Integrating Project and Group Based Learning to Develop Hands-On Precision Manufacturing Skills in Post-Graduate Students

Zareena Gani
Mechanical Engineering
University College London
London, United Kingdom

INTRODUCTION

In the rapidly evolving field of precision manufacturing, it is crucial to equip postgraduate students with practical, hands-on experience alongside theoretical knowledge. As the advanced manufacturing industries increasingly demand precision and efficiency, this study presents a novel pedagogical approach integrating Project-Based Learning (PBL) and Group-Based Learning to teach precision manufacturing skills effectively. The strategy focuses on applying Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies, advanced manufacturing techniques, and metrology in real-world contexts. Students work on projects in a state-of-the-art facility, utilising a high-precision 5-axis CNC machine, 3D printers, and advanced characterisation techniques, closely mirroring industry conditions. Through collaboration in small groups, students share diverse perspectives and allocate tasks based on individual strengths. This framework prepares them to understand precision manufacturing principles and apply them in practical situations, ensuring they are well-equipped for successful careers in the industry.

PRECISION MANUFACTURING MODULE

Precision Manufacturing is a core module for MSc students in the Future Manufacturing and Nanoscale Engineering (FMNE) [1] program taught at the new UCL East campus, starting September 2023. It is also an optional module for other programs, such as the MSc in Manufacturing with Innovation and Enterprise (MIE) [2]. This module is designed to equip students with essential skills and knowledge in advanced manufacturing practices.

The module Learning Outcomes include:

1. Recognize the difference between precision manufacturing and macro-scale manufacturing.
2. Evaluate product requirements and choose appropriate additive or subtractive manufacturing techniques.
3. Demonstrate hands-on skills in operating advanced manufacturing machine tools and characterization/metrology equipment.
4. Design and fabricate solutions as a team for a given manufacturing challenge scenario.

The module covers various aspects of precision manufacturing, including design methodologies, machine tool requirements, consumer needs, and applications. It addresses current industry practices related to advanced machine tools for both additive and subtractive manufacturing, as well as software, production techniques, surface generation, quality inspection, measurement methods, and testing equipment. Additionally, the module discusses the relevance of machine dynamics for adequate dimensional accuracy and surface generation in precision manufacturing.

In the prerequisite module on Advanced Characterization, students gain hands-on training in various characterisation techniques, including Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), Atomic Force Microscopy (AFM), and white light interferometry. This training equips them to select the appropriate techniques for obtaining critical information on specific material properties.

METHODOLOGY

PBL is learning and not teaching, thus being an open investigation or knowledge-creation process. In PBL, a real-world problem is the starting point of the learning process, and learning is active and participant-led [3].

In group-based learning, students work in small groups to simulate an industry-like work environment. They engage in team-building activities to get to know one another, discussing their strengths and areas for growth. This collaborative approach allows students to allocate tasks based on individual interests and abilities, offering opportunities to learn from each other and develop technical and interpersonal skills.

One of the main challenges in engineering education is keeping pace with rapidly evolving technologies while simultaneously managing knowledge delivery and avoiding curriculum overload [4]. This course addresses these challenges through a central group-based project in which teams of three to four students design and fabricate a precision toolmaker's vice. The majority of the learning takes place in groups, allowing students to develop essential collaborative skills while managing all stages of the project [5].

The project spans several vital stages, starting with a comprehensive two-day workshop on Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). This workshop is about learning the software and gaining foundational skills to apply these critical areas in real-world projects. The students also acquired in-depth insight into the available machine tools, fixtures, and cutting tools and learned to develop their CAD models and tool paths in context.

Following the workshop, students proceed to the design phase, where they utilise CAD software to create detailed models of the Precision Toolmaker's vice, as shown in FIGURE 1. The students then generate the tool path (CAM program) for their part designs for 5-axis CNC machining. The CNC machining process is not just a part of the project; it is pivotal, requiring students to acquire knowledge and practical skills in workpiece set-up and orientation, selection of cutting tools for various operations, and application of their theoretical understanding of machine dynamics, surface finish, and sustainability requirements of the project.

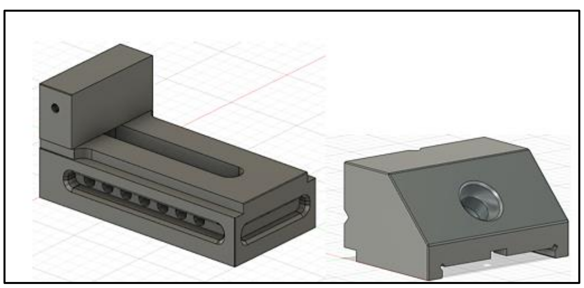

FIGURE 1 CAD Model of the Precision Toolmaker's Vice

All these PBL elements are designed to work together synchronously so that the graduating students get equipped with all the essential skills needed to work in the evolving precision manufacturing industry.

Challenges and Solutions

In Project-Based Learning (PBL), the instructor acts as a primary source of information, drawing on their expertise and industry experience. This role is crucial, as educators need to possess substantial practical experience and up-to-date knowledge of current industry practices to facilitate learning through this approach effectively [6]. The overarching goal is to equip graduates with future-focused skill sets in next-generation synthesis and manufacturing technologies to support sustainable growth across key industry sectors.

One of the primary challenges is making micro- and nanoscale precision manufacturing accessible through real-world, industry-relevant experiential learning. This challenge is particularly pronounced in many advanced engineering programs, which often focus on specialised and niche areas of study [7]. For instance, manufacturing at the nanoscale and conducting nano-inspection typically require specialised equipment and techniques that students may not encounter before entering postgraduate programs. As a result, many students begin their studies with limited hands-on experience and practical skills upon which to build.

This situation underscores the significant investment needed for both specialised tools and infrastructure. The newly established UCL East campus features state-of-the-art facilities designed to address these needs, including the Manufacturing Futures Lab (MFL) and the Precision Fabrication Workshop. The MFL includes world-class research laboratories and purpose-designed engineering teaching spaces specifically focused on developing next-generation manufacturing technologies. In addition, the Precision Fabrication Workshop is equipped with advanced machinery, including a high-precision 5-axis CNC machine (FIGURE 2), along with various advanced machine tools and additive manufacturing capabilities.

These facilities not only enhance students' technical skills but also foster innovation and collaboration, better preparing them for the demands of the modern manufacturing industry.

FIGURE 2 DMU 40 high-precision 5-axis CNC machine

One of the main challenges faced during the project is ensuring a surface finish in the sub-micron range. This level of precision requires careful planning and execution in both the CAD design and machining phases. To address this challenge, students receive training in advanced metrology techniques, particularly using a 3D optical profilometer (FIGURE 5) to accurately measure surface finish and tool wear.

These measurements are essential for validating the quality of machined components and ensuring compliance with stringent tolerance requirements. The use of the optical profilometer enables students to gain practical experience in assessing surface quality, a critical aspect of precision manufacturing.

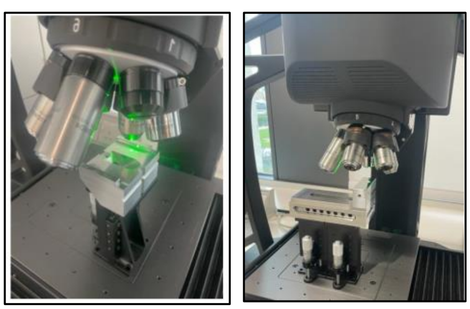

FIGURE 3 Surface Roughness measurement in Alicona G6 optical profilometer

Integration of 3D Printing Technology

The project also integrates advanced additive manufacturing technologies alongside precision machining, providing students with a comprehensive skill set in subtractive and additive manufacturing processes. Students are trained to use cloud-based design software, enabling remote collaboration and real-time project updates, which are critical skills in today's increasingly connected manufacturing environments. Using a composite 3D printer (FIGURE 4), students fabricate specific components of the precision toolmaker's vice in carbon fibre (FIGURE 5), a material known for its high strength-to-weight ratio and durability. This hands-on experience introduces students to the unique properties of composite materials and teaches them to navigate the complexities of additive manufacturing with high-performance materials.

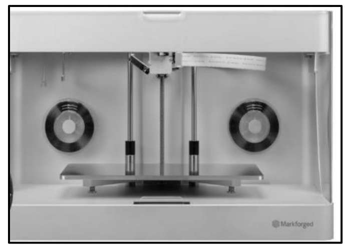

FIGURE 4: Markforged composite 3D printer

By combining top-down (subtractive) and bottom-up (additive) manufacturing methods within the same project, students gain practical insights into the strengths and limitations of each approach. This blended method emphasises the versatility of additive manufacturing for creating intricate shapes and lightweight structures while allowing students to experience how precision machining achieves tighter tolerances and finer surface finishes. Such a comprehensive approach prepares students to make informed decisions on which techniques to use for different industrial applications, underscoring the practical advantages of combining these manufacturing methods in a modern, adaptable production environment.

OUTCOMES AND EVALUATION

This pedagogical approach fosters a deeper understanding of precision manufacturing principles by immersing students in real-world challenges. Through iterative design, machining, and quality control processes, students develop critical thinking and problem-solving skills that enhance their learning experience. The hands-on nature of the project reinforces theoretical concepts, making the knowledge gained more applicable and robust.

Students working in a team successfully fabricated the components of the precision toolmaker's vice (FIGURE 5) and then evaluated aspects like dimensional accuracy, tolerance, surface roughness (FIGURE 6) and tool wear (FIGURE 7). These analyses allowed students to study the effects of machine dynamics and tool wear on surface finish, deepening their understanding of precision manufacturing requirements.

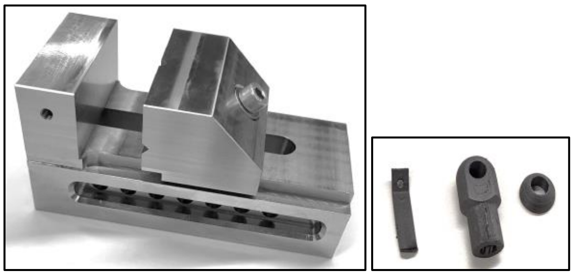

FIGURE 5 Precision machined & 3D printed vice components.

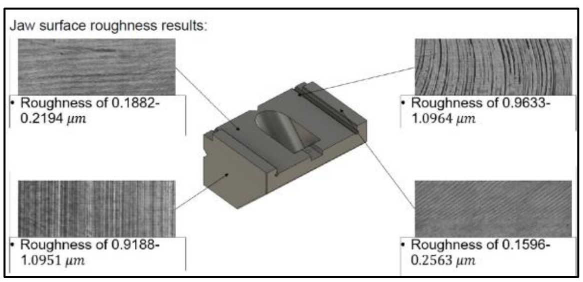

FIGURE 6: Surface roughness measured on the precision tool maker's vice

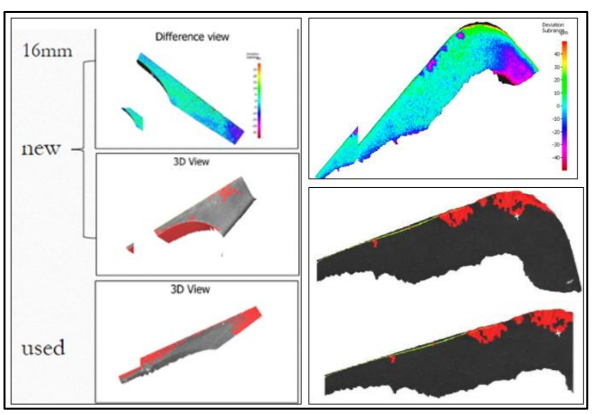

FIGURE 7: Tool wear measurement using Edge Master

Evaluation and Peer Assessment

Student progress was assessed through formative evaluations at each stage, which included reviews of CAD models, tool paths, and machined component quality, such as surface finish and tool wear, in correlation with machine dynamics and sustainability. Student feedback from these assessments supported continuous improvements in both the project and instructional methods.

Summative assessments involved a weighted evaluation of the practical components (50%), a written group report and presentation (10%), and peer assessment scoring to recognise individual contributions. This peer assessment method aims to give students marks based on their individual contributions rather than awarding the same group mark to all members. It also promotes student engagement, self-reflection, and peer feedback at early stages, which helps students learn the group dynamics and improve their work. The students also learnt to be empathetic and provide constructive feedback as required in any professional setting.

In addition, each group completed a case study (40%) on topics like Challenges in precision manufacturing of thin wall structures, Leveraging nanotechnology and additive manufacturing for healthcare innovations and Industry Practices in additive and subtractive precision manufacturing. These case studies demonstrated the students' extensive understanding of industry practices and requirements.

Student feedback was overwhelmingly positive, with many highlighting the course's structure and the practical relevance of its content. Students appreciated how the project-based approach allowed them to directly apply theoretical knowledge to real-world challenges, enhancing their confidence in using advanced manufacturing tools and techniques. Many found the hands-on experience with precision equipment, like the 5-axis CNC machine and composite 3D printer, invaluable for building industry-relevant skills that they could immediately envision applying in their future careers. The integration of teamwork and peer assessments was also well-received, as students felt that collaborating on complex tasks and receiving constructive feedback helped them grow both technically and interpersonally.

A few students noted that the time allocated to complete certain stages of the project was challenging, particularly given the complexity of tasks like machining setup and precision measurement. They expressed that a longer project timeline or additional scheduled practice sessions would have allowed them to refine their skills further and achieve even higher accuracy in their work. Overall, students rated the course as highly satisfactory, recognising it as a comprehensive and professionally relevant preparation for careers in precision manufacturing.

CONCLUSIONS

Integrating project-based and group-based learning into precision manufacturing education offers postgraduate students a comprehensive, hands-on approach to mastering industry-relevant skills. By engaging directly with real-world challenges and utilizing advanced manufacturing technologies, students are better prepared to meet the demands of careers in the precision manufacturing sector. This approach enhances their technical expertise while fostering critical skills like adaptability and innovation, which are essential in today's dynamic industrial landscape. Beyond technical competencies, the course equips students with effective communication skills, enabling them to convey complex ideas to both specialised and general audiences. This combination of practical and interpersonal skills ensures that graduates are well-prepared to contribute effectively to the future of precision manufacturing. Future iterations of this course may explore additional technologies and methodologies to further enhance student learning and adaptability in this dynamic field.

ACKNOWLEDGEMENT

The author would like to thank the UCL Centre for Engineering Education for their invaluable support in publishing this work.

REFERENCES

[1] https://www.ucl.ac.uk/prospective-students/graduate/taught-degrees/future-manufacturing-and-nanoscale-engineering-msc.
[2] https://www.ucl.ac.uk/prospective-students/graduate/taught-degrees/manufacturing-innovation-and-enterprise-msc.
[3] E. Graaff and A. Kolmos, “Characteristics of Problem-Based Learning,” I*nternational Journal of Engineering Education.*, vol. 19, pp. 657–662, Jan. 2003.
[4] A. L. Andersen and C. Rösiö, “Continuing Engineering Education (CEE) in Changeable and Reconfigurable Manufacturing using Problem-Based Learning (PBL),” in *Procedia CIRP*, Elsevier B.V., 2021, pp. 1035–1040. doi: 10.1016/j.procir.2021.11.174.
[5] O. Skovsmose, P. Valero, and O. R. Christensen, *University science and mathematics education in transition*. Springer US, 2009. doi: 10.1007/978-0-387-09829-6.
[6] Z. Gani, *Project Based Learning for a Computer Integrated Manufacturing Course*. 2019. doi: 10.18260/1-2--33202.
[7] E. Bele, E. Galindo-Nava, Z. Gani, L. Guo, and M. Michalska, “Work In Progress: Design of a PBL-Centred Masters Programme in Nanoscale Manufacturing.