AC 2011-580: INTEGRATION OF E-QUALITY CONTROL MODULES WITH ENGINEERING COMPUTER NUMERICAL CONTROL LABORATORY

Richard Chiou, Drexel University

Dr. Richard Chiou's background is in mechanical engineering with an emphasis on manufacturing. Dr. Chiou is currently an associate professor in the Goodwin School of Technology and Professional Studies at Drexel University. His areas of research include machining, mechatronics, and internet based robotics and automation. He has secured many research and education grants from the NSF, the SME Education Foundation, and industries.

Yalcin Ertekin, Drexel University (Engineering Technology))

Dr. Ertekin received his BS degree in mechanical engineering from Istanbul Technical University. He attended the Business School of Istanbul University and received an MS degree in Production Management. After working for Chrysler Truck Manufacturing Company in Turkey as a project engineer, he received dual MS degrees in engineering management and mechanical engineering from Missouri University of Science and Technology (MS&T), formerly the University of Missouri-Rolla. He worked for Toyota Motor Corporation as a quality assurance engineer for two years and lived in Toyota City, Japan. He received his Ph.D. in mechanical engineering from MS&T in 1999 while he worked as a quality engineer for Lumbee Enterprises in St. Louis, Missouri. He was a faculty memer at Trine University teaching mainly graduate courses in engineering technology and mechanical engineering. Dr. Ertekin's area of expertise is in CAD/CAM, Computer Numerical Control (CNC) machining and quality control. His research interest includes sensor based condition monitoring of CNC machining, machine tool accuracy characterization and enhancement, non-invasive surgical tool design and bio materials.

Dr. Michael G Mauk P.E., Drexel University
Robin Kizirian, Drexel University

Robin Kizirian completed his M.S. degree in Computer Engineering at Drexel University in Philadelphia and his B.S. degree in Computer Engineering with a minor in Computer Science at the University of Hartford in Connecticut. He is currently serving as a research assistant at the Engineering Technology department at Drexel University. Robin has been involved in various projects funded by Pfizer, NASA, NSF and Department of Education. His areas of research include Embedded Systems, Mechatronics, Efficient Solar Energy Systems, Internet-based Quality Control and 3-D Online Education.

Integration of E-Quality Laboratory Modules with Engineering Computer Numerical Control Course

Abstract

The paper presents an innovative approach for integration of multidisciplinary web-based quality control topics into the advanced manufacturing engineering technology core discipline. This is aligned with current trends in the manufacturing industries, which include remote monitoring/control/diagnosis, product miniaturization, high precision, zero-defect manufacturing and information-integrated distributed production systems. The use of modern sensors and data acquisition instrumentation for manufacturing processes is implemented into computer numerical control (CNC) laboratory practices in undergraduate classes for Web-based measurement, inspection, diagnostic system, and quality control at Drexel University. The network hardware and software components are integrated with quality methodologies to achieve maximum effectiveness in teaching Web-based quality concepts in MET 316 CNC. In MET 316, a 10-week upper-level undergraduate course was offered that included a classroom component presenting lectures on CNC integrated with quality control principles and methods, combined with hands-on laboratory sessions. The class includes product manufacture and quality assessment measurements to support statistical data analysis in a quality control framework. Students made various measurements of CNC-machined parts using a coordinate measuring machine (CMM), machine vision (i.e., a charge coupled device (CCD) camera with image processing software), and laser scanning. Students then analyzed measurement data to compare measurement techniques (Gage R&R), establish part variations, correlate quality metrics with process parameters, and optimize the CNC machining process.

Background

In the United States, undergraduate curricula in Engineering Technology (ET), Mechanical Engineering, Industrial, or Manufacturing Engineering generally include a course in Computer Numerical Control (CNC). The course syllabus comprises topics mainly on machining and CNC. At Drexel University (DU), all the students in the Engineering Technology Program learn the basics of machining, Computer Aided Design and Manufacturing (CAD/CAM), dimensioning and tolerancing, and statistical process measurement in a CNC course. In machining process planning, selection of machine tools and process tolerances is critical as they directly affect the part quality and the machining time. An optimum process plan should be designed with the least number of operations. On the other hand, one must fully understand the limited conditions and the cost-tolerance relationship of various machine tools before engaging in the optimization of tolerance allocation. In practice, the existence of a large number of machine tools, in a factory, may lead a complicated problem in tolerance intricate[1-3].

The authors believe exposing students to the tolerancing issues for manufacturing processes in their CNC class improves their ability in design and for design for assembly. All students in the CNC class learn the fundamental quality control issues in CNC machining. During this course, the students learn that there is no such thing as a perfect dimension in the real world. Even if we violated all rules of probability and miraculously achieved a perfect sized dimension, it would be impossible to verify! Variation in size, form, location, and orientation is always present. No two independent measurements are exactly the same. Even the best measuring devices and precision inspection tools have a calculated margin of error, even though the error may be miniscule in size. Likewise, every viable dimension on a drawing has a related tolerance—a range of acceptable variation (or error) from the specified size[4-12].

Roughness is a parameter that signifies the measure of the texture of a surface. This kind of inspection is normally performed through the use of stylus type instruments, which correlates the motion of a diamond-tipped stylus to the roughness of the investigated surface. The stylus techniques have both advantages and disadvantages. One disadvantage is the risk of surface scratching. On the other hand, , there is increasing use of non-contact surface roughness measurement techniques permit rapid surface roughness measurements with acceptable accuracy. Whereas, traditional CNC courses include exercises on contact surface roughness measurements, more up-to-date courses should include non-contact measurement methods as well. . Accordingly, we developed an E-quality laboratory case study where students made remote roughness measurements, and collected and analyzed data using quality control methods[13-20]. In addition, this course built quality measurement experiments by adding a web-based interface to allow students to remotely access and inspect the milled part surface via the Internet. The proposed methodology is different from others in that instead of developing customized client-server architecture, it focuses on development of LabVIEW to be served by time tested web server over HTTP (hypertext transfer protocol)

Students from the ET program are required to complete the CNC machining course that increase the student's quality control knowledge for design-for-manufacturability. Providing students with a hands-on approach when teaching CNC machining classes in the ET curriculum enables students to become aware of how their dimensioning and tolerancing in design can drastically influence the downstream of manufacturing processes. In industry, having mechanical and manufacturing engineers "cross-train" is not a new concept. When mechanical engineers understand machining and manufacturing processes, they are able to make more accurate decisions during the design process. This reduces the time it takes for the product to reach the market, ultimately saving the enterprise money. This paper describes the machining courses offered within the ET Program and describes how these courses have lead to successful design and build projects in the engineering technology curriculum. This is especially helpful for students in the design and manufacturing concentrations as they have a high probability of designing parts that will require machining processes during their manufacture.

Course Delivery on MET 316 Computer Numerical Control

The course MET 316 Computer Numerical Control has been developed since 2006 and offered in every fall term by the authors at Drexel University. The overview of MET 316 is shown in Table 1. The course provides a requisite understanding of machining processes, computer numerical control, CAD/CAM, and quality control for students to progress to the advanced level in the course. The course also serves as a means for students to gain exposure to advanced manufacturing concepts before students take senior design project. MET 316 Computer Numerical Control is not only offered for the full time program at Drexel University, but also for the dual enrollment program with Burlington County College (BCC) and Delaware County Community College (DCCC).

Table 1. Overview of MET 316 Computer Numerical Control

Week	Topic
1	Intro. to Machine Tools, CNC, and Quality Control
2	Machining Processes, Blueprints and Tolerancing
3	Machine Feeds & Speeds and Accuracy
4	Tapping and Threads
5	Basic CNC Programming/Languages
6	Circular Interpolation and Tool Wear
7	Canned Cycles and Tool Offset
8	CAD/CAM
9	CAD/CAM and CMM
10	Remote Roughness Measurement
11	Review of Statistics and Probability in Machining

Since the concepts of CNC milling are best conveyed through application-based learning, the course is divided into two components: a classroom lecture component and an associative laboratory component. The laboratory component is central to the course and is available to the students outside of normal class time. This allows the students the freedom to explore the concepts of each lesson without time constraints inhibiting their learning. In order to provide an enhanced laboratory experience, the students work with real-world industrial components. Weekly experiments have been developed for the course as a part of this practicum and are necessary for the completion of many of the exercises. The laboratory exercises are closely tied to the classroom lecture topics, and the students are required to explore and use supplemental resources to complete the exercises. During the laboratory exercises, the students have an opportunity to apply their knowledge by integrating several components together to develop an integrated solution to a manufacturing problem. To instill the team concept desired by professional in the industry, students are required to use a collaborative team approach in completing the exercises.

The lab equipment consists of computers, machine tools, and a HAAS high speed CNC milling machine. Students learn the Mastercam to draw and generate G code for CNC machines. Also, AutoCAD is incorporated in development on G code language. Students use machine tools and CNC machines to cut various shapes using aluminum materials. All equipment and software were tested, and course development began. Classroom, laboratory and field experiences in machine tools, CNC, and CAD/CAM were focused in the course, allowing a professor to define and develop the course in many conceivable directions. The course, as it had been taught, concentrated on machine tools, CNC programming, mechanisms, and Internet based CAD/CAM. Although it is extremely interesting, the topics appeared much more appropriate to mechanical engineering than to industrial and manufacturing engineering. Laboratory assignments were used to emphasize important technological issues and provide hands-on design experience with the technologies.

Eight laboratory assignments were used to reinforce lecture information and to give hands-on experience. It is believed that hands-on experience is required when learning about computer-based quality control technology. Having students experience manual ways of accomplishing manufacturing tasks, new computer-based approaches, testing and simulating computer results, and CNC milling operations, were believed to be important. Giving students exposure to several assignments, yet having a common theme across all laboratory assignments was also important.

Labs 1-4 – Fundamentals in Tolerancing and Operations of Machine Tools

These labs expose students to the machine tools and the workpiece specifications and tolerances in different CNC operating environments. Different machine tools, such as lathe, milling machine, and drilling machine, were introduced. This labs introduces students to the machine tools (shown in Figure 1), which is hands-on experience of industry equipment. Students operate the machine tools manually – guiding the machine tools step by step. Students learn the principles of machine feeds & speeds for lathe, milling and drilling machines, and tapping and threads.

Figure 1: Lab experiment introduced students with hands-on experience in machine tools, and dimensioning and tolerancing.

For example, we specify .500 ± .005 for a size dimension on a drawing feature. The specified dimension is one-half inch, but we have concluded (through a tolerance analysis) that we can accept the feature size as long as its actual measurements do not exceed the limits of the tolerance range—that is to say, the actual measurement will be no smaller than .495, nor any larger than .505. If the part measurement lies anywhere within the specified tolerance range, it is acceptable. If mating parts (a shaft and a hole) were both dimensioned exactly the same way, using the example dimensions above, we could actually end up with a shaft that is .495 in diameter, and a hole with a diameter of .505. In that case, the total difference between the shaft and the hole would be .010 clearance. Or, we could have a shaft diameter of .505 and a hole diameter of .495—a ten-thousandths interference. Or, we could be at any increment in between those limits. While there may be several ways to calculate the tolerances for mating part fits, they all eventually narrow down to essentially one concept—part *function* and the particular feature being dimensioned.

Therefore, the range of permissible sizes, or tolerance, must be specified for all dimensions on a drawing. A successful design creates a product assembly which contains parts that fit together well, performs desired functions efficiently, and maximizes tolerances to create a cost-effective manufactured part. It is very critical to specify a tolerance since this will impact selection of a particular manufacturing process to implement the specification, and thus it is equivalent to assigning the cost to this operation.

Lab 5 - Computer Aided Design

Students are introduced to CAD – the beginning of computer-based manufacturing technologies. Students use a widely used CAD product - AutoCAD. The major goals are: to provide an overview of 2D and 3D design concepts and software; to provide practice designing parts; to understand that there are differences between CAD products in their presentation and use; to introduce CAD industry standards, file compatibility and file conversion issues; and to expose students to file translations. An example of one tutorial's CAD drawing is shown in Figure 2. Students also try to transfer the AutoCAD drawing files over to MasterCAM systems using DXF, IGES, and other file formats. CNC operating systems and their variations among different manufacturing equipment were discussed. Common computer operations, such as creating files, viewing file contents, editing files, copying files, and deleting files are explored. The lab computers are connected to other networked computers. From the lab computers, Windows operating environments can be illustrated. Students are challenged to create files in one environment and move them to others. The importance of the ASCII text file is explained.

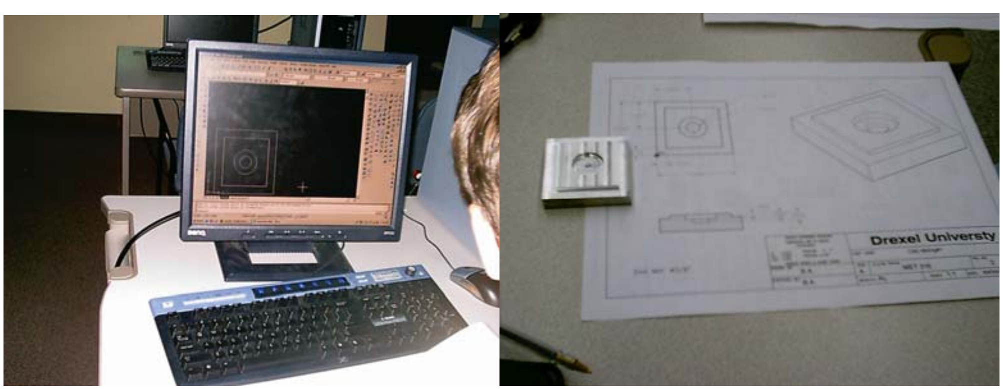

Figure 2: CAD drawing of square aluminum plate produced with AutoCAD

Tolerance settings are crucial for the machining of curves (splines). The CAD/CAM software must recreate the shape of the curve using lines that can be easily read by the machine. However, for more complicated curves, numerous lines are required that will not only increase the toolpath file size to be exported to the CNC machine, but also the time it will take longer for machining. This is an example of when the software user must decide what is more important – the speed at which the machining can be calculated and machined. For most users, finding the right balance involves some trial and error, especially for those who are new to both a CNC machine and the software. CAD/CAM software programs today can help with the process of balancing speed and detail by simulating the toolpath to see how the piece will look according to the specific tolerance and also calculating how long the machining will take. This allows the CNC programmer to choose the best tolerance for the specific application, without expending valuable machining time.

Lab 6 - Process Planning and CNC Parts Coding

This lab introduces students to manual CNC parts coding. Students must design the CNC codes for the part drawing shown in Figure 3. Students are directed to use a cutting tool, machinable aluminum (or wax) as the material, and to set feeds and speeds to realistic values. Machining techniques and process planning are introduced, and the students must submit a weekly lab report that includes an estimate for machine time. Using an editor of choice, students create the CNC code required to machine the part on the CNC milling machine. This file is saved as an ASCII text file.

Figure 3: CAD drawing imported into CAM software for machining aluminum plate

Tolerances of CNC machines completely depend upon the type of CNC machine. Each machine offers different tolerances. Tolerances are directly related to the accuracy of the CNC machines. One of the great benefits of CNC machining is the ability of high tolerances on a repetitive basis. Because the machines are computer operated, repetitive work is easy to perform. The machine keeps running to the programs specifications until the work is complete. Programmers, machinists, operators and the machines, have to work in direct relationship to one another. If all aspects are all the same page, the better the performance. If students have quality programmers and machinists, students will be able to get better performance out of the CNC machine. It takes individuals who are skilled and knowledgeable in the area of CNC machining to perform to the best of the machines ability.

Lab 7 - CNC Programming/Languages and operations

Most computer generated codes that control manufacturing equipment must be tested before producing parts or initiating equipment action. Students use a software product called 3-D Solid Verification, to simulate (animate) their CNC code created. When their code does not operate properly, they must decide how to debug and fix the code. Students then learn how to use CAM software to create the same part. The part is drawn with CAD software, the file is converted to DXF format and imported into MasterCAM software, the code is post-processed for the Light milling machine, NC code is created, and the code is tested with the 3-D Solid Verification software. An understanding of the advantages and limitations of CAM and simulation software is obtained. Students compare the CAM generated code with their manually created code (see Figure 4).

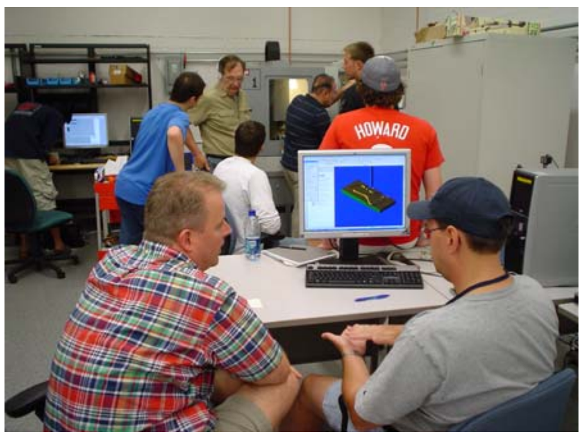

Figure 4: MasterCam 3-D model of a bottle opener

Lab 8 - Part Design and Production on CNC Milling Machine

Students have the opportunity to use knowledge gained throughout the previous laboratory assignments to manufacture a product. The knowledge includes designing parts with CAD, creating CNC code with CAM software, testing and verifying the CNC code with simulation, and machining the part on the Light CNC milling machine (see Figure 5). Students learn to operate the High Speed CNC milling machine and execute the CNC code. Proper machine safety procedures are also learned.

Students machine a part, which was created in previous assignments as shown in Figure 5. After creating the CAD drawing, the drawing is imported into MasterCAM. The cutting path is then generated. Finally, the CNC code is generated, tested in 3-D Solid Verification, and a part is machined on the CNC milling machine. Students are asked to compare actual machine times with estimates and explain any differences. Students attempt to optimize their code for minimum machine time. An integrated design challenge is presented for extra credit where students can create an operator incentive standard, develop a process plan, calculate production cost, and discuss quality control issues about the manufacturing process.

Figure 5: Tool path generation and bottle opener produced on the CNC milling machine

Lab 9 - CMM for Contouring Error

A TESA (Renens, Switzerland) CMM (co-ordinate measurement machine) is used to measure the dimensions of test pieces. A CMM is an instrument for dimensional measuring. It is a machine that is used to move a measuring probe to obtain the coordinates of points on an object surface. These machines are commonly used to measure the dimensions of target objects. For any machined part, a number of metrics (dimensions, angles, or other geometric features) can be measured as an indicator of function, conformance, or quality. For circular holes, the diameter, cylindricity, and roundness are measured. For rectangular holes, two widths, as well as the edge angle are measured. The students, working in groups, collected data for some assigned subset of the workpieces. Data was entered into an EXCEL spreadsheet for analysis.

Figure 6: CMM probing of a machined workpiece.

Figure 6 shows details of the measurement step with the CMM probe contacting the laser machined features of the acrylic test piece. Replicate (10X) measures on a single hole to ascertain the variance of the measurement process were made. The variance is denoted as σ^2_{meas}. The variance of measurements for a set of holes in the workpiece σ^2_{wp} is then found from the observed variance σ^2_{obs}

$$\sigma^2_{\text{obs}} = \sigma^2_{\text{meas}} + \sigma^2_{\text{wp}}$$

which takes into account the inherent variance of the measurement process.

Lab 10 – Remote Surface Roughness Measurement

Figure 7 describes the architecture of the remote surface roughness measurement system. The system is composed of a machine vision smart camera, an IP Surveillance camera, and a PC-based remote inspection system. The machine vision camera has a built-in processor which allows it to perform real-time algorithms, along with live-time monitoring. The process is designed to be Ethernet based using TCP-IP communication. After a successful TCP handshake, images and extracted measurements can be sent back and forth remotely between the servers and clients. The machine vision camera is properly programmed with necessary algorithms to calculate the various surface roughness parameters. In the LabVIEW-based graphic user interface (GUI), statistical quality algorithms for remote measurement are calculated. The controller communicates with the robot to instruct it to perform the required operations. In addition, the Internet-based vision system is integrated through the IP surveillance camera, displaying the products that are being analyzed. The most significant part of this automation system is the vision module.

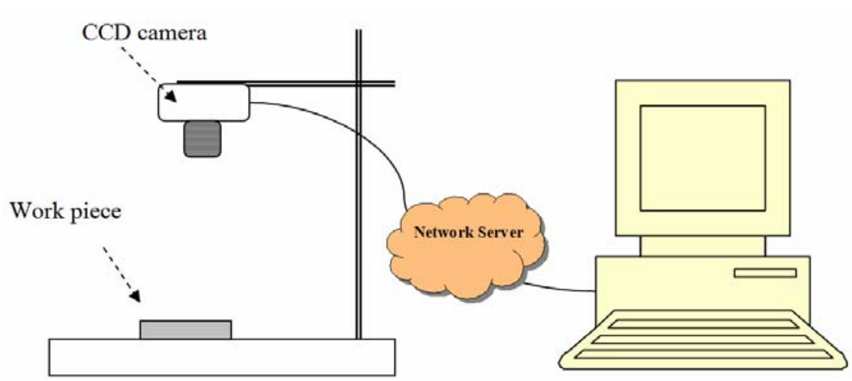

Figure 7: System Configuration

The machine vision set-up is comprised of a CCD camera connected to network electronics and a PC with image processing software (Figure 7). Machine vision packages for the Cognex DVT 540 computer vision system are configured as a set of tools for Internet-based inspections and measurements. SoftSensors are the working class inside Smart Image Sensors. Every type of SoftSensor serves a specific purpose, and the combination of the SoftSensor results represents the overall result of the inspection. The machine vision camera is initially trained to learn the profile and make measurements of a part being tested through the FrameWork software. Details of the machine vision inspection include:

- Machine Vision System = CCD camera + electronics + PC + software
- Camera: Smart Image Sensor Model 454C with LED illumination
- Image processing software: Intellect
- Works on contrast (difference in intensities of pixels) in 2-D plane
- Gray scale 1→ 255 levels
- 640 x 480 pixels = 307 K
- 1280 x 1024 pixels = 1.3 million

Figure 8: Students capturing images of CNC-machined test part features with machine vision setup.

In Figure 8, the machine vision camera is used to inspect standard roughness specimens. Quantified data will be directed through Ethernet to the system controller. To make the system work efficiently, different programs were used in the system. For machine vision camera, the program handles the measurement of surface roughness. The IP surveillance camera is utilized to send surveillance images to the system controller. To integrate the whole system with multi-sensors, the system controller has LabVIEW software installed. A PC based controller has the advantage of higher compatibility of Ethernet functional sensors. The surface roughness can be measured by machine vision as shown in Figure 8. The students, working in groups, collected data for some assigned subset of the workpieces. Data was then entered into LabVIEW for analysis.

For the accomplishment of remote surface finish measurement, the LabVIEW program is applied for monitoring and collecting the data results. Moreover, the quality inspection algorithm is also integrated. It will determine if the pieces fail of and send commands to the robot controller through Ethernet via this program. The graphical user interface for this LabVIEW program is designed as Figure 9.

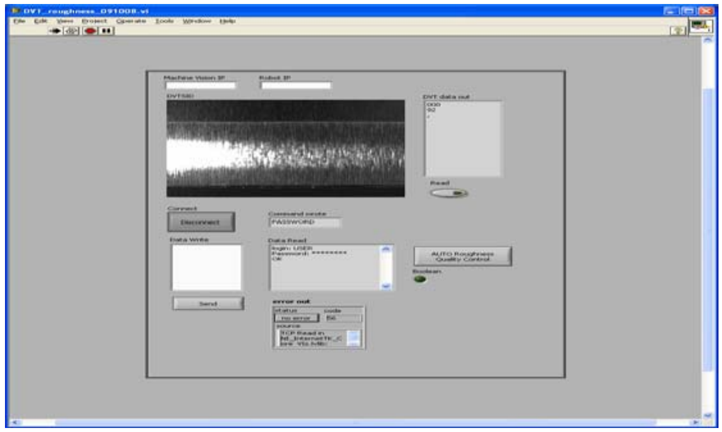

Figure 9: Graphic User Interface of the LabVIEW program.

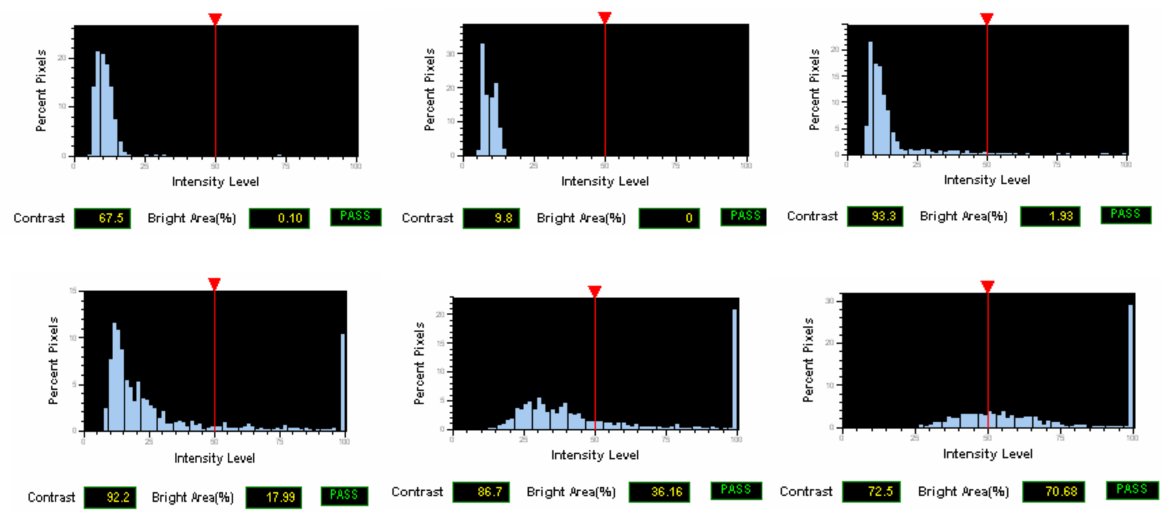

Figure 10: Histograms of the six milled surface roughness specimens

The results were collected through the LabVIEW program. There are six different work pieces utilized in this experiment. Figure 10 shows the results of their mean intensity, standard deviation, and root mean square value. From the utilization of machine vision, images of the workpieces are shown on the programming software. Six different surface roughness pieces are discussed here. Their average surface roughness is 0.05, 0.1, 0.2, 0.4, 0.8, and 1.6 micro meters. The properties and the intensity distributions of these image histograms are corresponding to six different surface roughness parameters. It can be seen that the histogram tends to move rightward and the standard deviation of Percent Pixels increases as the average of surface roughness increases. The rougher surfaces seem to reflect more of the projected light which consequently increases the intensity level captured by the machine vision camera. This can be supported by the fact that rougher surfaces contain rougher edges that tend to scatter the light in the direction of the camera. For this reason, the percentage of bright area is higher in rough surfaces compared to the smoother ones.

Course reviews by students were very positive. The benefits of an active learning model are derived. Some students complained about the extensive report writing, and the time involved with the lab assignments, but many commented positively about their knowledge on quality control gained. Students commented that the enjoyed hands-on working in the lab. Many students, at the beginning of the semester, do not believe that they are going to learn enough to machine parts from CAD/CAM and CNC code, and inspect part quality by the end of the term. An additional benefit to students was that they could claim on their resumes that they had experience with machine tools, computer operating systems, CAD/CAM, simulation, CNC programming, and quality control.

Conclusion

The laboratory development efforts for the engineering technology course MET 316 Computer Numerical Control at Drexel University are described in this paper. Quality control is usually part of an engineering technology major's curriculum. The study of CNC-machining surface quality for application with internet based non-contact diagnostics devices provides an instructive case study of E-quality concepts and methods. The manufacturing quality issues are conceptually straightforward with the CNC machining. The CMM and machine vision inspection laboratories can each be performed in a CNC laboratory session. From the experimental results, the algorithms for statistical process inspection are in good agreement with basic vision-based roughness characterization results. In addition to CNC code programming and CAD/CAM skills, the course MET 316 CNC has successfully provided the students with the skills in specifying geometry and surface roughness of a part and learning GD&T (Geometric Dimensioning & Tolerancing) for quality control.

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