AC 2012-4239: A MECHATRONICS CAPSTONE PROJECT WITH AN INTERDISCIPLINARY TEAM AND AN INDUSTRIAL PARTNER

Dr. Blair T. Allison, Grove City College

Blair T. Allison is professor and Chair of the Mechanical Engineering Department at Grove City College. He teaches courses in engineering design, mechanics of materials, materials science, control systems, and finite element analysis. Areas of research interest include the modeling and control of metal forming processes, manufacturing automation and control, and dimensional control of components and assemblies. He received his Ph.D. and M.S. degrees in mechanical engineering from the Massachusetts Institute of Technology and his B.S.M.E. degree from Carnegie Mellon University. Address: 100 Campus Drive, Grove City, PA 16127; Email: btallison@gcc.edu.

Dr. Stephen Ludwick, Aerotech, Inc., and University of Pittsburgh

Stephen Ludwick develops high-precision automation systems for Aerotech, Inc., in Pittsburgh, Penn. His main emphasis is on mechatronics and control system design. In addition, he teaches in the Mechanical Engineering Department at the University of Pittsburgh.

Dr. William P. Birmingham, Grove City College

A Mechatronics Capstone Project with an Interdisciplinary Team and an Industrial Partner

Abstract

A team of undergraduate mechanical engineering and computer science students carried out a capstone project focused on the design, fabrication, assembly, and testing of a three-axis computer controlled milling machine for notching thin-walled tubes. These notched tubes are joined to other tubes to produce frames for vehicles for student competitions (e.g., Mini Baja or human powered vehicles). This paper reviews mechanical design efforts, fabrication, assembly, derivation of axis trajectories, software development efforts, and the integration of the hardware and software components that resulted in a successful three-axis tube notcher. This multidisciplinary project required close cooperation between mechanical engineering and computer science students.

The students in the first year of the project designed and built a two-axis (linear-rotary) CNC machining center. Particular emphasis was placed on determining the functional requirements of the design as set by the eventual "customers" in the Mini Baja and human powered vehicle groups. Different sub-groups of students focused on collet design (including finite-element analyses), mechanical design of the motion axes, cutting force tests for spindle sizing, servo tuning for the motion axes, and programming for readily converting solid models of the intended parts into trajectories.

In the second phase of the project, two years later, the students increased the functionality by adding a third controlled axis to the machining center. This axis allowed the appropriate bevel to be cut on the tube ends for a flush mate to the adjoining part. This required a substantial rewrite of the user interface software, redesign of the mechanical systems for the integration of the third axis, metrology and calibration techniques, and a focused study on ergonomics and safety. This project concluded with a functional device that is in use by the student design teams as intended.

The nature of the team interaction is described. Positive and negative aspects of the team experience are discussed. The project was made possible through the involvement of an industrial partner (Aerotech, Inc.) who provided equipment (actuators, controllers, and associated software), technical support, and input during design reviews.

Introduction

Grove City College (GCC) routinely participates in the SAE Mini Baja competition and the ASME Human Powered Vehicle Challenge. Frames for these vehicles are typically fabricated from sections of thin-walled steel tubing that are TIG welded together (see Figures 1 and 2). Tube ends must be notched prior to welding to insure proper fit-up and to maintain small gaps in the joint area. Figure 3 shows a typical joint – in this case a 90° intersection of tubes of the same diameter. While more complicated joints with three or more tubes intersecting at a single location are occasionally required[1], the most common joint involves only two tubes intersecting at a specified angle. A common method for tube notching is to fixture a tube in a specific orientation on a vertical milling machine followed by notching using a hole saw (see Figure 4).

The diameter of the hole saw is chosen to match the outside diameter of the mating tube. While this method produces a good fit-up for welding, the setup on the milling machine is very time consuming and cumbersome. Other methods for tube notching (such as an abrasive belt notcher) require expensive equipment that is hard to justify for an academic institution[2].

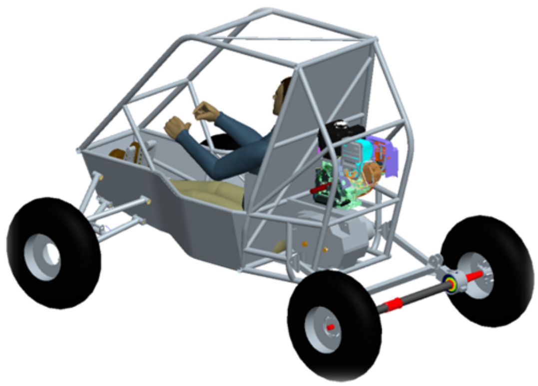

Figure 1. SAE Mini Baja vehicle.

Figure 2. Human powered vehicle.

Figure 3. Typical notched tubing joint.

Figure 4. Notching a tube on a vertical mill.

Requiring this type of machining operation on a regular basis led us to the development of a dedicated tube-notching machine as part of the capstone design program. At GCC, capstone design projects span an entire academic year. During one year, a team of nine mechanical engineering students designed, built, and tested a two-axis tube notching machine. While this project will be described briefly below, the main focus of this paper is a follow-up project that added a third controlled axis to the tube notcher. The latter project involved five mechanical engineering (ME) students, three computer science (CS) students, two faculty supervisors, and an industrial partner. It culminated in the successful development of a three-axis machining center for the notching of tubes. Details of this project will be presented with an emphasis on the interdisciplinary nature of the project and industrial involvement.

Mechanical Engineering capstone project organization at Grove City College

Within the Mechanical Engineering department, each capstone design project team typically consists of five to nine students and a faculty supervisor. When appropriate, students from other departments join the project, creating an interdisciplinary team. Successful teams involving students from electrical engineering, computer science, business, and entrepreneurship have been formed over the years.

Candidate projects for a given year come from a variety of sources. During their junior year, students are encouraged to identify potential capstone projects for their senior year. To be selected, a project must meet a rigorous set of guidelines that have been established by the faculty member that has overall responsibility for the capstone program. Faculty members can also propose projects based on their areas of expertise and interest. The most desirable projects are those with significant industrial involvement. Based on the working relationships we have established with industrial firms in the surrounding region, these firms will often propose projects that are of interest to them but also are appropriate in scope and cost for a senior design project. Their support of the project varies widely and can include just the suggestion of an idea for a project, providing financial support, donation of components and equipment, and provision of technical support and guidance.

Industrial sponsors benefit from these projects in several ways: from the increased exposure to students as possible full-time employees, in the ability to experiment with new design concepts in a low-risk environment outside of mainstream corporate operations, and in the increased access to the expertise of faculty members. Not surprisingly, the most successful partnerships develop over several years as the different parties learn their relative needs, strengths, and abilities. Regular meetings (electronically and in-person) are critical for full engagement. Heybruck and Thurman[3] highlight these and other benefits that are derived from industrial participation in undergraduate education. They suggest industrial involvement not only in the corporate sponsorship of undergraduate programs, but also by way of site visits, co-op programs, establishing of mentoring relationships, sponsored research, *et cetera*.

For the tube notching project that is the subject of this paper, the project was selected based on the needs described above. Due to the high cost of hardware and software associated with this project, it was clear from the start that we could only succeed with the support of an industrial partner. At that point, we contacted Aerotech, Inc., a company that we had worked with on previous capstone projects. The project team worked together with Aerotech to identify hardware and software components that would be appropriate for our application. Aerotech provided these components at no cost to us along with the technical expertise required to incorporate these items into our tube notching system. They also provided input during design reviews as the team faced critical decisions.

During the fall semester, the project team followed an established design process which includes definition of the problem to be solved (including the establishment of product design specifications), a review of pertinent literature (e.g., patents, trade literature, *et cetera*.), development and evaluation of design concepts, and in-depth design activities associated with the chosen concept. These activities closely follow the engineering design process as put forth by Dieter and Schmidt[4]. Spring semester activities include finalizing the detailed design, fabrication and assembly of components, testing, redesign and revision of hardware as necessary, final testing, and documentation.

History of the tube notching project

Based to some extent on anticipated hardware donations, the first capstone tube notcher project focused on the development of a two axis (linear-rotary) CNC machining center. Team members placed particular emphasis on the requirements of the eventual users of this system – namely the faculty, staff, and students that were involved with the Mini Baja and Human Powered Vehicle projects.

A computer based rendering of this system is shown in Figure 5 while a close-up of the linear and rotary axes is shown in Figure 6.

Figure 5. Two axis tube notcher.

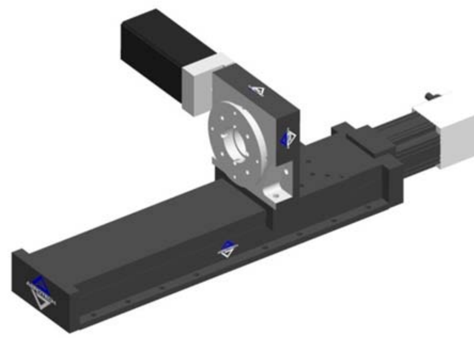

Figure 6. Linear and rotary axes.

A collet system (see Figures 7 and 8) mounts to the face of the rotary axis to secure the tube to be notched. Since there were no commercially available collet systems with sufficient capacity that were priced within our budget, a team member designed and fabricated the system shown. This effort included extensive finite element analysis to verify an acceptable design. The collet system can accommodate tubes ranging from ¾ to 1¾ inches in diameter.

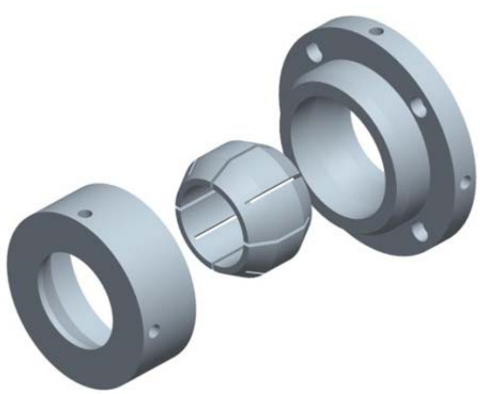

Figure 7. Collet system.

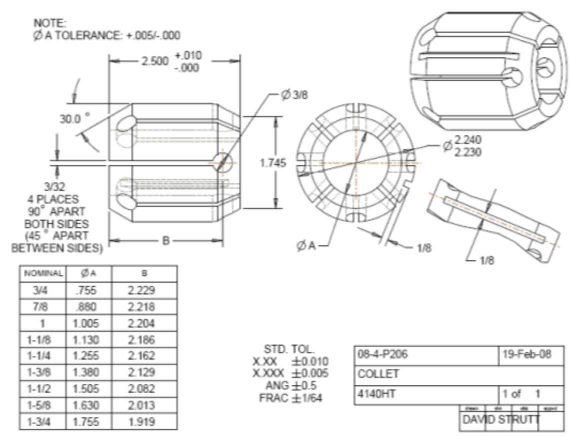

Figure 8. Collet drawing.

A pneumatically driven spindle is mounted under a protective shield to the left of the linear axis (see Figures 9 and 10). Its position is adjusted vertically so that the cutting surface of the carbide end mill mounted in the spindle will intersect the tube wall. The mount for the spindle ensures that the vertical axis of the spindle intersects the horizontal tube axis. The spindle remains fixed in its position throughout the notching operation. It should be noted that in the two-axis system, the axis of the end mill is always perpendicular to the surface of the tube to be notched (i.e., machined edges on the tube are always at 90° to the surface of the tube).

Figure 9. Spindle assembly.

Figure 10. Spindle (pneumatic die grinder).

The control architecture is shown in Figure 11. Software for the user interface and control of the tube notcher was developed using LabVIEW. Calculations that determine the position of the linear axis for a given rotary axis position and joint geometry were carried out within MATLAB. Communication with the Aerotech controllers was accomplished using Aerotech supplied LabVIEW VI's.

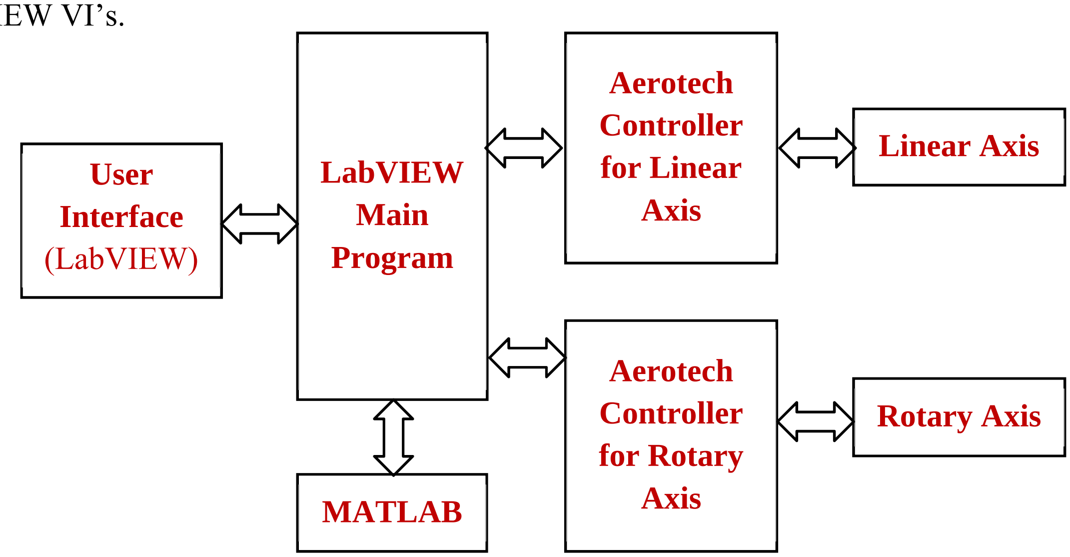

Figure 11. Controller architecture for the 2-axis system.

During operation of the tube notcher, the tube is mounted in the collet and positioned a specified distance from the cutter. The operator enters required information as requested on the user interface (see Figure 12). This includes the tube outside diameters, intersection angle, wall thickness of the notched tube, cutter diameter, and the distance from the end of the tube to where the cut should begin. The user selects the *"Get Coords"* button to calculate rotary and linear axis trajectories and then selects the *"Run"* button to initiate the machining operation.

This two-axis system can be used to notch steel or aluminum tubes with diameters ranging from ¾ to 1¾ inches, angles of intersection from 10° to 90°, and wall thicknesses up to ⅛ inch. While tubes notched on this two-axis machine could be TIG welded, the joint geometry was not ideal for welding when the wall thickness approaches the upper limit of ⅛ inch. This is because the machined edge of the notched tube is always at 90° to the surface of the tube. There are also some occasions when brazed joints on tubular frames are desirable. The gaps between tubes produced by the two-axis machine are unacceptable for brazing.

During testing and use, it was noted that the spindle easily stalled and it was sometimes difficult to regulate the cutter speed to a desired value. The spindle was essentially an inexpensive die grinder. The project team recommended a more robust spindle be considered for the future.

While the two-axis system generally met the product design specifications, its performance was sometimes marginal. This led to the addition of a third controlled axis, an improved spindle, and a new user interface two years later.

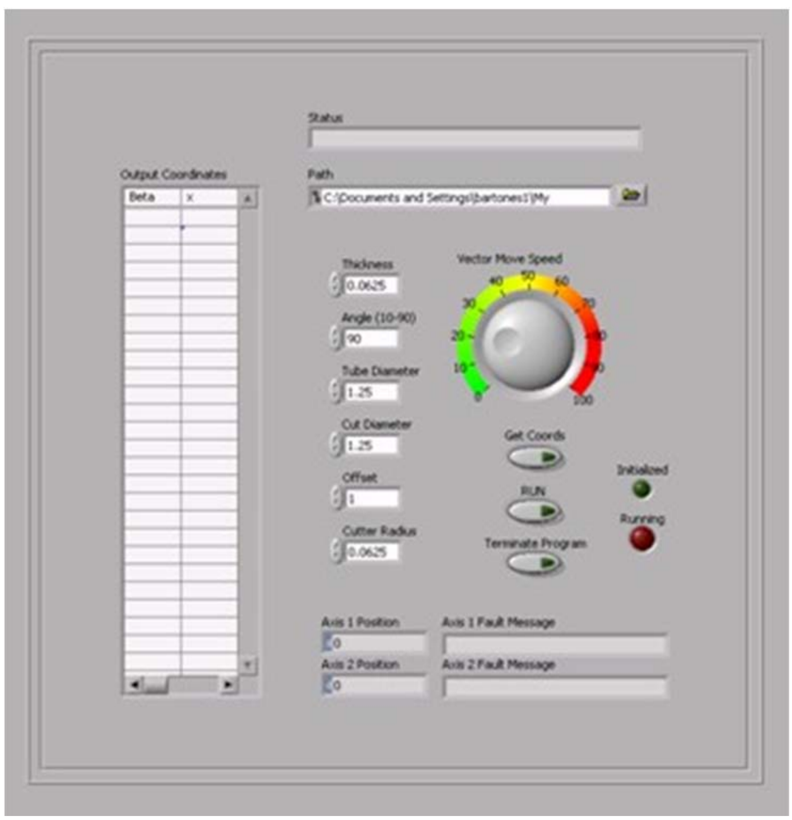

Figure 11. User interface for two-axis tube notcher.

Development of the 3-axis tube notching CNC machine – mechanical details

From a mechanical perspective, the 3-axis tube notching machining center was primarily a modification of the 2-axis machine to include a third controlled axis and an improved spindle that was better suited for machining operations. Figure 12 shows the three axes (linear axis X and rotary axes A and B). Figure 13 shows the 3-axis CNC machining center with the controls cabinet and the safety cover in place. The cover reduces noise levels for the operator and provides protection in the event of cutting tool breakage or the ejection of debris from the cutting operation.

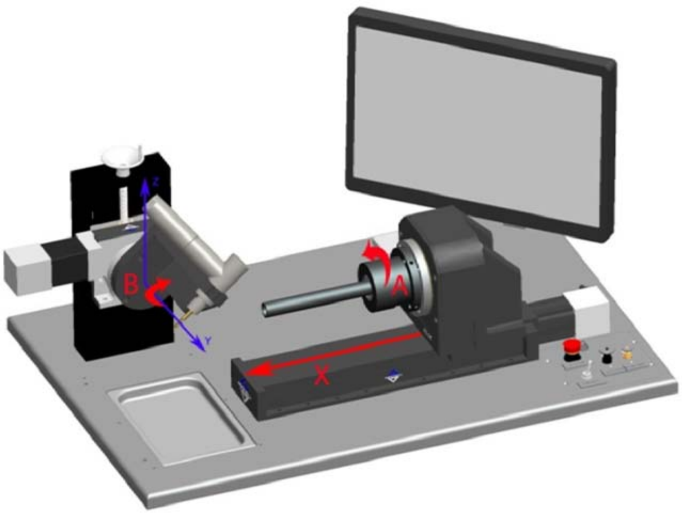

Figure 12. 3-axis tube notching machine.

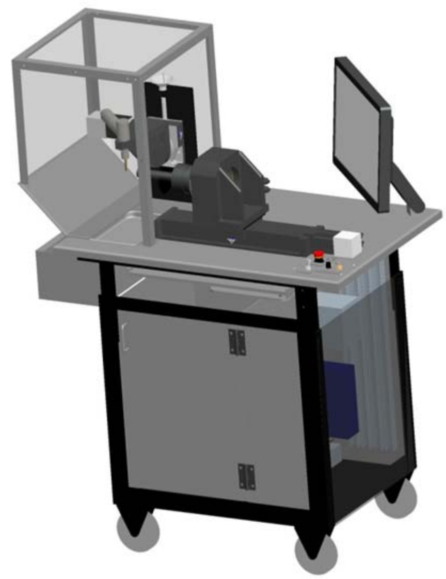
Figure 13. Machine with controls cabinet and safety cover.

The mechanical engineering student design team began their efforts with a product definition phase similar to that undertaken by the 2-axis team two years earlier. They developed a modified product design specification with an emphasis on adding a third controlled axis and an improved cutting spindle. The mechanical team was also responsible for deriving the equations used to generate axis trajectories for the machining operation.

The rotary axis that was part of the earlier project became the axis that rotates the spindle in the 3-axis machine (shown on the left in Figure 12 above). A new rotary axis that can accommodate larger tube diameters was added to the system, replacing the smaller rotary axis used on the 2-axis machine. This larger rotary axis is mounted to the linear axis using a cast iron angle plate that was machined with a through hole to accommodate the tubing being notched.

A significant effort went into selection of an improved cutting spindle. Options considered included an electrically powered die grinder, a plasma cutter, a conventional electric spindle motor, and an air driven spindle motor. Using a weighted Pugh's selection matrix, these were compared to the pneumatically powered die grinder that was used on the two axis machine. Design criteria considered in the selection of the spindle included affordability, safety, precision, power requirements, weight, size, variable speed capabilities, availability, and noise level while cutting. The spindle selected was a pneumatically driven spindle manufactured by Finley Enterprises and is shown in Figure 14. This right angle air motor driven spindle is intended for high speed drilling or milling operations and is ideally suited to tube notching operations. The power output is 0.34 HP (0.25 KW). It uses standard RD 16 collets and can hold tools up to 10 mm. in diameter.

Figure 14. Finley pneumatic spindle.

These students also handled all of the wiring tasks and layout of electrical components as shown in Figure 15.

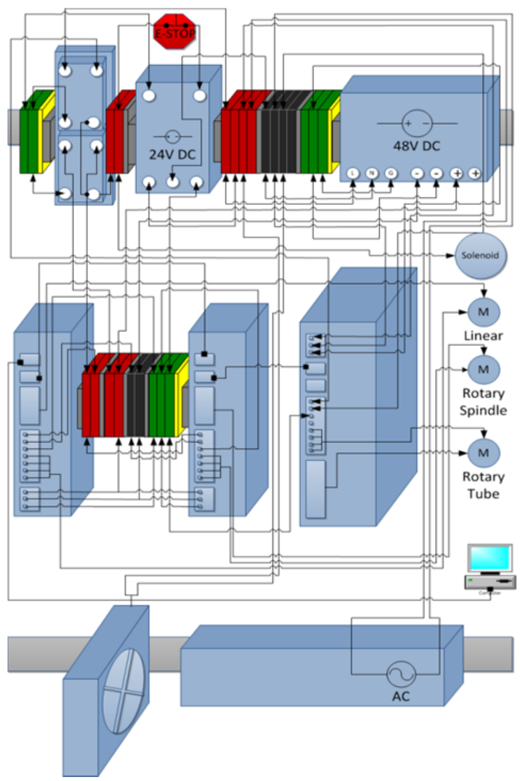

Figure 15. Layout of electrical components.

The equations that determine the axis trajectories can be derived in a straight forward manner since the notch profile geometry is simply the intersection of two cylinders whose axes are coplanar. The results of this derivation are shown below along with a list of variables. The variables *x*, *y*, and *z* are intermediate variables that describe the intersection between the outside diameter of the primary (uncut) tube and the notched tube at the midpoint of its thickness.

$\theta =$ rotation angle about axis of notched tube (rotary axis A)

$\alpha =$ angle of intersection between the notched tube and the primary or uncut tube (α equal to 90° corresponds to a perpendicular joint)

$r =$ radius of notched tube midway through the wall thickness

$R_0 =$ outside radius of the primary (uncut) tube

$r_{ct} =$ cutting tool radius

$$x(\theta) = r\sin\theta$$

$$y(\theta) = \frac{1}{\tan\alpha}\left[\sqrt{R_0^2 - r^2\sin^2\theta} - r\cos\theta\cos\alpha\left(1-\tan^2\alpha\right)\right]$$

$$z(\theta) = \sqrt{R_0^2 - r^2\sin^2\theta}$$

$y_d(\theta) =$ intermediate value used in cutter angle calculation

$$= \frac{z(\theta)\left[z(\theta) - y(\theta)\tan\alpha\right] + x(\theta)^2}{\tan\alpha}$$

$\beta(\theta) =$ angle of cutter axis with respect to tube axis ($\beta = 90°$ corresponds to a cutter that is perpendicular to the tube, this is rotary axis B)

$$= \frac{\pi}{2} - \cos^{-1}\left[\frac{y_d(\theta)^2 + x(\theta)^2\tan\alpha}{\sqrt{\left(1+\tan^2\alpha\right)\left(x(\theta)^2 z(\theta)^2 + y_d(\theta)^2 + x(\theta)^4\right)}}\right]$$

$d(\theta) =$ position of linear axis X with cutter radius compensation

$$= \sqrt{\left[r\cos\theta\sin\alpha - y(\theta)\right]^2 + \left[r\cos\theta\cos\alpha - z(\theta)\right]^2} + \frac{r_{ct}}{\cos\left[\beta(\theta)\right]}$$

The equations do not include any adjustments in the position of the linear axis for offsets related to the original positioning of the tube. Axis position commands are θ, $\beta(\theta)$, and $d(\theta)$. Theta (θ) varies from 0° to 360°.

These equations were verified in MATLAB by plotting tube intersection curves and cutter angle settings for a number of anticipated cutting situations. An example of a 1.00" diameter tube with an 0.083" wall thickness intersecting a 1.25" diameter tube at an 80° angle is shown in Figure 16. The black line represents the axis of the notched tube, the blue oval represents the intersection of the notched tube (midway through its thickness) with the primary tube, and the red line is the axis of the cutter at one position during the cutting cycle.

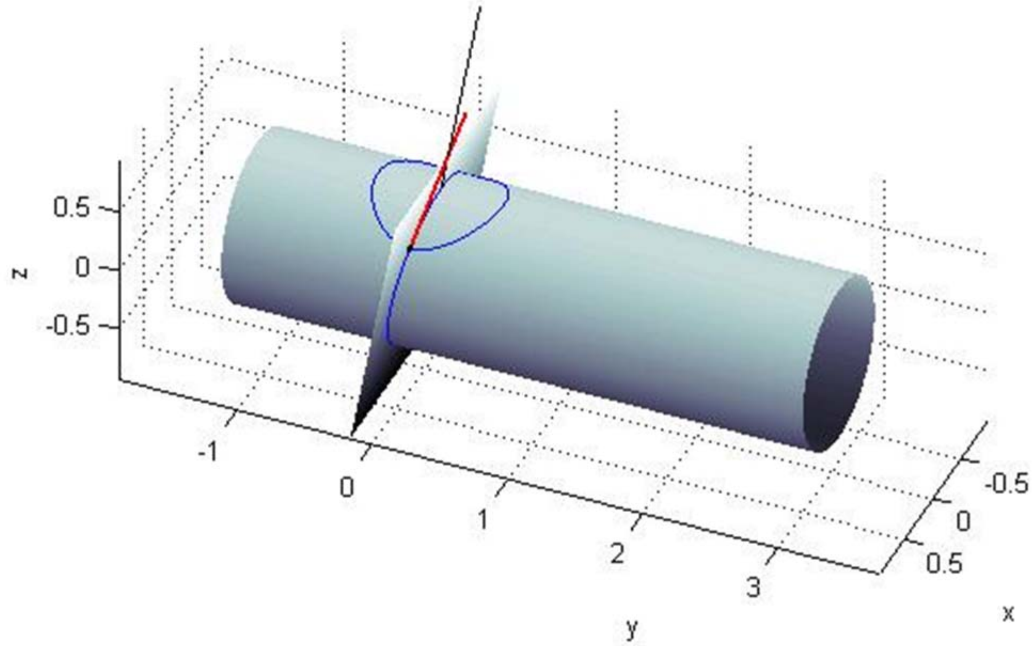

Figure 16. Graphical verification of axis trajectory equations.

Development of the 3-axis CNC tube notcher – computer science team efforts

Students in computer science (CS), like ME students, are required to take a two-term senior project sequence. The main purpose of this course sequence is to give students in-depth experience in designing, implementing, and testing a complex software system, building upon their experience in software engineering. The fall semester course focusses on design, particularly user-interface (UI) design. The spring semester course focusses on implementation (system building) and extensive testing. Part of the pedagogy in the sequence is to give the students time to think about UI design and testing. Generally, these things get short shrift even in project classes (like software engineering) because students tend to focus on implementation.

Students are free to pick their projects and their teams. The major project selection criteria are the following: there must be an outside user community for the software system; and, the system must be able to be implemented and tested in a single term. These very general criteria give the students as much flexibility as possible in picking their projects. The faculty want students to have "ownership" of their projects and feel a good way to do this is let them build something they want to build.

UI design is a very important element of senior projects. Our students, like those in most other CS programs, gain experience in constructing graphical UIs for applications ranging from video games to databases to web sites. However, they do not get instruction on the principles that distinguish a good UI from a bad one. In our fall semester course, students spend time designing and then evaluating their UI without implementing it. The students use a GOMS-style design methodology based on human factors, cognitive psychology, and best practices (Lewis & Rieman[5]). This methodology rounds out their implementation knowledge, allowing them to understand how to design an interface that a user will want to use. When it comes to implementation in the spring term, they have a proven UI design.

The tube-notching project provided an excellent UI design opportunity for the CS students. There were two interesting criteria for the design, as the follows:

- The interface had to simple, since the users did not expect to learn a complex interface.
- The interface had to support an emergency stop—abort—button.

Both these criteria permeated the design. While a series of complex calculations involving several different pieces of software, each with their own interface, were necessary for the system to operate, the CS students abstracted all but the most basic information necessary for operation. This is an excellent example of good UI design, as it is often easier to design complex interfaces than simple ones. This is because choosing the correct information to expose to the users is a difficult problem. Through interviews with the ME students and application of the UI design methodology, they developed a simple, yet elegant, design. The interface is shown in Figure 17.

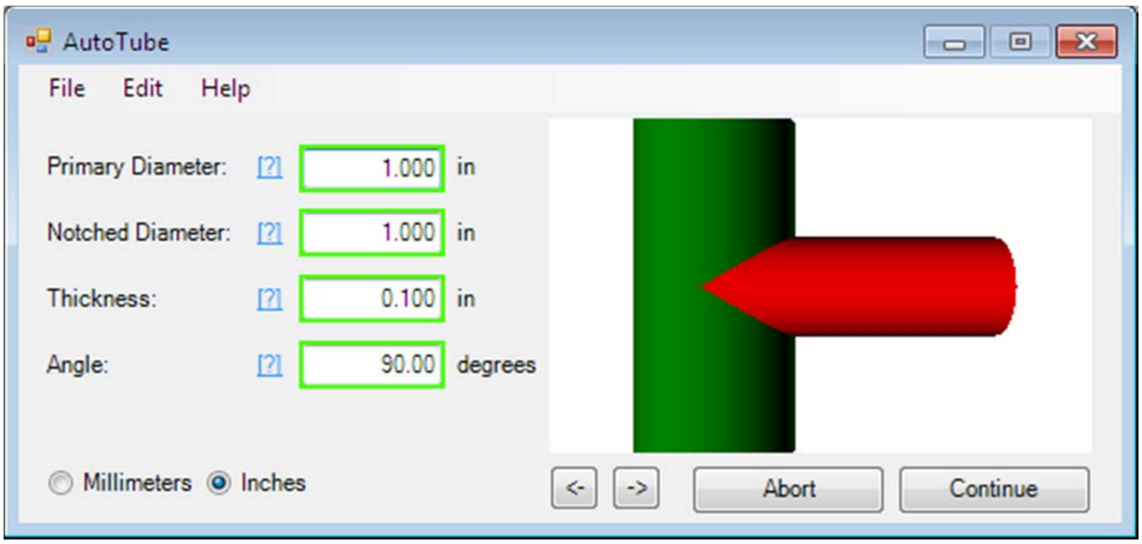

Figure 17. Interface to the tube-notching system.

The UI presents four parameters to the user needed to properly cut the tube: primary diameter of the tube, the notched diameter, tube thickness, and the angle for joining the tubes. The diagram on the right of the UI shows the relationships between the tubes, with tube width and angle changing in accordance with the user-input values. The UI also provides an extensive help system (not shown in Figure 17).

The incorporation of an abort button has major implications for the system. Incorporating the button in the UI is simple. However, the students had to create a way of getting the corresponding abort signal directly to the tube notcher, bypassing all the intermediate pieces of software that comprised the system.

During the spring semester, the students implemented their design. The controller architecture (both hardware and software) is shown in Figure 18. The students used a rapid prototype development process, where they created a new version every four weeks. Each version was an operational, albeit with limited functionality, and tested system. New functionality was added to the to each new version. Each iteration went through a complete "small to large" testing regime: unit testing, then integration and regression testing, then system testing. All bugs were tracked and fixed on subsequent iterations.

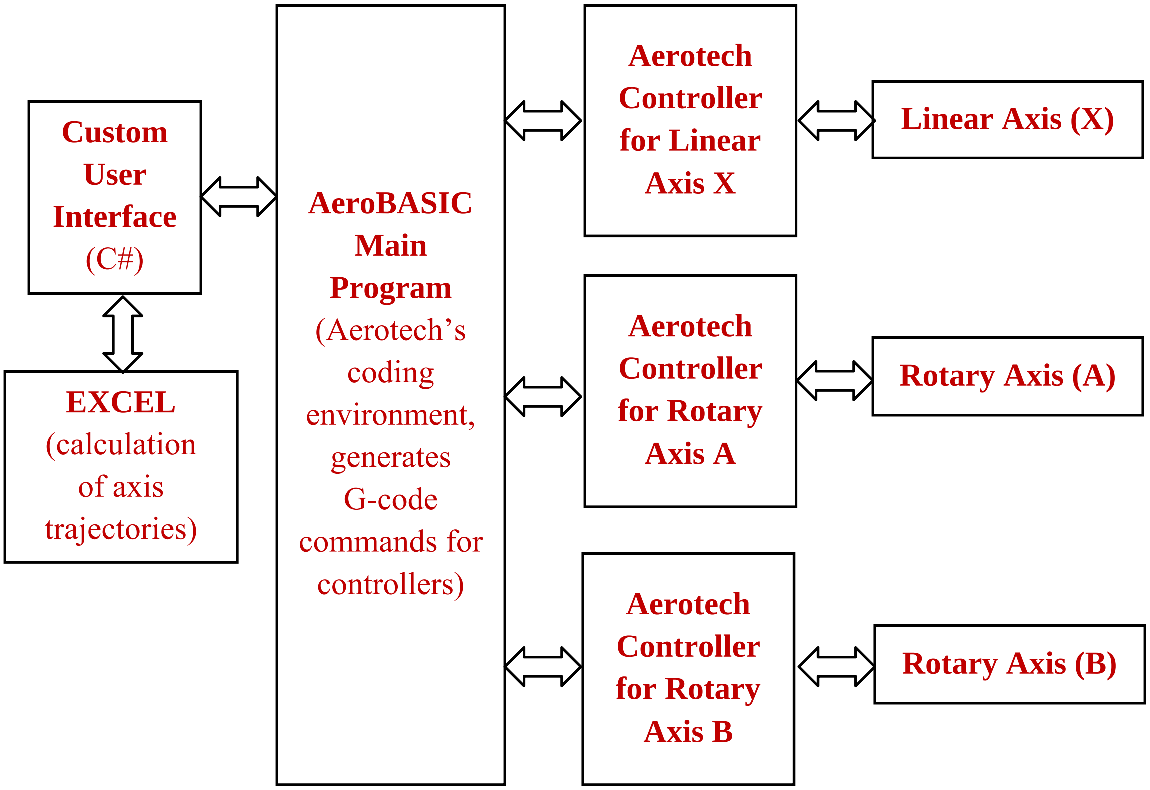

Figure 18. Controller architecture for the 3-axis system.

During each iteration, ME students were asked to evaluate the system. This included evaluating the UI, and testing the software on the notching hardware and related equipment. Through this iterative process, a completely implemented and thoroughly tested software system was available at the end of the term.

Several minor changes were made to the system during implementation. A set of software safety checks were added. The validity of the inputs was checked to ensure that, for example, tube wall thickness was within limits of the tube notcher. A help system and a safety checklist were also added. However, there were no major changes from the specification completed in the fall.

The entire system was successfully tested. Users were able to notch a tube using the software and hardware developed by the students. In fact, the system is still being routinely used.

Interdisciplinary nature of the project

Interdisciplinary capstone design projects present some unique challenges. Most academic departments have their own set of requirements, guidelines, and procedures for capstone projects and they typically differ from program to program. Each department typically defines what makes an acceptable project, project duration and timeline, milestones, written report and presentation requirements, *et cetera*. Meshing differing sets of capstone requirements calls for well coordinated and careful oversight on the part of the faculty advisors and a true team effort on the part of all students involved.

As mentioned earlier, the three-axis CNC tube notching project involved five mechanical engineering students, three computer science students, two faculty supervisors (one ME, one CS), and an industrial partner. The project began with a joint meeting of all participants (with the industry representative joining us on-line using WebEx™ through which we were able to share audio and video). It was during this meeting that the overall scope of the project was refined and many of the differing requirements of the ME and CS departments were addressed. In addition, all student team members visited our industrial sponsor, Aerotech, Inc., and toured its facility. This gave students the opportunity to see first-hand some of the hardware and software they would incorporate into their design. During this visit we also met to discuss project details with representatives from Aerotech.

The many discipline specific tasks led to separate weekly meetings for the mechanical engineering and computer science students. Faculty advisors joined the students during these regular meetings. To insure good communication between disciplines, one mechanical engineering student participated in the weekly computer science meetings and one computer science student took part in the regular mechanical engineering meetings. This greatly enhanced the flow of information and minimized miscommunication between project participants. The entire project team met occasionally for periodic updates. This became more critical as we approached the phase where mechanical components, control hardware, and software were integrated into a working system. As described by Edmonson and Summers[6], multidisciplinary team participants require a good understanding of their fellow team members, need good negotiating skills, must pay close attention to good time management practices, and need to conduct effective project meetings. These skills were emphasized in instructor-led portions of the capstone course.

Industrial involvement in this project was crucial. Without the donation of positioning stages, controllers, and associated software this project would not have been possible due to the high cost of these components. Beyond the equipment donations, Aerotech involvement in the design process was beneficial. Their knowledge of high-precision positioning systems was particularly helpful to the mechanical design team. We tapped into this expertise largely through web conferencing facilitated by WebEx™. This allowed for two-way audio and the sharing of computer desktops. This type of on-line collaboration is crucial when the company involved is located some distance from the academic institution, as discussed by Schlemer[7]. Representatives from Aerotech periodically traveled to our campus for onsite meetings.

The final product – a 3-axis tube notcher

The result of this year-long capstone project was a three axis machining center that operated as intended (see Figures 19 and 20). The final machine is capable of notching tubes up to 1¾ inches in diameter with tube intersection angles that can range from 40° to 150°. This device is primarily intended to machine thin walled steel or aluminum tubes. The process produces joints that are suitable for TIG welding or brazing.

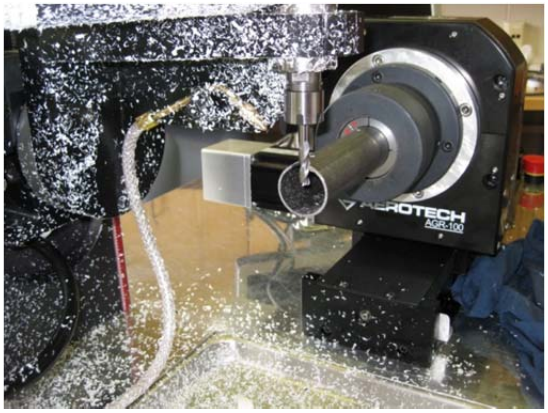

Figure 19. Tube notcher in operation.

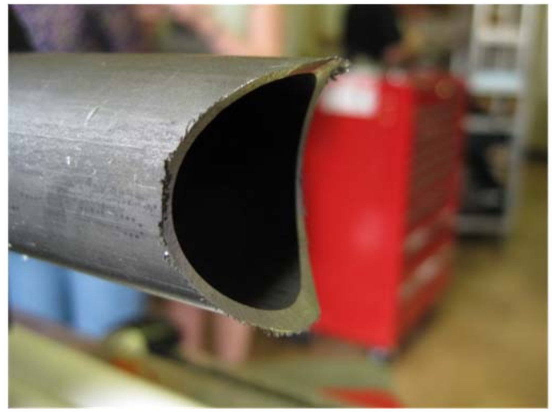

Figure 20. Notched tube.

The close collaboration of mechanical engineering and computer science students resulted in the problem-free integration of the electromechanical systems and the supporting software. The user interface developed by the computer science students was easy to understand and use. This was due in part to the frequent interaction between the software developers and the end users of the tube notcher. The software portion of the project functions well and the calculations for axis trajectories (implemented in Microsoft EXCEL) can be easily modified if needed by someone without a programming background.

A separate effort (not described in detail here) concentrated on the generation of G-code directly from a CAD model of the tube to be notched. This G-code can be downloaded directly to the Aerotech controllers. Pro/ENGINEER (now CREO) and Pro/MANUFACTURING in conjunction with a custom post-processor were used for this purpose. Due to time limitations, this method for generating axis trajectories was not fully implemented and tested.

While the project was successful, extensive testing of the system and optimization of cutting parameters did not occur. The students simply ran out of time at the end of the second semester. This is a common problem since many students underestimate the time required to complete the system integration and testing tasks. This could be rectified with closer faculty supervision of the project schedule and/or reducing the scope of the project.

Many tubes for vehicle frames are notched on both ends. The project team established a methodology for maintaining tube orientation for the second notch and for ensuring the correct overall length of the tube. This method was never implemented during the second semester because of insufficient time in the testing phase.

Lessons learned

One of the major challenges of multidisciplinary projects is learning the language of the "other" teams. During the fall term, the student teams had to learn what the others did and the language that they used. The CS students, for example, were unfamiliar with tube notching machinery and the workflow. One of the things that helped the groups to develop a common language was shared artifacts. At the start of the project, the CS students could show the MEs their UI design and software flowcharts to explain what they were doing, while the ME could show the CS students notched tubes and cutters. As the project went on, the students were able to integrate various components over the course of the spring term, rather than waiting until the end of the term.

We compare this experience with a past project between CS students and electrical engineering students. In that project, the shared artifacts did not materialize until late in the project (mid spring term). This kept the groups isolated and eventually doomed the project.

During implementation, the rapid prototyping methodology helped the CS students get quick feedback on the actual software system, not simply the design. It also helped them debug their software by running it on the actual hardware used in the project. If we had waited until the end of the term, we doubt the project would have been successful.

Summary and conclusions

A three-axis computer controlled milling machine was built to notch thin-walled tubes. These tubes are joined to other tubular components to create vehicle frames for student competitions (e.g. Mini Baja or human powered vehicles). The tube-notcher project provided ME and CS students with a multidisciplinary experience. The scope of the project required teams from disparate disciplines to learn how to communicate, organize their work, implement, and test a complex system. Through this project, the students gained an understanding of the other discipline, particularly as they had to depend on each other to complete the project.

This project also had significant support from Aerotech, Inc., our industrial partner. Aerotech provided equipment donations, software, technical expertise, and design review assistance. Frequent communication between the student teams and our industrial partner was crucial to the success of this project.

A summary of some of the key lessons learned are listed below.

- Excellent communication between students from different disciplines is crucial.
  - Frequent (typically weekly) project team meetings for the individual disciplines are essential. A CS student attended the regular ME team meetings and similarly, an ME student joined the CS team during their regular meetings. Meetings involving all team members (students and faculty advisors) were held less frequently.
  - Shared artifacts should be made available during the entire design and implementation process. Within this project, for example, CS students developed a candidate user interface (without software implementation initially) and shared it with the ME students for comment and review. ME students shared samples of notched tubes and described in detail the axis motions required to machine a tube. This allowed the team to develop a shared vocabulary and to test ideas quickly.

- Frequent contact with the industrial project sponsor is critical to the success of the project.
  - An initial face to face meeting with the industrial partner is required to help the students understand the nature of the sponsor's involvement with the project and to meet key contacts within the sponsor's organization. In the case where equipment and software donations are involved (as in this project), the initial visit helps students and faculty from the educational institution understand the capabilities, features, and operational characteristics of the sponsor's physical contributions to the project.
  - The industrial partner plays a key role in design reviews – from the early stages as design concepts emerge to the final stages of detailed design. Industry representatives should be kept informed of all major project decisions.
  - Communication should take place through face-to-face meetings if the industrial partner is located close to the educational institution. Another excellent method of communicating is through web based conferencing (e.g. WebEx™). Regular phone calls and E-mail messages complement the aforementioned methods of keeping in contact with the industrial partner.
- From a project management perspective, the faculty advisors need to help their teams establish a realistic project schedule and assist them in keeping that schedule. Too many capstone design projects fall behind schedule, resulting in a project team that may complete the design and build stages but fails to complete the testing phase of the project. This leaves no time for thorough testing and any necessary project revisions.

The ME and CS team successfully completed the three-axis tube notcher. The equipment was tested and handed over to the Mechanical Engineering department machine shop for use as needed. This tube notcher is still in use today.

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