical Integration Concept

After evaluating both alternatives against the established design requirements, the direct ball screw drive was selected for the proposed CNC retrofit. Although the belt-driven system offers greater flexibility in motor placement and enables torque multiplication through gear

reduction, these advantages were outweighed by its increased mechanical complexity, larger installation footprint, additional maintenance requirements, and potential reduction in positioning accuracy due to belt compliance [23].

The main goal for this project is to create an economically viable upgrade that retains use of the current mill machine. The best way to achieve this goal is to couple servo motors directly onto the original ball screws of the mill. This reduces the total number of parts needed, makes it easy to manufacture and assemble the unit, reduces the need for long-term maintenance, and maximizes the rigidity of the system and the accuracy of its positioning. For these reasons, using this method to integrate the mechanical elements of the new prototype was the chosen alternative.

Motor Placement and Alignment

Following the selection of the direct ball screw drive, the next stage of the retrofit consisted of determining the optimal location and orientation of the servo motors. The placement strategy was guided by preserving the original machine architecture while minimizing the number of modifications required to install the new actuation system. To achieve this, each servo motor was positioned in the location previously occupied by the corresponding manual hand wheel, allowing the existing ball screw mechanism to be retained without altering the machine's kinematic configuration.

The design objective during this phase was to adequately align the ball screw axis to the drive motor shaft axis. Since the drive motor shaft and ball screw are directly coupled together via a flexible coupling, their respective centerlines should be maintained as close to each other as possible. Any excessive angular or parallel misalignments between the two axes will create additional loads on the bearings; thereby, contributing to increased vibration, premature wear on components leading to decreased accuracy when machining the parts. For these reasons, the drive motor mount geometry was designed to ensure that the drive motor shaft is collinear with the existing ball screw and allow only limited deviations from alignment that can be accommodated with the flexible coupling.

Another important consideration was the structural rigidity of the motor supports. Since any deformation of the mounting brackets directly affects the relative position between the motor and the ball screw, the support structures were designed to provide sufficient stiffness while remaining compact enough to fit within the available space around each machine axis. The brackets were also designed to facilitate assembly, maintenance, and future motor replacement

without requiring significant disassembly of the milling machine.

Finally, the complete motor placement and alignment were verified using the SolidWorks CAD assembly. The virtual assembly allowed the identification of possible interferences with existing machine components, confirmed adequate clearance for maintenance operations, and verified the concentric alignment between each servo motor and its corresponding ball screw. This verification ensured that the final mechanical integration satisfied the alignment and packaging requirements established during the conceptual design stage.

Final Motor Mounting Assembly

The final motor mounting assembly was designed to physically support each servo motor in the position and orientation determined during the placement and alignment phase. The assembly had to satisfy the structural, dimensional, and manufacturability requirements established for the retrofit while introducing the fewest possible permanent modifications to the original milling machine.

Structural Support Strategy. The primary structural elements of the motor mounting assembly consist of standard aluminum extrusion profiles (commonly referred to as T-slot or item profiles). Aluminum extrusion profiles were selected for this application due to their high strength-to-weight ratio, dimensional standardization, ease of machining, and wide commercial availability at low cost. Their modular T-slot geometry allows brackets, fasteners, and accessories to be positioned and secured at any point along the profile length without requiring additional drilling or custom machining of the profiles themselves.

Each motor mounting frame was assembled from a combination of profile segments oriented to form a rigid rectangular structure. Corner brackets and standard T-slot fasteners were used at each joint to ensure structural continuity and to allow disassembly without permanent deformation of the components. This approach allows the mounting frames to be reconfigured or replaced independently of the milling machine structure, supporting the maintainability objective of the retrofit.

Interface with the Milling Machine Structure. To anchor the aluminum profile frames to the milling machine, a minimal number of threaded holes were introduced into specific non-critical surfaces of the machine casting. The hole locations were selected to avoid existing structural features, fluid passages, and bearing seats of the original machine. Each anchor point uses a standard metric socket head cap screw threaded directly into the cast iron body of the machine, providing a rigid and permanent connection between the aluminum profile frame and the

machine structure.

The decision to use threaded fasteners rather than adhesive bonding or external clamping was based on three considerations. First, threaded connections provide the structural stiffness required to maintain motor alignment under machining loads and dynamic forces. Second, they allow the mounting frames to be removed and reinstalled without damaging either the machine casting or the aluminum profiles, preserving the reversibility of the retrofit. Third, the small number of holes required represents a minimal and localized modification to the original machine body.

Motor Bracket and Coupling Interface. A custom motor bracket was designed for each axis to serve as the interface between the aluminum profile frame and the servo motor body. Each bracket was designed as a flat plate with two sets of through-holes: one pattern matching the bolt circle of the servo motor face mount, and a second pattern aligned with the T-slot fastener positions of the aluminum profile frame. The brackets were designed to be manufactured from 10 mm thick aluminum plate (Alloy 6061-T6) using standard milling operations, keeping manufacturing requirements within the capability of the target SME environment.

The flexible jaw coupling connecting the servo motor output shaft to the ball screw was housed within the space between the motor face and the end of the ball screw support bearing. The coupling selected for this application is a three-piece jaw type, consisting of two aluminum hubs and a polyurethane spider insert. This coupling type was selected because it tolerates small residual angular and parallel misalignments (typically up to 1° angular and 0.2 mm parallel offset), dampens torsional vibration transmitted between the motor and the ball screw, and requires no lubrication during its service life. The coupling hubs were bored to match the motor output shaft diameter and the exposed end of the ball screw shaft, and secured using radial set screws.

Axis-Specific Implementation. Although the general mounting strategy is consistent across all three axes, the specific geometry of the aluminum profile frame differs between the X, Y, and Z axes due to the distinct spatial constraints and structural context of each axis on the Supermax YC-1.5VA machine.

For the **X-axis**, the servo motor is mounted at the right-hand end of the table travel, replacing the original hand wheel. The aluminum profile frame is anchored to the saddle casting and oriented so that the motor shaft is concentric with the X-axis ball screw. The compact size of the 750 W ELM2H-0750LA80E motor allows the frame to remain within the original machine

envelope without protruding beyond the table overhang.

For the **Y-axis**, the servo motor is installed at the front face of the saddle, replacing the cross-feed hand wheel. Given the higher mass and gravitational load on this axis, the aluminum profile frame for the Y-axis was designed with additional cross-bracing members to increase out-of-plane stiffness and resist the bending moments generated during vertical saddle movement. The 2000 W ELM2L-2000LA100ET-H motor used on this axis has a larger frame size, which was accounted for in the bracket geometry and profile frame depth.

For the **Z-axis**, the servo motor is positioned at the top of the knee column, replacing the knee elevation hand wheel. This location presents the most constrained installation envelope of the three axes due to the proximity of the column structure and the knee locking mechanism. The aluminum profile frame for this axis was therefore designed with a reduced depth profile to respect the available clearance, while maintaining the required structural stiffness through the selection of a heavier profile cross-section (40 mm × 80 mm versus the 40 mm × 40 mm profiles used on the X and Y axes).

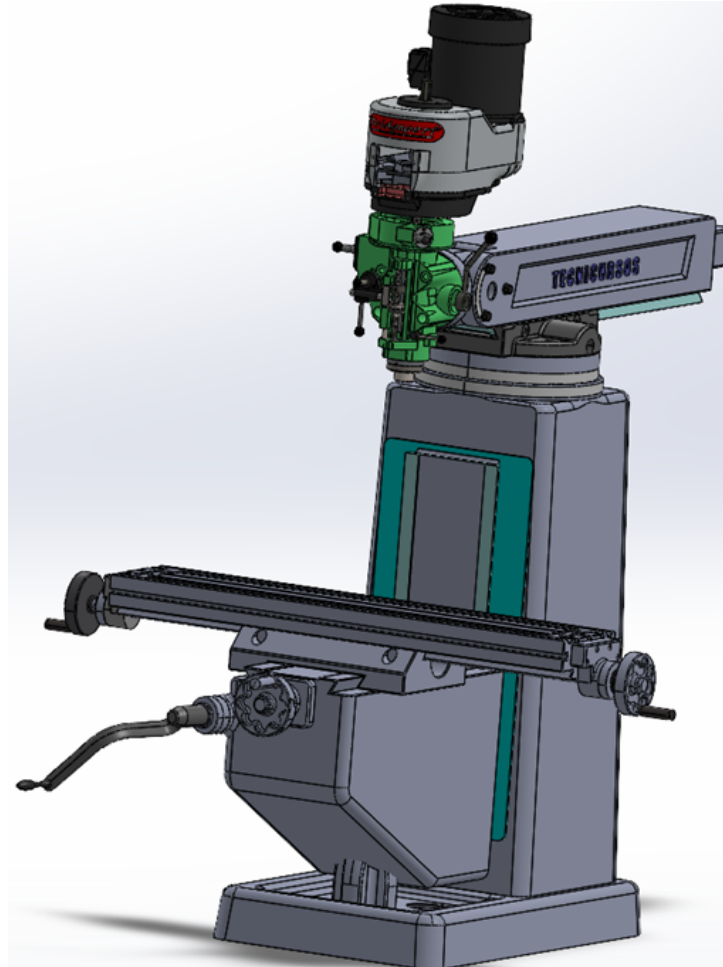
Assembly Verification. The complete motor mounting assembly for each axis was modeled and verified within the SolidWorks CAD environment prior to finalizing the design. The virtual assembly confirmed the absence of geometric interferences between the mounting frames, motor bodies, flexible couplings, and the existing machine components throughout the full travel range of each axis. Shaft concentricity between each servo motor and its corresponding ball screw was verified by inspecting the alignment of the mating component axes in the assembly model, confirming that residual misalignment at each coupling location remained within the manufacturer-specified tolerance of the selected flexible jaw coupling.

Digital Model Development and Assembly Preparation

The development of a digital representation of the milling machine constituted an essential stage of the proposed retrofit methodology. Since no publicly available CAD model of the Supermax YC-1.5VA milling machine could be obtained, a geometrically similar model was sourced from the GrabCAD online repository to serve as the foundation for the mechanical design. Two candidate models were evaluated during this process: a Bridgeport-type turret milling machine and a 45-type milling machine similar to the OPTIMILL MB4. Owing to its closer resemblance in overall geometry, dimensions, and machine configuration, the Bridgeport-type model was selected as the most appropriate reference for the proposed retrofit. Figure 1 illustrates the CAD model adopted as the baseline for the subsequent design and simulation

stages.

Fig. 1. Bridgeport-type CAD model used as the reference for the retrofit design.



Although the selected CAD model closely represented the original machine, several modifications were required before it could be used for simulation. The original assembly contained a high level of geometric detail that unnecessarily increased computational complexity without contributing to the objectives of the dynamic analysis.

In addition to simplifying the geometry, the original solid body was restructured into individual mechanical components corresponding to the moving machine axes. This process involved defining separate bodies for the table, saddle, knee, and remaining structural members, allowing the appropriate kinematic joints and degrees of freedom to be assigned during simulation. These modifications enabled the digital model to accurately reproduce the translational motion of each machine axis while maintaining the overall structural behaviour of the milling machine.

After the assembly was simplified and prepared, the full CAD model of the assembly

was exported from SOLIDWORKS to MATLAB via the Simscape Multibody Link plug-in. The plugin automatically created the XML file and associated geometric shapes for the system hierarchy, component properties, and coordinate system, permitting direct import into Simscape Multibody. The resulting digital assembly served as the foundation for the subsequent implementation of the CNC retrofit, including servo motor integration, control system development, and dynamic performance evaluation.

Digital Model Integration in MATLAB Simulink

Following the completion of the 3D CAD model and the manual calculation of the required servo motor torque and speed specifications, the next phase of the project involved the development and implementation of the control system within the MATLAB Simulink environment. The digital assembly of the retrofitted CNC milling machine was imported into Simulink using the Simscape Multibody Link plugin, which automatically translated the CAD geometry and joint structure into a Simscape Multibody model. This provided a physically representative simulation environment in which the mechanical behavior of the machine could be evaluated under realistic motion control conditions.

Joint Configuration and Axis Motion Mapping

Upon importing the model, the first stage of the control system setup involved organizing and configuring the joints and rigid body elements to correctly replicate the independent motion of each machine axis. The imported model contained a combination of revolute and cylindrical joints, representing the rotational motion of the lead screws driven by the servo motors, and prismatic joints, representing the linear translational motion of the machine's moving assemblies along the X, Y, and Z axes. Dependency relationships were established between these joint types so that the rotational output of each servo motor joint was correctly coupled to the translational displacement of its corresponding prismatic joint and attached structural component. This configuration ensured that the simulated kinematics accurately reflected the physical actuation mechanism of the retrofit system.

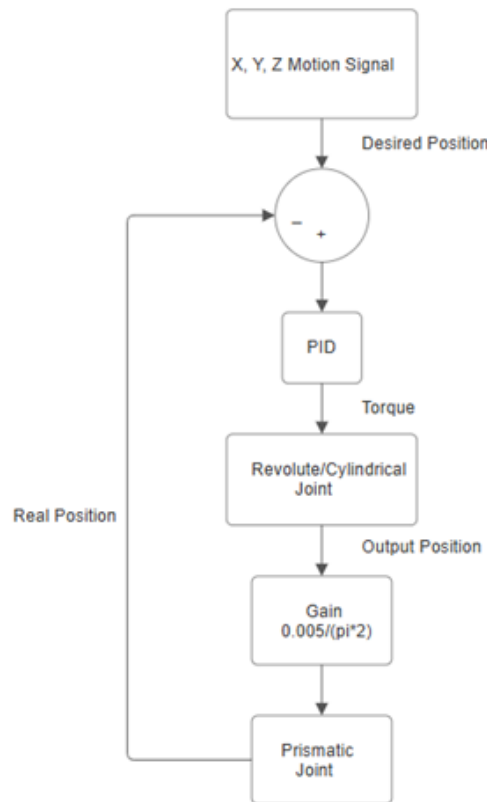
Lead Screw Kinematic Relationship. With the joint dependencies established, the kinematic relationship governing the conversion of rotational motor motion into linear axis displacement was formally defined. This relationship is determined by the lead screw parameters, for the lead screws selected in this retrofit, a lead of $L = 0.005 \text{ m/rev}$ was used. The linear displacement of each axis is therefore expressed as:

$$x = \frac{L}{2\pi}\theta \quad (2.17)$$

This relationship was implemented as a gain block within the Simulink model, converting the angular output of each revolute or cylindrical joint into the corresponding translational input for the associated prismatic joint. The accuracy of this conversion was verified by comparing the simulated axis displacements against expected values derived from the manual calculations, confirming that the model was correctly approximating real-world mechanical behavior before the control layer was introduced.

Closed-Loop PID Controller Implementation. Once the validation of the mechanical model was complete and the movements of each axis were confirmed to function properly, a closed-loop PID (Proportional-Integral-Derivative) controller was successfully applied to each axis of the system. Closed-loop systems function by taking the desired reference position of an axis and continuously comparing it to the actual simulated position of the same axis, producing an error signal that is then used by the closed loop PID controller to determine what corrective torque command should be sent to the servo motor, see Figure XIV for reference. This closed loop feedback mechanism allows for real-time detection and correction of any deviation from the intended path, providing the necessary accuracy and repeatability for CNC machining operations.

Fig. II. Block diagram of the simulation and control logic.



Each of the three axes was assigned a separate PID controller because the X, Y, and Z axes function as independent mechanical systems that have different inertial and friction characteristics. In order to obtain stability in response to a dynamic system for each axis, tuning of the proportional, integral, and derivative gains for each controller occurred within the Simulink environment, which resulted in the minimization of overshoot, steady-state error, and settling times for representative machining trajectories.

Performance Evaluation

During the data collection process, the analytical calculations and the dynamic simulation were used to evaluate the machine under different operating assumptions. Analytical calculations represent a conservative analysis by including all effects of gravitational load, inertial force, friction and estimated cutting forces to arrive at the maximum actuator requirement that can occur due to the operation of machinery in the real world. On the other hand, the Simscape Multibody simulation is an analysis of the dynamic performance of the CNC system that does not include modeling of the entire cutting process between the tool and the workpiece. Therefore, the simulated actuator requirements will be a function exclusively of the machine's dynamics, controller performance, inertia and gravitational load.

The performance metrics extracted from the simulation were selected according to the manner in which each axis is actuated within the multibody model. For the X- and Z-axes, the revolute joints directly represent the lead screw actuation responsible for generating linear motion; therefore, the motor torque measured at these revolute joints provides the most representative indication of actuator demand.

Conversely, the Y-axis supports the vertical spindle assembly and is continuously subjected to gravitational loading. In this case, the prismatic joint actuator force provides a more representative measure of the mechanical load acting on the axis than the revolute joint torque. The measured linear force can be directly compared with the analytical force calculations or converted to an equivalent motor torque using the lead screw relationship when required. This approach ensures that the quantities compared between the analytical model and the simulation are physically meaningful and accurately represent the dominant loading mechanisms of each axis.

PID Gain Sensitivity Analysis Using a Full Factorial Design

The objective of this experiment was to evaluate the influence of the proportional (K_p), integral (K_i), and derivative (K_d) gains on the positioning accuracy and torque requirements of the proposed CNC retrofit system. A 2^3 full factorial design was employed, in which each controller parameter was varied between 50% (Low) and 150% (High) of its nominal tuned value while maintaining the remaining parameters at their prescribed test levels. This approach enabled a systematic assessment of the individual effects of each controller gain, as well as their interaction effects. Tables VIII–X present the root mean square (RMS) position error, the maximum trajectory error, and the peak motor torque recorded during the machining simulation for each experimental run.

TABLE VIII
Gain sensitivity data results for the X-axis.

Run	K_p, K_i, K_d	RMS Error (mm)	Max Error (mm)	Peak Torque (N m)
1	L-L-L	0.198	0.682	4.145
2	H-L-L	0.073	0.257	3.985
3	L-H-L	0.198	0.724	4.244
4	H-H-L	0.072	0.249	4.032
5	L-L-H	0.081	0.347	3.971
6	H-L-H	0.058	0.186	4.138
7	L-H-H	0.101	0.461	4.210
8	H-H-H	0.061	0.200	4.211

TABLE IX
Gain sensitivity data results for the Y-axis.

Run	K_p, K_i, K_d	RMS Error (mm)	Max Error (mm)	Peak Torque (N m)
1	L-L-L	0.009	0.057	2.233
2	H-L-L	0.003	0.022	2.227
3	L-H-L	0.006	0.061	2.236
4	H-H-L	0.002	0.018	2.227
5	L-L-H	0.007	0.047	2.228
6	H-L-H	0.002	0.022	2.226
7	L-H-H	0.007	0.049	2.229
8	H-H-H	0.002	0.017	2.226

TABLE X
Gain sensitivity data results for the Z-axis.

Run	K_p, K_i, K_d	RMS Error (mm)	Max Error (mm)	Peak Torque (N m)
1	L-L-L	0.194	0.486	1.589
2	H-L-L	0.063	0.167	1.513
3	L-H-L	0.186	0.463	1.852
4	H-H-L	0.062	0.170	1.474
5	L-L-H	0.070	0.269	2.714
6	H-L-H	0.052	0.129	2.411
7	L-H-H	0.085	0.319	2.785
8	H-H-H	0.055	0.144	2.412

As shown above, increasing the proportional gain K_p resulted in a noticeable improvement in tracking accuracy for all three machine axes. Variations in the integral gain K_i produced comparatively small changes in both the RMS and maximum positioning errors, whereas increasing the derivative gain K_d generally reduced the tracking error at the expense of a slight increase in the required peak motor torque.

The Y-axis exhibited the highest positioning accuracy among the three machine axes. The RMS tracking error remained below 0.01 mm for every experimental run, indicating that the controller maintained excellent tracking performance regardless of the gain combination. The Z-axis displayed behavior similar to that of the X-axis; however, the derivative gain had a more pronounced influence on the required motor torque. Increasing K_d improved the positioning accuracy but increased the peak torque demand from approximately 1.5 Nm to nearly 2.8 Nm, illustrating the trade-off between tracking performance and actuator effort.

Following the collection of the positioning and torque data for all experimental runs, a one-way Analysis of Variance (ANOVA) was performed on the measured performance metrics. The RMS tracking error, maximum positioning error, and peak actuator torque were selected as the response variables to evaluate tracking performance, quantify positioning accuracy, and identify the PID gain parameters that contributed most significantly to the dynamic behavior of the system. This statistical approach enabled a structured comparison of the eight factorial experiments and provided a basis for identifying the controller gain combinations that produced the most favorable dynamic response.

$$\text{RMS}_{\text{overall}} = \sqrt{\frac{\text{RMS}_x^2 + \text{RMS}_y^2 + \text{RMS}_z^2}{3}} \quad (2.18)$$

TABLE XI
Overall RMS tracking error from X, Y, and Z-axis.

Run	RMS _X (mm)	RMS _Y (mm)	RMS _Z (mm)	Overall RMS (mm)
1	0.198	0.009	0.194	0.160
2	0.073	0.003	0.063	0.056
3	0.198	0.006	0.186	0.157
4	0.072	0.002	0.062	0.055
5	0.081	0.007	0.070	0.062
6	0.058	0.002	0.052	0.045
7	0.101	0.007	0.085	0.076
8	0.061	0.002	0.055	0.047

Effect of Feed Rate on Tracking Accuracy and Actuator Demand

The objective of this experiment was to evaluate the influence of machining feed rate on the dynamic performance of the proposed CNC retrofit system. While maintaining identical controller parameters and toolpath geometry, the trajectory execution speed was progressively increased by varying the programmed feed rate from 800 mm/min to 2400 mm/min; see table XII. For each operating condition, the overall RMS tracking error, overall maximum position error, and peak actuator torque were recorded. This analysis established the relationship between machining productivity and control performance, enabling identification of practical operating limits before positioning accuracy or actuator loading became unacceptable.

TABLE XII
Effect of feed rate on the overall tracking error and peak actuator torque.

Feed Rate (mm/min)	Overall RMS (mm)	Overall Max (mm)	Peak Torque (N m)
800	0.026	0.077	2.411
960	0.032	0.096	2.916
1200	0.045	0.131	4.138
1600	0.067	0.202	6.796
2400	0.110	0.353	13.391

Effect of Gear Geometry Complexity on CNC Tracking Performance

This experiment was to investigate the influence of gear geometry complexity on the dynamic performance of the proposed CNC retrofit system. The complexity of the machining trajectory was varied by modifying two key geometric parameters of the gear profile: the number of teeth (N) and the tooth height (h); as detailed in table XIII. Four representative gear geometries were evaluated while maintaining identical controller parameters, feed rate, and machine configuration. For each test, the overall RMS tracking error, overall maximum position error, and peak actuator torque were recorded and placed in table XIV to assess the retrofit system's ability to accurately follow increasingly demanding machining trajectories.

TABLE XIII

Experimental conditions used to evaluate the influence of gear complexity on controller performance.

Run	Number of Teeth (N)	Tool Height (h) [mm]
1	10	5
2	30	5
3	10	10
4 (Nominal)	20	10
5	30	10

TABLE XIV

Influence of gear complexity on tracking accuracy and peak actuator torque.

Run	Teeth	Tool Height (mm)	Overall RMS (mm)	Overall Max (mm)	Peak Torque (N m)
1	10	5	0.018	0.040	2.411
2	30	5	0.041	0.143	4.970
3	10	10	0.022	0.053	2.411
4	20	10	0.045	0.131	4.138
5	30	10	0.073	0.241	9.381

Chapter III

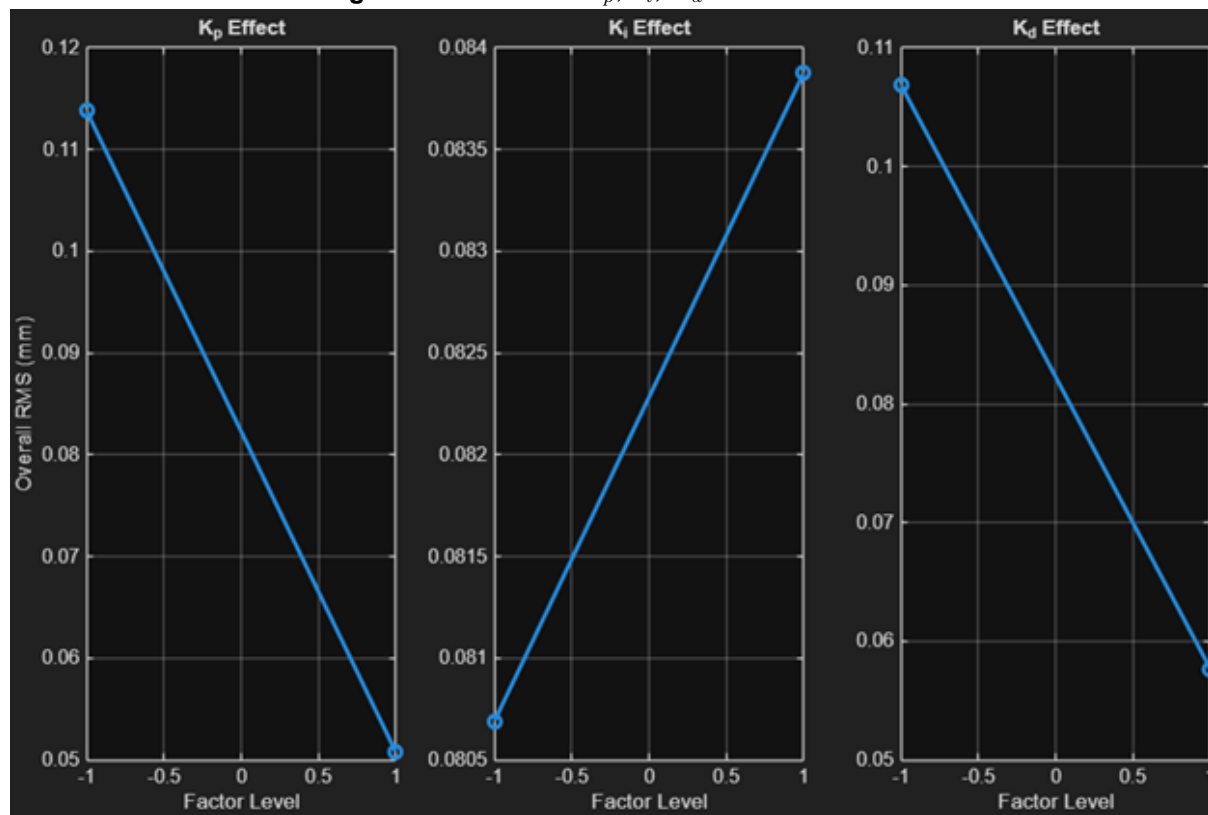
Results & Discussion

Obtained Results

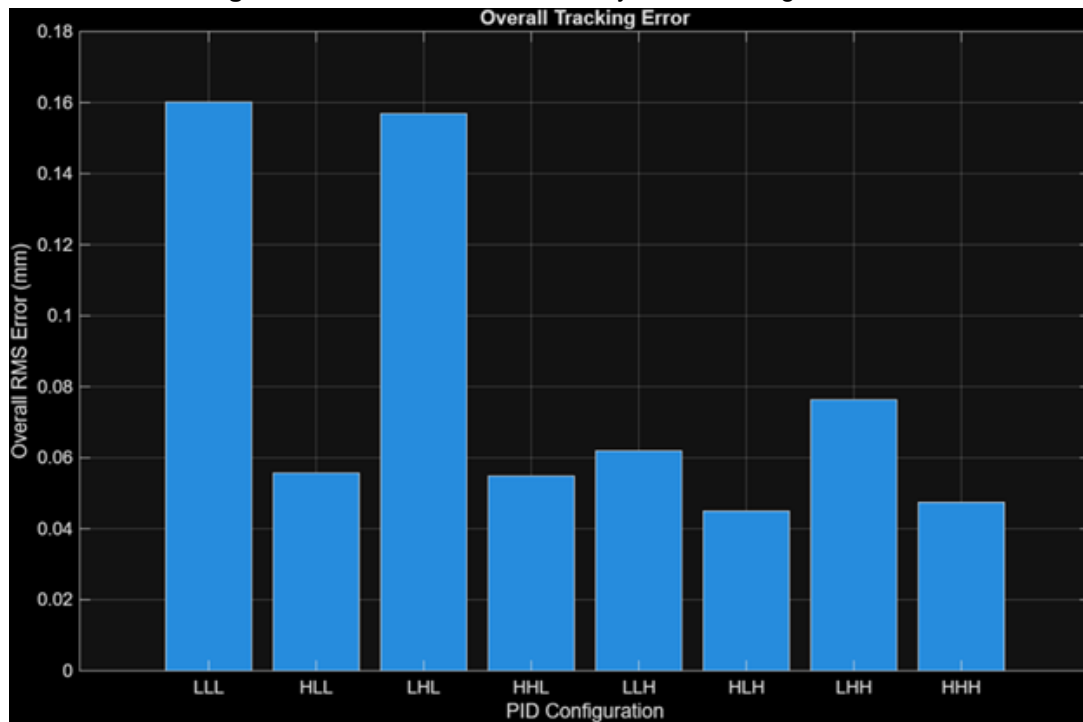
Overall RSM Analysis

The ANOVA results indicated that the proportional gain K_p is the dominant factor influencing overall RMS tracking error as seen in Figure III.

Fig. III. Influence of K_p, K_i, K_d over RMS error.

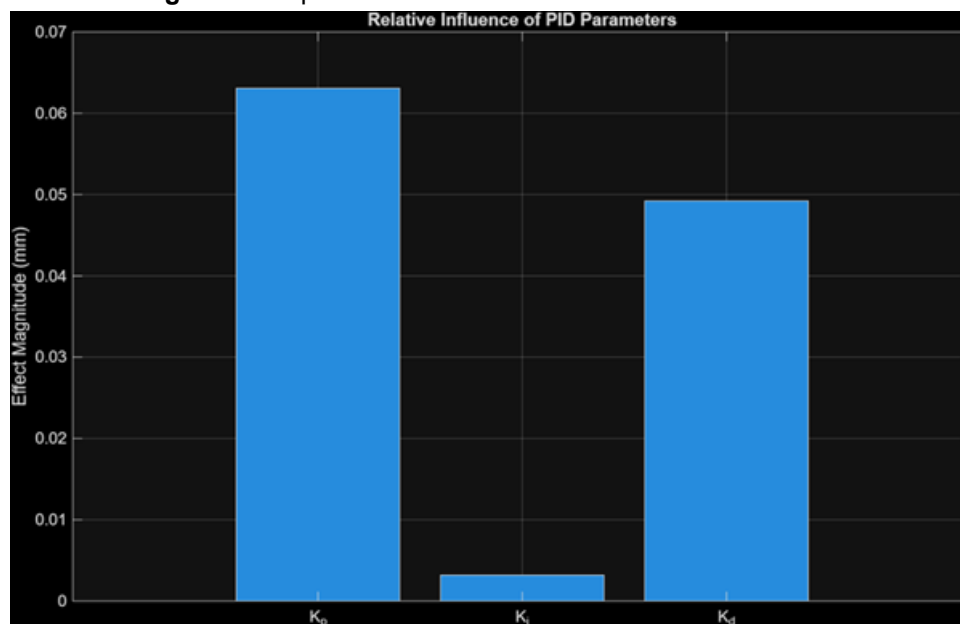


Runs in which K_p was set to its high level consistently produced lower positioning errors regardless of the K_i and K_d settings, confirming that the proportional term is the primary contributor to steady-state tracking performance. Runs 6 and 8 produced the most accurate overall machine performance, achieving the lowest overall RMS tracking errors of 0.045 mm and 0.047 mm, respectively. Conversely, Runs 1 and 3 produced the highest overall RMS tracking errors, demonstrating that reducing the proportional gain significantly degrades tracking accuracy across all machine axes, as shown in Figure IV.

Fig. IV. Overall Error influenced by control configurations.

Overall Max Error Analysis

The overall maximum error results are consistent with the RMS error findings. The ANOVA analysis confirms that K_p remains the most influential parameter on worst-case positioning deviation, while the effect of K_i was found to be comparatively minor, as evidenced in Figure V.

Fig. V. Comparison between influence of PID Parameters.

Unlike the RMS and maximum error metrics, peak actuator torque was not averaged across the three axes. Since each axis is driven by an independent servo motor, the torque demand on one axis does not influence the loading of another. Therefore, reporting a combined average would obscure the true mechanical demand placed on individual actuators. Instead, the X-axis peak torque was selected as the representative metric for this analysis, as the X-axis consistently exhibited the highest torque demand across all experimental runs due to its dominant role in executing the primary cutting trajectory.

Fig. VI. Comparison of X-Axis Position Tracking Performance Between the Best and Worst PID Configurations.

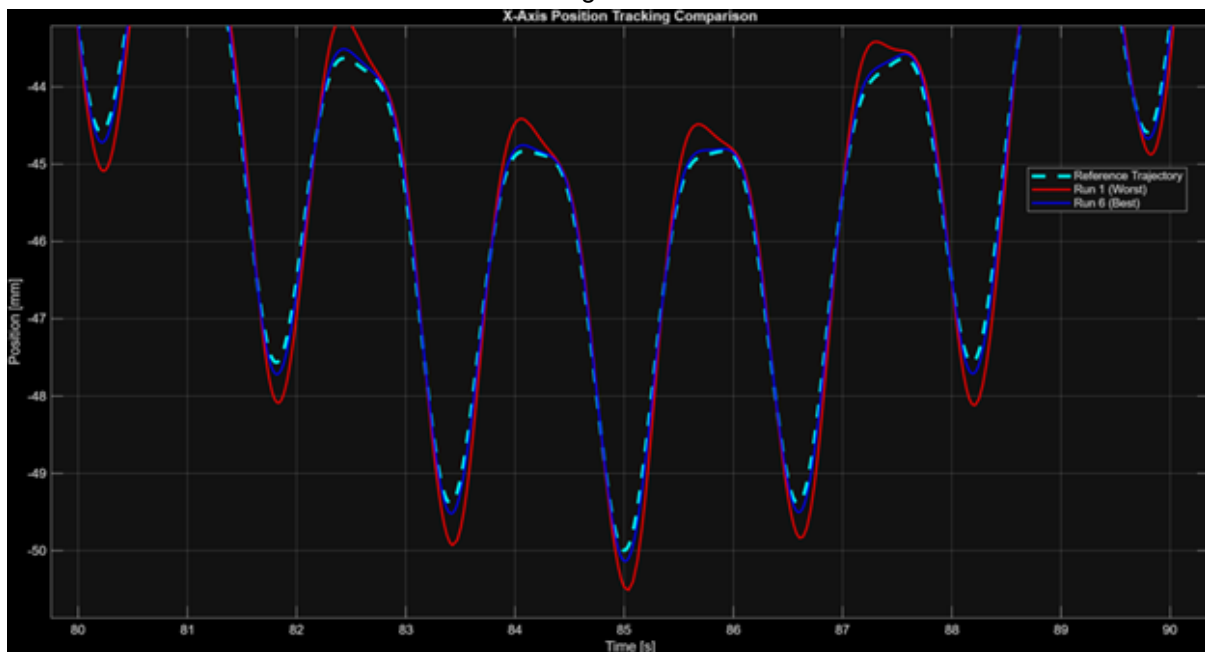
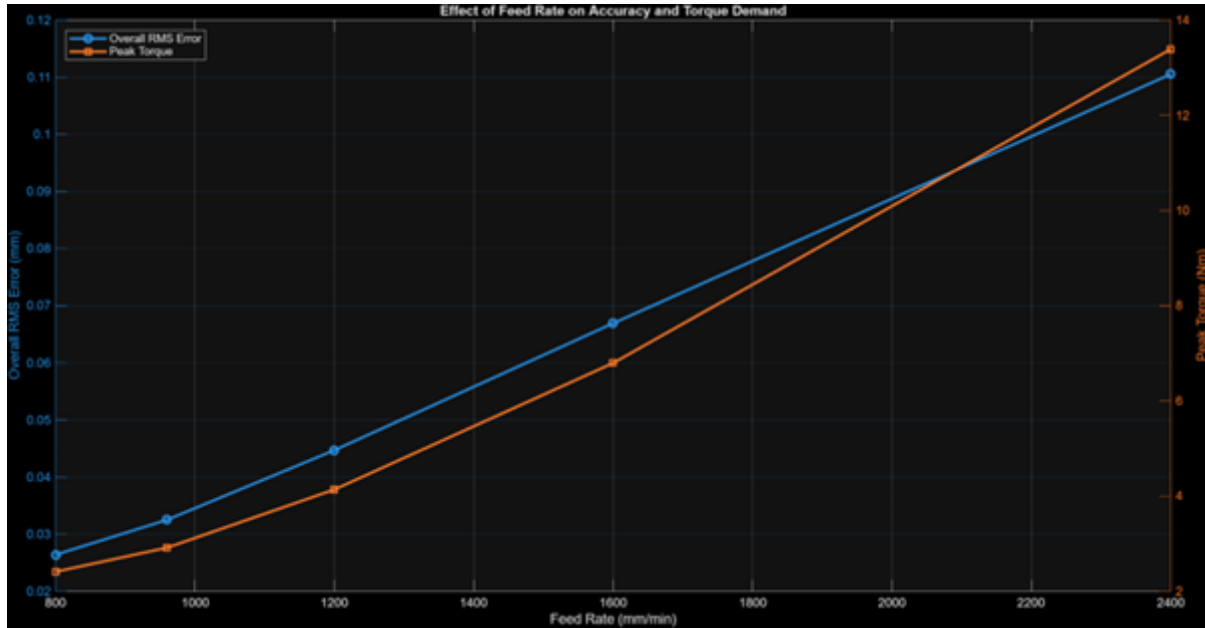


Figure VI presents a direct comparison of the X-axis position tracking performance between the best-performing configuration (Run 6) and the worst-performing configuration (Run 1). The largest differences between the two controllers are observed at the peaks and valleys of the trajectory, where rapid changes in direction impose the greatest dynamic demands on the servo system. Run 6 consistently maintains a smaller tracking error than Run 1 throughout the entire machining cycle, corroborating the RMS and maximum error results obtained from the ANOVA analysis. This visual comparison further confirms that the optimized PID gains provide superior dynamic performance and more accurate positioning of the retrofitted CNC milling machine, particularly during the most demanding phases of the toolpath.

Feed Rate influence Analysis

The experimental results demonstrated a clear relationship between feed rate and system performance. As the machining feed rate increases, both the tracking error and actuator torque demand increase consistently, as visually seen in Figure VII.

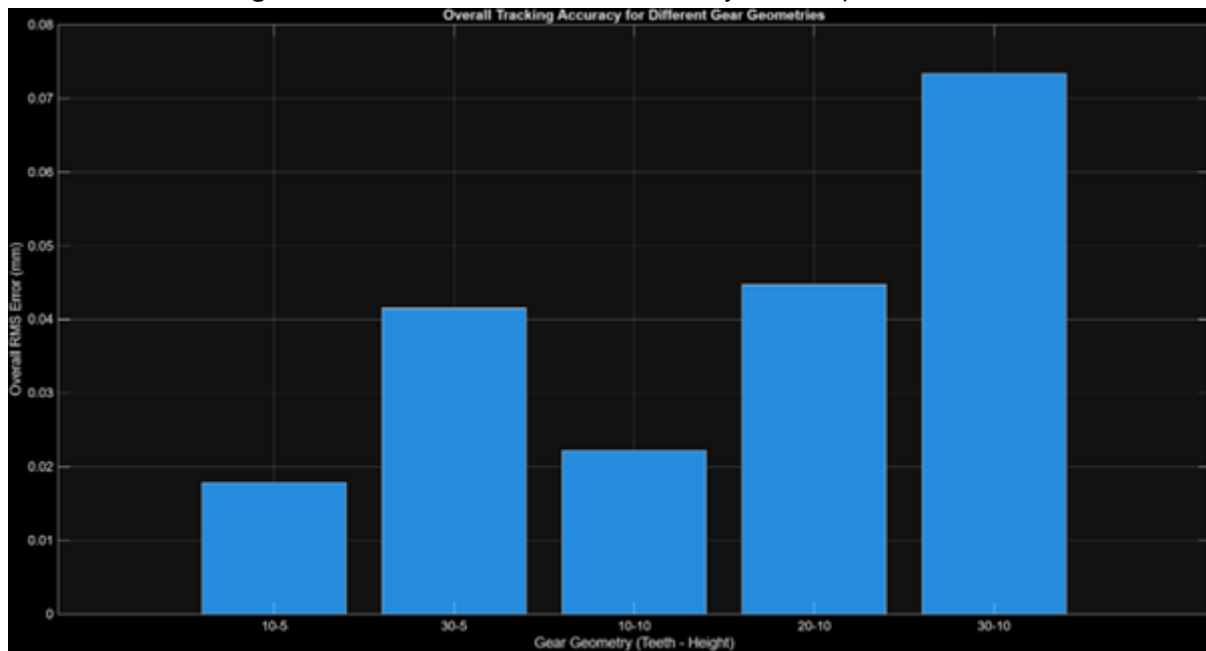
Fig. VII. Effect of Feed Rate on Accuracy and Torque Demand.



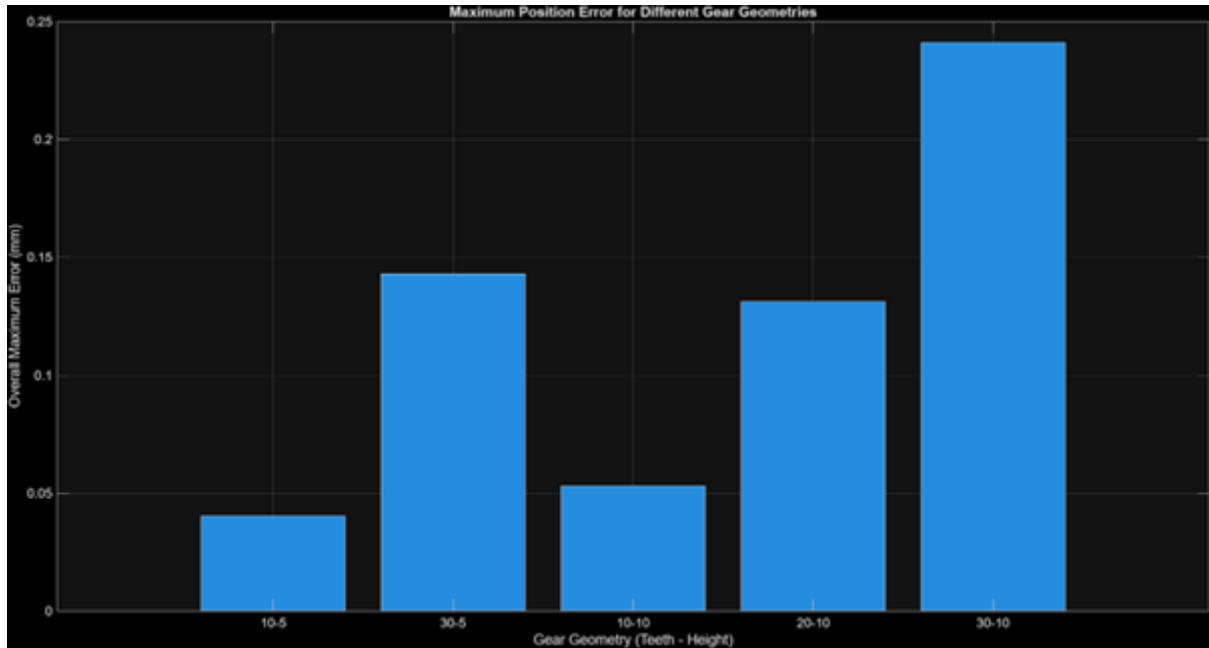
The overall RMS tracking error rises from 0.026 mm at 800 mm/min to 0.110 mm at 2400 mm/min, while the overall maximum positioning error increases from 0.077 mm to 0.353 mm over the same operating range. Similarly, the peak actuator torque increases from 2.411 Nm to 13.391 Nm, indicating that higher machining speeds require substantially greater motor effort to accurately follow the prescribed trajectory. Although increasing the feed rate improves machining productivity by reducing cycle time, the results indicate an inevitable compromise between productivity and positioning performance.

Gear Geometry Complexity Analysis

The experimental results demonstrate a consistent relationship between gear geometry complexity and controller performance. The lowest positioning error and actuator demand occurred for the simplest geometry (10 teeth, 5 mm tooth height), whereas the highest values were observed for the profile containing 30 teeth and a 10 mm tooth height, as seen in Figure VIII.

Fig. VIII. Effect of Feed Rate on Accuracy and Torque Demand.

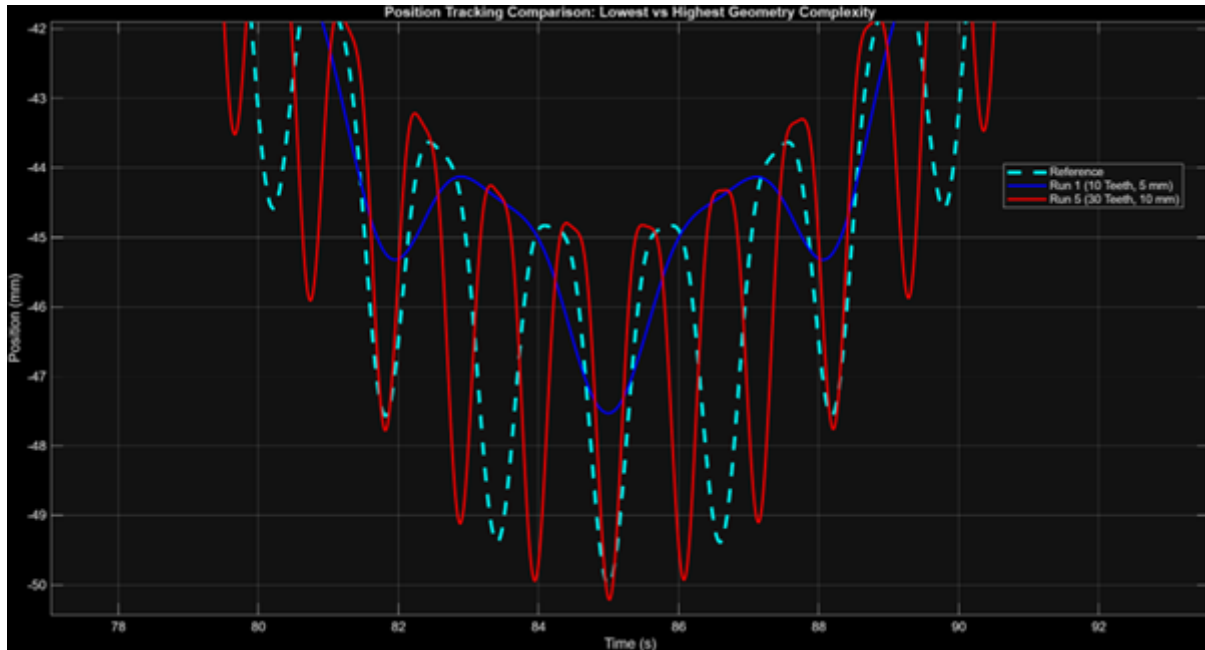
The influence of tooth count is particularly evident when comparing Runs 1 and 2, which share the same tooth height of 5 mm but differ in tooth count. Increasing the number of teeth from 10 to 30 caused the RMS error to more than double, the overall maximum error to increase by approximately 258%, and the peak torque demand to rise from 2.411 Nm to 4.970 Nm. This pattern is further reinforced by comparing Runs 3 and 5, where the same increase in tooth count at a height of 10 mm produced a similar escalation across all three metrics, as seen in Figure IX, with peak torque rising dramatically from 2.411 Nm to 9.381 Nm, representing an increase of nearly 290%.

Fig. IX. Maximum Position Error for Different Gear Geometries.

In contrast, the effect of increasing tooth height from 5 mm to 10 mm while keeping the tooth count constant was considerably more modest. Comparing Runs 1 and 3, which both contain 10 teeth, the increase in tooth height produced only a marginal rise in RMS error from 0.018 mm to 0.022 mm and in maximum error from 0.040 mm to 0.053 mm, while peak torque remained unchanged at 2.411 Nm.

The nominal geometry (20 teeth, 10 mm height, Run 4) produced intermediate values across all response variables, with an RMS error of 0.045 mm, a maximum error of 0.131 mm, and a peak torque of 4.138 Nm, confirming that it represents a realistic and representative machining condition between the two performance extremes, as shown in Figure X.

Fig. X. Position Tracking: Lowest vs Highest Geometry Complexity.



The results confirm the expected behavior of a closed-loop servo control system under varying trajectory demands. Gear profiles containing a larger number of teeth require the machine axes to perform more frequent accelerations and decelerations within the same machining distance. Consequently, the servo motors experience greater dynamic loading, resulting in increased tracking error, larger worst-case positional deviations, and significantly higher peak torque demand. Although increasing tooth height also increases the required axis displacement per cycle, its influence on system performance was found to be considerably smaller than that of increasing tooth count. Importantly, even under the most demanding geometry tested, the system remained stable and operational, with all performance metrics within acceptable bounds for precision machining applications, demonstrating the robustness of the proposed CNC retrofit design.

Discussion

Motor Selection and Actuator Performance Validation

The initial actuator selection for the retrofit system was performed analytically, based on the mechanical load requirements of each axis derived from cutting force estimations, inertia calculations, and lead screw dynamics. This analysis yielded a maximum continuous torque requirement of 0.39 Nm for the X-axis, which, after applying a safety factor of 2, established a design target of 0.78 Nm. Based on these calculations, the X and Z axes were assigned the Leadshine ELM2H-0750LA80E servo motor paired with the EL7-RS 750W servo driver, at a combined unit cost of \$680.09 per axis, while the Y-axis was assigned the higher-capacity Leadshine ELM2L-2000LA100ET-H MS10A servo motor with the EL7-EC 2000W servo driver, at a combined cost of \$1,223.25.

However, simulation results revealed a significant discrepancy between the analytically predicted and simulated torque demands on the X-axis. The simulation recorded a peak torque of 4.244 Nm and an average continuous torque of 0.716 Nm on the X-axis, representing values nearly 7 times greater, at their peak, than the analytically calculated design target of 0.78 Nm. This finding suggests that the analytical model, which was based on idealized cutting conditions and simplified dynamic assumptions, underestimated the true torque demands imposed by trajectory pathing under varying machining geometries and feed rates.

In light of these simulation results, it is recommended that the Leadshine ELM2L-2000 LA100ET-H MS10A servo motor paired with the EL7-EC 2000W driver be adopted for the X-axis as well as the Y-axis, replacing the originally specified lower-capacity unit. This motor demonstrated a rated torque capacity consistent with the simulated peak demands observed during the geometry complexity and feed rate experiments, providing adequate operational margin. Under this revised configuration, the total actuator cost for the X and Y axes increases to \$2,446.5, while the Z-axis retains the originally specified ELM2H-0750LA80E and EL7-RS 750W combination at \$680.09, bringing the combined actuator investment for all three axes to approximately \$3,126.59.

Economic Feasibility

A central motivation for the proposed retrofit approach is the economic barrier associated with acquiring new CNC milling equipment. Commercial three-axis CNC milling machines suitable for SME manufacturing environments are available within a price range of approximately \$10,000 to \$30,000 USD. As a representative benchmark, the WMT CNC 3-Axis Pre-

cision Small Milling Machine XH7122 is commercially available at \$13,900 USD, a figure that represents the lower segment of the market for machines of comparable capability.

Under the revised actuator configuration informed by simulation results, the total estimated investment for the primary electromechanical components of the retrofit system amounts to approximately \$3,126.59 USD. Even when accounting for additional system components such as the CNC motion controller, wiring, mechanical couplings, mounting hardware, and integration labor, the total retrofit cost is expected to remain substantially below the \$13,900 benchmark, and well within a range that is economically accessible to SMEs.

These results confirm that CNC retrofitting represents a viable and scalable economic alternative for manufacturing environments where capital investment is constrained, provided that the actuator specification is informed by simulation-validated torque demands rather than analytical estimates alone.

Simulation Limitations and Design Considerations

While the simulation environment provided valuable insight into the dynamic behavior of the retrofit system, several limitations must be acknowledged. The Simscape Multibody model, although geometrically representative, does not account for thermal effects on motor performance, mechanical backlash in the lead screw assemblies, structural deflection of the machine frame under cutting loads, or tool-workpiece interaction forces. These factors may introduce additional sources of error and torque demand in a physical implementation that were not captured in the present simulation.

Furthermore, the discrepancy between the analytically calculated and simulated X-axis torque highlights the importance of simulation-based validation as a necessary complement to analytical sizing methods, particularly in systems where dynamic trajectory complexity and multi-axis coupling can significantly alter the actual load profile experienced by each actuator. Future work involving physical implementation should incorporate empirical torque measurements during actual machining operations to further validate and refine the actuator specifications established in this study.

Conclusions

A geometrically representative three-dimensional digital model of the Supermax YC-1.5VA milling machine was successfully developed by sourcing and adapting a Bridgeport-type CAD model from the GrabCAD online repository. The model was modified to separate individual moving assemblies, assign appropriate kinematic joints, and reduce computational complexity, enabling accurate representation of the X, Y, and Z axis translational motion within the MATLAB Simulink and Simscape Multibody simulation environment. This confirmed that publicly available CAD resources can serve as viable foundations for retrofit design studies when proprietary machine models are unavailable.

A closed-loop PID motion control system was successfully implemented and validated across all three machine axes. The 2^3 full factorial sensitivity analysis identified the proportional gain K_p as the dominant controller parameter influencing positioning accuracy, while the integral gain K_i had a comparatively minor effect. The optimal controller configuration (Run 6: High K_p , Low K_i , High K_d) achieved the best overall tracking performance, with an RMS error of 0.045 mm and a maximum positional error of 0.131 mm, demonstrating that the proposed retrofit system is capable of achieving positioning accuracy consistent with CNC milling requirements.

Feed rate analysis established that a machining speed of 1200 mm/min represents the recommended operating point for the proposed retrofit, providing an acceptable balance between positioning accuracy and machining productivity. Beyond this threshold, both tracking error and actuator torque demand increase significantly and non-linearly, with the peak torque rising from 4.138 Nm at 1200 mm/min to 13.391 Nm at 2400 mm/min, indicating that higher feed rates impose rapidly escalating dynamic demands on the servo system that may not be sustainable in continuous machining operations.

Gear geometry complexity analysis confirmed that trajectory frequency, determined by the number of gear teeth, is the primary driver of both positioning error and actuator torque demand, while tooth height exerts only a marginal influence on system performance. When the number of teeth increases from 10 to 30, there is approximately a 400% increase in the maximum positional error and up to a 297% increase in the peak actuation torque. The closed-loop control system has shown to possess stability and functioning ability, throughout all of the geometries that were used to test the performance of the system, which confirms that the

closed-loop control structure is robust regardless of the range of the trajectory requirements.

A significant discrepancy was identified between the analytically calculated and simulation-derived torque requirements for the X-axis. The static analytical model predicted a maximum design torque of 0.78 Nm for the X-axis, whereas the dynamic simulation recorded a peak torque of 4.244 Nm and an average continuous torque of 0.716 Nm. This finding demonstrates that static analytical sizing methods, while useful for preliminary motor selection, are insufficient on their own to characterize the true dynamic load demands of a CNC retrofit system. As a result, the actuator specification for the X-axis was revised to the Leadshine ELM2L-2000LA100ET-H MS10A, bringing the total three-axis actuator investment to approximately \$3,126.59.

The economic feasibility analysis confirmed that CNC retrofitting represents a cost-effective and scalable alternative to the acquisition of new CNC equipment for (SMEs). The revised total actuator cost of approximately \$3,126.59 represents a potential cost reduction of over 77% compared to the \$13,900 benchmark price of a comparable commercial three-axis CNC milling machine. This economic advantage is further reinforced by the preservation of the existing machine structure, which eliminates capital expenditure on a new machine frame while extending the productive life of existing equipment and reducing industrial material waste.

Recommendations

Future work should pursue the physical implementation of the proposed CNC retrofit on the Supermax YC-1.5VA or a mechanically equivalent milling machine. Physical implementation would allow empirical validation of the simulation results, including the torque demands recorded for each axis, and would provide the experimental data necessary to fully characterize the system's performance under real cutting conditions with tool-workpiece interaction forces.

Advanced controller tuning methods, such as model-based predictive control, adaptive PID, or iterative learning control, should be explored to further improve trajectory tracking accuracy, particularly during high-speed and high-complexity machining operations where the fixed-gain PID controller demonstrated increasing tracking error. These approaches may also reduce the sensitivity of system performance to variations in K_p identified in this study.

It is recommended that future retrofitting projects include a simulation-based dynamic torque analysis prior to final motor selection, rather than relying exclusively on static analytical sizing methods. The significant discrepancy between the analytically predicted and simulated X-axis torque demonstrated in this study confirms that dynamic simulation is essential for accurate actuator specification, and that analytical safety factors alone may not adequately account for trajectory-induced torque peaks.

A comprehensive cost analysis incorporating all retrofit components, including the CNC motion controller, mechanical couplings, motor mounting hardware, electrical enclosures, wiring, and integration labor, should be conducted to provide a complete and accurate total investment estimate. This would allow for a more precise comparison with new CNC equipment and would strengthen the economic feasibility argument presented in this study.

References

- [1] C. Maqshudi, "Specific cutting force k_c (mpa)," *N/A*, p. 1, 2020.
- [2] A. Ladj, A. Ennouri, and M. Kardas, "A knowledge-based digital shadow for machining industry in a digital twin perspective," *Journal of Manufacturing Systems*, 2023.
- [3] G. Martinov, S. Arakelian, E. Ivanov, and I. Pavlov, "An approach to using a cnc machine digital shadow and cloud-based technologies at the machine shop floor level," *The International Journal of Advanced Manufacturing Technology*, vol. 129, pp. 2415–2427, 2023.
- [4] J. Belanger, "Cnc retrofits," *Modern Machine Shop*, vol. 92, no. 5, pp. 56–60, 2020.
- [5] S. P. Granados, "Conversión de una fresadora manual a automática para uso didáctico," 2023.
- [6] K. Zhuang, L. Wu, B. Xu, and D. Wang, "Digital twin-driven tool wear monitoring and predicting method for the turning process," *Symmetry*, vol. 13, no. 8, pp. 1–23, 2021.
- [7] J. Wen, C. Liu, W. Huang, H. Zhao, and D. Zhou, "Evolution and development trend prospect of metal milling equipment," *Chinese Journal of Mechanical Engineering*, vol. 36, no. 1, pp. 1–14, 2023.
- [8] R. G. Sánchez, "Reacondicionamiento (retrofit) de una fresadora cnc de sobremesa: Construcción del controlador cnc," 2024.
- [9] J. C. Cardona, "Rehabilitación de fresadora didáctica cnc e integración a una celda de manufactura flexible de mecanizado," 2020.
- [10] P. Stepanic, G. Vilic, Z. Sasa, and I. Ivica, "Retrofitting a conventional horizontal milling machine to cnc machine tool," *Annals of Faculty Engineering Hunedoara – International Journal of Engineering*, vol. 18, no. 3, pp. 185–188, 2020.
- [11] K. K. G. Anusha, K. Divya, K. B. Reddy, and S. Priyanka, "Retrofitting of cnc bench milling machine with raspberry pi," *International Research Journal of Engineering and Technology (IRJET)*, vol. 8, no. 8, pp. 3937–3940, 2021.
- [12] M. Askin, Z. Campise, D. Lonczak, and F. Samano, "Final design review: Cnc retrofits," California Polytechnic State University, Tech. Rep., 2023.
- [13] N. Hatem *et al.*, "Interpreting the G-code of drilling machining to use in open CNC controller machine," *Journal of Physics: Conference Series*, pp. 1–7, 2021.
- [14] K.-C. Yao, D.-C. Chen, C.-H. Pan, and C.-L. Lin, "The development trends of computer numerical control (CNC) machine tool technology," *Mathematics*, pp. 1–33, 2024.
- [15] M. Soori, F. K. G. Jough, R. Dastres, and B. Arezoo, "Robotical automation in CNC machine tools: A review," *Advances in Manufacturing Engineering*, vol. 18, no. 3, pp. 1–17, 2024.
- [16] Rahmatullah, A. Amiruddin, and S. Lubis, "Effectiveness of CNC turning and CNC milling in machining process," *International Journal of Economic, Technology and Social Science*, vol. 2, no. 2, pp. 575–583, 2022.
- [17] H. Gai, X. Li, F. Jiao, X. Cheng, X. Yang, and G. Zheng, "Application of a new model reference adaptive control based on PID control in CNC machine tools," *Machines*, vol. 9, no. 11, p. 274, 2021.
- [18] S. T. Almeida, J. P. T. Mo, C. Bil, S. Ding, and X. Wang, "Servo control strategies for vibration control in robotic wire EDM machining," *Archives of Computational Methods in Engineering*, pp. 1–15, 2021.
- [19] K. Tsutsui, K. Kaji, K. Naito, N. Chujo, and T. Mizuno, "High-performance synchronized control between spindle and servo motors for CNC equipment," *International Journal of Informatics Society*, vol. 13, no. 2, pp. 1–11, 2021.
- [20] S. S. H. Al-Maeni, C. Kuhnhen, B. Engel, and M. Schiller, "Smart retrofitting of machine tools in the context of industry 4.0," in *Procedia CIRP*, 2023, pp. 1–6.
- [21] J. Anziani, "G-code based toolpath simulation for predicting CNC energy consumption," Master's thesis, Massachusetts Institute of Technology, 2025.

- [22] K.-H. Chang, *Motion Simulation and Mechanism Design with SOLIDWORKS Motion 2021*. SDC Publications, 2021.
- [23] X. Luan, H. Yu, C. Ding, Y. Zhang, M. He, J. Zhou, and Y. Liu, "A review of research on precision rotary motion systems and driving methods," *Applied Sciences*, vol. 15, no. 12, p. 6745, 2025.

Annexes

Fig. XI. X-Axis support frames.

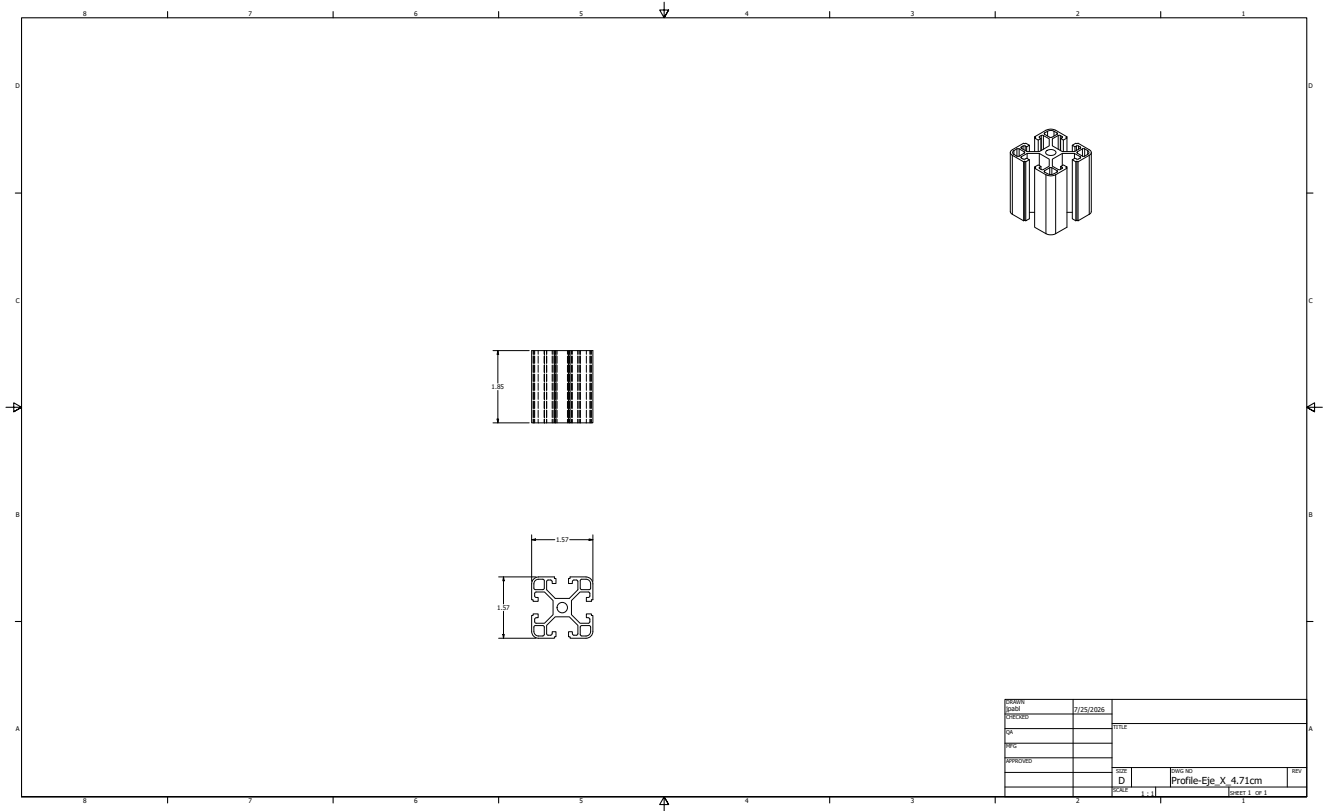


Fig. XII. Z-Axis support frames.

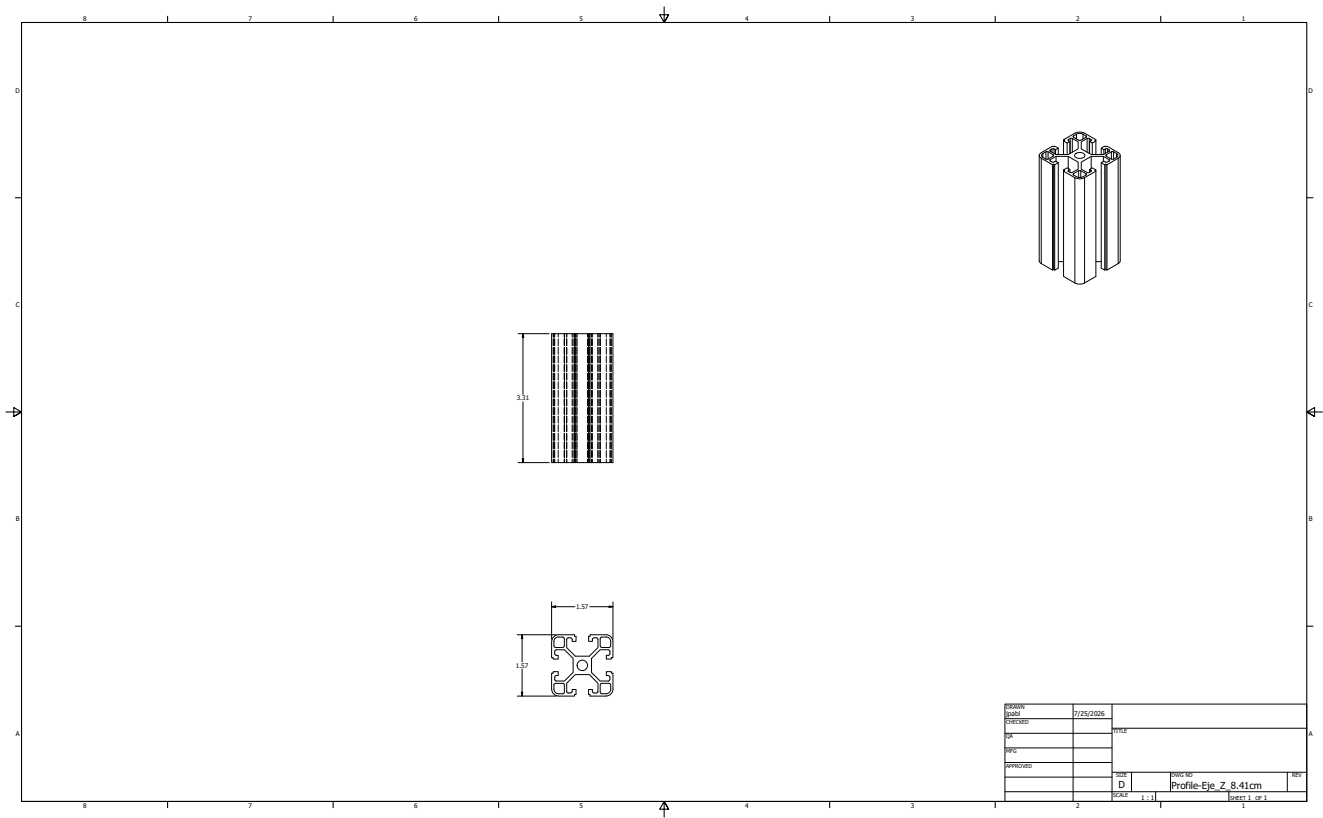


Fig. XIII. Y-Axis 7.11 cm support frames.

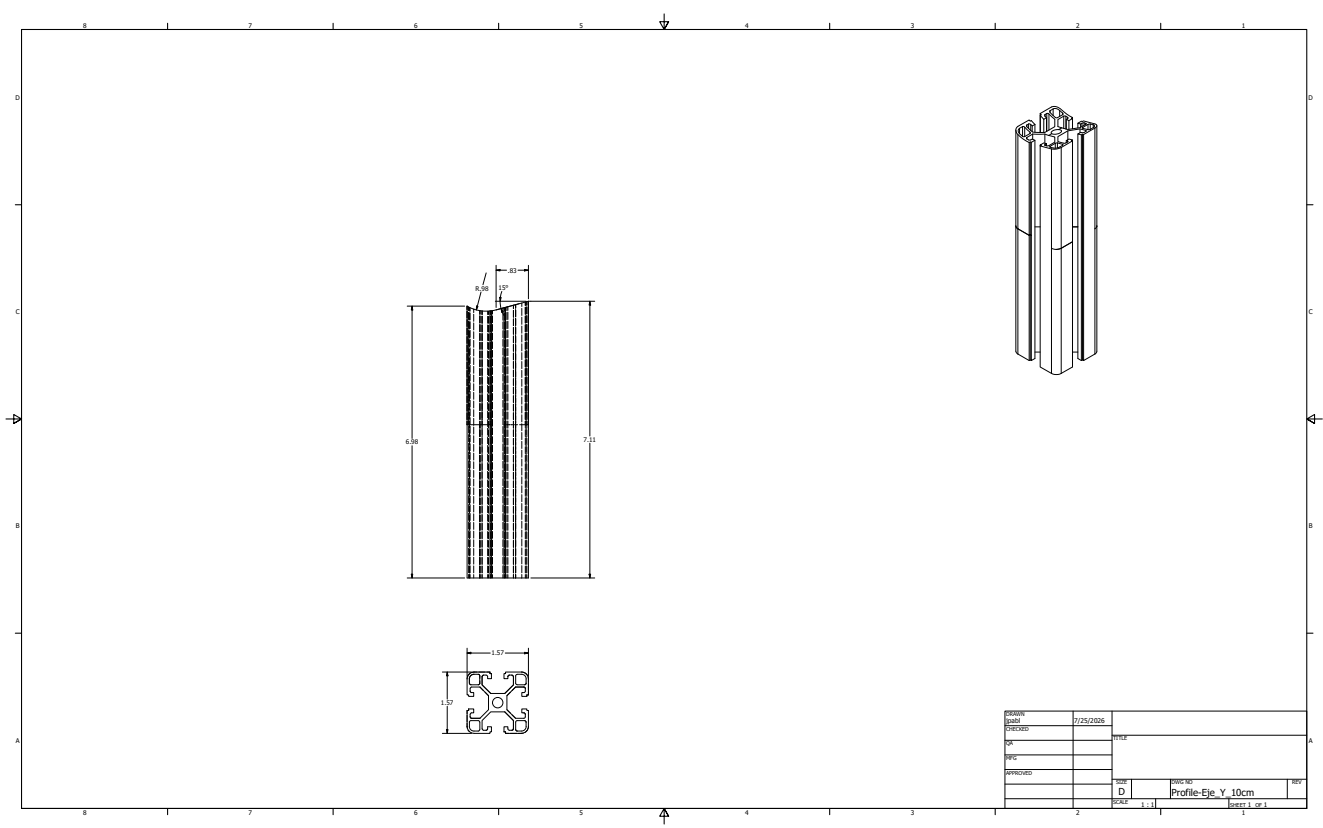


Fig. XIV. Y-Axis 17.8 cm support frames.

