

Concept of a Remote CNC Teaching Classroom for External Students in Manufacturing Technology Education

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Abstract: The transition toward distance and blended learning in engineering education has exposed a persistent gap in the delivery of practically oriented courses, particularly in the field of CNC programming, where hands-on interaction with machine tools is traditionally considered essential for developing professional competence. This paper addresses the lack of practical training in CNC programming within distance and blended learning formats and presents a proposed solution based on the establishment of a dedicated classroom equipped with CNC milling routers and online camera access, supplemented by multimedia teaching tools and a web portal for remote interaction and assessment. The proposed approach is positioned relative to three established families of methods for supporting practical CNC education, CNC simulation software, extended reality (XR) environments, and router-based teaching machines for CAM courses with the aim of identifying the relative advantages and limitations of each approach in terms of educational value, cost, scalability, and fidelity to real machining conditions. Particular attention is given to the integration of multi-layer automated evaluation mechanisms that support objective, efficient, and immediate feedback on student performance in CNC programming tasks. The presented concept is explicitly framed as a design-stage proposal and contributes to the modernization of higher education in computer-aided manufacturing technologies, providing a structured basis for subsequent pilot implementations and empirical evaluation in technically oriented study programs.

Keywords: DISTANCE AND BLENDED LEARNING, CNC PROGRAMMING, COMPUTER-AIDED MANUFACTURING

1. Introduction

Distance and blended learning formats have become an integral part of engineering education, driven by increasing student diversity, the need for flexible study arrangements, and the broader digitalization of higher education. In manufacturing-oriented programs, this shift raises specific challenges because many learning outcomes are tightly coupled to hands-on laboratory experience and direct interaction with physical equipment. Computer numerical control (CNC) programming and machining represent a prime example: beyond mastering G-code syntax and process planning, students must develop an understanding of machine setup, workholding, tool selection, process monitoring and safety, all of which traditionally rely on repeated practice at real machine tools.

To accommodate larger and more heterogeneous cohorts, universities and vocational institutions have increasingly complemented traditional laboratory teaching with simulation-based CNC training. Modern CNC simulators provide virtual control panels, graphical toolpath visualization, and three-dimensional representation of machining processes, allowing students to experiment with programs and process parameters in a safe, cost-effective environment [1]. These tools support distance learning scenarios by enabling learners to work on programming tasks without access to a physical machine, and they have demonstrated benefits in terms of accelerated skill acquisition and reduced risk of collisions and tool breakage during early training phases. At the same time, simulation environments inherently abstract away many sensory and contextual aspects of machining, such as chip formation, vibration, acoustic feedback, and real tool wear, which are important for developing professional judgement and tacit knowledge.

Extended reality (XR) technologies [2], virtual reality (VR) [3], augmented reality (AR), and mixed reality (MR) have gained attention as potential enablers of immersive CNC training, particularly in the context of Industry 4.0 and technical and vocational education and training (TVET) [4]. Systematic reviews of XR applications for CNC machine training indicate that VR and AR can enhance safety, support spatial understanding of machine setup, and reduce reliance on physical machines and expert mentors by allowing trainees to rehearse operations in virtual environments [5,6]. Experimental work on immersive VR error-management training for CNC milling setup shows that such environments can improve error identification and correction, increase learner engagement, and boost confidence compared to conventional

video-based instruction. In the broader TVET context, AI-ready VR machine workshops are proposed as a means to modernize CNC machining education and align pedagogical practice with digital manufacturing paradigms [4].

In parallel, router-based teaching machines have been designed and implemented as cost-effective platforms for computer-aided manufacturing (CAM) courses, providing students with access to three-axis CNC milling in an educational setting. Such systems demonstrate that CNC routers can serve as practical enablers of machining education, but they are typically used in conventional face-to-face laboratory formats and are not systematically integrated into distance-learning infrastructures or accompanied by automatic assessment mechanisms.

Despite these promising developments in simulation, XR and based teaching machines, there remains a gap between flexible remote access and authentic exposure to real machining conditions in regular university courses. Simulation software, although highly scalable and relatively inexpensive, does not provide direct experience with the mechanical behaviour of machine tools, workpiece setup and clamping, or the practical aspects of coolant, chip evacuation and tool life management. XR environments depend on specialized hardware and content development and are still limited in their ability to reproduce haptic feedback and process signals at engineering-relevant fidelity. Existing machines implementations, while valuable for on-campus teaching, do not address the specific constraints of external cohorts nor the need for integrated online assessment.

Against this backdrop, remotely accessible physical laboratories have emerged as a complementary approach in engineering education, enabling students to observe and sometimes control real equipment via networked interfaces and audiovisual streams. In CNC machining, pandemic-era initiatives showed that live camera feeds, screen sharing and interactive communication can provide realistic exposure to machine operation for geographically dispersed learners, but these arrangements were often ad hoc and temporary. Systematic designs of camera-instrumented CNC classrooms that are embedded into institutional distance-learning infrastructure, and that combine remote observation with structured automated assessment, are still rarely documented.

The present paper addresses this gap by proposing a concept for a specialized remote CNC teaching classroom built around educational three-axis milling routers, multi-camera online access, and a custom web portal with multi-layer automated assessment for

CNC programming tasks. The concept is developed for a bachelor-level course in programming of CNC machine tools for external students and is positioned relative to three established families of approaches: CNC simulation software, XR-based CNC training, and router-based teaching machines used in on-campus CAM courses. In contrast to prior router machines implementations, the proposed design explicitly targets distance and part-time cohorts, integrates remote video observation into the course workflow, and couples it with a structured automatic evaluation scheme.

The central research question is: "How can a remote CNC teaching classroom based on educational routers, online video transmission, and automated assessment support practically oriented CNC programming education for external students, while minimizing, but not eliminating the need for on-site laboratory exercises?"

The paper answers this question at the level of concept and design: it lays out the course context, the proposed hardware and software architecture, a five-stage workflow from home programming to on-site production-machine work, and a multi-layer assessment scheme, and it discusses anticipated benefits, limitations and future developments. The work is explicitly positioned as a design-stage proposal; pilot implementations and empirical evaluation are identified as future work rather than claimed as completed.

2. Background and related work

The teaching of CNC programming in manufacturing technology curricula has long relied on intensive laboratory practice at industrial machine tools, where students learn to translate drawings and CAD models into executable programs and observe the immediate consequences of their programming decisions on the machining process. Simulation tools and CNC training software have been widely introduced to support this process, enabling safe experimentation with G-code, toolpaths, and process parameters on standard PCs. These environments help reduce the risk of tool and machine damage in early training phases and allow for the repetition of typical programming scenarios without consuming material or machine time.

Extended reality technologies form a second major strand of work. Systematic reviews report that XR, including VR and AR, can support complex manual tasks, improve safety, and enhance learner engagement by providing immersive visualization and guided interaction. In CNC machining specifically, VR-based environments have been developed to teach machine setup and error management, showing that trainees can improve error recognition and confidence while retaining conceptual knowledge.

Remote and virtual laboratories represent a third relevant line of work. Virtual laboratories provide simulated experiments via software, while remote laboratories connect students to real equipment through network interfaces and audiovisual channels. In the CNC domain, pandemic-driven experiences with online teaching have demonstrated that streaming from shop-floor machines, combined with interactive discussion, can maintain some level of practical exposure when students cannot attend in person. These initiatives, however, were largely improvised responses to constraints and seldom evolved into systematically designed, permanent remote classrooms with integrated assessment.

Router-based teaching machines form a fourth strand. Designs of three-axis CNC routers for CAM courses show that such systems can deliver valuable hands-on experience at lower cost than full industrial machining centers, and they can be closely integrated with CAD/CAM workflows in educational settings. These implementations generally assume on-site student presence, and while they sometimes include software for toolpath verification, they do not typically address remote video integration or multi-layer automated assessment for distance learners.

The concept presented in this paper builds directly on this body of work. It adopts educational CNC routers as the physical machining platform, uses simulation tools as a preparatory step, and acknowledges XR and digital twins as promising future extensions. Its specific contribution lies in treating a multi-router, camera-instrumented classroom as a *remote physical resource* for external cohorts and in tightly coupling this resource to a web portal that provides automated, data-driven assessment of CNC programs.

3. Course context and educational requirements

The proposed concept is developed for a bachelor-level course titled *Programming of CNC Machine Tools*, delivered primarily to external (part-time) students within a manufacturing technology program. The course aims to equip students with practical skills in programming milling operations, understanding and using machine coordinate systems, and verifying and implementing CNC programs on real equipment. Students enter the course with basic computer literacy and introductory experience in CAD systems, which provides a foundation for linking geometric representation of parts to toolpath generation and G-code.

Key learning outcomes of the course are:

- to create CNC programs for standard milling operations on prismatic parts,
- to correctly apply workpiece and machine coordinate systems,
- to test programs using simulation tools and detect programming and logical errors,
- to implement and execute validated programs on CNC machine tools in a safe and controlled manner.

In the traditional delivery format, the practical part of the course has been realized first with CNC simulators and later with direct programming and operation of CNC machining centers in the university laboratory. External students, however, have limited access to these laboratories due to work commitments and geographical constraints, which restricts their opportunities to observe real machining processes and to link theoretical and simulated programming tasks to the behaviour of physical machine tools. This situation motivates the development of a remote teaching concept that maintains authentic exposure to machining while reducing the number of required on-site sessions.

4. Concept of the remote CNC teaching classroom

To address the constraints of external students while leveraging existing practices in CNC education, a dedicated remote CNC teaching classroom is proposed, built around educational CNC milling routers rather than full-scale production machining centers. Routers are chosen because their control systems are typically PC-based, which simplifies data transfer, screen sharing, and integration with a web portal, and because they are well suited for educational milling tasks on wood, plastics, or, in controlled cases, light metals.

In its initial configuration, the classroom is envisaged to host *four* CNC routers, each equipped with a camera system providing a live view of the machining process. The number four is treated as an illustrative starting point rather than a fixed optimum: it reflects a balance between the desire for multiple parallel demonstrations and the assumption that a single lecturer can feasibly supervise setup, workpiece exchange and monitoring across several routers within a session.

Each router is fitted with at least one camera focused on the cutting zone, with the option of additional views showing the overall machine workspace and the control panel. The camera feeds are connected to the web portal, which distributes synchronized video streams to external students during remote sessions. While detailed bandwidth and latency requirements will depend on chosen resolution and frame rate, the design assumes that the video subsystem must enable sufficiently smooth visualization of tool

motion, chip formation and coolant behaviour on typical home connections of external students; concrete performance targets are to be refined during pilot deployment.

The custom web portal serves as the central interface for external students. Through the portal, students can:

- access live video streams from the routers during scheduled remote practical sessions,
- upload their CNC programs for simulation and potential execution on the routers,
- receive structured feedback and assessment results for their programming tasks,
- complete auto-graded quizzes on theoretical aspects of CNC machining.

The physical handling of workpieces, fixtures, and machine setup remains the responsibility of the lecturer or technical staff on site, ensuring that safety is maintained and that the machines are operated within appropriate limits. External students thus interact primarily through the visual and informational channels provided by the portal and video streams, while still being able to see how their programs affect the real machining process. Viewed against previous three-axis router implementations for CAM courses, the novelty of this concept lies not in the router hardware itself but in its *systematic configuration as a remote resource* (multi-camera instrumentation, streaming integration with a portal) and in the *tight coupling with automated assessment workflows* that are designed from the outset to serve distance and part-time cohorts.

5. Proposed workflow and remote practical exercises

The teaching workflow is organized into several stages that combine simulation, remote observation, and limited on-site practice. This staged approach is designed to support external students, who cannot attend frequent laboratory sessions, while still guiding them from abstract programming concepts to real machining experience.

5.1. Program preparation at home

External students receive the design of a part (drawing or CAD model) and a description of the required milling operations, as part of regular assignments. Based on this, they prepare CNC programs using the designated control formats (e.g., Sinumerik, Heidenhain) and basic process planning guidelines covered in the lectures. The programming tasks are chosen to match the intended learning outcomes, focusing on contour milling, pockets, slots, and simple drilling sequences.

5.2. Program verification in simulation

Students test their programs using CNC simulators that provide graphical toolpath visualization and basic collision detection. The course has previously employed simulators for Sinumerik and Heidenhain controls, which allow students to verify syntax, see graphical representation of toolpaths, and check basic technological parameters. This step enables them to correct errors, adjust toolpaths, and refine process parameters in a risk-free environment, strengthening their understanding of coordinate systems and motion commands.

5.3. Submission and selection for remote execution

Verified programs are uploaded to the web portal, where they may undergo automated checks and preliminary assessment. The lecturer reviews the submissions and selects representative or particularly instructive programs to be executed on the CNC routers during the remote practical session. Criteria for selection may include diversity of approaches, common mistakes, or illustrative examples of good practice. Students whose programs are selected are informed in advance so that they can prepare to discuss their solutions during the session.

5.4. Remote observation of machining on routers

During scheduled online sessions, the lecturer prepares the routers (tool setup, workpiece clamping) and executes the selected student programs while sharing live video and, if needed, the control screen. External students connect through the portal to observe the machining process, listen to explanations, and discuss observed phenomena such as toolpaths, cutting conditions, surface quality, and the impact of programming decisions on process outcomes. The lecturer can pause the execution at key moments to highlight specific aspects (e.g., safe clearance moves, entry into material, transitions between roughing and finishing passes) and relate them back to the G-code segments. Students are encouraged to ask questions via chat or audio, and short formative questions can be posed to check understanding (for example, identifying the coordinate system in use, or explaining why a particular feed rate was chosen).

5.5. Final on-site exercises on production machining centers

To ensure that essential hands-on experience is not lost, the course includes one or two mandatory on-site laboratory sessions at production-grade CNC machining centers (e.g., DMG). In these sessions, students implement and adapt their programming skills in a real industrial environment, under direct supervision, consolidating the competencies acquired through simulation and remote observation. They perform basic setup operations, load and verify programs, and carry out machining tasks on metal workpieces, experiencing the differences in machine behaviour, safety procedures, and process constraints compared to the educational routers. The overall aim of this workflow is to minimize the number of on-site sessions required for external students while still providing a coherent progression from abstract programming concepts through simulation and remote visualization to authentic machining practice.

6. Concept of automated assessment and feedback

The web portal associated with the remote teaching classroom is designed not only as a communication and streaming platform but also as a tool for automated assessment of student CNC programs. The assessment concept builds on multiple layers, inspired by automatic grading approaches in programming courses and by assessment features in modern CNC training software.

6.1. Syntactic and structural validation

Submitted programs are automatically checked for syntactic correctness and for the presence of essential structural elements, such as safety blocks, tool definitions, coordinate system initialization, and proper program termination. This layer is intended to detect basic errors and provide immediate feedback, helping students avoid invalid or potentially dangerous code before simulation or machine execution, in line with experiences from automatic assessment in programming tools courses.

6.2. Simulation-based analysis of toolpaths and parameters

The portal then integrates with CNC simulation tools to evaluate the geometric and technological characteristics of the programmed toolpaths. Metrics may include collision-free motion, total path length and machining time, the distribution of rapid versus feed movements, and the plausibility of feed rates and spindle speeds relative to reference ranges. At the current conceptual stage, these metrics are envisaged to be combined into scoring schemes that reflect both correctness and efficiency of the programming solution; exact weighting and calibration against lecturer grading are reserved for future empirical work.

6.3. Comparison with reference solutions

For typical educational tasks, reference programs representing technically sound solutions can be prepared and maintained. Automated comparison between student and reference toolpaths and

simulated workpiece geometry is expected to allow quantification of deviations in contour accuracy, remaining material, or process time. In combination with logs from router executions and lecturer annotations, this is anticipated to support more consistent and transparent assessment while also generating learning-analytics data on error patterns and progression.

6.4. Integration with remote router execution

Programs that pass the simulated assessment may be marked as candidates for execution on the routers during remote sessions. The portal logs which student program is executed, and the lecturer can add qualitative annotations based on observed machining behaviour, such as surface quality, stability, or practical issues during setup. These annotations complement the automated scores and contribute to a richer feedback profile for each student. Such a combination of automatic scoring and lecturer judgement mirrors approaches used in interactive CNC training and assessment systems, which aim to standardize evaluation while still allowing expert input.

6.5. Automated quizzes and theoretical tests

In addition to program assessment, the portal can host auto-graded quizzes on theoretical aspects of CNC programming and machining (e.g., coordinate systems, G-functions, and safety principles). Immediate feedback on these quizzes supports self-paced learning and helps external students identify gaps in their understanding. Quiz performance can be correlated with practical programming results to gain insight into the relationship between theoretical knowledge and applied skills.

6.6. Anticipated benefits of automated assessment

By combining these layers, the automated assessment concept aims to: - provide external students with rapid, structured feedback on their programming performance, - reduce the manual grading workload of lecturers, - generate data for analysing learning progress and typical error patterns in CNC programming, - support fair and transparent evaluation across large cohorts. At the present design stage, these benefits are understood as anticipated outcomes that require validation in pilot implementations rather than as empirically established effects.

7. Discussion: benefits, limitations, and future developments

The proposed remote CNC teaching classroom and workflow offer several anticipated benefits for manufacturing technology education, especially in the context of external cohorts. For students, the concept is intended to increase accessibility to practically oriented learning activities by enabling them to prepare and test programs at home, observe real machining processes via online video, and receive systematic feedback without frequent travel to campus laboratories. For lecturers, the combination of simulation, remote router execution, and automated assessment is expected to provide a scalable way to manage larger groups, allowing them to concentrate limited on-site time on high-impact sessions at production machining centers rather than on basic programming practice. At the same time, important limitations must be acknowledged. Work on educational routers, even when observed remotely, cannot fully replicate the experience of programming and setting up industrial machining centers, where machine dynamics, safety considerations, and process constraints differ significantly. The concept therefore explicitly retains a minimal number of mandatory on-site laboratory exercises on production machines to ensure that students encounter real industrial conditions. Moreover, the quality of remote observation will depend on camera placement, video resolution, and network stability; these design parameters must be specified and validated during implementation, since inadequate video quality could undermine the pedagogical value of the remote sessions. From a methodological perspective, the current work is limited to concept and design. No empirical data on learning outcomes, student satisfaction, or grading reliability are yet available, and any claimed

benefits must therefore be treated as hypotheses rather than established findings. Planned next steps include pilot deployment with a small cohort of external students, collection of quantitative data (e.g., assessment scores, error rates, time-on-task) and qualitative data (student and lecturer feedback), and comparison with cohorts taught in purely on-site formats. Looking forward, the remote classroom concept can be extended toward more advanced digital manufacturing paradigms. One envisioned direction is the integration of virtual reality representations of the machine tools and the creation of digital twins of the routers and production centers, which would allow students to experience setup and operation in immersive environments while maintaining synchronization with real processes. Beyond machining, similar remote and virtual teaching workplaces could be developed for other manufacturing technologies such as forming, welding, and robotics, supporting a broader modernization of practical education in manufacturing technology programs.

8. Conclusions

This paper has presented a concept for a remote CNC teaching classroom designed to support practically oriented CNC programming education for external bachelor students in manufacturing technology. The concept combines educational CNC milling routers equipped with cameras, a custom web portal, CNC simulation tools, and a structured workflow that leads from program preparation and simulation through remote observation of machining on routers to focused on-site practice at production machining centers. An accompanying automated assessment framework is outlined, which is intended to provide immediate feedback on student programs and to generate data for analysing learning progress and typical error patterns. In contrast to prior work on simulation, XR training and router-based CAM teaching, the proposed design treats a multi-router, camera-instrumented classroom as a remotely accessible physical resource specifically tailored to external cohorts and tightly integrated with an online assessment portal. By reducing the reliance on frequent on-site laboratory sessions while maintaining authentic exposure to machining processes, the concept addresses a concrete challenge in delivering CNC programming courses to part-time and distance learners. At the same time, it is explicitly positioned as a design-stage proposal: empirical validation through pilot implementations and systematic evaluation remains future work. As such, the paper is intended to provide a structured starting point for institutions considering similar investments in remote machining infrastructure for manufacturing education. The authors anticipate that subsequent implementations and studies will refine the design parameters, validate the assessment mechanisms, and explore extensions toward digital twins and VR-based training environments in this domain.

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9. References

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