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Board 126: Work in progress: Incorporating Virtual Programming Concepts in an Advanced Robotics Course for Machining Processing and Quality Inspection of CNC Machines and Industrial Robots

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Global competitions and technological advances are forcing manufacturers, designers, and engineers to constantly innovate new product manufacturing strategies in reducing product development cost and time. Contemporary manufacturers have the option of selecting optimum technologies or processes to suit their manufacturing environment. Fast paced transformations in Engineering Technology (ET) field require new and enhanced learning and teaching strategies in engineering technology curriculum. More than ever, the educational advance is leaning towards meeting the demands of industrial world. Engineering Technology curricula needs to adapt to novel technologies and modern tools by enabling students to acquire meaningful and relevant practices. Laboratory activities should be incorporated into dry-lectured courses, being vital to ET programs, since they are ultimately enhancing the understanding process, leading towards developing experience-led engineering technology degree.

This paper describes a work-in-progress for a junior level Advanced Robotics and Mechatronics course that incorporates offline and virtual manufacturing engineering programming and automation concepts through a six axes industrial robot. The course itself is part of a seven-course minor sequence in robotics and automation. Blended online and physical laboratory activities are used to achieve both overall and project-specific learning objectives.

The overall course learning objectives include learning extensive knowledge of digital manufacturing using industrial robots and other common mechatronic components as well as performing Robodk virtual reality simulation and off-line programming of industrial robots for automated work cells in manufacturing. Authors are adding process simulation for robotics machining as well as part quality inspection with Ballbar methods to virtual modules to introduce more advanced topics to the existing curriculum. This paper focuses on the use of a ball-bar system to compare the theoretical and actual path of a robot as it moves in a circle. The problem addressed in this paper is how to enhance student understanding of path tracking accuracy in circular motions of CNC machines and industrial robots. This information eventually will be used to develop more accurate tool path planning using the robot as a machining tool.

The significance of the methodology used in this course redevelopment is to combine theory and practice with modern tools to prepare the students to become better problem solvers and obtain practical solutions to real life/simulated problems using a hands on, lab-project-based approach.

1. Introduction

One of the key objectives in durable goods-manufacturing is to create faster industrial processes throughput by eliminating the needs for off-line quality control and part inspection. Nowadays, as automation, high performance machining and labor savings are introduced in machining of discrete component designing, prototyping and manufacturing, it is desirable to reduce the time and the manpower for inspection, and have an intelligent and real-time quality control of the products. This is typically performed by using coordinate measuring machines (CMMs) and related inspection tools. Great savings of both time and labor during the inspection process can be realized in the machining of discrete components through gains in automation, information technology and high-performance machining. The major goals and objectives of our project is to integrate strategic process optimization concepts and intelligent controls in high speed robotics machining, creative thinking and solutions-based applications, robot calibration, on-machine quality control, precision metrology applications into the existing engineering curriculum through the development and implementation of learning modules that will simulate industry approach to product development cycle that is design, analysis, prototyping and improvement into selected required coursework in each engineering discipline.

Increasing demand for both higher machine tool accuracy and machining tolerances bas resulted in a great need to measure and characterize the accuracy of both Numerical Control machine tools and industrial robots and minimize machine induced systematic errors on processed components before processing (i.e. cutting, welding, assembly, instead of inferring it from parts already processed (i.e. machined). Statistical process control (SPC) provides no more than after-the-fact deduction of process capability.

The increasing global market competition has focused the attention of manufacturers on how to manufacture products at the least cost and in the shortest time with the highest precision to increase manufacturing efficiency, productivity, and improved quality [1]. Most of the accuracy characteristics of machine tools and robots deteriorate as a function of running time due to wear of tool and machine components and linkages [2]. Accuracy also decreases after any job involving high cutting forces, whenever the tool is moved, after any spindle crash into the workpiece and also due to environmental influences. Any machine tool and robot which is out of alignment operates under less than optimum conditions, resulting in higher maintenance, part and labor costs, scrap and re-work rates. Out of alignment tools will wear out faster under increased stresses and break down more often, thus both productivity and operational profits may be reduced [3].

There are three main sources of errors in machine tools that determine machine tool accuracy. 1) Errors due to geometric inaccuracies that are caused by the mechanical imperfections of the machine tool structure and the misalignment of machine tool elements. They all change gradually due to wear of the components. The effect of the geometrical inaccuracies is to produce errors in the squareness and parallelism between the machine's moving elements. 2) Thermally induced errors are generated by environmental temperature and local sources of heat from drive motors, gear trains and other transmission devices, thus causing expansion, contraction and deformation of the machine tool structure and resulting in positional errors between the cutting tool and workpiece. The machine elements particularly effected by self- generated thermal distortion are spindles and ball-screws. 3) Load induced errors which are produced by varying mechanical loads due to processing loads (such as cutting forces), therefore, causing elastic strain of the machine structure [4]. It is well established that among the above error sources of the machine tool, geometric and thermally induced errors of the machine may exceed 50% of the total processing (such as machining) error [5, 6].

Machining technology influences both part quality and machining time. Experts need to strike a balance between part quality and machining time with respect to this technology. Standards are not sufficient to assist experts for solving this problem. In this context, test procedures that enhance machine tool and robot accuracy, the machining quality and machining time evaluation must be further developed. An original approach to analyze machine tool and robot behavior during circular interpolation is presented in this paper.

2. Development of the Experiential Framework

The development of the experimental framework builds upon the current manufacturing trends and advances in industry including product miniaturization, high precision, remote monitoring/intelligent control/diagnosis, and information-integrated distributed manufacturing systems. The technical advances, especially the Internet and computing technology, have been the major driving force of this movement. Correspondingly, we developed industry-like activities and project scenarios for collaborative student teams, using existing and newly acquired Internet-based Computer Numerical Control (CNC) machines, industrial robots and quality assurance systems that include cutting-edge, production equipment such as high speed computer numerical control milling machine(s) and ABB IRB120 6-Axes industrial robot.

Renishaw QC20-W (Wireless) Ballbar System

The Renishaw QC20-W Ballbar and the software package is used to measure geometric errors present in a CNC machine tool and detect inaccuracies induced by its controller and servo drive systems. Errors are measured by instructing the machine tool to "Perform a Ballbar Test" which will make it scribe a circular arc or circle. Small deviations in the radius of this movement are measured by a transducer and captured by the software [24]. The resultant data is then plotted on the screen or to a printer, to reveal how well the machine performed the test. If the machine had no errors, the plotted data would show a perfect circle. The presence of any errors will distort this circle, for example, by adding peaks along its circumference and possibly making it more elliptical. These deviations from a perfect circle reveal problems and inaccuracies in the numerical control, drive servos and the machine's axes. In theory if we program a CNC machine to trace out a circular path and the positioning performance of the machine was perfect then the actual circle would exactly match the programmed circle. In practice many factors in the machine geometry, control system and wear can cause the radius of the test circle and its shape to deviate from the programmed circle. If we can accurately measure the actual circular path and compare it with the programmed path then we would have a measure of the machine's accuracy. This is the basis of all telescopic ballbar testing and of the Renishaw QC20-W ballbar system. The user has a choice of several report formats according to international standards (e.g. ISO, ASME) and the comprehensive Renishaw diagnostics (including volumetric analysis) with a number of different screens views and links to the help manual [25].

Figure 1 Renishaw QC20-W (Wireless) Ballbar System in its protective carrying case (left). Ballbar application simulation software (center). Ballbar test for volumetric error characterization (right)

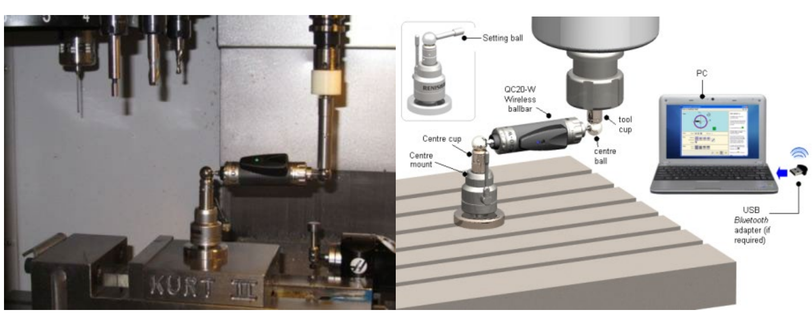
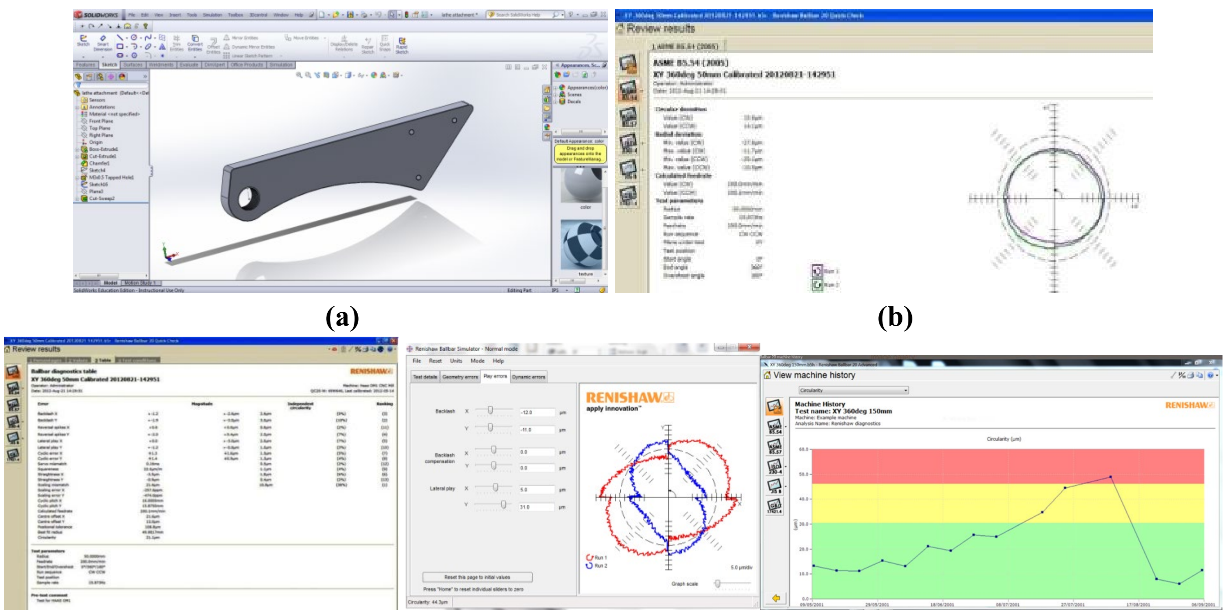


Figure 2 Ballbar measurement set-up (left) & nomenclature (right) in Haas CNC machining center.

Students follow simple steps during a ballbar test. Connecting to the QC20-W is simple, and test set-up is quick and easy with Windows® based software guiding the operator through each step. There is a G-code part program generator to help user to set up the corresponding program on the machine tool. The center pivot is positioned on the machine table and (using a setting ball provided in the QC20-W kit) the spindle is moved to a reference point and the test 'zero' coordinates set. The spindle is moved to the test start position and the QC20-W is mounted between two kinematic magnetic joints. A simple G02 and G03 command program is required to start the test. The "classic" test calls for the machine tool to perform two consecutive circles; one in a clockwise direction, the other counter-clockwise. In practice there is an extra arc added before and after the test circle to allow for the machine accelerating and then slowing down. By using extension bars the test radius can be selected to reflect the size of the machine and the sensitivity to particular issues (e.g. large radius circles are better at highlighting machine geometry errors, smaller circles are more sensitive to servo mismatch or lag). Figures 1, 2 and 3 are exemplifying the procedures and techniques.



(a) (b)

(c) (d)

Figure 3 (a) Ballbar fixture adapter for EMCO CNC turning center **(b)** Ballbar measurement output with different Quality standards. **(c)** Ballbar measurement output error values. **(d)** Ballbar error measurement output

Robot Ballbar testing

The ballbar test is often used to test the performance of computerized numerical control (CNC) machines. This test can also be performed to robots to check their performance and degradation. The measuring system requires two spheres of 0.5 in diameter. This test shows the error, repeatability, and backlash of a circular path.

An offline robot programming software such as RoboDK can prepare the robot program in the 3D simulation environment, record ballbar measurements, and generate a performance report specific to the industrial robot.

(a) **(b)** **(c)**

Figure 4. Ballbar measurement program being generated by Robodk simulation tool for ABB IRAB 120 robot.

When the Ballbar accuracy test utility is run, a target Ballbar center will be created automatically using the software. If the robot has no Tool Center Point (TCP), the TCP Tool 1 will also be created automatically. Then the user can set the target Ballbar center and enter the robot joints (joint axes 1 to 6). When user selects make ballbar program, the program can be created. Two programs are needed for ballbar testing of an industrial robot as follows:

i. Ballbar Setup: This program is used to place the center toolcup pivot point (center of the circle) in the same place it was previously positioned. (Figure 5a)

ii. Ballbar Test: This program is used to make the circle around the pivot point (center of the circle) for data acquisition with the Ballbar. (Figure 5a)

Figure 5. a) Sample Ballbar setup and measurement program (left) generated by Robodk. b) Robodk tool path simulation for ABB IRAB 120 robot.

Student user can start with the test by selecting start test. The user must properly enter the mastering parameters of the ballbar (Figure 4c). The ballbar will be able to measure these distances plus or minus 1 mm with one micrometer accuracy. The accuracy is enough for industrial robots, but the measurement range can be limited in certain cases.

When the ballbar offline simulation (Figure 5b) and actual test is completed, a PDF report is obtained. The report will show the ballbar readings in mm (Y axis on the left) for the clockwise and counter clockwise movements (blue and red lines respectively) with respect to the time in seconds (bottom X axis).

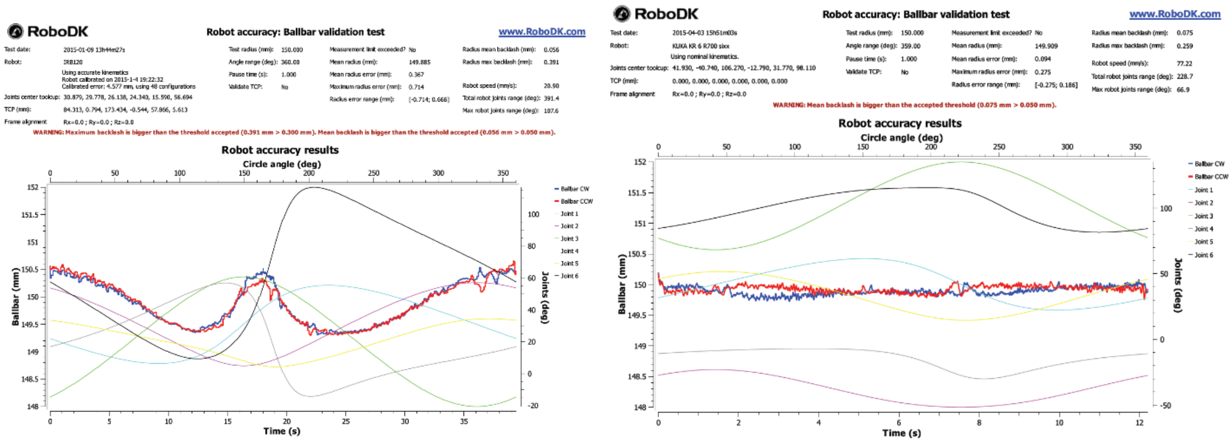
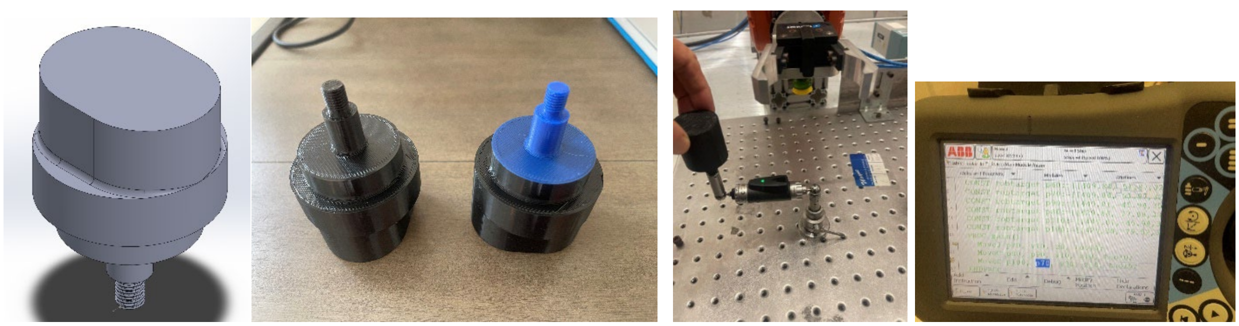


Figure 6. Ballbar accuracy measurement plots generated for ABB IRB 120 robot.

The robot joints are also displayed. The robot joints are displayed in degrees (right Y axis) with respect to the circle angle (360 degrees mean a full turn). A faulty motor would show considerable measurement changes when the corresponding joint movement changes the direction, noticing a considerable backlash.



(a) **(b)**

Figure 7. a) Gripper adaptors developed for Ballbar accuracy measurement for ABB IRB 120 robot b) teaching pendant.

3. Course developments: Lectures and Labs:

3.3 MET 310 Advanced Robotics & Mechatronics (undergraduate course)

This course improvement aims to add robot accuracy testing as a hands-on activity to laboratory modules within the course content. This activity will be run in physical lab as well as Virtual Reality robotics simulation (still under being developed). The course is designed to be very hands on and focuses on applications of industrial robots from 3 to 6 axes robots.

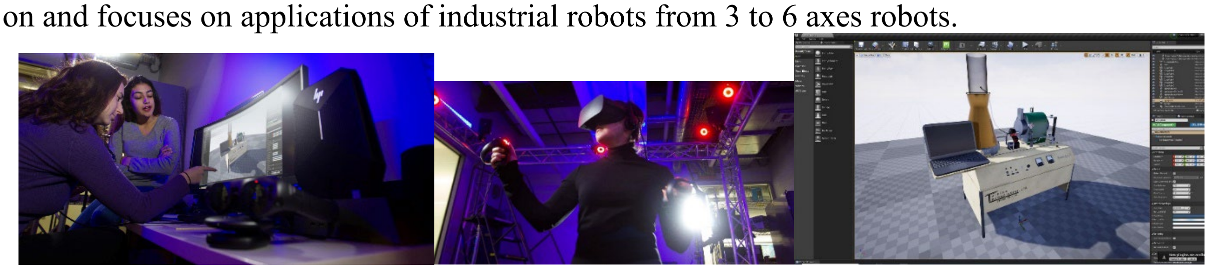


Figure 8. Virtual reality applications for lab development (being developed with Unity/ Unreal VR Engine)

Course Description: Advanced automation concepts using industrial robots. Robotic workcells, process automation, internet-of-things (IoT), computer vision, and virtual reality (VR) robotics. Applications and case studies.

Course Outcomes:

Upon successful completion of the course in this discipline, the student will be able to:

1. Learn extensive knowledge of digital manufacturing using industrial robots and other common mechatronic components.
2. Design the sensor monitoring and tooling with basic programmable logic controller (PLC) for robotic workcells and automation.
3. Understand fundamental digital image processing and machine vision concepts and their application to the fields of robotics and automation.
4. Perform basic RobotStudio/Robodk virtual reality simulation and off-line programming robotics for automated work cells in manufacturing.
5. Deal robotic real-time experiments associated with internet-of-things (IoT).

Table 1:Topical Outline:

W	Topic	Labs
1	Introduction to modern manufacturing	Drexel Robotics Lab
2	Programmable Logic Controller (PLC)	Lab 1 Basics – Remote PLC I
3	PLC for process automation and material handling	Lab 2 Basics – Remote PLC II
4	Single-station manufacturing cells Robotic workcell automation	Lab 3 PLC integrated With Robotics
5	Multi-station manufacturing cells	Lab 4 Workcell SCARA w 1-D robots
6	Midterm Exam, inspection principle	Lab 5 Workcell ABB w. 1-D robots Auto mode
7	Robotic inspection technologies Machine vision	Lab 6 Basics – Machine Vision
8	Vision-based robotic control	Lab 7 Vision for Smart Robotic Control
9	Product design and CAD/CAM Virtual Reality robotics	Lab 8 ABB RobotStudio/Robodk Simulation
10	Virtual Reality robotics simulation	Lab 8 ABB RobotStudio/Robodk S Simulation
11	Virtual Reality robotics for process planning	Lab 8 ABB RobotStudio/Robodk S Simulation

4. Progress and Future Lab Development

Currently in the Engineering Technology curriculum, there is an opportunity to expand knowledge involving the integration of automation into a production system. In order to better prepare students for this subject and the job market, an interdisciplinary senior design team is designing and constructing a cobot system which will simulate a cobot assisting in CNC manufacturing (Figure 9). This newly developed integrated cell will have a new co-robot with vision camera for the robotics lab and will be used as an educational module involving the integration of automated machinery. This module is still under development and will be integrated to this course in next year offering.

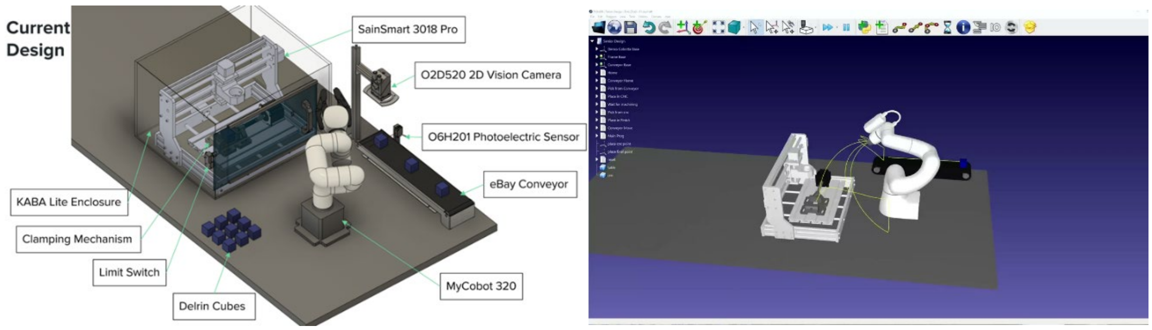


Figure 9. Conceptual co-robot integrated cell and simulation with Robodk.

5. Conclusions

We are successfully developing and implementing several experiential activities into an undergraduate robotics and mechatronics course as described in this paper, along with our efforts for the integration of hardware and software virtual reality simulators in engineering technology courses at our University. It is imperative to incorporate necessary technologies and tools into Engineering Technology curriculum to make sure quality control is also a natural part of an engineering technology major's curriculum. Since these newly developed and implemented activities are pertinent to courses that are currently offered for this Spring term, the assessment of the course will take place during and at the end of the term and will be presented in our final version of this paper (term ends mid-June 2023). The main questions that the students will be asked are:

- What were the best aspects of the course?
- To what extent these activities enhanced your learning experience?
- Did the laboratory/project provide you with hands-on approach to problems and solutions in the industrial world?
- How useful this activity is for you in your preparation for employment in the process development and control.

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