Interdisciplinary Senior Design Project to Develop a Teaching Tool: Mini CNC Mill

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Abstract

The desired current set of skills required of modern engineers and technologists has been steadily expanding. In addition to familiarity with manual machining and fabrication techniques, mastering CAD/CAM, Computer Numerical Control (CNC), and automation methods are increasingly becoming essential tools in the design, prototyping and manufacturing of complex systems. In this paper, an inter-disciplinary design project towards the development of a mini CNC milling machine is presented. Since purchasing and installing traditional CNC equipment is not an option for every campus of Drexel University or similar engineering schools, an alternative solution to providing hands on experience with CNC equipment is desirable. A CNC machine with a desktop form factor which would be easily transported between campuses would eliminate the need for multiple traditional CNC machines and would improve the quality of the MET316-CNC course by providing more hands-on lab experiences. The desktop CNC machine which was developed by student design team fits on a standard desktop or table, would interface with commonly available CNC / Computer Aided Manufacturing (CAM) software, would be powered by a standard AC outlet, would be easy to use and robust enough for educational use, and would not be cost prohibitive. Students in the Mechanical, Electrical, and Industrial fields along with many others can learn many new skills from multi-disciplinary projects such as the design and development of a desktop CNC mill. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an actual application. This project teaches future engineers and technologists various advanced skills that can be used in their careers. Overall, many different fields of engineering can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes. As this capstone design project provides opportunities for students to design & manufacture, it stimulates the students' interest in real-world product realization. As manufacturing laboratories are very expensive to develop, this project can also be adapted at other institutions that have limited funding to improve manufacturing process facilities.

Background

In Drexel University's School of Technology and Professional Studies, many courses related to robotics, design, and materials are offered to the students in the Bachelor of Science in Engineering Technology program. Courses such as Robotics and Mechatronics, Quality Control, Manufacturing Materials, Microcontrollers, and Applied Mechanics can benefit from the laboratory experience in applications of mechatronics, robotics, and rapid prototyping. As well as helping in the teaching of various courses, such experience benefits students who are pursuing degrees in the engineering field. Students in the Mechanical, Electrical, and Industrial fields along with many others can learn many new skills from multi-disciplinary projects such as designing and fabricating a desktop CNC machine. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an actual application. This project instills future engineers and technologists with various advanced skills that can be used in their careers. Overall, many different fields of engineering can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes.

Students in the Engineering Technology programs are required to complete a series of capstone course MET 4XX Senior Design. This course aims to train the students in identifying projects of relevance to the society, in planning and scheduling a solution, and in entrepreneurial activities that may result from the project. The course is also intended to cover an industrial project starting from the proposal writing and conceptual design to final steps. The course is focused on proposal and project progress report writing.

Problem Description

Since purchasing and installing traditional CNC equipment is not an option for every campus of Drexel University or similar engineering schools, an alternative solution to providing hands on experience with CNC equipment is desirable. A CNC machine with a desktop form factor which would be easily transported between campuses would eliminate the need for multiple traditional CNC machines and would improve the quality of the MET316 course by providing more hands-on lab experience. The proposed desktop CNC machine would fit on a standard desktop or table, would interface with commonly available CNC / Computer Aided Manufacturing (CAM) software, would be powered by a standard AC outlet, would be easy to use and robust enough for educational use, and would not be cost prohibitive.

Design Constraints

Student design team proposed a desktop CNC machine that met a number of requirements to be considered acceptable for use as a teaching aid for the MET316 course. Some of these requirements placed additional constraints on the design which may limit its functionality and usefulness (Figure 1).

The first significant constraint for the design was that the machine be small enough to fit on a standard desktop or table in a typical classroom. The targeted desktop footprint for the machine would have a standard letter size table of 8.5in x 11.0in. This would limit the work piece size to approximately 7.5in x 8.5in x 3.0in. This was smaller than the work piece size of many traditional CNC machines on the market.

| | | Product Technical Requirements (PTR) | | | | | |
		Light Weight	Stepper Motors	Standard G & M Code	Soft Materials	Universal Tool Mount	Accurate Cutting
Customer Requirements	Standard Outlet		1		1		
	Portable	9			3	1	
	Table Size of 8.5" x 11"	3	1		1		3
	Light Duty Operation	1	3		9		3
	Multiple Spindle Options	1			9	9	3
	3 Axis CNC / 2.5 Axis Control		3	9			3
	Utilize Common Software			9			
	$500 Cost Target	3	9		3	1	9
	Absolute Importance	234.1	245.1	241.5	285.4	131.7	285.4
	Relative Importance	16.5%	17.2%	17.0%	20.1%	9.3%	20.1%
	Rank	5	3	4	2	6	1

Figure 1. Quality Function Deployment for the desktop CNC machine design.

The next significant constraint which would impact the design was cost. The desired target cost for the desktop CNC machine was $500. While this cost target was achievable, it limited

some of the additional features and lowered the quality of the design with regard to material selection, work piece materials, speed of operation, accuracy of milling, and ease of operation. Significant attention was devoted to ensuring that the cost of the desktop CNC machine was kept as low as possible while still meeting the design requirements.

Additional constraints include the ability for the machine to be controlled by common CNC/CAM software, configurability for various spindle tools, development of comprehensive assembly documentation, and the ability to build the machine using used and/or scavenged materials. The ability to control the machine using common CNC / CAM software was an important feature and was concentrated on as a primary design goal. The G&M code which is used to control this type of equipment is an industry standard interface and is referenced in several design patents. Careful consideration was required to ensure that student team's design did not violate any existing patents relating to the use of G&M code or in the design of the machine hardware and electronics. The ability to use various spindle tools was desirable for the future use of the machine for MET316 and potentially other courses. The development of comprehensive documentation required significant time and Computer Aided Design (CAD) software design expertise during the course. Lastly, the requirement that the machine be able to be built using used and/or scavenged materials may not be possible, while at the same time delivering a quality product which will be robust enough to meet the demands of the educational user. Strict guidelines regarding the selection of materials were required to ensure that their use did not impact the operation of the machine.

Design Selection

The intended design of the desktop CNC machine included all of the features detailed in the product design specification (PDS) which is partially shown in Table 1. These features include a desktop sized footprint, which will fit on a standard classroom desktop or table. The machine was designed to provide 2.5-Axis control allowing for X/Y Axis control and Z Axis plunge. The machine includes a moving milling table which is approximately 8.5in x 11.0in in size and allows for milling of small to medium sized objects. The gantry which supports the spindle is stationary. The targeted desktop footprint for the machine was a standard letter size table of 8.5in x 11.0in. The actual external dimensions of the machine are 11.50in x 10.25in x 16.00in. The maximum work piece size is 5.37in x 5.81in x 3.37in. This size better fits the design goal of allowing the machine to be portable while keeping the cost of the machine within target cost and budget. The intended standard workable materials include machinable wax, plastic, and balsa wood. The machine is designed to use a small rotary tool, which is integrated into the computer control of the machine. Provisions made to use not only the default rotary tool but also a standard sharpie marker for testing.

The spindle holder is removable and allows for other working tools to be added to the machine. The machine is designed so that it is small enough to be transported by a single person and setup quickly. The machine is able to be controlled by a computer running standard CAD / CAM software using a parallel port for control and interface. The machine is powered by a standard 115V / 15A outlet. Three concept scoring matrices were developed to assist with decisions regarding the gantry design, the PCB design, and the control system design (Figure 2 only shows concept scoring matrix for the gantry design)

		Concept						
		A (MyDIYCNC)		B Moving Gantry / Fixed Table		C Fixed Gantry / Moving Table		
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	
Cost Efficiency	0.25	3	0.75	2	0.5	4	1	
Ease of Construction	0.15	3	0.45	2	0.3	3	0.45	
Design Complexity	0.20	3	0.6	1	0.2	4	0.8	
Least Load on Motor	0.15	3	0.45	2	0.3	3	0.45	
Wiring Complexity	0.15	3	0.45	2	0.3	3	0.45	
Axis Accuracy	0.10	3	0.3	2	0.2	3	0.3	
	Total Score	3.00		1.80		3.45		
	Rank	2		3		1		
	Continue?	NO		NO		YES		

Figure 2. Concept scoring matrix for the gantry design.

Open-loop positioning system

The student design team decided to incorporate an open-loop positioning system to control the movement of the stepper motors instead of a closed-loop system. A closed-loop control system uses an optical encoder feedback circuit to very accurately control the movement of the stepper motors. The feedback circuit adds complexity to the design and a possible source of malfunction as the machine is used over time. The open-loop control does not use a feedback circuit which makes it less accurate then the closed-loop but still provide enough accuracy to meet our design requirements while reducing design time as well as material costs. The open-loop control system uses control pulses generated at a certain frequency to drive the stepper motors which move the work table at a corresponding velocity in the direction of the lead screw.

Mechanical Design

The mechanical design of the desktop CNC machine consists of multiple sections. The first is the base, which all of the remaining components are mounted to. Second is the gantry, which consists of the uprights on either side of the machine. Third is the spindle mount/X/Z carriage, which rides on the rails between the gantry supports and provides a mounting location for the rotary tool. Fourth is the combination of bearing sub-frames, guide rails, lead screws, and anti-backlash units, which all work together as a system to allow axis movement. Lastly, is the work table, which is where all work pieces will be secured to during milling operations.

The machine base is the main structure of the desktop CNC machine. The base provides a solid mounting location for the gantry, a mounting location for the Y axis stepper motor and guide rails, a mounting location for the emergency stop switch, and it also provides a location to house the PCB board (Figure 3). The base is constructed of ½ in thick medium density fiberboard (MDF). This material was decided upon because it provides the structural integrity needed, but also because it is very affordable compared to other materials that could have been used such as metal or high density polyethylene (HDPE). The front of the base has a mounting location for the Y axis stepper motor as well as two 3/8 in diameter holes that the guide rails are press fit into. The rear of the base also has two 3/8 in diameter holes for the guide rails, as well as a 1/2 in diameter hole that a nylon bushing is press fit into to act as a bearing for the Y axis

lead screw. The right side of the base was chosen as the mounting location for the emergency stop switch. Inside of the base is a false floor that was designed to add a compartment underneath the machine to house the PCB board and all of the wiring. At all four corners of the base are pieces of 1 ½ in, 1/8 in thick aluminum angle brackets. These brackets connect all four pieces of the base together and allow for screws to be secured into the face of the MDF as opposed to the ends, which tend to split when screwed into. Secondly, because these brackets are ninety degree angles, they helped to ensure that the base was square and true when assembled.

The gantry of the desktop CNC machine provides a mounting location for the X axis stepper motor, as well as mounting locations for the guide rails that the Z axis carriage rides on. Both the left and right pieces of the gantry are made of the same ½ in medium density fiberboard (MDF) that the base is constructed of. The right gantry upright has the mounting holes for the X axis stepper motor, as well as two 3/8 in diameter holes that the X axis guide rails press fit into. The left gantry upright has the same 3/8 in diameter holes as the right side, but also has a ½ in diameter hole for a nylon bushing to be press fit into to be used as a bearing for the X axis lead screw. Connecting the left and right gantry is a support beam made of 3/8 in thick high density polyethylene (HDPE). This beam ties the upper portion of the machine together and adds much needed stability to the structure and prevents the gantry from flexing.
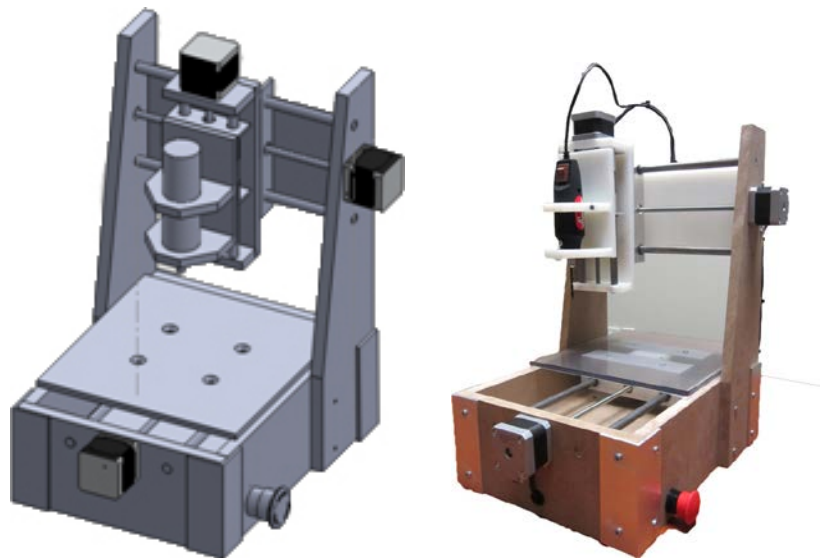
Figure 3. Solidworks 3D Rendering Compared with Desktop CNC Machine Prototype

The spindle mount/X/Z carriage shown in Figure 4 is one of the more complicated assemblies on the desktop CNC machine. This part of the machine allows for movement in both the X and Z axis. The carriage itself mounts onto the guide rails between the gantry uprights where it moves in the X axis direction. In addition, the spindle mount on the front portion of the carriage allows for movement in the Z axis direction. The material used to construct the spindle mount/X/Z carriage is 3/8 in thick high density polyethylene (HDPE). This material was chosen because of it durability and ease to work with. The Z axis stepper motor is mounted to the Z guide rail top mount. This mount also has 3/8 in diameter pockets drilled into the underside for the guide rails to fit into. The Z guide rail bottom mount has 3/8 in diameter through holes drilled in it for the rails to slide into. In addition, the bottom mount has a ¼ in diameter pocket drilled into it that the end of the lead screw fits into and acts as a bearing. The spindle tool

mounts are located on the front side of the Z back plate. There is an upper mount and a bottom mount, which work together to secure the rotary tool to the carriage.
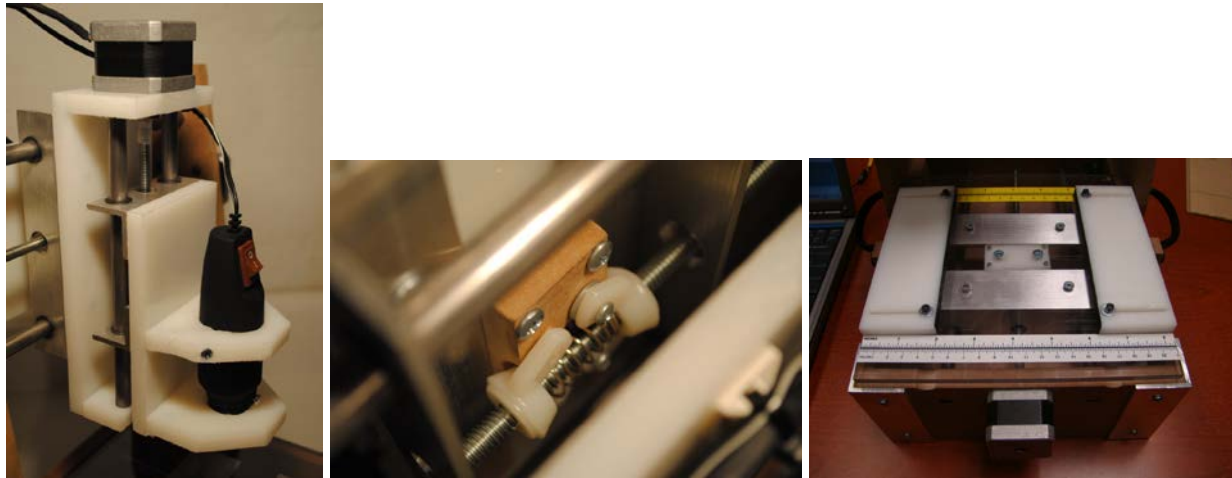
Figure 4. Spindle Mount/X, Z Carriage (left) and Anti-Backlash Assembly (middle), Work Table with Clamping System and Positioning Scales (right)

The combination of bearing sub-frames, guide rails, lead screws, and anti-backlash units are what make movement of the axis possible on the desktop CNC machine. Every axis, X, Y, and Z, on the machine has this combination of parts incorporated into it. The bearing sub-frames are made of 1/8 in thick aluminum angle. There are two bearing sub-frames per axis, six sub-frames total on the machine. Each bearing sub-frame has two 7/16 in diameter holes drilled in it to accept the Igus linear bearings used to slide along the guide rails. In the center of each bearing sub-frame is ½ in diameter hole, which allows for an opening for the threaded rod to fit through. Each axis has a pair of 3/8 in guide rails made of precision steel rod. This diameter rod was chosen because it is the specified diameter needed to fit the inner diameter of the Igus bearings. The guide rails are used to create a track system that the bearing sub-frames ride along.

The lead screw is the component of the desktop CNC machine that makes movement of the X, Y, and Z axis possible. The lead screw picked for this machine is ¼ in-20, which was chosen to provide the gearing to produce a 0.001 in per step resolution. On each axis the lead screw is connected to a stepper motor using a coupling made of PVC tubing. This coupling acts as a failsafe in the event that the machine for any reason binds up, or the axis is overrun. If binding occurs the coupling will slip or tear from the motor preventing any permanent damage to the machine or the stepper motors. On both the X and Y axis, the end of the lead screw opposite the motor is supported by a nylon bushing that acts as a bearing for the lead screw. One bushing is mounted on the left gantry, the other on the rear section of the base. On the Z axis there is a ¼ in diameter pocket drilled into the Z guide rail bottom mounting block that the end of the lead screw fits into to act as a bearing.

The anti-backlash unit shown in Figure 4 ensures that there is a minimal amount of slack or play in the drive train of the machine. Each unit is constructed of two ¼ in-20 nylon wing nuts threaded onto the lead screw with a spring in between the two wing nuts. The purpose of the spring is to keep a small amount of tension on the wing nuts to take up any slack between the lead screws and the wing nuts themselves.

The work table (Figure 4) is where the work piece will be secured to during operation of the desktop CNC machine. The material used for the work table is 1/4 in Plexiglas, which is durable

and easy to work with. The work table also serves as a mounting location for a clamp system that was added to the machine during the final term. The clamping system securely holds the work piece during machine operation.

Electrical Design

The electrical design of the desktop CNC machine consists of two concentrations. The first is a control board which allowed the machine to interface with and be controlled by a computer running Computer Aided Manufacturing (CAM) software named KCAM. The second includes the selection of appropriate electrical components and the design of two cable assemblies.

The control board, shown in Figures 5 is the control center of the desktop CNC machine. This PCB incorporates the computer interface, a standard IEE1284 parallel port, which is used to directly control the various I/O functions of the machine. The parallel port was chosen based on the ease of design and because each of the CAM software packages that we reviewed have support for this interface. The CAM software controls the motion of the desktop CNC machine by interpreting G&M Code, and setting the enable, step and direction signals on the control board. For each axis of the machine, the CAM software controls three bits. The first is the enable bit, which enables the motor driver on the control board. The second is the direction bit, which controls the rotation direction of the stepper motor. The third is the step bit.
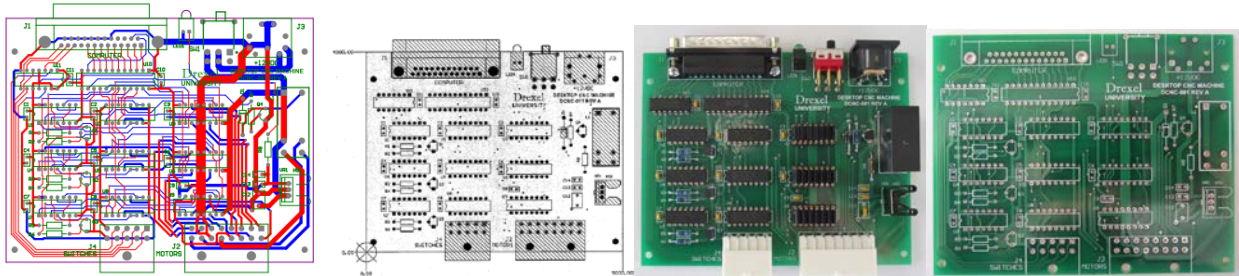
Figure 5. Control board fabrication diagrams, assembled and fabricated control board.

This bit is used to control the rotation of the stepper motor which moves the desired axis a specified distance. In addition to the control bits for each axis, the CAM software also controls the rotary tool when required, and monitors the status of the axis limit switches and emergency stop switch. Each of the outputs from the computer's parallel port is connected through a SN74ABT827 signal buffer which provides isolation between the computer and the control logic. Each of the switch inputs is connected to an SN74ABT126 signal buffer which provides isolation between the switches and the computer. Isolation is desirable for two reasons, ESD protection of the computer and control board, and for ensuring that the signal is properly driven to the appropriate TTL levels required by the computer and the control board.

The control board contains three stepper motor drivers. The driver IC used for this design is the L293 Push-Pull Four Channel Driver. This device is an integrated IC which is designed to accept standard TTL logic for control of high voltage relays, solenoids, and stepper motors. The driver IC is capable of supplying 0.6A of continuous current and up to 1.2A of peak current which is more than required for the stepper motors which we have selected. The stepper motors are driven by an excitation voltage of 12VDC which is sequenced by the driver IC and associated control logic. The step / direction logic for each of the three motor drivers is derived using two J-K flip-flops in a standard 4027 IC package, and four exclusive OR gates in a standard 4070 IC package. When the CAM software generates a step command, the appropriate motor driver logic is generated using these components. This control technique is based on an example circuit

provided by the motor driver IC manufacturer and was successfully simulated using LTSpice, [7] a circuit simulation tool provided by Linear Technologies. The simulation schematic diagram is shown as Figure 6. The standard spindle tool is powered by 12VDC. We chose a PCB mounted mechanical relay to control the spindle tool. The relay, an Omron G2RG, is capable of switching up to 8A which accommodates a wide array of spindle tools. The standard spindle tool requires only 0.7A. In addition to the 12VDC output for the spindle tool, a second set of relay contacts is available on the motor connector for control of external devices such as AC loads, a high voltage power supply for laser etching, and other devices. In addition, the standard spindle tool also has an integrated power switch which is used as a safety override for use during testing or working tool replacement.

In addition to the outputs described above, the control board also contains the logic for the X, Y, & Z axis limit switches and the emergency stop switch located on the side of the machine. The status of each switch input is monitored by the CAM software during machine operation. If any of the axis limit switches are actuated, the CAM software will know that the machine has traveled outside of its workable dimensions and stop the stepper motors to prevent damage to the machine. If the emergency stop switch is pressed by the operator, the CAM software will immediately stop and disable each of the motor outputs to prevent injury or damage to the machine / workable object which would have otherwise not been detected. Each of the switches is configured to be active low, which means that when the switch is pressed, the CAM software will read a "0" on the respective input pin.
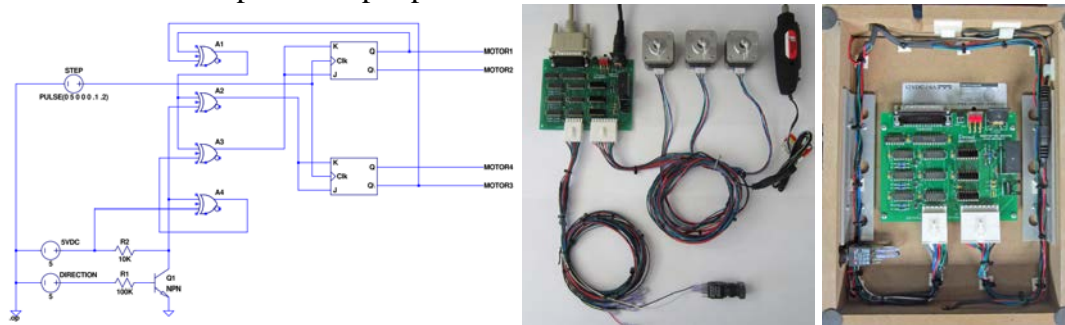
Figure 6. LTSpice Motor Control Simulation Circuit, Electrical Bench Testing, Prototype Control Board Wiring

The control board design also includes a 5V power supply circuit which provides logic power for the motor drivers, and other interface components. This simple 5V power supply consists of a LM7805 positive voltage regulator, heat sink, and three small capacitors to provide up to 1A of current. We estimated that our circuitry required less than 0.25A, so we are well within the capabilities of this circuit. Each of the logic chips on the board are accompanied by a 0.1uF bypass capacitor which helps to eliminate signal noise and ground bounce which can occur when multiple loads are switched at the same time. This is a standard design practice when designing with TTL control logic. The control board was designed using standard through-hole components, which were selected primarily for ease of assembly. Each of the components was in stock and available from a number of sources, including our primary electronics supplier, Digikey. The construction of the board uses standard FR4 material with 1oz. copper traces on the top and bottom layers. All of the power and signal traces were routed on just two layers which reduced the fabrication costs considerably. The board dimensions are 5.0in x 4.0in and it has 4 mounting holes for attachment to the bottom of the machine. The fabricated boards were

manufactured by Silver Circuits[8] in Malaysia. The cost for 4 prototypes, with a 5 day turnaround was $70, an excellent value, and well within the budget.

The control board has four connectors. A 5 pin DIN connector which is used for the 12VDC power input, a DB25 connector which is used as the interface to the computer parallel port, a 16 pin MNL connector which is used to interface with the stepper motors and spindle tool, and a 10 pin MNL connector which is used to interface with the axis limit and emergency stop switches. These connectors allow the control board to be easily removed in the event that a repair is necessary. The connectors also allow for quick assembly of the machine. The cable assemblies, one for the motors and one for the switches, were designed and documented using Microsoft Visio, [9] using an industry standard wire-list format, which is accepted by most contract vendors. 26AWG stranded wire was used for all external connections. With a rating of 2.2A per conductor, this wire provided the appropriate safety margin for each of our I/O devices, while keeping the cost low. The prototype wiring and packaging of the control board are shown in Figure 5. The power connector was selected to match the 12VDC power supply. To determine the power rating of the power supply we estimated the total power requirement for the stepper motors, spindle tool, switches, and logic power, and selected a switch mode power supply from Elpac Power Systems[10] which provided more than enough current, a five year warranty, and fit within the budget constraints.

Future Development

The machine was designed such that future development to the machine would be possible. A number of features were designed into the base machine with this purpose in mind. The first of these features is the integrated spindle tool control relay on the control board. In addition to the standard 12VDC control of the spindle tool, the control board has two additional pins on the motor connector, from a set of auxiliary relay contacts, for control of external devices such as AC loads, a high voltage power supply for laser etching, and other devices. This relay is controlled by the standard "CW Spindle On" M-Code, "M03". The second of these features is the removable working tool bracket which is currently designed to hold a 12VDC rotary tool. Additional working tool brackets can be designed for a wide variety of working tools including a laser etching tool, an electric engraver, a high performance rotary tool, or a drafting marker for non-destructive projects. In addition to the features added specifically for the purpose, the control system design lends itself to future development as well. The parallel port interface could be interfaced directly from a microcontroller based controller or a high-speed PLC, and the control logic is relatively simple to understand. Many of the USB based CNC control systems on the market produce similar step/direction control signals like the KCAM software. In theory a USB controller could be added by simply connecting the appropriate parallel port pins of the control board to the respective outputs of the USB control system.

Figure8b depicts a concept of remotely operated manufacturing cell that is being developed. Remotely operated cell includes a desktop CNC machine that was designed and built by Drexel University senior Engineering Technology students. The CNC machine is used in conjunction with other machines in a work cell configuration for educational purposes. Multiple machine interoperability would include the desktop CNC machine, the Scorbot ER IV robotic arm, a 3D printer, and a conveyor or holding area. In this example the desktop CNC machine would be loaded with a 3D printer manufactured part, to perform a final milling step. The robotic arm would remove the part from the 3D printer after the printing process is complete and place it on the working table of the CNC machine. A machine controlled clamping system would be

required on the working table of the CNC machine to fully automate this process. Once the milling process was complete the robotic arm would remove the part from the CNC machine and place it on a conveyor or in a separate holding area. The process could then be repeated[8, 9].

In addition to three computers and a TCP/IP communication network, I/O connections would be required to communicate the current status of each device, and to control the conveyor and CNC clamping system, if required. The Scorbot ER IV robotic arm controller has significant I/O capability for the robotic arm and conveyor control. The desktop CNC machine has unused pins on the parallel port which could be used for I/O connections to and from the robotic arm. The output pins can be controlled directly by using the unused M-Codes for CCW spindle operation, coolant spray, and others which are included in the KCAM software. An example would be the M-Codes for "Coolant Mist", "M07 and M09", to pulse Pin 14 of the parallel port when the milling process is complete. If this signal was connected to the robotic arm controller, it would indicate that it is now safe for the part to be removed from the CNC machine. Likewise, the "Auxiliary Switch" input could be used to receive a start pulse from the robotic arm controller when the CNC machine is clear to start the milling process. These additional functions would be mapped to the unused I/O pins of the parallel port in the "LPT Setup" tab of the "Port Setup" window of the KCAM software. In addition, the 3D printer may have I/O capability or it may be able to communicate its status with the robotic arm controller via the TCP/IP network.

Integration of Desktop Mini CNC Mill in MET316-CNC Course

The desired current set of skills required of modern engineers and technologists has been steadily expanding. In addition to familiarity with manual machining and fabrication techniques, mastering CAD/CAM, Computer Numerical Control (CNC), and automation methods are increasingly becoming essential tools in the design, prototyping and manufacturing of complex systems. Since purchasing and installing traditional CNC equipment is not an option for every campus of Drexel University or similar engineering schools, an alternative solution to providing hands on experience with CNC equipment is desirable. A CNC machine with a desktop form factor which would be easily transported between campuses would eliminate the need for multiple traditional CNC machines and would improve the quality of the MET316-CNC course by providing more hands-on lab experiences. The desktop CNC machine which was developed by student design team fits on a standard desktop or table, and interfaced KCAM Computer Aided Manufacturing (CAM) software (Figure 8).

Development is still under progress for a remote online laboratory for computer numerical controlled machines in Engineering Technology Laboratory. Desktop Mini CNC mill is set-up similar to remote programmable logic controller (PLC) station (Figure 8c). Figure 8a shows the PLC workstation and host computer that are remotely programmed and used at remote labs at Drexel University. The web camera in the foreground allows the student to monitor the behavior of the system visually. The camera's image can be seen on the computer monitor. The panel at the top of the PLC station is the electro-pneumatic panel. A Remote Desktop client is built into all versions of Windows. To connect to laptop computer that controls Desktop CNC mill, student needs to enter the IP address of the remote laptop computer, and controls the machine using KCAM software (Figure 8c). Machine can be jogged remotely for work origin set-up and a G-code program can be executed remotely to machine a work-piece. For safety reasons, a lab technician monitors the CNC machine and laptop controller at all times.

(a)

(b)
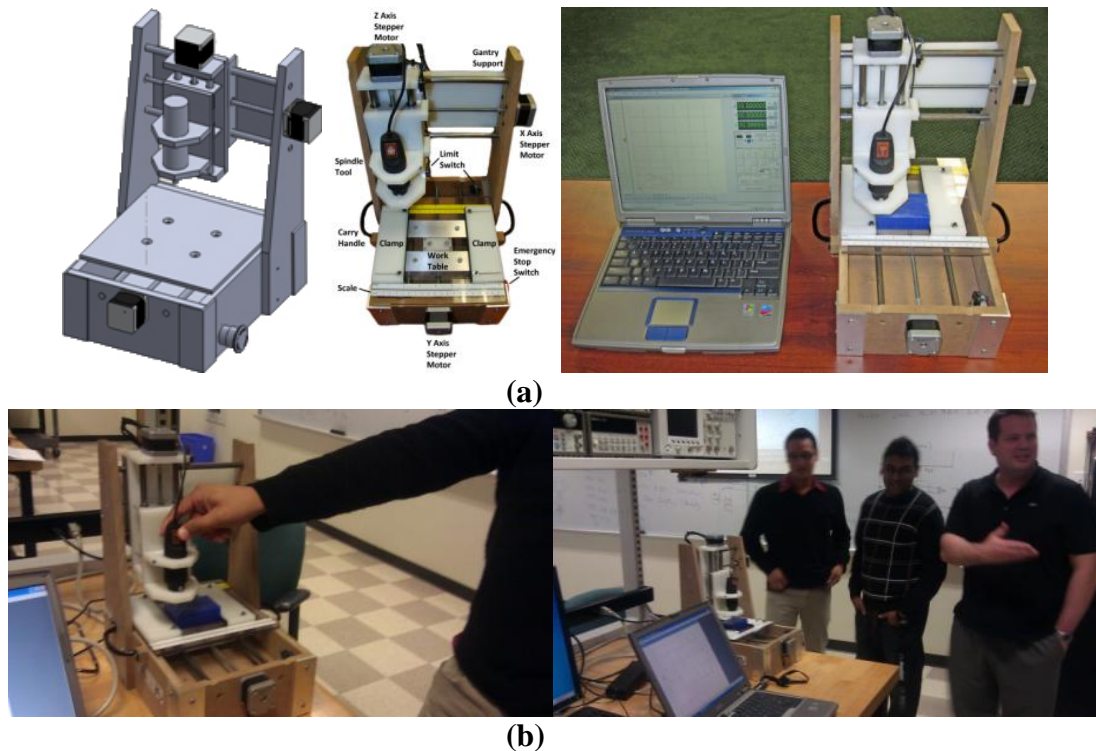
Figure 7. (a) CNC Desktop mini milling machine & control computer with Completed Working Table. **(b)** MET 316 CNC students running the desktop machine for G& M code testing.

(a)   **(b)**

(c)
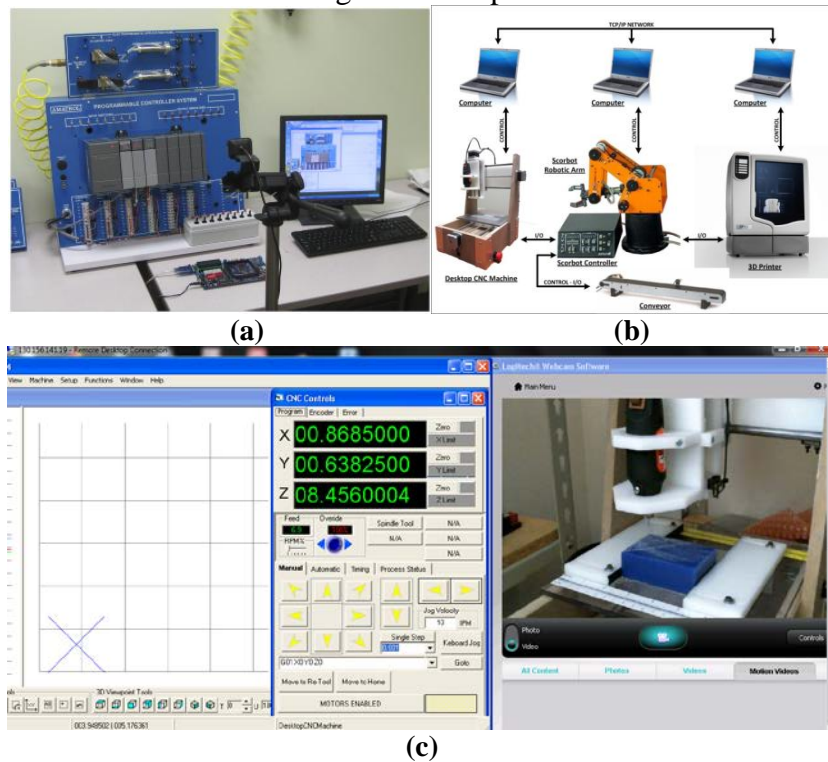
Figure 8. (a) Workstation used for online laboratory exercises at Drexel University. The board on the table is used in microcontroller experiments. **(b)** Future machine development remote Work Cell Example at Drexel University. **(c)** Remote online access to CNC mill currently located at BCC campus.

Development of an Agent-based Tutor & Training System

Development of an agent-based tutor and simulator training system (ATSTS) is in progress with an embedded-intelligence and knowledge base to guide and support students in remote operations within the safety and functional boundaries of the equipment. Its main function is to aid remote users in lieu of the teacher's absence through the graphical projection of process plan and process knowledge in machining and robotics operations. Figure 9 indicates a screen view of online tutorial system that is being developed using Emco campus modules for machining applications.
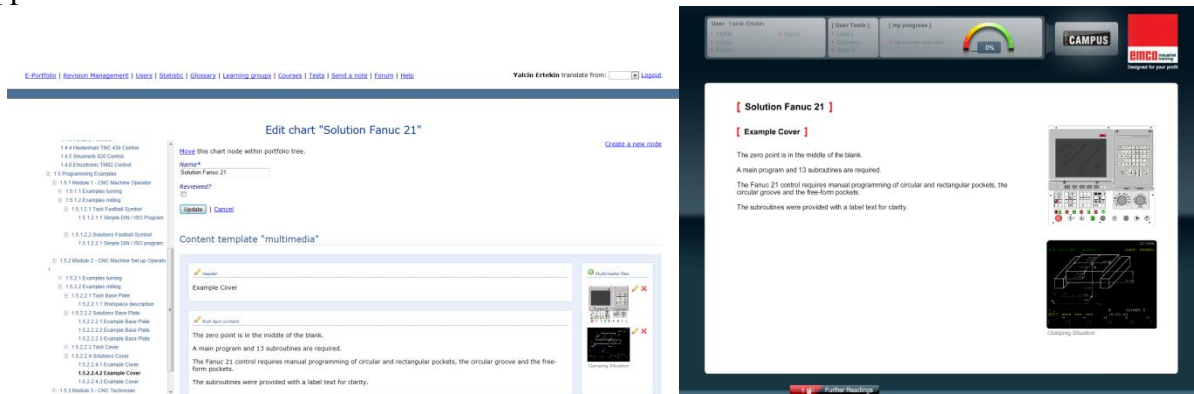
Figure 9. Example online tutorial system developed in cooperation with Emco company.

Senior Design Course Evaluation and Student Feedback

Prior to finishing the course, students filled out evaluation forms using Drexel's Academic Evaluation, Feedback and Intervention System (AEFIS). Based on this evaluation system the overall course and instructor ratings were 4.25 out of 5.0 (max. scale) as indicated in Figure 10. ***The best aspects of this course, as perceived by students can be summarized as follows:*** They were highly satisfied by the opportunity provided by this class to be creative and to use interesting materials and software. Students particularly embraced using SolidWorks® for product design and structural simulations. The course really changed the way that they regarded design, simulation, prototyping and manufacturing. Quoting of several of the student reviews are provided below:

Question1: What were the best aspects of the course?

- *Prototype assembly and testing.*
- *Developing and testing our project. Designing the circuitry*
- *Assembling and designing our project and actually see the project perform the task we wanted it to do*

Question 2: What specific, practical changes can you recommend that might improve this course?

- *More guidance on deliverable dates / meetings early in the term.*
- *More definitive direction of course objectives.*
- *Nothing*

Conclusion

Engineering Technology student design team has produced a solid design and has applied the required engineering expertise to complete and deliver a functional desktop CNC machine to Drexel University. Prototype testing has gone well and the team has proven that their design was feasible and that the electrical and mechanical design selections were appropriate. The design team also completed an FMEA analysis which helped to ensure that the various failure modes of

the machine design were identified and designed for. The economic analysis indicated a decreased material cost trend at higher production volumes and has determined potential selling prices accordingly. The prototype cost is well under the target cost and feasible to be duplicated other teaching institutions.
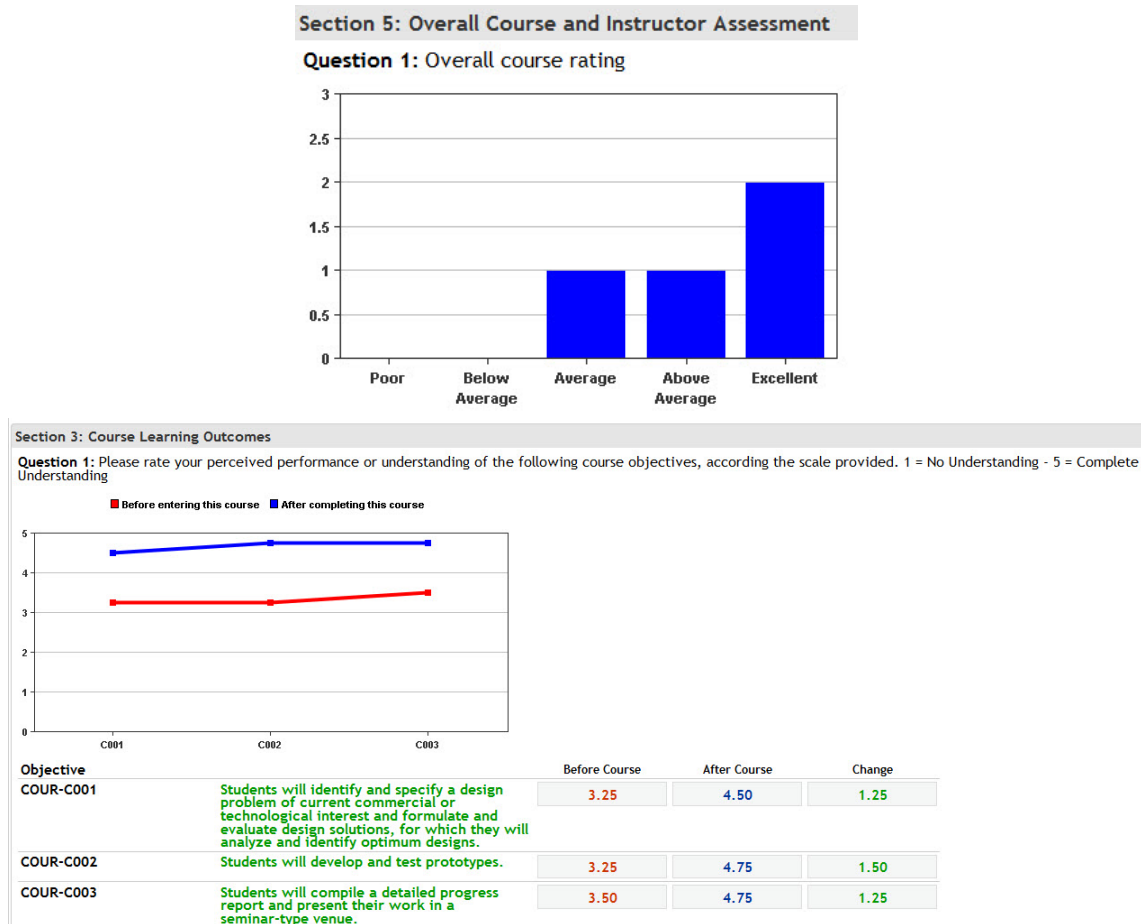
Figure 10. AEFIS student survey responses by the design team after completing the senior design sequence.

Acknowledgement

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Table 1: Product Design Specification (PDS)
Product Title: Desktop CNC Machine
A. Purpose

Currently while completing the MET316 CNC course at Drexel University, the only opportunity for the student to interact with CNC equipment is on the Drexel campus in Philadelphia. Since this course is taught at other locations, the equipment is not readily available to all students. If a small, portable, low cost CNC machine was available for use in the classroom, it would provide additional practical learning opportunities and improve the quality of the MET316 course.

The purpose of the design project is to develop a low cost, desktop size, portable CNC machine for use as a teaching aid for the Drexel MET316 CNC class.

B. Features
A review of several comparable desktop CNC machines has provided valuable information with regard to features that would meet or exceed the requirements of the primary classroom usage requirements.
The following features and requirements are proposed for the design of a Desktop CNC Machine.

1. Desktop Form Factor
2. Standard Letter Table Size of 8.5in x 11.0in
3. Workable Object Size of 7.5in x 8.5in x 3.0in
4. 3-Axis CNC / 2.5-Axis Control (XY w/ Z Plunge)
5. Light Duty Operation (Plastic, Wax, Aluminum)
6. Portable (Easily moved between Classrooms / Campus)
7. Computer Controlled (Parallel Port and/or USB)
8. Compatible w/ Common CNC Software (Feature CAM, K-CAM)
9. Configurable for Various Spindles / Working Tools (Rotary Tool Standard)
10. Comprehensive Operation Manual
11. Novice Level Build Plans and/or Build Kits
12. Powered By Standard Outlet (115V / 60Hz / <15A)
13. Able to be built From New or Recycled Components

C. Competition
Based upon market review, the following competitors were identified as meeting some or all of the desired features for this project.
MyDIYCNC - Desktop CNC Machine, Advanced Control Technology (ACT) – DMC-III CNC Machine, Roland - iModela iM-01 3D Hobby Mill

D. Intended Market
The intended market is primarily educational users. This machine, when combined with a structured education in CNC manufacturing will provide valuable hands-on experience for students that would typically not have access to a traditional CNC machine costing thousands of dollars. Additional markets for this equipment exist for hobbyists, in-house prototyping of small parts for engineering / design companies, and for manufacturing of micro-fluidic devices for medical research.

E. Performance Requirements
The following performance requirements have been proposed:

Workable Object Dimension (X Axis)	7.5 in (190.5 mm)
Workable Object Dimension (Y Axis)	8.5 in (215.9 mm)
Workable Object Dimension (Z Axis)	3.0 in (76.2 mm)
Precision (X/Y/Z Axis)	0.001in (0.0254mm)
Rotary Tool Speed	16000 RPM

F. Target Cost
The total cost of this machine is intended to be less than $500 when manufactured from new materials.