Examining the Integration and Motivational Impact of Hands on Made4Me: Hands-on Machining, Analysis and Design Experiences for Mechanical Engineers

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Abstract

This paper presents the results of an ongoing effort to integrate hands-on machining, analysis and design experiences in several courses in the Department of Mechanical Engineering at the University of Massachusetts Lowell. Ten inexpensive, desktop computer numerical control (CNC) prototyping machines have been introduced to provide students with direct access to hobbyist level prototyping capability (machining wax, wood, ABS plastic, etc.), which might not otherwise be possible with more expensive CNC machines. Example course projects are presented to illustrate how desktop CNC machines can be used to integrate part and prototype realization in engineering education. Results of student motivation surveys in these hands-on courses were compared with results from more traditional lecture-based courses. Our qualitative and quantitative survey results show that, on average, students in the hands-on courses experience higher levels of intrinsic motivation and identified regulation when compared with students enrolled in more traditional, lecture-based courses.

1 Introduction

Problem- and project-based learning pedagogies have been linked to improved student learning\(^1\) and increased diversity in STEM related fields\(^2\). It is believed that hands-on learning activities allow students to practice and internalize abstract concepts. In doing so, students connect related concepts and improve their overall understanding of a subject. Furthermore, facilitating engaging, open-ended, hands-on projects can increase student autonomy while timely feedback can improve student’s feelings of competence. These projects with high relevance to engineering can increase connectedness and discipline engagement.

Understanding and experiencing modern prototyping and manufacturing processes are important aspects of the part and product development cycle. Students and practitioners that possess a deeper appreciation of the manufacturing process can often design parts that consider the capability of the manufacturing method. In many schools, colleges and universities the availability of practical, hands-on interaction with computer numerical controlled machines (CNC machines) is limited due to the expense and operational complexity of these machines. Many of the higher end CNC machines are reserved for expert machinists. As a result, students do not experience modern manufacturing beyond the “black-box” interactions with a machinist. The goal of this paper is to present the implementation of a CNC laboratory comprising inexpensive, hobbyist CNC machines.

This paper presents the development of a computer numerical control (CNC) laboratory and the associated preliminary data supporting an increase in student motivation as a result of project-versus lecture-based instruction. Ten inexpensive CNC milling machines have been deployed in an undergraduate teaching laboratory at the University of Massachusetts Lowell. Because these are inexpensive, hobbyist CNC machines, the fundamental concepts behind modern prototyping and manufacturing become accessible for hands-on exploration by students with little to no manufacturing expertise or background. For example, incoming freshman mechanical engineering
students are able to ideate, digitize and realize their first CNC manufactured part within two to three weeks of the beginning of the semester. This accelerated prototyping schedule would not be feasible using an industrial grade CNC machine.

An overarching question in this study is how hands-on, project-based courses, such as those employing desktop CNCs, can impact student motivation. Using self-determination theory as a theoretical basis, the study characterized engineering students’ situational motivations at regular intervals with the SIMS survey instrument. A preliminary exploration of the quantitative motivation data from the SIMS survey was made possible through qualitative open-ended questions.

This paper (1) introduces the deployment of a CNC laboratory at the University of Massachusetts Lowell (2) summarizes examples of hands-on projects using the CNC laboratory and (3) presents the results of a motivation study being performed to assess student motivation in traditional lecture-based courses versus hands-on, project-based classes.

2 Description of the CNC Lab

Over the past year, a teaching laboratory comprising ten desktop CNC machines has been deployed and integrated into several courses at the University of Massachusetts Lowell. A brief summary of the laboratory setup process is presented here; however, a complete laboratory deployment is described in detail in Vaillant et al. 5,6

2.1 Machine Selection, Setup and Use

The hobbyist maker movement has resulted in a proliferation of open source, inexpensive solutions for computer numerical control (CNC) machines as kits or fully assembled products. The majority of these machines take the form of subtractive manufacturing CNC mills (Shapeoko, Zentoolworks, Zenbot, Roland CNC, etc.) and additive manufacturing three-dimensional printers (RepRap, Solidoodle, Makerbot, Form-1). While possessing precise computer numerical controlled motions, these machines are typically best suited for lower grade milling (softer materials) and simpler prototyping tasks (printing free of support material).

One of the overarching goals of this project was to instrument an undergraduate laboratory with a sufficient number of CNC machines to allow students to work in small groups to conceive, design, analyze and prototype parts and products. The actual realization of physical products is deemed important to the iterative design process – students should not only experience a design and manufacturing process, but also reflect on the physical manifestation of their ideas and ultimately experientially improve their engineering design abilities. To this end, several inexpensive kit-based CNC machines were compared on the basis of cost per working area/volume, machining capability and simplicity of use. 5,6 The following two CNC platforms were selected for the mechanical component in the initial deployment:

- **Inventables Shapeoko II**: The Shapeoko II is a kit-based, hobbyist CNC machine designed by Edward Ford and distributed by Inventables.com. The machine comprises two belt-driven linear axes, with a third linear screw-driven axis. All axes use a linear track-and-wheel linear motion constraint system. Comprised of a series of similar parts, this CNC machine has a stationary MDF spoilboard that is used to clamp and secure parts that will be machined. The Shapeoko II’s machinable volume is approximately 12” x 12” x 2.5” (in the x-, y- and z-axes
respectively). The Shapeoko II with University of Massachusetts Lowell modifications included is illustrated in Figure 1-a.

- **Zentoolworks 7” x 12”:** The Zentoolworks family of hobbyist kit CNCs (7”x7”, 7”x12” and 12” x 12”) are fabricated from machinable PVC sheets. The model number refers to the approximate x-y-plane cutting dimensions. The machines all share a similar design comprising a moving table that generates motion in the y-axis direction, and a stationary gantry that supports x- and z-direction translation of the tool. The linear motion in the Zentoolworks CNC is generated using a threaded rod-and-nut combination that is constrained using precision rods and bearings. A Zentoolworks 7” x 12” CNC machine is illustrated in Figure 1-b.

By simply changing the working tool, the desktop CNC machines are able to both mill and 3D print; however, to date projects have been exclusively focused on CNC milling. Several milling tools have been considered ranging from inexpensive AC rotary tools to more expensive DC spindles. Off-the-shelf rotary tools are easily integrated in these desktop CNCs by simply fabricating an appropriate mount and instrumenting the spindle with an appropriate collet. Of the tools used thus far, the DC spindles offer accurate, quiet, controllable operation while AC tools tend to emit greater noise and can range in their degree of accuracy. However, in the context of prototyping in the undergraduate curriculum, both AC and DC rotary tools have proven to be acceptable solutions.

![Figure 1: (a) A Shapeoko II with the University of Massachusetts Lowell modifications shown. (b) A Zentoolworks 7” x 12” CNC machine.](image)

Nowadays, a wide range of CNC controller hardware is available for hobbyist CNC’s. Hobbyist-level controllers are defined by parameters including the number of controllable axes, controller-computer connection (USB vs. DB-25), and breakout vs. all-in one electronics boards. For simplicity, this project focused on a control strategy consisting of USB connected, GRBL controllers. The majority of the desktop CNCs in the laboratory are controlled using an Arduino UNO coupled with a GRBL-shield, with a machine using the similar, but more capable TinyG controller board.

In order to successfully machine a part, the computer must be able to connect to the CNC controller and command the CNC machine to perform the desired motions. These desired motions
are interpreted from a G-Code comprising a list of specific commands and coordinates. G-Code can be created manually or using a number of software tools; however, some combination of CAD-CAM is typical in most applications. In the laboratory, there are several options for creating G-Code including a simple in-house Matlab (Mathworks, Natick, MA) CAD/CAM program that allows rapid specification and generation of simple G-Codes. This Matlab program allows students to generate G-Code within minutes of being introduced to the CNC machines. Once created, the G-Code commands must be sent from the computer to the CNC controller using G-Code transmission software. The UniversalGCodeSender software is used in the laboratory; however, several G-Code senders are available. The G-Code commands once sent to the controller, are subsequently converted into electrical signals that drive the stepper motors on the CNC machine.

2.2 Laboratory Setup
A total of ten CNC machines are available for use by students in the laboratory. These machines are setup as CNC-stations, each comprising a computer, an enclosed controller, a CNC mill and a safety enclosure. Safety is a primary concern in the laboratory – with significant setup time being devoted to the design and construction of both electronics and machine enclosures. These enclosures are designed to mitigate the risk of electrical shock, to reduce the danger from ejected material and chips and finally to dampen the noise due to milling. The enclosure designs are illustrated in Figure 2.5,6.

3 Introducing CNC Machines in Mechanical Engineering Courses
The CNC machines have been introduced into several Mechanical Engineering courses to varying degrees, with the goal to continue adding courses through the completion of the project. A description of several courses and projects is included in the sections below.

3.1 Introduction to Engineering
The first year engineering sequence at the University of Massachusetts Lowell was recently examined using student feedback for introducing freshmen to the discipline. As a result, the first year mechanical engineering course was redesigned to cover:

Figure 2: (left) Several electronics enclosures have been implemented for safety (right) the CNC machine enclosure fabricated using corrugated plastic, angle aluminum and a clear PVC front window.
• **Core topics in mechanical engineering:** Topics such as forces, moments, materials science, thermo-fluid systems, and strength of materials are now introduced in the course.

• **Hands-on design, analysis and machining activities:** Experiential learning has been introduced through project-based learning.

• **Curriculum and discipline essential skills:** Curriculum essential skills such as Matlab computer programming, technical presentations and technical writing are taught in lecture and in online modules.

This first year course has made significant use of the CNC laboratory to perform both short and long projects. With approximately 160 students in the course in the Fall 2014 semester and 51 students in the 2015 spring semester, this represents a relatively high student volume for hands-on manufacturing activities. Laboratories are run through the week with 18-19 students per section. The goal of the course is to maintain a relatively low-cost, project-intensive experience while covering the appropriate content. Three categories of projects are performed during a semester, with approximately 10-15 CNC machining hours per student group:

• **Introduction to the design process and CNC milling:** The first project in the Spring and Fall 2014 course offerings provided a rapid introduction to the engineering design process and CNC milling within the first three weeks of the semester. This was accomplished by tasking the students to brainstorm and ideate a team logo, gain feedback on the logo design, redesign, sketch, and draw scale versions of the logo. Subsequently, students used the in-house Matlab CAD/CAM program\(^a\) to digitize CNC tool paths and generate G-Code for the desktop mills. Students were introduced to CNC machine safety and operation so they could mill wax molds of their logo designs (Figure 3 left). The wax molds were filled with platinum-cure silicone to create logo stamps (Figure 3 center and right). Overall, this project engaged students in a complete design cycle from idea to product. Students were required to individually write a short memo summarizing the project and related outcomes.

![Figure 3: An example of a student logo stamp. (left) The milled machinable wax mold (center) The silicone stamp and (right) the resulting ink stamp.](http://faculty.uml.edu/dwillis/HOM4ME/)

• **Understanding core concepts/science in Mechanical Engineering:** The second module in the Introduction to Engineering course supports a hands-on exploration of key concepts in mechanical engineering. In the Fall 2014 semester, this was accomplished by assigning three-mini laboratories. The laboratories were structured to provide machining experiences in addition to laboratory testing and reporting opportunities. The three mini-labs were:

\(^a\) [http://faculty.uml.edu/dwillis/HOM4ME/](http://faculty.uml.edu/dwillis/HOM4ME/)
- **Introduction to material science using paper mache:** Students machined ‘dog bone’ material coupon molds in EPS (expanded polystyrene) foam in order to cast three paper mache material coupons. The first coupon was a common recipe for a paper mache material. The second coupon was an assigned paper mache recipe with each group being assigned a slight variant of the paper, glue and manufacturing process. The third coupon was open ended, where the students could design their own paper mache material with the only constraint being the material must remain biodegradable. Students were then tasked to test their own materials using desktop tensile testing machines and report the results. The compiled class results were shared amongst the class as a materials database. A formal lab write-up was required to introduce and exercise technical writing.

- **Introduction to strengths of materials using beam bending and kerfing:** In this laboratory, students were asked to explore bending using wooden beams. Teams were tasked to alter a wooden beam’s properties by precisely kerfing the beams to alter the bending stiffness and overall strength of the beam. The students then used a desktop, hand-driven, universal testing machine to perform a three-point beam bend test. The students shared the results of their beam bending tests with the class so that a database could be explored. Students were required to write a short technical report on this project.

- **Introduction to thermal-fluid processes using aerodynamics:** The aerodynamics laboratory is a traditional laboratory activity that required no CNC machining. Students performed a simple experiment to explore the relationship between wing angle of attack and lift coefficient using an instructional wind tunnel and a small model wing. The laboratory introduced thermal-fluid scaling through the calculation and presentation of traditional lift and drag coefficients. Students were required to write a short technical report on this project.

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**Figure 4:** (left) An EPS ‘dog bone’ coupon mold was manufactured using the CNC machines to cast paper mache materials for tensile testing (center) A three-point bending test is used to test student beam samples (with kerfing) and (right) a low speed educational wind tunnel was used to relate angle of lift coefficient to angle of attack.

- **Wind turbine product ideation, design and prototyping:** The first year mechanical engineering course semester project required the completion of an early product development cycle for a portable (maximum 16” diameter) wind turbine. Students had to identify the user base and the relevant product. Students were encouraged to explore/define potential user groups for a small wind turbine and formulate need statements and desired product specifications. Students were given a brief introduction to the theory of wind-power
conversion and wind turbine blade design. A simple Matlab code was designed and written in each lab section to enable the design of a basic wind turbine blade shape (including spanwise twist and taper). Students were provided a simple Matlab Blade Element Momentum² routine to virtually test and iterate on their blade designs. At the conclusion of this design/analysis phase, students were tasked to construct an adjustable blade mold using the CNC machines with the goal of using engineering drawings to create a multi-component part. Once complete, students could prototype paper and cardboard wind turbine blades for their product. Finally, the students used two test stands to evaluate their turbine performance and iteratively improve their designs. These test stands were setup to evaluate:

- **Wind to Mechanical Power Conversion:** Wind-to-mechanical power conversion was evaluated by examining the time rate of change of potential energy in a wind turbine weight-lifting experiment. In this experiment, students designed the test protocol and collected the data they judged was necessary to evaluate their prototype blades. Students were provided with a universal hub onto which their blades could be integrated. This hub was designed and manufactured using the CNC machines in the laboratory.

- **Wind to Electrical Power Conversion:** Students characterized the efficacy of wind-to-electrical power conversion using one of three gear ratios (2:1, 4:1 and 6:1) and a variety of electrical resistance loads (1-Ohm through 7-Ohms) in conjunction with a three-phase RC model electric motor. Current rectification and filtering circuitry was provided along with a multi-meter for recording output voltage. Students were again required to design the experiment and data collection protocol.

This wind turbine project culminated in a final design expo, during which students presented their concepts, designs and results of prototyping to their peers, the instructional staff and invited visitors. In addition, the groups were required to write a short final design report detailing the product development complete with test results, the final design and the proposed manufacturing process.

![Figure 5: (left) A CNC manufactured, adjustable wind turbine blade mold. (center) a collection of different wind turbine blades manufactured using the blade mold and variants on paper mache. (right) Testing the wind turbine using the mechanical test stand.](image-url)
3.2 Mechanical Design II
The mechanical design II course at the University of Massachusetts Lowell introduces cams, gears and related mechanical design from a design theory standpoint. The course requires a hands-on project to design and test a cam. In previous years, the cam designs were handed over to the university machinist to fabricate and a cam product was provided to the student. In the Summer 2014 and Spring 2015, the course integrated CNC machining into the project by allowing students to machine their own cam designs. This CNC integration added minimal additional course time, but provided the students with a new hands-on machining experience. Thecams were designed using MS Excel, Matlab or Solidworks. The resulting cam coordinates were used in a custom matlab G-Code generator to develop toolpaths for the desktop CNCs. Students then mounted and machined their cams to produce a final product in machinable ABS plastic.

3.3 Capstone Design and Other Project-Based Courses
A variety of capstone projects exploited the CNC laboratory to manufacture wax and foam molds for products. Projects include wind turbine blade mold manufacturing, molded fixtures for plasma torches and molds for composite parts of a human-powered boat. These activities have all yielded hands-on CNC experiences that enrich the student experience by enabling direct student participation in the build process.

In addition to the courses that directly use the CNC laboratory, there are several other courses (Design Lab I and Design Lab II) that use recently acquired three-dimensional printing and laser cutting equipment in their projects. These courses integrate Arduino electronics and rapid prototyping to engage students in a hands-on design cycle. While not directly using the CNC laboratory, the hands-on, project-based learning pedagogy has similar goals for student engagement.

Motivation Study
One of the project hypotheses is that hands-on design and machining will improve student motivation towards learning and engineering when compared with more traditional lecture-based pedagogies. To test this hypothesis, quantitative and qualitative surveys were deployed at regular intervals in courses with a range of pedagogies, from traditional lecture to project-based and design. In the sections that follow, the concept of motivation as an evaluation metric as well as methods used to collect motivation data are presented. This motivation study has been approved by the University of Massachusetts Lowell Institutional Review Board under protocol # 13-020-WIL-XPD.

4.1 Extrinsic vs. Intrinsic Motivation
It is well established that motivations are important to consider in learning, as motivations are linked in powerful ways to a wide range of desirable outcomes such as cognitive strategy use, self-regulation, creativity, and academic performance. According to Deci and Ryan’s self-determination theory (SDT), motivational responses may be described along a continuum that ranges from internal to external, or autonomous to controlled, motivations. Along this “self-determination continuum” appear several different categories of increasingly self-determined behavior, including:

- **Amotivation**: A condition in which learners find no reason to engage in a task, and they disconnect their actions from any outcome.
• **External Regulation**\(^{14}\): External pressures, in the form of rewards, praise, demands, or punishments, drive participation in an activity.

• **Identified Regulation**\(^{14}\): Students identify importance, usefulness, or value in a task, and link the activity to personally desirable goals or outcomes.

• **Intrinsic Motivation**\(^{14}\): Participation in a task or activity that is described by inherent enjoyment or interest.

Educational research illustrates that not all types of motivation are equally beneficial to learning. Generally, studies show that internalized or autonomous types of motivation, such as intrinsic motivation and identified regulation, are more positively correlated with desirable learning outcomes compared to externalized motivations\(^{10,14,15,16}\). Furthermore, self-determination theory\(^{14}\) suggests that an individual’s motivational orientation is influenced by how that person feels in a given context, such as a classroom. According to the theory, learners will tend to adopt more internalized motivations when three basic needs are satisfied:

• **Autonomy**: Increasing feelings of autonomy (choice, control, volition) are linked to increasing intrinsic motivation in an activity.

• **Relatedness**: Being able to identify with and form interpersonal relationships with others can increase student motivation. In the case of engineering students, relatedness may be realized in several ways, e.g., identification with engineering as a discipline, or relationship building with other students or instructors.

• **Competence**: Having a feeling of competence (mastery, improvement, progress) in a particular task or activity tends to increase intrinsic motivation. Competence in the learning environment can relate directly to the student’s comfort with a task as well as timely and meaningful positive feedback.

Based on these concepts, the introduction of hands-on machining and design experiences at the freshman level has been deemed a critical pathway to increase the impact of this project. The ideation and design activities engage and encourage students to act with increased autonomy to accomplish the credit-bearing tasks. The majority of the hands-on projects introduced with the CNC lab encourage students to take control and command of the project and also design their own experiments to assess engineering content. In regards to relatedness, hands-on machining and design activities are expected to directly relate to engineering students’ identification with engineers as a group or discipline. Furthermore, students work primarily in teams increasing interpersonal interactions and relatedness to the department. Finally, hands-on projects and mini-laboratories are designed with re-submission opportunities to provide students with valuable feedback and reflection. This combined with a focus on process success rather than product success aims to increase students’ feelings of competence while making allowances for learning from failure.

4.2 Situational Motivation Scale (SIMS) Surveys\(^{4}\)

In order to assess student motivation, the sixteen-item situational motivation scale (SIMS) survey\(^{4,14}\) is used. The SIMS has been developed and tested to assess participant motivation according to the following four categories of increasingly self-identified motivations from SDT (1) Amotivation (2) External Regulation (3) Identified Regulation and (4) Intrinsic Motivation\(^{4,14}\).
The SIMS provides a signal for each of the four motivational sub-categories, based on an average of four survey items. Student responses to the sixteen questions can be reduced to an overall measure of individual motivation, termed the self-determination index (SDI).

The SIMS survey is administered electronically (via automated surveymonkey.com) or on paper in classes in regular intervals throughout the semester to assess the changes in self-reported student motivation and how these changes relate to course content and activities. Depending on the course, the survey interval can be weekly, bi-weekly or approximately monthly. The research team processes the surveys during the semester, and provides anonymous, averaged course motivation indicators to course instructors at different points during the semester. This set-up gives instructors awareness of student motivation during the semester and affords the opportunity to make adjustments to the course delivery as needed or desired. Full processing of data is performed after the students’ grades are submitted in accordance with the approved IRB protocol.

4.3 Motivation Study Results
The overall results of the SIMS motivation surveys across a collection of traditional lecture- and project-based classes are shown in Figure 6a. From these data, it is clear that project-based courses tend to have higher average self-determination index (SDI) than more traditional lecture based courses. This same trend is observed in the introduction to mechanical engineering course in which CNC’s were used extensively for labs and projects. As shown in Figure 6b, however, the data presented indicate a low response rate for most weeks, with some weeks showing no responses to the surveys for certain courses. Despite switching to paper surveys to improve response rates during the second semester of data collection, little increase in overall response rate was observed.

![Graph](a) The self determination index for Introduction to Mechanical Engineering compared with project-based lecture based courses.

**Figure 6:** (a) Overall SIMS motivation over time data for three courses in this study, and (b) survey response rates for the Introduction to engineering.

The data from Figure 6a can be examined in greater detail by isolating each of the motivation subcategories examined in the SIMS survey (*amotivation, external regulation, identified regulation* and *intrinsic motivation*). The subcategory results are presented in Figure 7. Despite the low response rate in the Introduction to Mechanical Engineering course, the results show the ex-
pected trends for the different pedagogical environments. In general, the average amotivation across all class types is quite low (Amotivation = 2 → 3), a positive indication that students in all courses are able to find a reason for engaging, either extrinsic or intrinsic. The external regulation is slightly higher than amotivation; however, there are only small differences between traditional lecture-based courses and project-based courses (including the CNC machining intensive Introduction to Engineering). This indicates that students in all courses experience a moderate to (at times) strong sense of external pressure to engage in their learning tasks. Figure 7c and Figure 7d illustrate the identified regulation and intrinsic motivation, both of which show higher values in project-based classes than more traditional lecture based courses. Intrinsic motivation (Figure 7d) presents the most marked difference between student motivations across courses, suggesting students engaged in project-based instruction and hands-on learning find more enjoyment and interest compared to students in lecture-based courses.

Figure 7: The average results for the different class types including (i) introduction to engineering with CNCs (ii) project-based courses and (iii) lecture based classes.
All class types show a general trend of increasing amotivation and external regulation toward the end of the semester. This effect may result from an increased focus on exams and grades toward the end of the semester, or it could be due to sampling bias in the lower response rate data collected at the end of term. Further statistical analyses of the week-to-week responses, as well as tracking of individual students’ responses throughout the semester, may provide more detailed insights into the end-of-term shifts, as well as the linkages between specific course activities and motivational signals.

In addition to the SIMS survey, qualitative surveys were administered throughout the semester in order to begin to explain the quantitative student responses. Students were asked the following five questions:

1. How well do you feel you did over the past week in the course? How do you know?
2. Thinking about your experience over the past week in the course, what particular activities and/or interactions both inside and outside the classroom stand out for you?
3. Thinking about your experience over the past week in the course, what particular emotions and/or thoughts about the course both inside and outside the classroom stand out for you?
4. What factors contributed to your motivation over the past week in the course?
5. Please reflect on the extent to which your experience over the past week in the course was personally relevant for you now and in the future.

While the responses to these questions on the surveys were somewhat sparse, some interesting initial insights emerged in the open-ended responses from students in the introduction to mechanical engineering course (with the CNC machine integration). In response to the “How well do you feel you did over the past week in the course? How do you know?” prompt, for example, students noted that:

- I feel we did well. My group is awesome and we share work well
- Pretty good… the lab was enjoyable
- Vacation is pretty much needed. Another day would be nice

The first two of these comments illustrate how students link a sense of positive learning performance with peer relationship building (relatedness) and enjoyment, two important characteristics of intrinsic motivation. The third comment, however, indicates some stress associated with the activity, with unspecified consequences on the person’s motivational state.

In response to the question about the “stand out” experiences in the classroom, students said:

- actually building stuff we can use
- I very much like the write-up compared to others to the lab reports I’ve done in the past
- home and lab seemed to be pretty tough today

As with the performance-related question, these responses show a mix of motivational signals, from identified regulation (building stuff we can use) and possibly intrinsic motivation (very much like), to experiences that are dominated by a sense of difficulty.
With regard to their emotions or thoughts about the course during the week, students described the experience as:

*Exciting*

*I enjoy this course a lot, especially compared to other engineering I've done in the past*

*passion, frustration when work is complicated*

Once again, the motivations in the qualitative survey responses are varied, from clear intrinsic drive (*exciting, enjoy[ment], passion*) to frustration. Although not prompted to do so, one individual contrasted the positive experience in the hands-on CNC course with less enjoyable experiences with engineering – a positive sign for this mode of learning.

When asked to comment directly on the factors in the course that contributed to their motivations, some responded with a range of influences, including *my grades* (likely external regulation), *good grades and wanting to learn* (a mix of external and internal motivation), and *the weekend! Football* (out-of-class factor). These responses illustrate the complexity of motivations that students may experience in undergraduate engineering courses.

Finally, when prompted to reflect on the personal relevance of their course experiences, student comments included:

*the windmill project*

*HW helped w/ some work study work b/c of lab work*

*It sure is relevant, communication, group work, maneuver skills critical thinking, etc.*

*played jenga the other day. It reminded me of this lab*

These qualitative responses show strong identification with the project topic (*windmill*) for one student, a valuing of the useful and transferable skill building (*communication, critical thinking, work study*) for some, and a linkage between the course project and an outside activity for one student, which may be directed at enjoyment or perhaps cognitive reasoning. Overall, an initial look at the qualitative data reveals promising findings regarding engineering students’ motivations in the more active course settings. Additional analyses are necessary, however, to gain a deep understanding of how students’ experiences shape their week-to-week motivations; and this analysis should be considered as preliminary due to the low observed response rates.

### 4 Summary of the Overall Project and Motivation Study

A CNC laboratory has been successfully setup at the University of Massachusetts Lowell and is currently being extensively used in a small number of courses. The integration of inexpensive CNC machines has overall been a positive experience. Considering the volume of students using the machines on a weekly basis (170+ students per week), the machines have had relatively minor maintenance and upkeep requirements. From an instructor standpoint, following a couple of experiences with supervision, students appear to be comfortable operating and using the desktop CNC machines for routine laboratory work. The students’ rapid familiarity and comfort with the CNCs is believed to be a function of the simpler and lower cost hobbyist nature of these machines. Due to being lower duty machines and with lower repair costs than professional CNCs, they may be less intimidating to students.
The CNC laboratory has also been successful for implementing several projects of multiple different classes. With this project, every freshman becomes familiar with basic CNC machining. Previous introduction to engineering courses involved simple hand tools, and in some cases, a minimal project-based activity. Through the integration of CNC machines earlier in the curriculum, we expect to see improved confidence, motivation and knowledge in our students.

The motivation data collected to date has been hampered by lower student response rates; however, clear trends appear to be forming, confirming the motivational benefits of hands-on, project-based courses over more traditional lecture-based courses (Figures 6 and 7). This preference is particularly noticeable in the intrinsic motivation and identified regulation portion of the SIMS survey (Figure 6c and 6d). These results indicate that students are able to more strongly self-identify with project-based learning environments. While this result may be unsurprising, the data do support course design initiatives such as the one presented in this paper.

5 Conclusions
A CNC laboratory comprising ten hobbyist-level CNCs has been successfully deployed and integrated in several mechanical engineering courses at the University of Massachusetts Lowell. Several high enrollment and moderate enrollment courses have started to integrate the CNC laboratory for hands-on, project-based learning opportunities. Thus far, the CNC machines have performed well and have only required a minimum of maintenance. A survey-based study examining student motivation in hands-on, project-based courses compared with traditional lecture-based courses has been performed. The results, though preliminary, indicate increased levels of student identified regulation and intrinsic motivation in the hands-on courses when compared with traditional lecture-based courses. Overall, this suggests that integrating hands-on CNC projects and other similar activities can have a positive overall outcome in student motivation and learning.

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