Unmanned Machining Excellence: VMC Optimization - A comprehensive report by Divyanshu Ray

1. Introduction & Background Research

Elmex Controls Pvt. Ltd. was established in 1963 and is one of the first manufacturers of the Indian electrical industry, specializing in terminal blocks, electrical connectors, and automation solutions. Through its strong commitment to innovation and precision-engineered products, Elmex has consistently been at the forefront in embracing modern technologies to achieve global standards of quality. The company serves clients across critical sectors such as industrial automation, renewable energy, infrastructure, and railways, making process optimization a strategic necessity.

Elmex has a range of CNC machines, including Vertical Machining Centers (VMCs) at its machining plant, which it uses to produce high-precision parts used in its product lines, such as various copper and steel electrodes. However, a large number of these VMCs operated in a more traditional, semi-manual way, which constrained their productivity as well as flexibility. The goal of this project was to implement industry-standard upgrades and transform the conventional method into a modern and semi-automated procedure.

Traditional VMC machining setups at Elmex required extensive manual intervention for every new job. Operators had to individually align and clamp workpieces, calibrate tool offsets by hand, and manually change tools between operations. This process resulted in long setup times of 20–25 minutes per work, low accuracy due to human influences, increased tool wear, and wide variation in production results depending on the skill of the operator. In addition, frequent stoppages to make manual adjustments decreased throughput, increased machine idle time, and made quality control more challenging. These problems made it clear that there was an urgent need for standardized, automated, and repeatable machining processes.

Research Undertaken:

In order to create a sound and workable solution, I started by dedicating one whole week in the machining division of Elmex. This enabled me to see the entire process of the VMC machines live — from the preparation of jobs and loading of copper electrodes to manual clamping, adjustment of tool offsets, machining, and even tool change. During this week-long period, I worked closely with several engineers and technicians to understand the end-to-end electrode production process. This included learning how electrodes are designed using CAD software, how the corresponding toolpaths and G-code are generated for the VMCs, and how the electrodes are clamped and machined.

Figure 1: Operator manually setting up a

I also observed how these electrodes are later used in EDM (Electrical Discharge Machining) for sparking operations, which demand extremely high precision. This practical exposure helped me connect theoretical automation concepts with the real-world challenges and opportunities on the shop floor. I conducted informal interviews with machine operators and process controllers to understand recurring problems — such as constant misalignment, high reworking rates, and time-consuming manual adjustments. In several job cycling observations, I had the opportunity to map root causes of inefficiency, benchmark setup times, and examine variability across different shifts.

In parallel, I conducted extensive **secondary research** into automation techniques and best practices in CNC-based precision manufacturing. The following systems were identified as potential interventions to address the core issues:

- **3R Clamping Systems**: High-precision quick-change pallet systems that enable consistent part placement across multiple machines.

- **Laser measuring systems and touch probes**: Automated in-machine measuring devices capable of setting tool lengths, detecting tool wear, and ensuring high repeatability. (This system may also be referred to as Blum Probes in the report, with 'Blum' denoting the probe manufacturing company.)
- **Automatic Tool Changers (ATCs)**: CNC-controlled systems that drastically reduce tool change time and eliminate manual intervention.

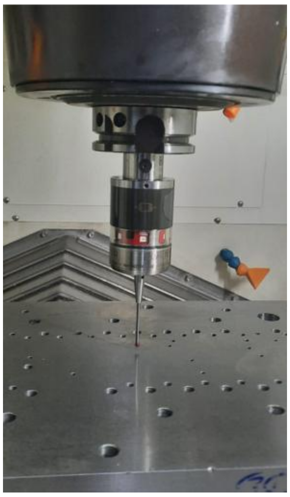

Figure 3: Fully loaded 3R clamping system with multiple

Figure 2: Laser

Justification of Method Selection:
Alternative probing systems and clamping mechanisms were considered but ultimately rejected due to compatibility constraints with Elmex's existing legacy CNC machines. The **3R system** was chosen over other modular clamping systems for its faster interchangeability, wide industry adoption, and the company's existing supplier relationship.**Laser measuring systems and touch probes** were selected for their strong performance record and ease of integration with the CNC controller. The **ATC solution** offered maximum return on productivity while requiring minimal retrofitting.

Supplier documents, case studies, and technical manuals were reviewed to understand compatibility, integration, and expected performance metrics. In addition, I conducted interviews with technical experts at Elmex and representatives from equipment vendors, which helped me gain deeper insights into how these systems could be adapted to Elmex's specific requirements and constraints, including operator training needs and machine compatibility.

Scientific and Engineering Principles Involved:
The project draws on principles of mechanical engineering, automation, precision manufacturing, and control systems. Key engineering concepts included:

- Kinematic repeatability in clamping mechanisms
- CNC tool offset calibration
- Pneumatic actuation and sensor feedback in probing
- Human-machine interface design
- Manufacturing ergonomics and productivity modeling

By grounding the project in both research and real-world application, the stage was set for implementing a comprehensive solution that would improve productivity, reduce variability, and deliver long-term savings for Elmex.

2. Aims and Objectives

The goal of the discussed project is to convert the usual work process of a Vertical Machining Center (VMC) into a semi-automated, high-precision model where human input is reduced to a minimum and process reliability is significantly increased. The project aims to demonstrate that unmanned machining can be implemented as a viable business case through the application of advanced industrial automation technologies.

The focus was not only on upgrading machinery but also on establishing a repeatable, operator-independent system that improves cycle efficiency, dimensional precision, and process consistency — all while aligning with Elmex's broader goals of digital transformation and manufacturing excellence.

Primary Aim

To enhance machining efficiency and precision by transitioning from manual setups to integrated, unmanned operations through automation technologies.

Specific Objectives

- **Tool Change Standardization**:
  Implement Automatic Tool Changers (ATC) to eliminate inconsistencies and reduce manual tool replacement time.

- **Cycle Time Optimization**:
  Shorten overall machining cycle times by minimizing operator-dependent activities.

- **OEE Improvement**:
  Track and improve Overall Equipment Effectiveness (OEE) post-automation to benchmark productivity.

- **Dimensional Accuracy Enhancement**:
  Use Laser measuring systems and touch probing and 3R clamping systems to achieve high precision and repeatability.

- **Error Reduction**:
  Minimize human-induced setup and measurement errors to lower rejection and rework rates (RJ/RW).

- **Batch Consistency**:
  Ensure uniform machining outcomes across multiple job runs with repeatable setup configurations.

- **Setup Time Reduction**:
  Reduce average setup time from 20–25 minutes.

- **First-Time Right (FTR) Rate**:
  Increase the First-Time Right (FTR) metric Percentage.

- **Precision Benchmarking**:
  Achieve sub-0.005 mm tolerance in machining dimensions to meet the precision demands of EDM-ready electrodes.

3. Methodology / Plan of Work

To effectively transition from manual VMC operations to an optimized semi-automated setup, a structured, hands-on methodology was followed over a six-week period. Each phase of the plan was designed to tackle specific pain points in the current workflow while ensuring smooth integration of automation systems and readiness of operators.

Week 1–2: Baseline Mapping and Familiarization

- Observed and documented the existing machining process in detail to identify bottlenecks in job setup, tool changing, and dimensional measurement.
- Analyzed recurring issues such as inconsistent tool offsets, fixture misalignment, and operator variability.
- Participated in focused team training sessions covering:
    - **3R Zero-Point Clamping System** – to ensure consistent job referencing across multiple machines.
    - **Laser measuring systems and touch probes** – for automatic tool length measurement, wear detection, and offset calibration.
    - **ATC Functionality** – to understand the tool change cycle logic, tool magazine indexing, and safety protocols.

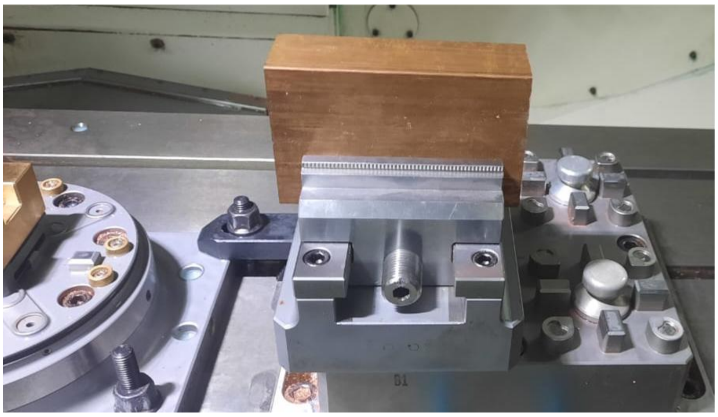

Figure 4: Manually clamped copper block using traditional fixtures prior to automation.

Week 3: Integration of Automation Tools

- Installed and aligned the 3R base plates on VMC tables for fast, standardized fixture mounting.
- Integrated Laser measuring systems and touch probes into the CNC control system for real-time measurement feedback and auto-calibration.
- Calibrated and tested the ATC (Automatic Tool Changer) magazine, tool holders, and spindle interface.
- Ensured coordinated operation and communication between the three automation systems (3R, **laser measuring systems and touch probes**, and ATC) through iterative testing.

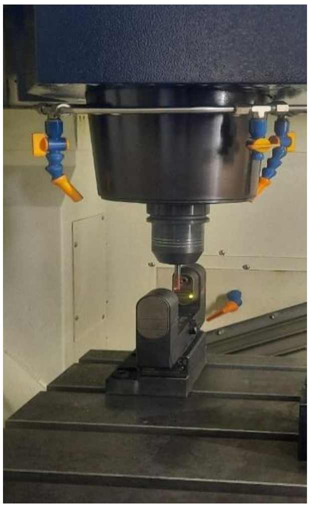

Figure 5: High-precision probing of a compact

Week 4: Pilot Trials and System Optimization

- Conducted **side-by-side trials** comparing manual and upgraded workflows on the same job types.
- Collected real-time data on:
  - Setup time
  - Tool change duration
  - Dimensional deviation
  - Operator involvement and intervention frequency
- Fine-tuned probing parameters, fixture alignment positions, and tool loading sequences based on feedback from both operators and CNC program diagnostics.

Week 5–6: Full-Scale Implementation and Validation

- Deployed the automation workflow across multiple VMCs and a broader set of copper and steel electrode jobs.
- Conducted **repeatability and interchangeability tests** to validate consistent job outcomes across different shifts and machines.
- Analyzed the effectiveness of the system in reducing setup time, increasing accuracy, and minimizing operator errors.

Key Activities Conducted

- **Job Setup Comparisons**:
  Evaluated the time, alignment precision, and repeatability between traditional manual setups and 3R clamping-based configurations.
- **Accuracy and Repeatability Testing**:
  Used micrometers, CMMs, and **readings from laser measuring systems and touch probes** to validate positional accuracy and geometric tolerances.

- **Tool Change Time Measurements**:
 Logged tools change durations using a stopwatch and control panel logs for both manual and automated cycles.

- **Ergonomics and Safety Evaluation**:
 Reviewed operator postures, movement fatigue, and risk of repetitive strain under manual vs. semi-automated setups.

- **Payback Analysis**:

    - **Productivity Increase**: Up to 40% increase in throughput per shift.

    - **Rejection/Rework Reduction**: Up to 50% drop in scrapped or reworked parts.

4. Data Collection & Analysis

A structured and evidence-based approach was used to assess the effectiveness of the transition from manual to semi-automated VMC operations. Data was collected both before and after the implementation of the 3R clamping system, **laser measuring systems and touch probes**, and Automatic Tool Changer (ATC), enabling direct performance comparisons across critical KPIs.

Data Collection Approach

Multiple tools and sources were used to ensure both quantitative and qualitative coverage:

- **Stopwatch Timing** – Used to measure setup duration, tool change intervals, and idle machine time.

- **Machine Diagnostics** – Provided real-time logs of cycle completions, tool changes, and offsets.

- **Micrometer and CMM (Coordinate Measuring Machine) Readings** – Captured dimensional accuracy and tolerance consistency.

- **Operator Logs** – Recorded manual steps, rework cycles, and observed anomalies.

- **Quality Control Reports** – Supplied rework/rejection (RJ/RW) rates and first-time-right data across multiple batches.

Key Metrics Tracked (Before vs After Implementation)

Metric	Before	After	Improvement
Setup Time	20–25 minutes/job	2–5 minutes/job	↓ Up to 90% reduction
Tool Change Time	~5 minutes	0–1 minute	↓ 80–100% faster
Accuracy Variation	±0.02 mm	±0.005 mm	↑ 4x improvement in precision
First-Time Right	83%	>95%	↑ Significant improvement in consistency
Operator Involvement	High (manual setup)	Low (automated setup)	↓ Minimal intervention required

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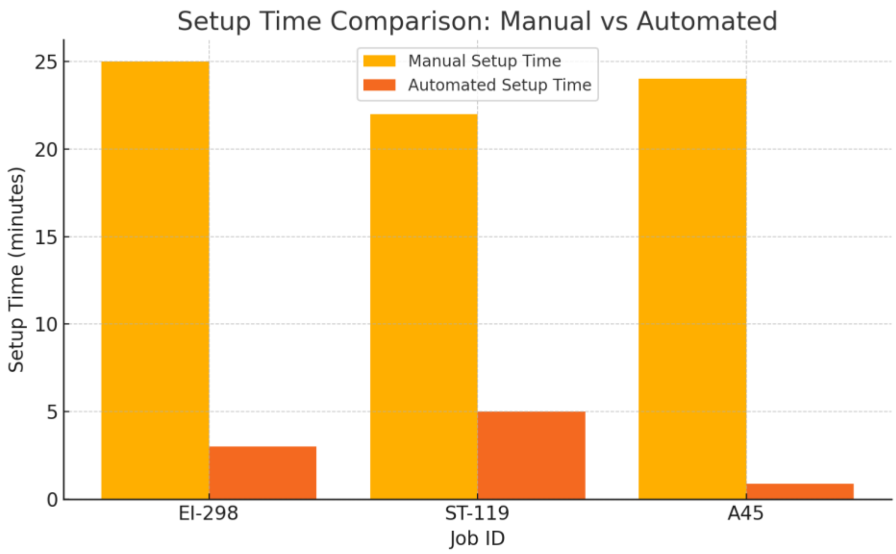
Case-Based Examples:

Copper Electrode: Job #EI-298 — Setup time reduced from 25 minutes (manual) to 3 minutes (automated).

Steel Electrode: Job #ST-119 — Dimensional accuracy improved from ±0.02 mm to ±0.005 mm after probe integration.

Batch Run A45 — Tool change time dropped from 4.8 minutes to 0.9 minutes using ATC.

Graphical Represention:



Analysis Summary

- **Productivity Gains**:
 Setup and tool change time were drastically reduced, allowing more jobs to be completed per shift with fewer delays.

- **Consistency**:
 Automation ensured that fixture positions and offsets were repeatable across machines and operators, removing variability caused by human factors.

- **Dimensional Accuracy**:
 High-precision probing and stable clamping reduced tolerance drift and enabled electrodes to meet sub-0.005 mm accuracy targets consistently.

- **Quality Improvement**:
 Fewer rejected parts and less rework directly correlated with improvements in offset calibration and fixture stability.

- **Ergonomics and Human Factors**:
 Reduced operator fatigue and fewer manual handling tasks enhanced safety and workflow comfort, especially during repetitive job setups.

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5. Discussion & Reflection

This project journey offered both technical challenges and valuable learning experiences. The shift from a conventional, operator-dependent VMC workflow to a semi-automated system required careful planning, iterative problem-solving, and real-time collaboration between engineering, operations, and vendor teams. Below is a reflection on what worked well, the challenges encountered, and how personal learning and system feedback shaped the final outcome.

What Worked Well

- **Standardization through ATC**:
  Before automation, tool loading was operator-specific and inconsistent. With ATC implementation, tool change time dropped significantly and operator involvement was minimized. Tool magazine indexing ensured higher consistency and reduced unplanned delays between operations.

- **Effective Integration of the 3R Clamping System**:
  The 3R zero-point referencing system enabled fast and reliable job interchangeability between machines. This drastically reduced the need for repeated alignment and minimized accumulated human error over multiple setups.

- **Laser measuring systems and touch probes Accuracy**:
  Real-time probing eliminated the need for manual tool length and wear checks. The system delivered immediate feedback on tool status and ensured that offsets were automatically corrected — boosting dimensional repeatability.

- **Cycle Time Reduction**:
  The synchronized functioning of ATC, Blum probing, and 3R clamping systems allowed for significantly faster setup and execution. Cumulative time savings led to measurable gains in productivity across all shifts.

Challenges Faced

- **Initial Setup and Calibration Complexity**:
  The alignment of tool holders, probing routines, and base plates required several iterations before achieving stable and repeatable outcomes. This was particularly important in older VMCs, where wear and control lag posed additional issues.

- **High Initial Investment**:
  The combined cost of System 3R plates, Blum probing kits, and compatible ATC tool holders represented a substantial capital expenditure. However, long-term gains and payback modeling justified the upfront cost.

- **Skill Gap and Operator Training**:
  Many operators were unfamiliar with automation protocols and error codes.

Structured training sessions were required to bring them up to speed, including how to handle probing cycles, tool change alarms, and fixture referencing.

- **Compatibility with Legacy Machines**:
  Some machines lacked native support for advanced sensors or interface logic. These required custom scripts and minor retrofits to synchronize new systems with old control software.

- **Tool Breakage and Offset Drift Risks**:
  During early trials, a broken tool went undetected due to a missed probe cycle. Post-analysis led to the incorporation of tool presence sensors and probe alerts into the CNC logic.

- **Unsupervised Process Validation**:
  Achieving confidence in full unmanned execution required extensive first-batch monitoring, backup probes, and logical fail-safes to prevent scrap or machine damage during unattended runs.

- **Subsystem Communication**:
  Initial integration issues between CNC logic, Blum probing sequences, 3R referencing, and ATC indexing caused sequencing problems. These were resolved by custom M-codes and synchronizing toolpath logic through layered testing.

Use of Feedback

- Based on operator feedback, 3R clamping plates were repositioned for better ergonomic access and visibility.

- Trial runs revealed small probe offset inconsistencies. As a result, probing cycles were recalibrated and programmed with double-check conditions, which led to higher offset reliability.

Creativity and Innovation

- Developed a **custom tool loading sequence** tailored to the magazine layout of Elmex's specific ATC model, optimizing tool access order and minimizing rotational lag.

- Designed a **visual layout guide** for 3R fixture referencing, reducing onboarding time for new operators and ensuring setup consistency across shifts.

Personal Reflections

- **Hands-on Learning in Industrial Automation**:
  Spending time on the shop floor provided practical exposure to how theory meets practice in manufacturing environments. From spindle alignment to machine interfacing, I witnessed firsthand how small details make a massive impact.

- **Application of Engineering Principles**:
  Concepts like tolerance stack-up, feedback control loops, and kinematic referencing came alive through real application. This strengthened both my conceptual understanding and decision-making under constraints.

- **Project and Problem-Solving Skills**:
  From mapping inefficiencies to implementing corrective action, every step demanded logical structuring, teamwork, and adaptability. I developed stronger planning skills and resilience when faced with unexpected failures.

- **Business Perspective**:
  Understanding the ROI implications, workforce implications, and long-term plant scalability added a strategic dimension to the technical work — connecting automation with measurable business value.

6. Risk Assessment & Safety Considerations

While the transition to semi-automated VMC machining provided major gains in efficiency and precision, it also introduced new operational risks that had to be identified and managed. A formal risk assessment was conducted to ensure that both personnel safety and process integrity were preserved during and after automation deployment.

Identified Hazards

- **Tool Breakage During Unmanned Operation**:
  A broken tool could damage the spindle, compromise the workpiece, or continue operating undetected without intervention.

- **Misaligned Setups**:
  Improper clamping or referencing could result in scrap parts and failed batches.

- **Software or Sensor Failures**:
  Malfunctioning probes or faulty tool presence detection could cause incorrect offsets or missed tool changes.

- **Operator Misuse or Lack of Familiarity**:
  Without proper training, operators could skip critical checks or misunderstand error

messages.

Risk Mitigation Measures

- **Sensor-Based Alerts and Probing Cycles**:
 Laser measuring systems and touch probes were configured to verify tool lengths and positions before each cycle. Alarms were programmed to notify operators in case of offset drift or missing tools.

- **Emergency Stop Protocols**:
 Machines were tested and confirmed to have responsive emergency stop mechanisms. Operators were trained on their usage and standard operating procedures during setup and runtime.

- **Error Handling Logic in CNC Programs**:
 Custom M-codes and if-else logic were added to probe sequences and tool change commands to ensure the system would halt on fault detection.

- **Operator Safety and Upskilling**:
 Training sessions covered safety protocols, hazard zones, emergency responses, and correct use of automation interfaces. This helped build confidence and prevent human-induced failures.

- **Trial Runs with Close Monitoring**:
 All new jobs and probing sequences were trialed under supervision for the first few cycles to detect risks and fine-tune system logic.

Example: ATC Tool Misclamp Incident

During one pilot trial, the ATC attempted to load a tool that had not been securely clamped into the holder. This caused a spindle stop and cycle failure. Investigation revealed an edge-case in the magazine indexing logic. The corrective actions included:

- Recalibrating the tool magazine
- Integrating a tool presence sensor
- Updating CNC logic to validate tool presence before execution
- Retraining operators on visual and system-level tool check procedures

Following this fix, no further incidents of this type were observed.

7. Ethical & Environmental Considerations

The automation of VMC operations at Elmex was guided not only by technical and financial objectives but also by a strong sense of ethical responsibility and environmental consciousness. The project demonstrated how industrial upgrades can be implemented without compromising workforce dignity or ecological sustainability.

Environmental Impact

- **Material Waste Reduction**:
  The increase in First-Time Right (FTR) rates and reduction in dimensional errors led to significantly fewer scrapped parts and rework jobs. This directly conserved raw materials like copper and steel, which are both energy-intensive to process.

- **Energy Efficiency**:
  Automated setups drastically reduced idle spindle time and machine downtime. Faster cycle execution meant fewer hours of power consumption per part manufactured.

- **Tool Life Extension**:
  The use of **laser measuring systems and touch probes** for real-time wear detection helped identify degraded tools before they caused defects, which extended tool life and reduced the frequency of tool replacement.

Ethical Considerations

- **No Job Displacement**:
  Automation was implemented with a firm commitment to retaining all staff. Rather than replacing workers, Elmex used this opportunity to **upskill** its machine operators and programmers. They were trained in CNC programming, probing cycles, and automation logic.

- **Workplace Ergonomics and Safety**:
  With the 3R clamping system and ATC integration, physically demanding and repetitive tasks such as manual tool changes and workpiece alignments were minimized. This reduced operator fatigue and exposure to occupational hazards.

- **Inclusive Change Management**:
  Operators were included in pilot trials, feedback loops, and training sessions. Their feedback was actively incorporated into process adjustments, ensuring that automation was seen as a collaborative advancement rather than a top-down

mandate.

Broader Implications for Sustainable Manufacturing

This project supports the vision of **responsible industrial transformation**, showing that it is possible to modernize traditional shop floors without compromising people or the planet. The integration of sustainable engineering practices, ethical labor engagement, and long-term efficiency planning positions Elmex as a role model for small-to-medium manufacturers adopting Industry 4.0 technologies.

8. Communication of Results

Ensuring that the outcomes of this automation project were effectively communicated across all levels of the organization was critical to building buy-in, securing future investments, and enabling process continuity. The communication strategy targeted both technical stakeholders and shop-floor operators, using a combination of data, visuals, and structured presentations.

Stakeholder Presentation to Management

A technical report and visual presentation were shared with the Elmex management team, summarizing:

- Before-and-after performance data (cycle time, setup time, accuracy, and FTR)
- Case-specific learnings from pilot trials and full-scale rollouts
- Strategic recommendations for scaling automation across more machines

Dashboards were used to present this information clearly, including side-by-side metric comparisons and real-time graphs pulled from machine diagnostics.

Team Briefings and Shop Floor Demonstrations

To ensure operational teams were aligned with the new workflow:

- Annotated photos of the upgraded setups (3R base plates, **laser measuring systems and touch probes**, and ATC configurations) were shared with operators to show key changes.
- Operators attended short sessions where probing cycles and error alerts were demonstrated live, reinforcing understanding of automated checks.

Figure 6: Operator performing job setup on VMC

Documentation for Long-Term Adoption

- **Internal Training Manual**:
  A written guide was created detailing the probe calibration steps, ATC sequencing logic, and setup procedures for 3R clamping. This document helps futureproof the process against operator turnover.

- **Knowledge Base**:
  Troubleshooting tips, frequently encountered alarms, and sensor calibration data were compiled into a shared digital folder for easy reference by both engineers and operators.

- **Data Archiving**:
  Logs from pilot trials, setup times, and tool wear analysis were archived to serve as a benchmark for similar projects or upgrades in other departments.

By making results transparent and accessible, the project ensured cross-functional alignment and laid a strong foundation for future improvements. Communication was not treated as an afterthought — it was integrated into every phase of the implementation.

9. Use of Feedback & Creative Decisions

While the automation solutions applied in this project—3R clamping, **laser measuring systems and touch probes**, and ATC—were based on proven technologies, their implementation at Elmex involved several layers of iterative feedback, adaptation, and creative thinking. This section highlights how stakeholder input and on-ground experimentation directly influenced design decisions and optimization.

Use of Feedback

- **Operator-Driven Fixture Positioning**:
  During pilot trials, multiple operators reported difficulty accessing clamping screws on certain job types. Based on this input, the 3R base plate layouts were repositioned to allow easier access without compromising kinematic alignment. This small adjustment improved setup speed and reduced operator fatigue.

- **Probing Cycle Recalibration**:
  Initial probing routines occasionally misjudged tool offsets due to minor wear inconsistencies. After reviewing probe logs and discussing with the toolroom team, the probing cycle was adjusted to add a double-read step with tolerance bands. This improved detection consistency, especially for smaller tools.

- **Simplified Error Messages**:
  Operators unfamiliar with **laser measuring system error codes** often misinterpreted alerts. As a solution, probe alarms were mapped to custom on-screen messages with plain-language instructions (e.g., “Re-check tool length” instead of “Z-Offset Exceeded”).

Creative and Original Contributions

- **Custom Tool Loading Sequence for ATC**:
  The default magazine loading order was found to increase indexing lag during job transitions. To solve this, I designed a custom sequence that reorganized the tool placement logic to minimize carousel rotation time. This improved efficiency during tool change-intensive jobs.

- **Visual Setup Reference Guides**:
  I created annotated diagrams showing optimal part positioning, fixture alignment, and probe paths for commonly machined electrodes. These were printed and mounted near machines to help newer operators complete setup faster and with more confidence.

- **Trial Data Dashboard**:
  A Google Sheets-based dashboard was built to log pilot trial results (setup time, accuracy, tool change duration, etc.). This helped visualize trends and made it easier to identify outliers and improvement opportunities.

This combination of feedback integration and inventive problem-solving ensured that the automation project was not only technically sound, but also tailored to Elmex’s unique operational realities. It highlighted that innovation isn’t always about creating something entirely new — it can also mean **reimagining how proven systems are adapted, communicated, and applied**.

10. Conclusion and Extensions

The automation initiative undertaken at Elmex Controls Pvt. Ltd. represents a transformative step in the modernization of its VMC-based manufacturing workflow. What began as an attempt to reduce setup time and improve part accuracy evolved into a comprehensive process re-engineering project that touched on engineering principles, operational strategy, workforce development, and ethical sustainability.

The integration of 3R zero-point clamping,Laser measuring systems and touch probes, and Automatic Tool Changers (ATCs) successfully delivered on its promise: to transition Elmex from a conventional, operator-reliant machining process to a repeatable, semi-automated, precision-driven production system. In doing so, it showcased how legacy systems can be revitalized through modular innovation and grassroots involvement — without the need for large-scale capital overhaul.

Project Achievements

- **Process Efficiency**:
  Setup time was reduced by up to 90%, and tool change duration was slashed by over 80%. This unlocked additional productive capacity within existing machine hours.

- **Precision & Quality**:
  Achieving dimensional repeatability within ±0.005 mm greatly reduced rework and scrap, especially critical in EDM-ready electrodes.

- **Operator Empowerment**:
  Rather than replacing workers, the automation process upskilled them, enhancing their role from machine operators to machine supervisors, capable of running probe cycles and troubleshooting systems.

- **Scalability**:
  The modular approach ensures this system can be easily replicated across additional machines and job types with minimal disruption.

- **Sustainability**:
  Reduced energy use per part, minimized material wastage, and extended tool life collectively contribute to Elmex's broader sustainability goals.

Lessons Learned

This project reaffirmed several important ideas:

1. **Change is successful when inclusive** — The involvement of operators, engineers, and management created a shared sense of ownership, reducing resistance and accelerating learning.

2. **Small technical tweaks can yield large benefits —** From changing probe calibration sequences to designing custom tool maps, incremental optimizations compounded to deliver massive efficiency gains.

3. **Digital transformation doesn't always require digital replacement** — By intelligently upgrading what already exists, this project demonstrated a cost-effective path to Industry 4.0 alignment for SMEs.

Recommendations & Future Improvements

While the project met all of its defined objectives, further enhancements can be made:

- **Real-Time Monitoring with IoT Sensors**:
  Implementing machine and tool monitoring systems using IoT could allow for predictive maintenance, live productivity tracking, and immediate fault alerts — especially useful during unmanned night shifts.
- **AI-Based Tool Life Prediction**:
  Leveraging data from the **laser measuring system and touch probe** and tool usage logs, machine learning models could be trained to predict tool wear patterns and auto-schedule replacements before breakage.

- **Digital Twin Simulation**:
  Building a virtual replica of the VMC workflow using a digital twin can allow new job paths to be tested and optimized in simulation before real-world execution.

- **Vision Systems for Final QC**:
  Integrating camera-based visual inspection could automate the post-machining quality check stage and provide another layer of assurance in critical jobs.

- **Cross-Training for Greater Resilience**:
  Training multiple operators across different machines and automation modules will ensure that system knowledge is not siloed and operational continuity is maintained during staff turnover.

Conclusion

Ultimately, this project is a proof of concept — not only for automated machining, but for how innovation can be driven from within an organization by combining research, observation, teamwork, and reflection. The transition to automation was not just a technical achievement; it was a cultural shift in how work is approached, how quality is defined, and how people and machines can complement each other.

This project marks a transformative step toward Industry 4.0 at Elmex — not by replacing people, but by enhancing their capability. By modernizing legacy systems through smart automation, we've proven that innovation doesn't always mean starting over — it can mean starting smarter.