Inexpensive Computer Numerical Controlled (CNC) Technology for Meaningful Hands-On Experiences in Introduction to Mechanical Engineering

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Abstract - **This paper presents the selection, deployment and use of (1) inexpensive, off-the-shelf, desktop Computer Numerical Control (CNC) technology and (2) an in-house Computer Numerical Control - Modular Block (CNC-MB) in the *Introduction to Mechanical Engineering* course at the University of Massachusetts Lowell. The inexpensive, off-the-shelf CNC machines present a valuable hands-on introduction to advanced manufacturing and an accessible gateway to hands-on making. Due to lower complexity, these machines minimize intimidation, allowing students to independently engage in advanced machining explorations. The recently developed, in-house CNC-MB presents a unique platform with which students can engage in CNC machine design, assemble and test application-based computer programming, as well as explore advanced machining.**

Index Terms – CNC Machines, Computer Programming, Design, Student Motivation.

INTRODUCTION

Typical freshman year introduction to engineering courses serve several functions, including: (1) orientation to the university environment, (2) transition to a college learning environment, (3) introduction to the general/specific engineering disciplines, and (4) introducing/reinforcing skills and/or content. Most universities offer these freshman experiences; however, the content can vary significantly from one program to the next. Many of these programs offer some level of hands-on experiences to the freshman students in the form of a cornerstone project composed of a sequence of smaller hands-on projects or via computer programming.

The freshman *Introduction to Mechanical Engineering* course at University of Massachusetts Lowell is a two-credit course comprising 1-hour of lecture per week (~160 students in the Fall semester and ~50 students in the spring semester) and a 2-hour hands-on laboratory experience (in student cohorts of <19). The course lectures cover orientation to the department/university, student success [1] and a general overview of mechanical engineering. The technical lectures introduce and explore basic mechanical engineering content (forces, moments, equilibrium, stress, strain, conservation of mass, design, prototyping and manufacturing) in the context of problem-solving techniques and computer programming. The lecture aims to highlight the curriculum and profession while also engaging students in the problem solving, programming logic and design process – as such, many concepts are presented in the context of a real-world problem or design. Computer programming is used to solve problems and explore trends. Due to the large class size, demonstrations, think-pair-share activities and clickers are used to promote student engagement. The homework portion of the course combines Matlab programming exercises/Onramp tutorials (Mathworks, Natick, MA) with online homework assignments. The laboratory component of the course is held in the new UML makerspace (Figure 1) and comprises hands-on projects and laboratory experiences. These hands-on periods are led by teaching assistants with frequent faculty interaction. In the spring 2016 course offering, two labs and two of the assigned course projects used the desktop CNCs and/or the CNC-MB. This represents approximately 85% of the allotted lab time.

Part 1 of this paper describes the inexpensive desktop CNC technology, the deployment and the laboratory activities that have been performed. For the past two years, CNC-based hands-on manufacturing/making and Matlab programming lab activities have used inexpensive, off-the-shelf, hobbyist CNC machines. These machines can CNC mill plastic, wood, foams and other softer materials. The machines can also be retrofit with a Sharpie Marker to draw/plot.

Part 2 of this paper describes an education-centric product designed for use in freshman classrooms to explore CNC machine design, control, programming and manufacturing. The CNC-MB permits multiple manufacturing configurations including: 3-axis CNC mills, 3D-Printers (delta and Cartesian configurations with moving bed and moving gantry), CNC drawing robots, CNC lathe, CNC filament winding, pick and place machines, CNC plotters, CNC-drag knife, etc. at very low cost and reduced student assembly/prototyping times (on the order of a single lab period).

The goal of the CNC-MB is to increase exposure to open-ended problem solving and meaningful computer programming, improve freshman engineering program-degree relatedness, introduce multiple manufacturing techniques, encourage design autonomy and provide opportunity for open-ended, user-centric design. The incorporation of autonomy, relatedness and competence is directed at increasing student intrinsic motivation levels [2] towards engineering self-directed learning activities. These are lofty goals considering introductory course enrollments; however, our experience with this hands-on approach demonstrates this to be reasonable and attainable.

FIGURE 1
THE PROTOTYPING AND CNC BAY IN THE UNIVERSITY OF MASSACHUSETTS LOWELL MAKERSPACE. EACH PICTURED ENCLOSURE CONTAINS A SHAPEOKO II CNC MACHINE.

PART 1: OFF-THE-SHELF DESKTOP CNC MACHINE DEPLOYMENT

The Introduction to Engineering course was redesigned during Spring 2013 to include inexpensive, off-the-shelf desktop CNC machines [3-6]. At start of the project, the recent "maker revolution" was gaining traction with several, build-it-yourself hobbyist CNC platforms in the $400-$800 range. Our research team deployed 7-10 of these desktop CNC machines at a given time [3-6]. Two different desktop CNC machines were used in this deployment:

1. **Shapeoko II Desktop CNC Machines [7]:** These desktop CNC machines comprise a traditional Cartesian gantry machine. X- and Y-axis motion is belt driven and guided by aluminum linear rails and plastic V-wheels, while a threaded rod and nut system drives Z-axis motion. The machine uses standard NEMA 17 stepper motors.

2. **Zentoolworks CNC Machines [8]:** The Zentoolworks 7" x 12" platform has a moving table and 2-axis stationary gantry. The machine uses threaded rods coupled to NEMA 17 motors to prescribe motion in each axis. We also have deployed 7" x 7" and 12" x 12" machines from ZenToolworks.

Over the first two years of extensive use, both of these machines have proven themselves to be robust for extensive student use. Only minor maintenance has been required, including fixing loose wires, re-soldering limit switches, etc.

One challenge associated with deploying these hobbyist machines is the considerable assembly time and learning curve associated with the machine deployment. Initially, the research team had hoped that the freshman class could assemble the machines in 1-2 laboratory periods; however, with the large number of non-unique parts and fasteners, assembly times of 6-12 hours per machine should be expected. Furthermore, there was concern that the student lack of experience coupled with written assembly directions could result in machines with poor operational characteristics. As a result a graduate research assistant assembled ten CNC machines over a period of 6 weeks of intensive work.

Some project/lab examples from the past two years are presented below:

a) Team Logo Project: The team logo project is deployed early in the semester as both an icebreaker activity and to expose students to the design process – from idea conception to testing the product. During this project, student groups perform a logo brainstorming and concept selection process similar to that used in *Design Thinking* or *User-Centric* product development. Each student then develops a scaled drawing of the logo and digitizes toolpaths using an in-house Matlab GUI program. A CNC safety, setup and use video is assigned for homework. Students are also guided through the safety and setup process in lab by the TA. The culminating in-lab experience involves CNC milling the logo in a wax block to develop a "stamp mold." Platinum cure silicone is then cast into the molds and the students validate the design and manufacture using an ink-stamp to evaluate the machining efficacy (Figure 2). This project provides a hands-on overview of the engineering design and manufacturing process in 3-4 weeks. Learning goals include: familiarization with Matlab program structure and advanced features, introduction to G-Code as well as how it works, how a CNC machine is set up and how to use the machine to manufacture complex parts. Overall, the student feedback for this project has been positive.

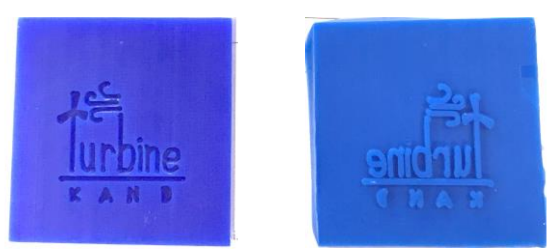

FIGURE 2
AN EXAMPLE PRODUCT FROM THE TEAM LOGO PROJECT. (LEFT) THE WAX MOLD THAT IS CNC MACHINED, (RIGHT) THE CAST SILICONE STAMP.

Wind Turbine Project Blade Molds: The freshman course usually has a final project that is more involved than previous labs/mini-projects. For several prior course offerings, the project has been focused on nano-wind energy solutions. In this project, students explore (using a Matlab BEMT computer code [9] and physical KidWind prototypes [10]) how wind turbine blade shape and pitch angle impact the power output of a wind turbine design. Using these explorations, students designed a final blade set and CNC-machine a wax mold corresponding to the final blade shape. Students are encouraged to explore material science of composite materials such as paper mache to determine how best to manufacture their wind turbine blades for final testing. Being slightly more open-ended, the efficacy of this project is influenced by TA mentoring as well as the commitment of the team members to the overall project success.

CNC Lab – Part A) Basic Motion Commands: We have recently introduced a hands-on CNC Matlab programming component. The first part of this this laboratory exercise is a heavily scaffolded activity that guides students through the basic steps for generating CNC-axis motion using Matlab. The process of sending Matlab commands is relatively easy when using a GRBL shield as a controller [11]. The Matlab programming includes: (a) opening up a communications port with the machine controller, (b) initializing the CNC machine operation, e.g., prescribing the unit system, relative vs. absolute coordinates, etc. (c) writing and sending 3-axis individual and sequential motion commands and (d) closing the communications port. Students explore buffer under/over-flow, primitive drawing and sequencing motion commands among. This lab takes 1-3 lab periods.

CNC Lab – Part B) Image processing: In part b of the CNC laboratory sequence students develop an image processing routine in Matlab that loads, converts and thresholds a color image to a two-tone representation that can subsequently be "dot-plotted" using a CNC machine and a sharpie marker (Figure 3). In this exercise, students practice image processing in Matlab (matrix and matrix entry manipulation), for loops with matrix element-by-element extraction/modification, if statements, vectors, and sequential communication with the CNC controller.

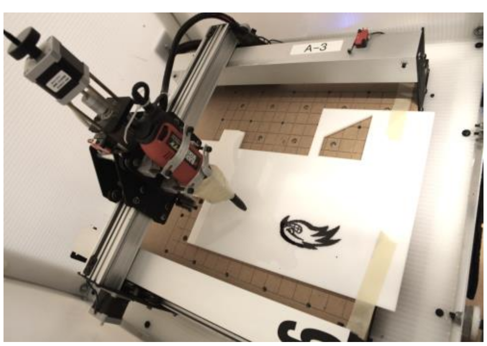

FIGURE 3
A STUDENT RESULT FOR IMAGE PROCESSING AND CNC "DOT-PLOTTING" THE UMASS LOWELL RIVERHAWKS LOGO.

Projects and laboratory experiences such as these provide mechanical engineering students valuable opportunities to learn computer programming while performing hands-on making. Using the off-the-shelf hobbyist CNC machines also provides a good introduction to modern manufacturing.

PART 2: CNC MOTION BLOCK DESIGN AND DEPLOYMENT

Although the off-the-shelf CNC machines are effective in an educational environment, the time investment required to setup a laboratory may not fully justify the cost savings [3-6]. Furthermore, the students using the machines could benefit from direct interaction with the assembly process – to gain a deeper appreciation of the controlled linear motion. In order to develop a CNC machine solution for an educational environment, the following goals were devised:

- **Time Efficient Classroom Deployment:** develop a computer numerical control-motion system that can be rapidly assembled by freshman students with a small number of widely available tools.
- **User-friendly, simple and modular:** develop a system that inexperienced and experienced engineering students alike could use for prototyping programmable linear motion and machine design. The approach should be modular to permit design flexibility and creativity.
- **Cost Effectiveness:** Since most Introduction to Engineering courses are large, cost effectiveness plays a significant role in product development. For our deployment, the goal was to reduce the per-axis electromechanical (motor + mechanical system) cost to below \$30. This allows each student to assemble and program a single axis (\$30 x 160 = \$4800 < \$5000).

In response to these goals, the research team recently completed the design, development and manufacture of an educational CNC Modular Block. The design process is presented in detail by Schiano et. al. [12] and Azhar et. al. [13]. It is only briefly presented here. Figure 4 illustrates the final CNC-MB block design.

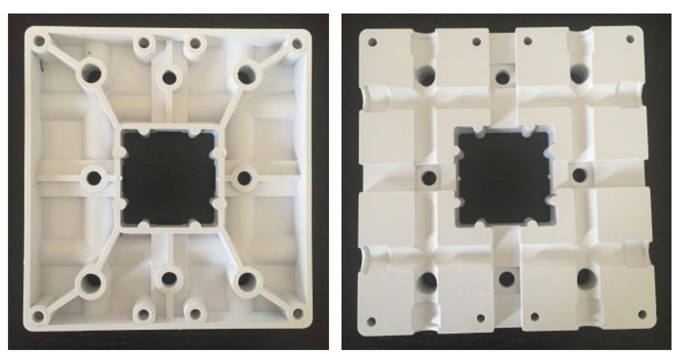

FIGURE 4
THE CNC-MB IS A CLAMSHELL BLOCK DESIGN. (LEFT) BLOCK EXTERNAL FACE, (RIGHT) BLOCK INTERNAL FACE.

The following product features are in response to the aforementioned design goals:

- **Single part, modular block:** The modular block has a clamshell design (Figure 4) that allows a basic injection molding setup and simple part assembly. This clamshell design is the only custom part that is required in the CNC motion system assembly (some additional custom parts/tools may be needed when attaching tools such as print heads and rotary tools). The block has been injection molded and is relatively cost efficient to produce.

- **Off-the-shelf, minimum unique part count:** The final design requires fewer than 15 unique parts to assemble a working machine. Similar components are used to assemble each axis and results in bulk parts purchasing power, simple instructions and reduced assembly time. With the exclusion of the modular block, all of the remaining components are readily available both online and locally. A basic parts list for an economy deployment of 200-single motion axes is presented in Table 1.

- **Modular and flexible block design:** The block was developed to maintain machine assembly and design flexibility. The block was designed to accept and anchor captive and non-captive motors as well as belt and screw driven axes. The block uses press-fits in rib-supported bosses to anchor stationary linear axis guide rods. Built-in bushing recesses, terminal screw posts and anti-backlash nut channels provide additional functionality [13] (Figure 5).

Overall, the CNC-MB design was carefully conceived to provide a meaningful and effective educational experience.

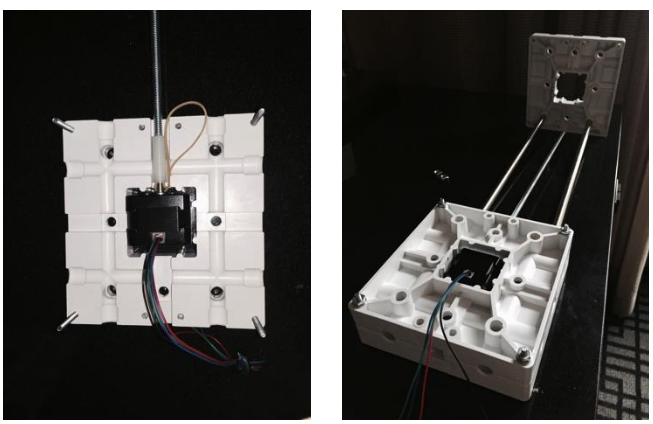

FIGURE 5
(LEFT) THE MOTOR AND DRIVE ROD MOUNTING AND (RIGHT) A SLIDING BLOCK (WITH MOTOR) AND THE AXIS SUPPORT END BLOCK.

CNC MOTION BLOCK DEPLOYMENT

The CNC-MB was recently deployed to support the final project in the Spring 2016 Introduction to Mechanical Engineering course. The students were tasked with designing their own unique, user-centric CNC machine. The students had previously performed the CNC laboratory Part A and B, so had the necessary familiarity with machine programming to develop a complete working machine. The students performed brainstorming, concept morphology charts, decision tables and prototyping tasks. Several student groups even developed CAD drawings of their designs.

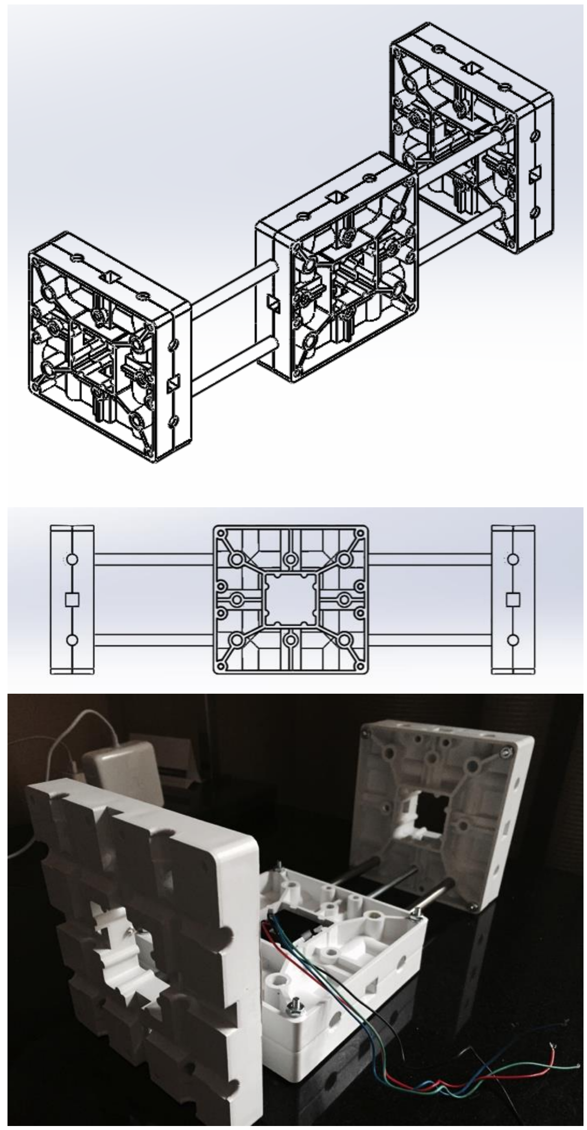

FIGURE 6
(TOP) AN ISOMETRIC SOLIDWORKS CAD RENDERING OF A SINGLE LINEAR MOTION AXIS. (MIDDLE) FRONT VIEW (BOTTOM) THE PHYSICAL SINGLE AXIS ASSEMBLY.

Students developed a wide array of machine designs using the CNC-MB. The projects ranged from vegetable processing machines for the elderly to wood-burning drawing machines and "Zen"-clocks. Several teams constructed their CNC machines in the last week of the semester when the blocks became available. An example student CAD rendering of a CNC pizza-cutting machine is shown Figure 7. Although the students only spent a short time interacting with the CNC-MB blocks, they provided positive feedback.

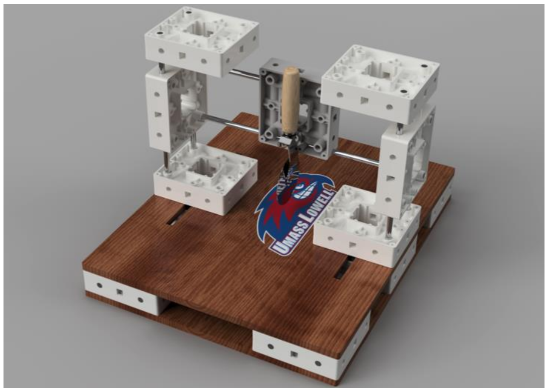

FIGURE 7
A CAD RENDERING OF A STUDENT DESIGNED CNC-PIZZA CUTTER.

CNC MOTION BLOCK FUTURE DEPLOYMENT STRATEGY

In the Fall 2016 semester, the *Introduction to Mechanical Engineering* course will use the CNC-MB extensively. The CNC-MB will be used in three-stages during the hands-on laboratories. This will include:

Stage 1 -- Single axis: Individual construction and manipulation: In this initial stage of the course (4-5 weeks), each student will receive sufficient supplies to assemble a single block (see Table 1, and Figure 6). Each student will construct his or her own electro-mechanical single linear axis. This distribution to each student will help to familiarize the students individually with the CNC-MB for later projects. In addition, students will learn the basic programming syntax and process (similar to the aforementioned CNC Lab part A), and which will support the Matlab programming taught in class and practiced during homework. Students will characterize their single-axis movements using position, velocity and acceleration. Concepts such as derivatives and integrals will also be explored during the mini-labs as a means for characterizing their machines.

Stage 2 -- Single and 2-axis, Laboratory Experiments: The CNC-MB will be used to perform computer numerical control laboratory experiments for several weeks to give students an opportunity to learn about lab reports and practice their writing. For example, students can perform beam bending and buckling experiments, as well as examining fluid valves and syringe pumps, using the CNC-MB. A collection of experiments will be provided for hands-on exploration of core mechanical engineering concepts. After this exploration, a programming competency based evaluation will be performed. Students must exhibit competency before they can continue to the final project.

Stage 3 -- Multi-axis: Group based, user-centric CNC solution design: The final project in the course (remaining 7-8 weeks) will task students with building a socially relevant, user-centric product. The product must either (a) be constructed using/assembling and programming the CNC-MB blocks (e.g., a CNC or (b) the product is manufactured using a machine based on the CNC-MB (e.g., student groups may build a 3D printer that prints prosthetic limb parts for the developing world). Several possible CNC-MB machine configurations are presented in Figure 8, including a Cartesian motion configuration and a delta motion configuration.

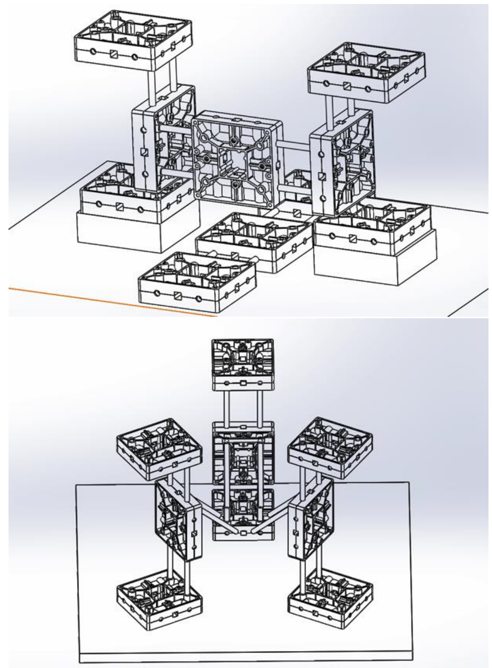

FIGURE 8
(TOP) A CAD RENDERING OF A CARTESIAN MOVING TABLE MACHINE CONFIGURATION USING THE CNC-MB (BOTTOM) A CAD RENDERING OF A DELTA CONFIGURATION MACHINE USING THE CNC-MB.

The components to build a single axis of the CNC-MB system are shown in Table 1. The cost for each component is listed assuming a 200-axis volume. The per-axis cost is relatively reasonable at under $25.

TABLE I
CNC-MB: ELECTRO-MECHANICAL PARTS LIST FOR A SINGLE AXIS AS AVERAGED OVER A 200-AXIS DEPLOYMENT. * NOTE THAT THE CNC-MB COST IS CALCUALTED ASSUMING HIGHER VOLUME PRODUCTION

#	DESCRIPTION	QTY	Per Axis Cost
1	Injection molded CNC-MB	6	$3.00*
2	3/8” O1 Drill Rod, 18”	2	$6.50
3	¼”-20 Threaded Rod (12”)	1	$0.85
4	¼”-20 Square Nuts	2	$0.08
5	#8-32 Washers	12	$1.01
6	#8-32 Machine Screws - 2”	12	$0.19
7	#8-32 Nuts	12	$0.24
8	Nylon Spacer (motor coupler)	1	$0.19
9	3/8” Nylon Bushing	4	$0.21
10	¼”-20 Rod End Cap	1	$1.25
11	NEMA 17 Motor	1	$9.50
12	Zip-Ties	2	$0.16
	TOTAL	**56**	**$23.19**

CONCLUSIONS

This paper illustrates the development and implementation of inexpensive CNC technology in the freshman mechanical engineering classroom. Two off-the-shelf CNC units have been successfully deployed and used to support both labs and student group projects. We also presented a CNC-modular block that can be used to assemble single and multiple axis linear motion machines. This first version of the CNC-MB is an inexpensive, flexible solution that accelerates the ability of students to design and prototype a multitude of computer numerical controlled machines. So far, this modular block approach has been successfully used in several freshman student hands-on projects.

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