

Retrofitting and Modernization Of Conventional Machines into CNC Systems

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Abstract: *A large proportion of the machine tools installed in small and medium manufacturing units worldwide are conventional, manually operated machines that remain mechanically sound but can no longer meet modern requirements for accuracy, repeatability, and productivity. Replacing every such machine with a new Computer Numerical Control (CNC) machine is often financially impractical, which makes retrofitting, the process of upgrading an existing conventional machine with a CNC controller, servo or stepper drives, and modern feedback systems, an economically attractive alternative. This paper presents a structured study of the retrofitting and modernization of conventional machines into CNC systems, intended for diploma and undergraduate mechanical engineering students. It explains the fundamentals of CNC technology, the limitations of conventional machine tools, and the concept, architecture, and major components of a retrofitted CNC system, including the controller, servo and stepper motors, ball screws, linear guides, encoders, and programmable logic controller (PLC) based auxiliary control. A systematic retrofitting methodology is described stage by stage, supported by design equations relating motor torque, linear force, spindle power, cutting speed, feed rate, and positioning accuracy, each with clearly defined symbols and realistic illustrative assumptions. The paper further examines the performance, economic feasibility, and comparative advantages of retrofitted machines against both their original conventional form and newly purchased CNC machines, along with the practical challenges, safety considerations, and optimization trade-offs involved. The study concludes that a successful CNC retrofit depends on the coordinated assessment of the existing mechanical structure, careful selection and sizing of electrical and control components, and disciplined calibration and commissioning, rather than on any single upgraded component alone.*

Keywords: CNC retrofitting, machine tool modernization, servo motor, ball screw, positioning accuracy, backlash compensation.

I. INTRODUCTION

Manufacturing competitiveness today depends heavily on a shop floor's ability to produce parts quickly, consistently, and to tight dimensional tolerances, requirements that a manually operated, conventional machine tool struggles to meet regardless of how skilled its operator may be. Yet a very large number of conventional lathes, milling machines, drilling machines, and boring machines remain in active service across small and medium manufacturing enterprises worldwide, many of them mechanically sound, rigid, and capable of decades of further service, but limited entirely by the absence of automated, programmable control. Replacing every such machine with a brand-new Computer Numerical Control (CNC) machine represents a very large capital outlay that many small manufacturers cannot justify, particularly when the existing machine's mechanical structure, its bed, column, and slideways, remains in good working condition.



This situation has made machine tool retrofitting, the process of upgrading an existing conventional machine by adding a CNC controller, servo or stepper motor drives, modern position feedback devices, and associated electrical and software systems, an increasingly attractive engineering and economic proposition. Retrofitting allows a manufacturer to gain most of the productivity, accuracy, and repeatability benefits associated with CNC operation while reusing the existing, often heavily built, mechanical structure, at a fraction of the cost and lead time of purchasing an entirely new machine. Beyond the immediate cost advantage, retrofitting also extends the useful service life of an existing asset, reduces the material and energy consumed in manufacturing an entirely new machine base and structure, and preserves the operational familiarity that experienced operators have already developed with a given machine.

Retrofitting a machine tool is, however, a genuine multidisciplinary engineering exercise rather than a simple parts-replacement task. It requires an honest mechanical assessment of the existing structure's rigidity, wear, and alignment; the correct selection and sizing of a CNC controller, servo or stepper motors, and drives matched to the loads the machine must move; the integration of position feedback devices and a programmable logic controller (PLC) for auxiliary functions; and a disciplined sequence of calibration, backlash compensation, and commissioning steps before the retrofitted machine can be trusted for production work. An error or shortcut at any one of these stages, from underestimating the torque needed to drive a heavy table to skipping a proper backlash measurement, can directly compromise the accuracy and reliability of the finished retrofit, regardless of how capable the chosen CNC controller may be.

This paper presents a structured study of the retrofitting and modernization of conventional machines into CNC systems, aimed at diploma and undergraduate mechanical engineering students. It explains the fundamentals of CNC technology and the specific limitations of conventional machine tools that motivate retrofitting, describes the architecture and major components of a typical retrofitted CNC system, and lays out a systematic retrofitting methodology supported by the key design equations an engineer must apply when selecting and sizing components. It then examines the performance, economic feasibility, and comparative standing of a retrofitted machine against both its original conventional form and a newly purchased CNC machine, before closing with a discussion of practical challenges, safety considerations, and the future direction of machine tool retrofitting.

II. OBJECTIVES

The specific objectives of this study are as follows:

- To study the fundamentals of Computer Numerical Control (CNC) technology and the evolution from conventional machine tools through Numerical Control (NC) to modern CNC systems.
- To identify the limitations of conventional machine tools that motivate the need for modernization and retrofitting.
- To describe the concept, architecture, and major mechanical, electrical, and control-system components of a retrofitted CNC system.
- To present a systematic, stage-by-stage retrofitting methodology and explain the importance of each stage to final machine performance.
- To derive and explain key design equations relating motor torque, linear force, spindle power, cutting speed, feed rate, and positioning accuracy, with clearly defined symbols and realistic assumptions.
- To evaluate the performance and economic feasibility of a retrofitted CNC machine using suitable indicators, including an illustrative payback period calculation.
- To compare conventional, retrofitted CNC, and newly purchased CNC machines, and to compare key retrofit component choices such as servo versus stepper motors.
- To identify the practical challenges, safety considerations, optimization trade-offs, and future scope of CNC retrofitting.



III. LITERATURE REVIEW

The fundamentals of numerical control and the evolution of machine tool automation are comprehensively documented in the classical automation literature, such as the widely used text by Groover [10], which traces the progression from purely manual machine operation, through early Numerical Control (NC) systems driven by punched-tape programs with no onboard computer, to modern CNC systems in which a dedicated computer stores, edits, and executes the part program directly. This foundational distinction between NC and CNC, and the closed-loop feedback principles that make consistent CNC accuracy possible, underpins the retrofitting methodology discussed later in this paper.

A growing and increasingly systematic body of research addresses retrofitting itself. Słowik and Sierocka [2] conducted a systematic literature review of equipment retrofitting in the context of Industry 4.0 and found that published research clusters around a small number of recurring themes, namely motion-control modernization, sensor and connectivity integration, and economic justification, while noting that comparatively few studies offer a complete, practically actionable retrofitting procedure that a smaller manufacturer could follow directly. Tantscher and Mayer [3] addressed this gap in part by proposing a holistic procedure model for digitally retrofitting legacy machines, structured around sequential phases of assessment, technology selection, and implementation, a structure broadly consistent with the stage-by-stage methodology presented in Section 8 of this paper. Lins and colleagues [4] proposed a specific methodology for retrofitting CNC machines within an Industry 4.0 context, emphasizing that a retrofit should be treated as a systems-engineering exercise that considers the mechanical, electrical, and information-systems aspects of the machine together, rather than as an isolated controller replacement.

Several case studies illustrate the practical implementation of retrofitting. Quatrano and colleagues [5] developed and implemented a low-cost, Arduino-based control system for a retrofitted CNC machine, demonstrating that a functional and accurate retrofit can be achieved using open, non-proprietary hardware and software rather than only expensive commercial CNC controllers. Kaarlela and colleagues [1] presented an especially valuable long-term perspective, reporting a feasibility study of a machine tool retrofitted using the open-source LinuxCNC controller and evaluated after seven years of continuous industrial use; their findings showed that the retrofitted machine achieved accuracy and vibration performance comparable to a modern CNC machine and had proven more profitable over its service life than either continuing to repair the aging original controller or purchasing a new machine outright, while also reducing the environmental impact associated with manufacturing an entirely new machine structure. Ilari and colleagues [8] extended the economic and environmental case for retrofitting by developing a triple-bottom-line, multi-criteria decision framework comparing retrofitting against new-machine purchase across economic, environmental, and social dimensions, concluding that the preferred choice depends strongly on the specific condition and remaining mechanical life of the existing machine rather than on cost alone.

On the technical performance side, positioning accuracy and repeatability, arguably the most important quality outcomes of any retrofit, have been studied in detail. Usop and colleagues [7] presented a systematic laser and ballbar testing methodology for quantifying the positioning, circularity, and static accuracy of a CNC machining centre, providing measurement techniques directly applicable to verifying a retrofitted machine's performance after commissioning. Farouki and Swett [6] addressed one of the most persistent sources of positioning error in retrofitted and conventional CNC machines alike, gear and ball-screw backlash, proposing a software-based, real-time feedrate modulation technique that compensates for backlash-induced positional error without requiring mechanical hardware changes, an approach particularly relevant to retrofits where replacing a worn ball screw may not be economically justified. Looking toward the ongoing operation of a retrofitted machine, Hesser and Markert [9] demonstrated that even a modestly retrofitted CNC milling machine, equipped only with a low-cost sensor platform and an artificial neural network, can support tool wear monitoring and predictive maintenance functions that were previously available only on new, fully instrumented machines, illustrating that retrofitting can extend beyond basic motion control to genuine Industry 4.0 condition-monitoring capability.

Taken together, this literature shows that machine tool retrofitting is both technically mature, with well-established methodologies for control-system selection, positioning-accuracy verification, and backlash compensation, and



economically well justified over the medium to long term, particularly for larger or heavily built machines whose mechanical structure represents most of the original asset value. At the same time, the literature also reveals a research gap that this paper directly addresses: most published retrofitting studies are either broad, high-level frameworks aimed at large-enterprise digital transformation planning [2][3], or narrow, single-technology case studies focused on one specific controller or sensor implementation [1][5][9], with comparatively few sources connecting the underlying mechanical and electrical design equations directly to a complete, practical, stage-by-stage retrofitting procedure suitable for a student or early-career engineer approaching the subject for the first time. This paper is structured specifically to close that gap, extending the useful life of conventional machine tools through an economically grounded, technically integrated modernization approach.

IV. FUNDAMENTALS OF CNC TECHNOLOGY

Computer Numerical Control (CNC) is a method of controlling a machine tool's motion and auxiliary functions using a dedicated computer that reads, stores, and executes a coded program describing the required tool path and machining operations. Understanding CNC requires first understanding its predecessor, Numerical Control (NC), and the closed-loop feedback principle that both technologies depend on.

4.1 From Conventional Machines to NC and CNC

A conventional machine tool is operated entirely by a human operator, who manually positions the tool and workpiece using handwheels and visual measurement, and whose achievable accuracy and repeatability are limited by skill, fatigue, and the inherent difficulty of reading a graduated dial to a fine tolerance repeatedly over a long production run. Numerical Control, developed from the 1950s onward, replaced manual positioning with motion commands encoded on punched tape or, later, magnetic media, executed by dedicated hardware logic with no onboard computer memory; every change to a part program on an NC machine required physically producing a new punched tape. Computer Numerical Control, which became dominant from the 1970s onward as computer hardware became smaller and less expensive, replaced this dedicated hardware logic with a general-purpose computer integrated into the machine controller, allowing part programs to be stored, edited, simulated, and re-run directly at the machine, and enabling far more sophisticated motion control, including smooth interpolation between programmed points and automatic compensation for known machine errors [10].

4.2 Open-Loop and Closed-Loop Control

A CNC axis can be driven using either open-loop or closed-loop control. In an open-loop system, the controller sends a motion command to the drive, typically a stepper motor, and assumes the resulting movement matches the command exactly, with no feedback device confirming the actual position achieved. In a closed-loop system, a feedback device, usually a rotary or linear encoder, continuously measures the actual position or velocity of the axis and reports it back to the controller, which compares the measured value with the commanded value and corrects any difference. Closed-loop control is inherently more accurate and more tolerant of variable cutting loads, since it can detect and correct for a motor that has stalled or slipped, but it requires additional feedback hardware and a more sophisticated controller, both of which add cost; this trade-off is discussed further in Section 7.

4.3 Axes, Interpolation, and Part Programming

A CNC machine's motion is organized around a small number of controlled axes, conventionally labelled X, Y, and Z for linear motion along three mutually perpendicular directions, with additional rotary axes, commonly labelled A, B, or C, added on more capable machines to rotate the workpiece or tool about one or more of these linear axes. The number of simultaneously controlled axes, and the total number of independent directions of motion available, is often described as the machine's degrees of freedom, and directly determines the complexity of part geometry the machine can produce in a single setup. To move the tool smoothly along a path that is not aligned with a single axis, such as a straight diagonal line or a circular arc, the controller uses interpolation, a real-time calculation that coordinates the simultaneous motion of two or more axes so that the resulting combined path follows the desired straight line or curve rather than moving axis by axis in a staircase pattern.



Part programs are written using a standardized instruction set consisting of G-codes, which specify machine motion and preparatory functions such as rapid positioning, linear interpolation, and circular interpolation, and M-codes, which specify miscellaneous machine functions such as spindle start and stop, coolant on and off, and program pause. Every part program is written relative to a defined coordinate system, and CNC controllers support both a fixed machine coordinate system, established once during homing, and one or more work coordinate systems, which allow an operator to define the program origin conveniently relative to the actual position of a specific workpiece on the table. Tool offsets similarly allow the controller to compensate automatically for differences in tool length and diameter between the values assumed in the part program and the actual tools loaded in the machine, without requiring the program itself to be rewritten.

V. CONVENTIONAL MACHINE TOOLS AND THEIR LIMITATIONS

Conventional machine tools, including manually operated lathes, milling machines, and drilling machines, remain valuable for low-volume work, toolroom tasks, and simple operations where the cost of CNC programming would not be justified. However, several inherent limitations restrict their suitability for modern production requirements and motivate the retrofitting approach discussed in this paper.

- Operator-dependent accuracy: Because the operator manually positions the tool using handwheels and reads graduated dials, achievable accuracy varies with operator skill, attention, and fatigue, and cannot be guaranteed to remain consistent across a long production run.
- Limited repeatability: Even a highly skilled operator cannot reliably return to exactly the same position on repeated cycles to the degree of consistency a closed-loop servo system achieves automatically, which is problematic for producing large batches of identical parts.
- Low productivity for repetitive work: Manual positioning, manual tool changes, and the operator's need to measure and verify dimensions during machining make conventional machining considerably slower than automated CNC operation for any operation repeated many times.
- Difficulty producing complex geometry: Simultaneously coordinated motion along two or more axes, needed to produce contoured surfaces, angled pockets, or curved profiles, is extremely difficult to achieve manually and is a routine capability of even an entry-level CNC system through interpolation.
- No data connectivity: A conventional machine provides no electronic record of what was produced, when, or under what conditions, making it incompatible with the data-driven condition-monitoring and traceability expectations of modern manufacturing quality systems.
- High dependence on skilled labour: Conventional machining requires operators with years of trained skill to consistently achieve good results, and such skilled labour is becoming increasingly scarce and costly in many regions.

Table 1: Comparison of Conventional, NC, and CNC Machine Control

Characteristic	Conventional / NC Machine	CNC Machine
Motion control	Manual (conventional) or fixed hardware logic reading punched tape (NC)	Onboard computer executing a stored, editable part program
Program editing	Not applicable, or requires producing a new punched tape (NC)	Directly editable at the machine controller
Accuracy / repeatability	Depends on operator skill (conventional); fixed by hardware (NC)	Consistent, governed by servo/feedback performance
Complex contoured geometry	Very difficult or impractical	Achieved routinely through interpolation



Characteristic	Conventional / NC Machine	CNC Machine
Data connectivity	None	Supports networking, monitoring, and Industry 4.0 integration
Typical suitability	Low-volume, simple, toolroom work	Medium-to-high volume, repeatable, or complex geometry work

VI. CONCEPT OF CNC RETROFITTING

CNC retrofitting is the process of upgrading an existing conventional or worn-out CNC machine by replacing its motion-control system, and where necessary its motors, drives, and feedback devices, while retaining and reusing the original machine's mechanical structure, namely its bed, column, ways, spindle housing, and major castings. The underlying premise of retrofitting is that the mechanical structure of a well-built machine tool, often the single most expensive and longest-lasting part of the machine, can remain fully serviceable for decades even after its original control system has become technologically obsolete or its servo components have worn out, so replacing only the control and drive systems can restore, and often improve upon, the machine's original accuracy and productivity at a fraction of the cost of a complete replacement [1][8].

Not every machine is an equally good retrofit candidate. The most favourable candidates are machines with heavy, rigid, well-preserved structural castings and slideways showing only normal wear, since no amount of control-system sophistication can compensate for a mechanically loose or badly worn machine base; Section 8 discusses how this mechanical condition is assessed as the first stage of the retrofitting methodology. Larger machines, and machines whose replacement cost would be very high due to their size or specialized configuration, tend to offer a stronger economic case for retrofitting than small, low-cost machines, for which purchasing a new unit outright may be simpler and only marginally more expensive.

The advantages of retrofitting, drawn from the case studies discussed in Section 3, include substantially lower cost and shorter lead time than purchasing a new machine, preservation of a mechanically sound structure that may be more heavily built than an equivalent new machine at the same price point, reduced material and energy consumption compared with manufacturing an entirely new machine base, and the ability to selectively modernize only the specific capabilities that are actually needed, such as adding two-axis contouring to a machine that previously supported only straight-line cuts [1]. These advantages, together with the specific architecture and components involved, are examined in detail in the sections that follow.

VII. ARCHITECTURE AND MAJOR COMPONENTS OF A RETROFITTED CNC SYSTEM

A retrofitted CNC system is built around a small number of major subsystems that together replace the manual control functions of the original conventional machine. This section describes each subsystem and its role in the overall architecture.

7.1 CNC Controller

The CNC controller is the central computer that interprets the part program, generates the coordinated motion commands sent to each axis drive, and manages auxiliary functions such as spindle speed and coolant control. Controllers used in retrofitting range from established commercial industrial controllers, offering high reliability and manufacturer support at a higher cost, to PC-based open-source options such as LinuxCNC, which run on standard computer hardware and substantially reduce cost while requiring more configuration effort from the retrofitting engineer [1][5]. Controller selection should be guided by the number of axes to be controlled, the interpolation and feedrate performance required for the intended work, and the availability of appropriate drivers for the specific motors and feedback devices chosen for the retrofit.



7.2 Servo Motors and Servo Drives

A servo motor is an electric motor paired with a feedback device, typically a rotary encoder or resolver, and controlled by a servo drive that continuously adjusts current to the motor so that the commanded position, velocity, or torque is achieved and maintained. Because the feedback loop directly measures actual motor position, servo systems automatically correct for variations in cutting load and can detect a stalled or obstructed axis, making them the preferred choice for higher-precision or heavier-duty retrofits. Servo drives are available in AC and DC variants; AC servo motors, using a permanent-magnet rotor rather than the brushes and commutator of a DC design, have become the dominant choice in modern retrofits because they eliminate the periodic brush maintenance and wear that DC servo systems require [1].

7.3 Stepper Motors

A stepper motor rotates in fixed, discrete angular increments for each electrical pulse it receives from its driver, and in its simplest form is operated open-loop, meaning the controller assumes the motor has moved exactly as commanded without any feedback confirming this. Stepper motors are simpler and less expensive than servo systems and are entirely adequate for lighter-duty axes with modest speed and load requirements, but they are prone to missing steps, and therefore silently losing position, if the load torque momentarily exceeds the motor's capability; closed-loop stepper systems, which add an encoder to detect and correct missed steps, are increasingly used in retrofits to close this reliability gap at a lower cost than a full servo system.

7.4 Spindle Motor and Spindle Drive

The spindle motor drives the rotation of the cutting tool or workpiece and, in a retrofit, is either the machine's original motor, retained if it is in good condition and compatible with variable-speed control, or a replacement motor paired with a variable-frequency drive that allows the spindle speed to be commanded directly by the CNC controller rather than fixed by a mechanical gearbox setting alone. Sizing the spindle motor correctly, discussed further in Section 8, is essential, since an undersized spindle motor will stall or overheat under heavy cuts, while an oversized motor adds unnecessary cost and electrical demand.

7.5 Ball Screws, Lead Screws, and Linear Guides

Linear axis motion is most commonly generated by converting the rotary motion of a servo or stepper motor into linear motion using a screw mechanism. A lead screw uses a simple sliding thread engagement between the screw and nut, is inexpensive, but has relatively high friction and, more importantly for CNC use, significant backlash, the small amount of free play that occurs when the direction of motion reverses, because the thread flanks are not preloaded against each other. A ball screw instead uses recirculating ball bearings riding in a helical groove between the screw and nut, dramatically reducing friction and, when supplied in a preloaded configuration, virtually eliminating backlash; this makes ball screws the standard choice for retrofits where positioning accuracy is important, despite their higher cost [6]. Linear guides, typically recirculating ball or roller rail systems mounted along the machine's slideways, similarly replace or supplement the original plain sliding ways to reduce friction and improve smoothness of motion, particularly important for maintaining consistent servo tuning performance, discussed in Section 9.

7.6 Encoders and Position Feedback

An encoder is a feedback device that converts a physical rotary or linear displacement into an electrical signal the controller can read, and is the key component that makes closed-loop control possible. A rotary encoder is typically mounted on the motor shaft or the screw itself and reports incremental or absolute angular position, while a linear encoder, sometimes called a linear scale, is mounted directly along the axis of travel and measures the actual position of the moving table or slide, independent of any error introduced within the screw and coupling. Mounting the feedback device directly on the load, an arrangement known as a direct or secondary feedback loop, gives a true measure of actual position and is not fooled by backlash or elastic wind-up in the drive train, whereas a feedback device mounted only on the motor shaft, a primary or indirect feedback loop, measures only motor rotation and cannot detect any mechanical error occurring between the motor and the actual load. Encoder resolution, the smallest angular or linear



increment the device can distinguish, directly limits the finest positioning resolution the axis can achieve, as discussed further in Section 10.

7.7 Limit Switches and Proximity Sensors

Limit switches and proximity sensors are simple, robust sensing devices mounted at the physical extremes of each axis of travel to prevent the moving table or slide from crashing into the end of its mechanical travel due to a programming error or control fault. A subset of these switches, home switches, are used specifically during the machine referencing and homing procedure described in Section 8, providing a repeatable physical reference point the controller uses to establish the relationship between its internal coordinate system and the actual physical position of the machine.

7.8 PLC, Machine Control Panel, and HMI

A Programmable Logic Controller (PLC) is a ruggedized industrial computer, distinct from the CNC controller itself, that manages the machine's auxiliary discrete logic, such as coolant pumps, chip conveyors, tool-change sequencing, safety interlocks, and the machine control panel buttons and indicator lamps, freeing the CNC controller to focus on coordinated axis motion. The machine control panel provides the physical buttons, switches, and indicators an operator uses for functions such as cycle start, feed hold, and emergency stop, while the Human-Machine Interface (HMI), typically a touchscreen or dedicated display integrated with the CNC controller, presents part-program status, axis positions, alarms, and diagnostic information to the operator in a readable form. Well-designed PLC logic and HMI presentation are particularly important in a retrofit, since operators experienced with the machine's original manual controls must be able to learn the new CNC interface quickly and safely.

7.9 Power Supply and Electrical Cabinet

The electrical cabinet houses the CNC controller, servo or stepper drives, PLC, transformers, circuit protection, and wiring terminals in an enclosure designed to protect these components from the dust, coolant mist, and vibration present on a typical shop floor. Correct electrical cabinet design, including adequate ventilation or cooling for drive heat dissipation, proper segregation of high-power motor cabling from low-voltage signal cabling to avoid electrical noise, and compliance with relevant electrical safety practices, is essential to the long-term reliability of the retrofit and is discussed further in Section 9.

Table 2: Key Retrofit Component Trade-offs

Comparison	First Option	Second Option
Stepper motor vs. Servo motor	Stepper: simpler, lower cost, open-loop, can silently miss steps under overload	Servo: closed-loop feedback, higher cost, corrects for load variation and detects faults
Lead screw vs. Ball screw	Lead screw: low cost, higher friction, significant backlash	Ball screw: low friction, minimal backlash when preloaded, higher cost
Open-loop vs. Closed-loop control	Open-loop: simpler and cheaper, no confirmation of actual position achieved	Closed-loop: feedback-verified position, better accuracy and fault detection

VIII. RETROFITTING METHODOLOGY AND DESIGN CONSIDERATIONS

A successful CNC retrofit follows a disciplined, sequential methodology rather than an ad-hoc replacement of parts. This section presents the methodology as a series of logical phases, condensed from the detailed stage-by-stage procedure followed in practice, and derives the principal design equations applied during the sizing phase. All numerical illustrations in this section use realistic, clearly stated assumptions and are identified as theoretical calculations rather than measured results, since no physical retrofit was performed for this study.



8.1 Assessment Phase

The methodology begins with an initial inspection and assessment of the candidate machine, covering both its mechanical condition, including the wear and straightness of slideways, the condition of the existing lead screws or ball screws, and the rigidity of the bed and column, and its existing electrical and control systems, including the condition of the original motors, wiring, and any usable sensors. This assessment directly determines the retrofit requirements: a machine with worn slideways may require regrinding or replacement linear guides before any control upgrade is meaningful, while a machine whose mechanical structure is in excellent condition may need only its motion-control system replaced. Skipping or rushing this assessment phase is one of the most consequential errors possible in a retrofit project, since every subsequent design decision, including the motor sizing calculations in Section 8.3, depends on accurate knowledge of the loads, friction, and inertia the existing mechanical structure presents.

8.2 Selection Phase

Based on the assessment, the retrofit team selects the CNC controller, motors and drives, and feedback devices appropriate to the machine's intended use and budget, following the trade-offs summarized in Table 2. This phase also determines whether existing mechanical components, such as the original lead screw, can be reused or must be replaced with a ball screw to achieve the required accuracy, and whether the original spindle motor can be retained or must be replaced or paired with a variable-frequency drive.

8.3 Design Equations for Component Sizing

Correct sizing of the servo or stepper motor for each axis, and of the spindle motor, is essential; an undersized motor stalls or overheats under load, while an oversized motor adds unnecessary cost, weight, and electrical demand. The following equations, using SI units throughout, support this sizing process.

The torque required to move a linear load through an effective radius, such as the pitch radius of a screw or pulley, is:

$$T = F \times r \quad (1)$$

where F = required linear force to move and accelerate the load (N),

r = effective radius at which the force acts, such as the ball-screw pitch radius (m),

T = required torque at that radius (N·m).

Where the linear force is instead generated by a motor driving a screw mechanism, the relationship between motor torque and the resulting linear force is:

$$F = (2\pi\eta T) / L \quad (2)$$

where η = mechanical efficiency of the screw mechanism (dimensionless; typically about 0.85-0.95 for a preloaded ball screw and considerably lower, around 0.3-0.5, for a plain lead screw, owing to its higher sliding friction),

T = motor torque delivered to the screw (N·m),

L = screw lead, the linear distance travelled per revolution (m/rev),

F = resulting linear force available at the load (N).

Equation (2) shows directly why replacing a lead screw with a ball screw during a retrofit, discussed in Section 7.5, allows a smaller motor to deliver the same usable linear force: the higher efficiency of the ball screw means less of the motor's torque is lost to internal friction. In practice, the motor must be sized not only for the steady cutting load but also for the torque needed to accelerate the axis to its programmed feed rate within an acceptably short time; this additional acceleration torque is estimated as $T_{\text{accel}} = J_{\text{total}} \times \alpha$, where J_{total} is the total inertia reflected to the motor shaft, including the motor's own rotor, the coupling, the screw, and the linear load converted to an equivalent rotary inertia, and α is the required angular acceleration. The motor selected for each axis must be capable of delivering the sum of the steady-state load torque from Equation (1) and this acceleration torque without exceeding its rated continuous or peak torque limits.

The spindle motor is sized differently, based on the mechanical power needed to remove material at the required rate rather than on linear force. Spindle power is related to spindle speed and torque by:

$$P = 2\pi NT / 60 \quad (3)$$

where N = spindle rotational speed (rpm),



T = spindle torque required to perform the cutting operation ($N \cdot m$),

P = spindle power (W).

The spindle speed itself is generally selected to achieve a recommended cutting speed for the given tool and workpiece material combination, related by:

$$V = \pi DN / 1000 \quad (4)$$

where D = diameter of the tool or workpiece at the point of cutting (mm),

N = rotational speed (rpm),

V = cutting speed (m/min).

The feed rate, the linear speed at which the tool advances into the workpiece, is calculated separately from the cutting speed of Equation (4), and is expressed here as v_f to avoid reusing the symbol F already used for force above:

$$v_f = f \times N \quad (5)$$

where f = feed per revolution, a value recommended for the given tool and material combination (mm/rev),

N = spindle rotational speed (rpm),

v_f = feed rate (mm/min).

As a theoretical, illustrative example only, consider retrofitting the X-axis of a mid-sized milling machine table with an assumed reflected load of 3000 N of static and frictional resistance, driven through a preloaded ball screw of 10 mm lead and 90 percent mechanical efficiency. From Equation (2), rearranged, the steady-state torque required is $T = FL / (2\pi\eta) = (3000 \times 0.010) / (2\pi \times 0.9) \approx 5.3 \text{ N}\cdot\text{m}$, well within the continuous rating of a typical mid-frame AC servo motor. For the spindle, assuming a required cutting torque of 8 N·m at a selected spindle speed of 1200 rpm, Equation (3) gives a spindle power requirement of $P = (2\pi \times 1200 \times 8) / 60 \approx 1005 \text{ W}$, indicating that a spindle motor rated at approximately 1.5 kW, allowing a reasonable safety margin, would be an appropriate selection. These figures are stated purely as an illustration of how the equations above are applied together and should not be read as measured or manufacturer-specified values for any actual machine.

8.4 Implementation, Calibration, and Commissioning Phase

Once components are selected and sized, the mechanical modifications, including installation of the new ball screw and linear guides where required, are carried out, followed by electrical panel modification and the physical integration of the servo and spindle drives and PLC. The CNC software is then configured with the machine's specific parameters, including axis travel limits, motor and encoder scaling, and acceleration limits, after which each axis undergoes calibration: measuring and compensating for backlash, as discussed in Section 9, verifying machine referencing and homing repeatability, and conducting dry-run testing of representative part programs with the spindle stopped and no workpiece loaded, to confirm safe motion before any actual cutting is attempted.

Only after dry-run testing is satisfactory should machining trials begin, starting with simple, low-value test pieces before progressing to production parts, with accuracy and repeatability verified against the performance indicators described in Section 10 before the machine is finally commissioned for regular production use. An incorrect or rushed decision at any single stage of this sequence, for example accepting an unmeasured backlash value, or skipping dry-run testing to save time, propagates directly into the finished machine's accuracy and safety and is often far more costly to correct after commissioning than it would have been to address at the appropriate stage; this is why the sequence is presented here as a strict progression rather than a set of independent tasks that can be reordered freely.

IX. MECHANICAL, ELECTRICAL, AND CONTROL-SYSTEM INTEGRATION

Beyond selecting and sizing individual components, a successful retrofit requires these mechanical, electrical, and control elements to be properly integrated as a single coherent system. This section addresses the integration considerations most often responsible for a retrofit falling short of its intended performance.



9.1 Machine Structure and Rigidity

No servo system, however well tuned, can compensate for a mechanically flexible or loose machine structure; if the bed, column, or slide deflects measurably under cutting load, the resulting error appears directly in the finished workpiece regardless of how accurately the CNC controller believes it has positioned the axis. For this reason, the mechanical condition assessment described in Section 8.1 must confirm adequate structural rigidity before proceeding, and any looseness in gib strips, way covers, or structural fasteners should be corrected as part of the mechanical modification stage, since rigidity, not control sophistication, ultimately sets the upper bound on achievable machining accuracy.

9.2 Backlash Measurement and Compensation

Backlash, introduced in Section 7.5, is measured directly by moving an axis a known distance in one direction, then reversing direction and measuring, using a dial indicator or the machine's own feedback device, how far the axis must travel before actual motion resumes. Once measured, backlash can be reduced mechanically, by fitting a preloaded ball screw and eliminating play in couplings, or compensated in software, where the controller is instructed to add a small extra movement each time an axis reverses direction to take up the measured clearance before continuing to the commanded position. Software compensation is convenient and requires no hardware changes, but it is a fixed correction that cannot fully account for backlash that varies with axis position or wears further over time, and advanced approaches such as the localized feedrate modulation technique described by Farouki and Swett [6] instead reduce the dynamic effect of backlash by slightly slowing the axis as it approaches a direction reversal, rather than relying on a single fixed offset value.

9.3 Servo Tuning

Servo tuning is the process of adjusting the gain settings of the closed-loop control algorithm, typically a proportional-integral-derivative (PID) controller, so that each axis responds quickly and accurately to commanded motion without overshooting the target position or oscillating around it. Gains that are too low produce a sluggish axis that lags behind its commanded position under acceleration, degrading contouring accuracy on curved paths, while gains that are too high cause the axis to overshoot and hunt back and forth around the target position, producing audible vibration and, in severe cases, visible marks on the machined surface. Correct servo tuning depends on accurately knowing the reflected inertia of the axis, discussed in Section 8.3, which is one further reason why an accurate mechanical assessment early in the retrofit process directly benefits control-system performance later on.

9.4 Machine Referencing and Homing

Because a CNC controller has no inherent knowledge of where its axes are physically positioned when first powered on, every retrofitted machine must perform a homing sequence, in which each axis moves toward its home switch, described in Section 7.7, until the switch is triggered, establishing a repeatable physical reference point from which the controller's internal coordinate system is defined. This homing sequence must be repeated at every power-on, and its repeatability, how consistently the axis returns to exactly the same physical position each time it homes, directly limits the overall repeatability of the entire machine, making the mechanical quality and consistent triggering behaviour of the home switches a small but critical detail in overall retrofit performance.

9.5 Electrical Integration and Noise Considerations

The electrical cabinet described in Section 7.9 must be wired so that high-power motor cabling is physically separated from low-voltage encoder and sensor signal cabling, since the rapidly switching currents in a servo or spindle drive can induce electrical noise into nearby signal wiring, corrupting position feedback and causing erratic axis behaviour that can be very difficult to diagnose after the fact. Proper earthing and shielding practice, together with adherence to the electrical drive manufacturer's cabling recommendations, is therefore treated as a design requirement during the electrical panel modification stage rather than an afterthought to be addressed only if problems appear during commissioning.



X. PERFORMANCE ANALYSIS OF RETROFITTED CNC MACHINES

Once a retrofit is commissioned, its performance must be verified against defined indicators rather than assumed from the specifications of the individual components selected. This section defines the principal performance indicators and the equations used to quantify them, following measurement approaches consistent with those demonstrated by Usop and colleagues [7].

10.1 Positioning Accuracy and Repeatability

Positioning accuracy describes how closely an axis reaches a commanded target position on average, and is generally reported as the mean positioning error together with its overall range across repeated tests at several points along the axis travel. Repeatability describes how consistently the axis returns to the same physical position when commanded to the same target repeatedly, and is generally reported as a band, often expressed as plus or minus several standard deviations of the measured positions, around the mean position for that target; because repeatability captures only the consistency of positioning and not its correctness, a machine can be highly repeatable yet still inaccurate if a systematic error, such as an incorrectly scaled encoder count, is present.

10.2 Resolution, Axis Travel, and Backlash as Performance Measures

Axis resolution is the smallest incremental movement the controller can command or the feedback device can distinguish, and is determined jointly by the encoder's pulses per revolution and the screw lead from Equation (2): a finer encoder resolution or a shorter screw lead both reduce the physical distance represented by one encoder count, improving the theoretical resolution of the axis, though actual achievable accuracy remains limited by the mechanical factors discussed in Section 9. Axis travel is simply the total usable linear distance available on a given axis and is a fixed mechanical property of the retrofitted machine rather than a control-system parameter. Backlash, measured as described in Section 9.2, is reported as a performance indicator in its own right, since even a well-compensated backlash value indicates a mechanical clearance that a software correction can mask but not eliminate.

10.3 Cycle Time and Productivity Improvement

Machine cycle time, the total time required to complete one part, can be expressed as the sum of the actual cutting or machining time and the non-cutting time spent on tool changes, rapid positioning moves, and part loading and unloading: $T_c = T_m + T_{nc}$, where T_m is machining time and T_{nc} is non-cutting time, both in consistent time units. Retrofitting typically reduces both components: machining time may fall because higher, more consistent feed rates from Equation (5) can be sustained without operator intervention, while non-cutting time falls because rapid positioning moves execute automatically at the machine's programmed rapid-traverse speed rather than at the pace of manual handwheel operation. The resulting productivity improvement is conveniently expressed as a percentage reduction in cycle time:

$$\text{Productivity improvement (\%)} = ((T_{c,old} - T_{c,new}) / T_{c,old}) \times 100 \quad (6)$$

where $T_{c,old}$ = cycle time achieved on the original conventional machine (min),

$T_{c,new}$ = cycle time achieved after retrofitting (min).

As a theoretical illustration only, if a particular part previously required 40 minutes of largely manual machining time on the conventional machine and the same part requires 15 minutes on the retrofitted machine due to automated positioning and consistent feed rates, Equation (6) gives a productivity improvement of $((40-15)/40) \times 100 = 62.5$ percent; this figure is presented solely to illustrate the calculation and does not represent a measured result from any specific retrofit project.

Table 3: Key Performance Indicators for a Retrofitted CNC Machine

Indicator	Definition / Significance	Primary Factors	Influencing
Positioning accuracy	Closeness of achieved position to the commanded target	Ball-screw calibration, thermal effects	quality,
Repeatability	Consistency of returning to the same commanded	Backlash, servo tuning,	



Indicator	Definition / Significance	Primary Factors	Influencing
	position		mechanical looseness
Axis resolution	Smallest distinguishable incremental movement	Encoder resolution, screw lead (Eq. 2)	
Backlash	Lost motion on direction reversal	Screw type, preload, coupling condition	
Cycle time	Total time to complete one part	Feed rate (Eq. 5), non-cutting time, tool changes	
Spindle power / cutting performance	Ability to sustain required material removal rate	Spindle motor sizing (Eq. 3), drive capability	

As with the performance indicators discussed for other engineered systems, these indicators are most informative when considered together rather than individually: a retrofit that achieves excellent positioning accuracy but only a modest reduction in cycle time may indicate that non-cutting time, rather than axis precision, is the dominant remaining bottleneck, directing further optimization effort, discussed in Section 14, toward tool-change and workflow improvements rather than further control-system refinement.

XI. ECONOMIC AND TECHNICAL FEASIBILITY ANALYSIS

A retrofit that is technically sound must also be economically justified before it can be recommended to a manufacturing business. This section outlines the principal cost components of a retrofit project and a simple method for assessing economic feasibility, noting throughout that all figures used are illustrative assumptions rather than measured data.

11.1 Retrofit Cost Components

The total cost of a CNC retrofit is the sum of several distinct components: the CNC controller itself; the servo or stepper motors and their drives; the spindle drive, if the spindle motor is replaced or a variable-frequency drive is added; mechanical modification costs, including any new ball screws, linear guides, or structural repair; electrical panel modification, including the enclosure, wiring, and circuit protection; installation labour; software configuration and parameter setting; and calibration and commissioning time, including backlash measurement and accuracy verification. Table 4 presents an illustrative, order-of-magnitude cost breakdown for a mid-sized two-to-three-axis milling machine retrofit, expressed as a percentage of total retrofit cost rather than as absolute currency values, since actual costs vary enormously with machine size, geographic region, and the specific controller and component brands selected.

Table 4: Illustrative Retrofit Cost Breakdown by Component Category

Cost Component	Typical Share of Total Cost	Primary Driver of Cost
CNC controller and software	20-30%	Controller sophistication, number of axes
Servo/stepper motors and drives	20-30%	Motor sizing (Section 8.3), number of axes
Mechanical modification (screws, guides)	15-25%	Extent of mechanical wear and required accuracy
Electrical panel and wiring	10-15%	Machine size, number of auxiliary functions



Cost Component	Typical Share of Total Cost	Primary Driver of Cost
Installation, calibration, and commissioning	10-20%	Labour rate, thoroughness of testing

This breakdown is illustrative and intended only to show the relative weight of different cost categories; a specific project quotation must be based on actual component pricing and labour estimates for the machine and region concerned.

11.2 Payback Period and Its Limitations

A simple and widely used measure of economic feasibility is the payback period, the time required for the accumulated savings generated by the retrofit to equal the initial investment:

$$\text{Payback Period} = \text{Initial Retrofit Investment} / \text{Annual Savings (7)}$$

where Initial Retrofit Investment = total cost of the retrofit project, summing the components in Table 4 (currency units),

Annual Savings = the net annual financial benefit attributable to the retrofit, typically arising from increased productivity (fewer machine-hours or fewer operators needed to produce the same output), reduced scrap and rework from improved accuracy, and reduced downtime compared with maintaining an aging or unreliable original control system (currency units per year),

Payback Period = time required to recover the initial investment (years).

As a theoretical illustration only, if a retrofit project costs an assumed 800,000 currency units and is estimated to generate 320,000 currency units of annual savings through the productivity improvement discussed in Section 10.3 and reduced scrap, Equation (7) gives a payback period of $800,000 / 320,000 = 2.5$ years; this figure is provided purely to illustrate the calculation method and is not a claim about the cost or savings of any actual retrofit project.

Simple payback analysis is easy to calculate and communicate, which makes it popular for an initial feasibility screening, but it has significant limitations that should be understood before relying on it exclusively. It ignores the time value of money, treating a unit of savings received in year one as equally valuable as the same unit received in year five, and it ignores any benefit or cost occurring after the payback point is reached, meaning two projects with identical payback periods but very different total service lives, and therefore very different total lifetime savings, would appear equally attractive under payback analysis alone. More complete economic evaluations address these limitations using net present value or internal rate of return calculations that discount future cash flows, and by explicitly estimating the machine's expected remaining service life, as demonstrated in the long-term, seven-year feasibility study reported by Kaarlela and colleagues [1] and in the multi-criteria triple-bottom-line framework proposed by Ilari and colleagues [8], both of which look considerably further ahead than a simple payback calculation.

XII. COMPARATIVE ANALYSIS: CONVENTIONAL, RETROFITTED CNC, AND NEW CNC MACHINES

Bringing together the technical and economic considerations discussed in the preceding sections, Table 5 compares the three options a manufacturer typically weighs when a conventional machine tool can no longer meet production requirements: continuing to operate it manually, retrofitting it with a CNC system, or replacing it entirely with a newly purchased CNC machine.

Table 5: Comparative Analysis of Conventional, Retrofitted CNC, and New CNC Machines

Characteristic	Conventional Machine	Retrofitted CNC Machine	New CNC Machine
Capital cost	None (already owned)	Low to moderate	High
Lead time to deployment	Not applicable	Weeks	Months



Characteristic	Conventional Machine	Retrofitted CNC Machine	New CNC Machine
Achievable accuracy	Operator-dependent, limited	Good, close to new-machine levels with careful design	Highest, benefits from latest structural design
Mechanical structure	Original, may be heavily built	Original, reused as-is	New, sized to current market cost targets
Access to newest features	None	Selective, as fitted during retrofit	Full, as offered by manufacturer
Environmental impact	None (no new manufacturing)	Lower, structure reused [1]	Higher, full new structure manufactured
Best suited when	Low-volume, simple work only	Structure sound, budget or lead time constrained	Budget available and latest capability required

As Table 5 shows, retrofitting occupies a genuinely intermediate position rather than being simply a cheaper but inferior substitute for a new machine. Where the existing mechanical structure is in good condition, a retrofit can approach new-machine levels of accuracy and productivity at a substantially lower cost and shorter lead time, while also reducing the environmental impact associated with manufacturing an entirely new machine base; this combination is precisely why Kaarlela and colleagues [1] found retrofitting to be more profitable over a seven-year service life than either continued repair of an aging original controller or outright replacement. Where the mechanical structure is significantly worn, undersized for current requirements, or the machine's designed configuration no longer matches the geometry of parts the business needs to produce, however, a new machine purchase, despite its higher cost, may be the more sensible long-term choice, since retrofitting cannot correct a fundamentally inadequate mechanical structure, as emphasized throughout Sections 8 and 9 of this paper.

XIII. CHALLENGES, LIMITATIONS, AND SAFETY CONSIDERATIONS

Despite its clear advantages, CNC retrofitting presents several practical challenges that a project team must plan for.

- **Hidden mechanical wear:** Wear in slideways, bearings, or the original screw may not be fully apparent until the machine is disassembled during the retrofit, occasionally requiring unplanned mechanical repair that increases cost and schedule beyond the original estimate.
- **Component compatibility:** Interfacing a modern CNC controller, servo drives, and feedback devices from different manufacturers requires careful attention to signal types, voltage levels, and communication protocols, and incompatible combinations can cause unreliable operation that is difficult to diagnose.
- **Operator retraining:** Operators experienced with the machine's original manual controls must be trained in CNC part programming, tool offset management, and the new control panel and HMI, and inadequate training can offset much of the productivity benefit the retrofit was intended to deliver.
- **Residual mechanical limitations:** As emphasized throughout this paper, a retrofit cannot exceed the accuracy or rigidity ceiling set by the original mechanical structure; setting unrealistic accuracy expectations for a retrofit of an older, lighter machine can lead to disappointment regardless of how capable the new control system is.
- **Emergency-stop and safety-circuit integration:** The retrofit must incorporate a properly designed emergency-stop circuit and safety interlocks, for example preventing spindle rotation while a guard is open, meeting applicable machine safety standards; retrofitting the control system without equal attention to safety circuitry is a serious and avoidable hazard.
- **Ongoing maintenance and spare-parts availability:** A retrofit built around a specific commercial controller or drive family depends on the continued availability of spare parts and technical support for that product line



over the machine's remaining service life, an important consideration when selecting components discussed in Section 7.

From a safety perspective, the machine control panel, PLC logic, and emergency-stop circuit described in Sections 7 and 9 together form the primary safeguards protecting the operator, and their correct design and testing during commissioning, discussed in Section 8.4, should never be treated as a lower priority than achieving the target positioning accuracy.

XIV. OPTIMIZATION AND FUTURE SCOPE

The design equations and trade-offs discussed throughout this paper show that CNC retrofit performance and cost-effectiveness cannot be optimized by maximizing any single subsystem in isolation. Investing in a very high-resolution encoder, for example, provides little benefit if the underlying ball screw and mechanical structure cannot physically hold the resulting positional resolution under real cutting loads; similarly, an oversized, expensive servo motor adds cost without improving performance if the machine's rapid-traverse speed is limited by a much smaller mechanical constraint elsewhere in the drive train. Effective optimization therefore proceeds by first identifying, through the mechanical assessment described in Section 8.1, which subsystem currently limits overall performance, and directing investment there first, rather than upgrading whichever component is easiest or most familiar to specify.

Several broader optimization approaches support this component-level decision-making. Parameter-based design calculation, following the equations derived in Section 8.3, allows candidate motor and screw combinations to be compared quickly before committing to a purchase. Servo tuning, described in Section 9.3, can often extract meaningfully better dynamic performance from already-selected hardware at no additional component cost. Where a retrofit is being planned at larger scale or higher precision, numerical simulation and Finite Element Analysis (FEA) of the machine structure can identify whether a specific casting or slideway is likely to be a limiting factor before physical modification begins, though such simulation work is outside the scope of the illustrative calculations presented in this paper and is not claimed to have been performed here. Multi-objective and cost-performance optimization approaches, weighing accuracy, speed, and cost together rather than any one criterion alone, are increasingly used to select among several technically viable retrofit configurations for a given budget.

Looking toward future development, the retrofitting field is increasingly extending beyond basic motion-control replacement toward full Industry 4.0 integration. Lins and colleagues [4] and Tantscher and Mayer [3] both frame retrofitting explicitly as a pathway into Industry 4.0 connectivity, rather than an end in itself, while Hesser and Markert [9] demonstrated that even a modest sensor and machine-learning addition to a retrofitted machine can enable predictive maintenance and tool-wear monitoring capabilities that were previously available only on new, fully instrumented machines. As open-source CNC platforms, low-cost sensors, and machine-learning tools continue to mature, future retrofits are likely to increasingly combine the core motion-control modernization described in this paper with predictive maintenance, remote condition monitoring, and data connectivity to plant-wide manufacturing execution systems, extending the value of retrofitting well beyond the immediate gains in accuracy and productivity discussed in Section 10.

V. CONCLUSION

This paper has presented a structured study of the retrofitting and modernization of conventional machines into CNC systems, covering the fundamentals of CNC technology, the limitations of conventional machine tools that motivate retrofitting, the architecture and major components of a retrofitted system, a systematic retrofitting methodology supported by design equations for motor and spindle sizing, and the performance, economic, and comparative considerations that determine whether a given retrofit project is worthwhile. The design equations derived in Section 8 show that a retrofit's achievable performance depends on a coordinated chain of decisions, from the mechanical efficiency of the chosen screw mechanism to the sizing of the servo and spindle motors, each of which must be



matched to the specific condition and load characteristics of the existing machine established during the initial assessment phase.

The performance analysis and comparative discussion in Sections 10 and 12 further show that a retrofit's ultimate accuracy and productivity are bounded by the mechanical structure it reuses, and that no amount of control-system sophistication can substitute for adequate rigidity, a well-preserved or upgraded screw and guideway system, and disciplined calibration during commissioning. The economic feasibility analysis in Section 11 reinforces that retrofitting is not universally superior to new-machine purchase; rather, as the literature reviewed in Section 3 consistently shows, it is the stronger choice specifically when the existing mechanical structure remains sound and the available budget or project timeline favours a lower-cost, faster-to-deploy solution.

For diploma and undergraduate mechanical engineering students, CNC retrofitting offers an unusually complete, practical introduction to mechanical design, motor and drive sizing, control-system integration, and engineering economics within a single, widely applicable project context. As manufacturing continues to seek sustainable, cost-effective paths to modernization rather than wholesale equipment replacement, the disciplined, stage-by-stage retrofitting approach presented in this paper is expected to remain a valuable and economically important skill for extending the useful life of the world's substantial installed base of conventional machine tools.

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