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Design of a Monitoring System for CNC-Machining Processes

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Design of a Monitoring System for Manufacturing Processes

Abstract

Data collection and visualization is a key enabler technique in the Industry 4.0 era. This paper describes a senior project that designs a monitoring system for manufacturing processes. It deploys multi-heterogeneous sensors for cutting force and vibration to monitor CNC machining processes. Students were trained to understand the working principles of sensors, data acquisition (DAQ) devices, programming, and data analysis. The development work includes: 1) part design and manufacturing process design in Siemens NX; 2) prototype the part using CNC machining; 3) integrate sensors and the DAQ system; 4) LabVIEW programming using field-programmable gate array (FPGA) and real-time techniques; 5) experiment to test the monitoring system and acquire data; and 6) digital signal processing and analysis on the experimental data. This work can support ABET accreditation for Virginia State University's Manufacturing Engineering Program particularly for the Student Outcome of "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusion."

1 Introduction

Smart manufacturing is based on cyber-physical systems (CPS), Industrial Internet of Things (IIoT), AI/ML data analytics, advanced control techniques and high-performance computing. It is revolutionizing the state-of-the-art for manufacturing [1]. The success for companies' implementation of smart manufacturing systems vitally depend on the ability of the workforce to act in the context of IIoT, specifically the skills of integrating sensing and control, and data analytics with digital manufacturing operations [2,3]. In response to industries urgent needs, the Digital Manufacturing and Design Innovation Institute (DMDII) released the "Digital Workforce Succession in Manufacturing" report in 2017 [2]. This report describes the job profiles for the next generation of manufacturing through inputs from global leading companies and universities. According to DMDII, the future manufacturing engineers "design and improve manufacturing systems at the mechanical, electrical, and software levels. Their focus is not just on physical manufacturing systems; also includes the enablement (sensing and acquisition) and use of data (analytics) around manufacturing systems to drive increases in productivity, product quality, and business feedback." That echoes the "Report to the President Accelerating US Advanced Manufacturing", which states two emerging technologies of national importance [3]: 1) advanced sensing, control and platform for manufacturing, and 2) visualization, information, and digital manufacturing. The ABET proficiencies also require Manufacturing Engineering programs to have curricular content covering "manufacturing laboratory or facility experience: measurement of manufacturing process variables and development of technical inferences about the process."

Instrumentation and Data Acquisition courses based on LabVIEW used to attract high interest in the engineering education community. Back to 2000-2002, many ASEE papers presented data acquisition using NI SCXI systems [4]. However, NI no longer supports legacy SCXI, and is replacing them with compactDAQ or compactRIO, which enables high-speed measurement and control using real-time and FPGA techniques.

Professors at the University of Portland designed and implemented a self-guided tutorial [5] on data acquisition in their Mechanical Engineering courses, ME351 (Mechanical Systems Laboratory) and ME443 (Systems and Measurement). They used the NI cDAQ-9172 chassis with the 9215 analog input module to acquire signals from a Fluke thermocouple modules. LabVIEW programs were developed to visualize and save the data. Student survey results proved useful in designing an effective cross-curricular approach to the topic and in tutorial development.

A real-time data acquisition and structure health monitoring system was presented at the 2016 ASEE Annual Conference [6]. This system uses strain gauges, NI hardware including the SCXI-1000 chassis, SCXI-1314 strain terminal block, SCXI-1520 strain module, NI PCI-6221 DAQ card, and LabVIEW to continuously measure strain and stress.

Researchers at the University of Arkansas explored different ways of building a DAQ system using LabVIEW or Arduino, and then process the data using MATLAB [7,8]. Students were aware of the importance of DAQ in engineering, and demonstrated applications of collecting and post-processing temperature, flow, and pressure data from heat/mass transfer experiments.

Purdue University, partnering with local industries, launched an innovative graduate course on Industrial Internet of Things [9]. This course aims to equip engineering graduate students with skills of data acquisition from IoT sensors and machine connectivity, and then interpreting these data using AI-driven analytics. Lectures and ten (10) hands-on lab sessions were developed to help students immerse in IoT and AI-related technologies, gaining practical experience and insights. Building on the knowledge acquired in the lectures and labs, students delivered semester-term projects collaborating with local manufacturers. Beyond academic advancement, the course offers a unique opportunity for regional firms to harness the transformative potential of IoT and Al, helping them navigate through their operational challenges. This study designed the course based on the experiential learning theory (ELT), and seamlessly integrated classroom learning with practical, real-world applications by collaboration between academia and industry.

Virginia State University (VSU) implemented a senior project to design a monitoring system for manufacturing processes. This senior project serves two purposes: 1) to enable a measurement platform to acquire machining data for advanced manufacturing research such as digital twin for machining, machining dynamics; and 2) to prepare students with skills for smart manufacturing jobs. The project team included three students: two (2) from Manufacturing Engineering and one (1) from Computer Engineering. This system desires to deploy multi-heterogeneous sensors for cutting force and vibration to monitor CNC machining. Students were trained to understand the working principle of sensors, data acquisition (DAQ) devices, programming, and data analytics. This paper details the design process of such a system.

2 Overview of the Senior Project

The Manufacturing Engineering program's major engineering design experience consists of a two-course sequence, Senior Project I in the fall semester followed by Senior Project II in the spring semester with a Course Coordinator/Instructor and faculty supervised project teams. In Senior Project I, the phases of the engineering design process are thoroughly covered. In addition to specific technical aspects of the design previously mentioned, other topics needed for successful project completion are emphasized as well. These include technical and professional skills such as project management, oral presentations, teaming, and acquiring and applying new knowledge. Students must conduct literature searches and reviews to obtain relevant information for their project. Senior Project II primarily focuses on implementation of the culminating major design with a prototype and includes technical design reviews, project advisor/team meetings, final report and presentation development. Projects will progress through a complete manufacturing cycle from design through implementation. This experience involves a team solution to a complex engineering problem typical to what graduates would encounter in their profession, and provides students with a design experience, including problem definition, investigation of the state-of-the-art, prototype design, implementation, and evaluation. Each team member's tasks must have a substantial design component that contributes to the overall project. In Senior Project II, formal oral presentations and technical reports are required of all teams.

In the Design of a Monitoring System project, a student designed the test part using NX's CAD capability; simulated the machining process and generated the G/M code using NX's CAM capability; selected cutting tools and cutting parameters; and finally prototyped the part with a 3-axis CNC machine. The other two students were tasked to design the monitoring system for the manufacturing processes. Their tasks involved sensor selection and LabVIEW programming to integrate sensors. The three students worked together on experimentation, testing the system with machining experiments, collecting data, and analyzing force and vibration on different machining features. During the project, students met among themselves weekly to discuss the project and tasks. The faculty advisor also had a weekly group meeting with them. During the group meeting, each student presented their individual progress in the project, the faculty reviewed the work and provided guidance in order for the team to progress. The Course Instructor emphasized the requirement that team members understand the overall project in addition to their individual tasks. Project faculty attended presentations during the semester, and asked questions of individual members to ensure an understanding of the team project. Other students listened to the presentations and asked questions as well. With this mechanism, students understood the project as a whole in addition to the individual project.

3 Project Details

3.1 Sensor Selection

The sensors used in the system include: 1) a 3-component Kistler dynamometer which can measure the cutting force in X, Y, and Z directions, and 2) a tri-axial Kistler accelerometer, which can measure vibration in X, Y, and Z directions. These two types of sensors are typical for machining dynamics, and can also be extended for other potential applications on machine tools, machined products, and cutting tools as summarized in Table 1 [10]. The adoption of a dynamometer and accelerometer enriches the curriculum in our Manufacturing Automation course. In that course, we have one chapter introducing analog sensors to students. Nevertheless, we previously focused on low cost sensors such as thermocouple and RTD due to restriction of equipment, a dynamometer cost approximately \$65k to \$70k, and an accelerometer costs from \$700 to \$2000. Now, we can connect these sensor measurements with machining dynamics to visualize the cutting force and vibration in a cutting process, which enhances students' learning in automation and manufacturing processes.

Table 1. Typical Applications for Accelerometer and Dynamometer for Machining Processes

	Measurements	Sensors	
		Accelerometer	Dynamometer
Machine Tool	Deflection	Yes/No	Yes
	Vibration	Yes	Yes/No
Machined Product	Straightness	No	Yes
	Surface Roughness	Yes/No	Yes
	Waviness	Yes/No	Yes
	Dimension Accuracy	No	Yes
	Material properties	Yes/No	Yes/No
Cutting Tool	Wearing	Yes	Yes

The dynamometer uses piezoelectric effect to measure a dynamic and quasi-static force in three (3) orthogonal components of a force (Fx, Fy, Fz) acting from any direction onto the top plate. Because the dynamometer delivers electrical charges (in pC) from the measuring sensor, it needs a charge amplifier for converting and conditioning the charge, which can be displayed, recorded and later analyzed using the monitoring system. The signal conditioner used for force in the system is Kistler 5171A4.

The accelerometer also uses the piezoelectrical effect for measurement, but it has Integrated Electronics Piezoelectric (IEPE) permitting vibration measurements. Thus, the accelerometer can be connected with a data acquisition without a signal conditioner. It only needs a NI 9234 module to connect the sensor with data acquisition.

3.2 Data Acquisition System

The data acquisition (DAQ) used in the system is National Instrument CompactRIO 9064 (NI cRIO 9064) chassis. The cRIO is a reconfigurable embedded system containing three components: a processor running a real-time operating system (RTOS), a reconfigurable field-programmable gate array (FPGA), and interchangeable industrial I/O modules. The modules used for monitoring include a Kistler 5171A4 charge amplifier module to record the cutting forces and a NI 9234 module for the accelerometer.

The cRIO system communicates with the host computer using Ethernet or USB protocols. The FPGA Target corresponds to the FPGA module, which is fitted in the chassis and communicates directly with the modules. Each of the module drivers in the FPGA processor will run at this level, allowing operations to be undertaken at high speed. All files embedded in the project structure under the FPGA Target can control the modules and swap data with one another. The drivers on the FPGA write data to a FIFO (First In First Out) data stack. In this way, data are continuously read from the Real-Time controller and processed by the programs at the real-time level.

3.3 Software Development

3.3.1 Software Architecture

The virtual instrumentation (VI) software was designed using LabVIEW. The cRIO DAQ supports three programming modes: LabVIEW FPGA Interface mode, CompactRIO Scan mode, and hybrid mode [11]. Because the cRIO 9064 chassis and 5171A4 module only support FPGA mode, the software was developed using LabVIEW with the Real-Time module and FPGA Module.

Figure 1 shows the architecture for the LabVIEW measurement software. The project was designed in three levels: 1) host VI, 2) Real-Time VI, and 3) FPGA VI. The host VI executes on the Windows computer and contains the user interface for the monitoring system, which visualizes and analyzes data from sensors. The host VI also handles commands from users and sends commands to Real-Time VI to control the hardware chassis and modules. The Real-Time VI, the real-time processor, is part of the cRIO hardware, listed in the project structure with a chassis name and IP address. The Real-Time VI executes on a host running a real-time operating system and adds deterministic, floating point processing and control algorithms. FPGA VI, the FPGA processor, is part of the cRIO hardware and communicates directly with the modules.

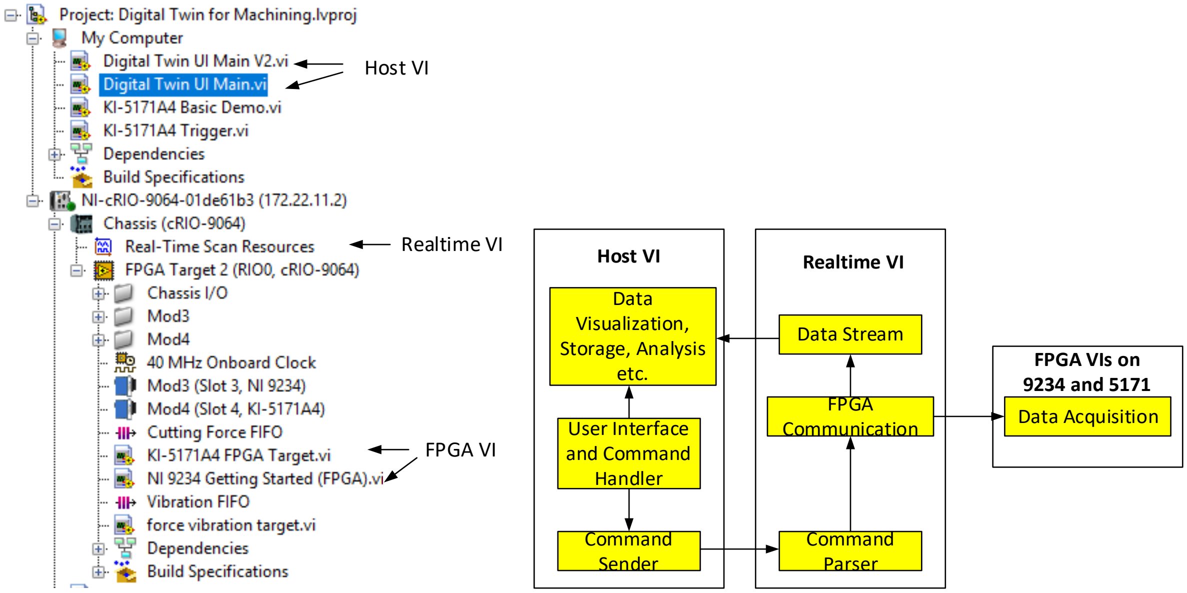

Figure 1. Architecture for the LabVIEW measurement software

The host VI provides an event-based user interface so an operator can interact with the embedded system. The Real-Time VI executes high-level control and the FPGA executes low-level control.

The Host VI allows the user to view data and interacts with the cRIO system. It has the following tasks:

- UI Event Handler process handles user events with Event Structures such as “Stop” and “Trigger Acquisition.”
- Command Sender process sends any commands received from the UI Event Handler to the cRIO controller using a Network Stream.
- Data Visualization receives the updated signal values and frequencies from accelerometer and dynamometer, and displays them in plots.
- Data Storage saves the signal in TDMS file or txt files.

The Real-Time VI handles three tasks, Message Handler, Command Parser, and Data Stream, in parallel While Loops.

- Message Handler loop receives any UI commands and distributes them to the appropriate Real-Time or FPGA process.

- Command Parser loop uses a Network Stream to receive commands from the user interface over Ethernet. The commands are placed into a Queue and sent to the Message Handler loop for distribution.

The FPGA module handles the task of “Data Acquisition” with high priority. It communicates with the modules connecting with accelerometers and the dynamometer. It sends a trigger to begin the finite acquisition, retrieves sensory data from the dynamic memory allocation (DMA) FIFO, and sends the collected and analyzed data to the user interface for display.

3.3.2 Programming on the NI 9234 Module

The 9234 module needs to be programmed at the FPGA target level and host PC level. The program was achieved by revising the example code on 9234 [12] provided by NI.

9234 Programming on FPGA Target and VI

The programming on the 9234 FPGA target has the following steps.
1) Configure the channel input mode (AC coupled, DC coupled, or IEPE AC coupled) for the 9234.
2) Set the sampling rate for the NI 9234 to acquire data. To avoid signal aliasing, the sampling frequency must be at least the Nyquist frequency, but usually is 5 to 10 folds of the signal frequency.
3) Assert interrupt on the interrupt line of the FPGA to inform host data rate has been set. Set true to wait until cleared by the host application to wait for acknowledgement from host.
4) Start the data acquisition loop on channels: set the number of samples to be acquired per channel and use the FPGA I/O Node to read AI channels; write the measured vibration data to a direct memory access (DMA) FIFO. If a timeout occurs on the FIFO Write, the FIFO is full, set the “FIFO full” indicator.
5) Stop the acquisition on channels and report any error that occurred.

A sample code for the 9234 FPGA programming is shown in Figure 2.

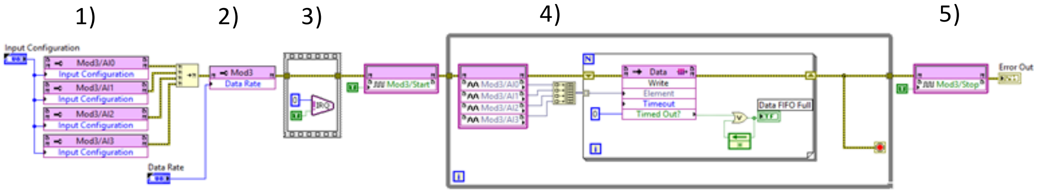

Figure 2. Sample code for the FPGA VI on 9234

9234 Host VI

The programming in the NI 9234 at the host level includes the following steps:
1) Open a reference to the FPGA VI and FPGA target.
2) Set sampling rate for the NI 9234 to acquire data.
3) Run the FPGA VI on the FPGA target.
4) Wait for the FPGA VI to assert an interrupt on the interrupt line of the FPGA.
5) Acknowledge the FPGA VI interrupt asserted by the FPGA.
6) Data acquisition loop: read the measured data from the vibration DMA FIFO, display the measured data, read status information from the FPGA, save the data to a TDMS file for later analysis.
7) Close the reference to the FPGA VI at the end of acquisition.

Figure 3 provides a sample code for the data acquisition loop.

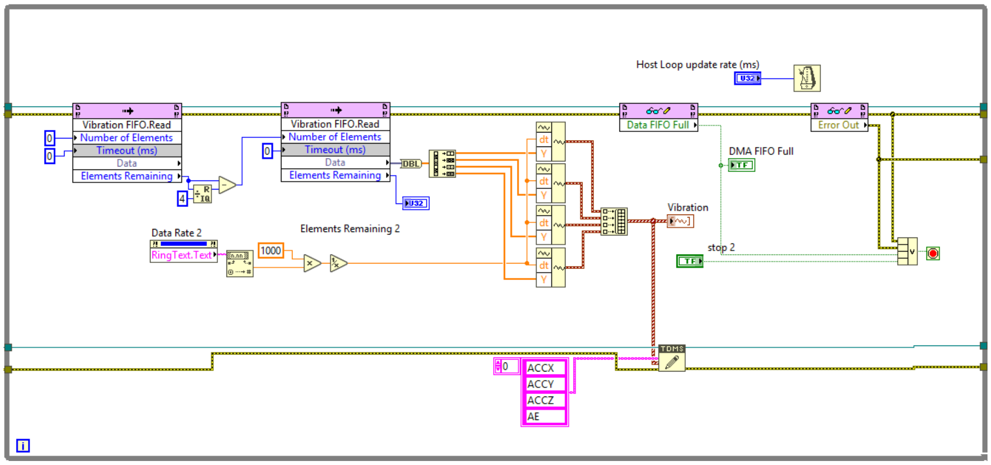

Figure 3. Sample code for data acquisition loop on 9234 host

3.3.3 Programming on the Kistler 5171A4 Module

The module of 5171 need to be programmed at FPGA target level and host computer level. The program was achieved by revising the example code on 5171 [13] provided by Kistler.

5171 FPGA Target VI

The programming on the 5171 target involves a "sequence structure," a "setting and state" loop, and a "data acquisition" loop. The sequence structure informs the host that the initial setting on the data acquisition is set. The host VI acknowledges set true on the "setting and state" loop. The "setting and state" loop sets data acquisition parameters such as signal range and sampling rate on the channels. It also observes states such as "overload" during the acquisition. The "data acquisition loop" reads data from sensors and send data to Host VI using FIFO. A sample code for the programming on 5171 FPGA Target is shown in Figure 4.

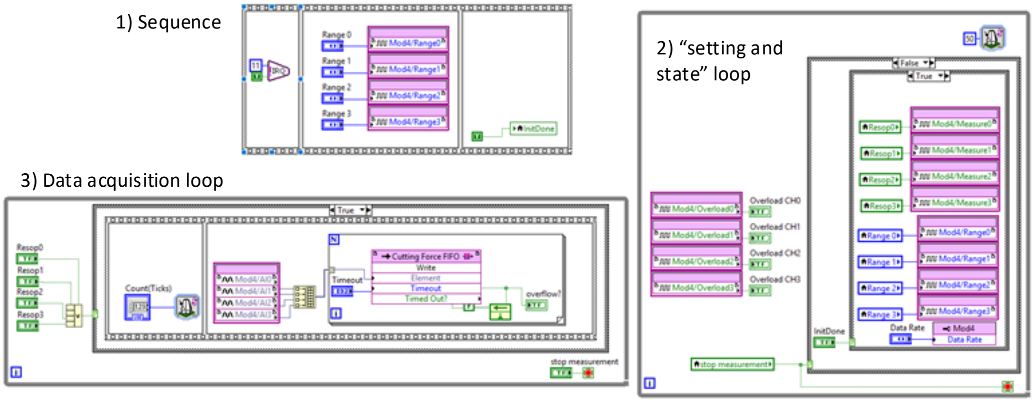

Figure 4. Sample code on programming on 5171 FPGA Target

5171 Host VI

The programming in the Kistler 5171 in the host level includes the following tasks:

1) Connect the controller and the chassis, set the chassis IP address and slot number for corresponding 5171 Target VI, and load slot specific Target.vi to FPGA;
2) Reset FPGA;

3) Configure cutting force DMA FIFO, start FIFO and run FGPA VI;
4) Wait on IRQ from 5171Target VI;
5) Set current front panel settings on 5171Target VI;
6) Acknowledge IRQ from 5171Target VI;
7) Start the data acquisition loop: read the measured data from the cutting force DMA FIFO, display the measured data, save the data, read status information from the FPGA, save the data to a TDMS file for later analysis.

Figure 5 displays a sample code for programming on the 5171 FPGA Target.

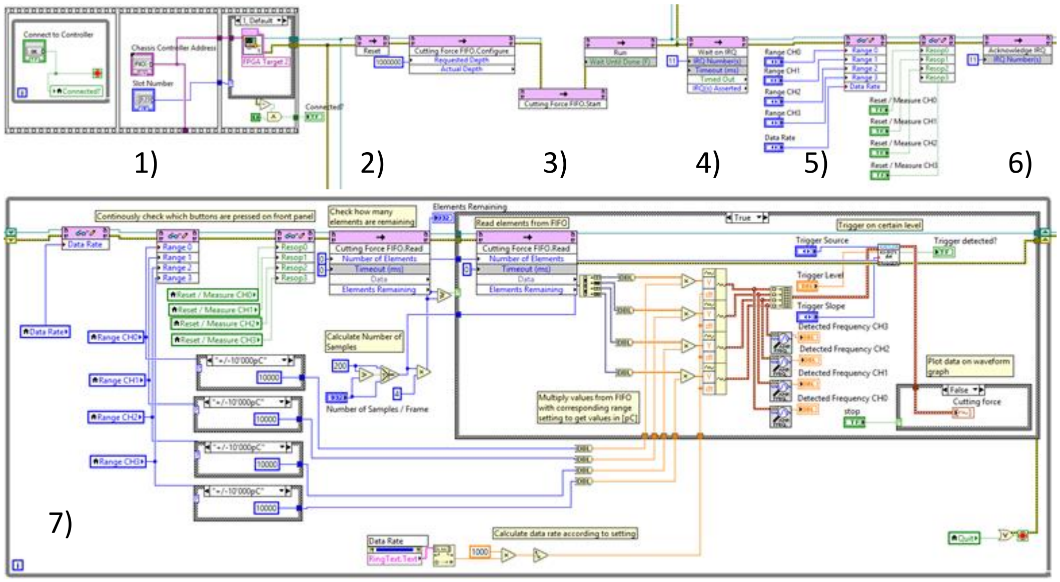

Figure 5. Sample code on programming on 5171 host

Note that the data received through 9234 is in millivoltage (mV), and the 5171A in picocoulomb (pC), which must be converted into acceleration (g) and force (N) by using sensitivity information from sensor manufacturers.

4. Test of the System

4.1. Part Design

The part to be machined is a modified NAS 979 part, which has the features of a diamond, a cylinder, a hole, and four corners. Because the machining of the corners with a slope needs a 5-axis machine or complicated fixture design, we did not machine these two corners. The digital model for the part as shown in Figure 6 was designed using NX CAD, and then generated the G code using NX CAM. The toolpath simulation and verification on cutting a corner are presented in Figure 7.

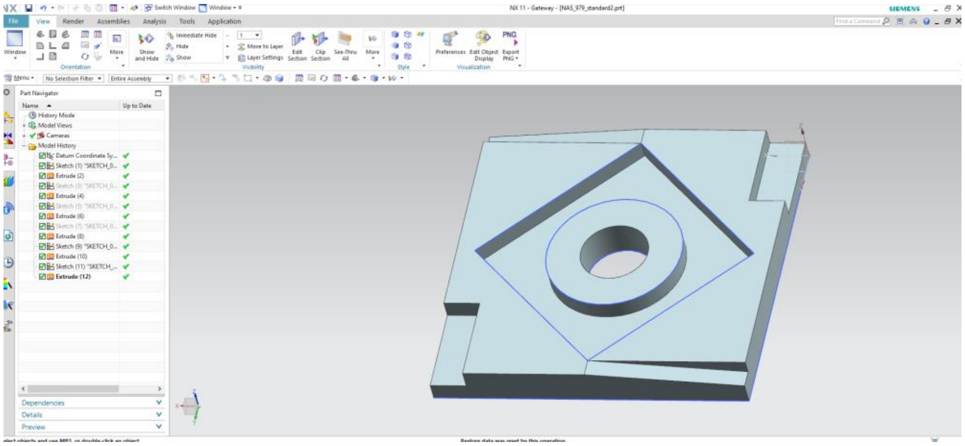

Figure 6. Part design for the test of monitoring system

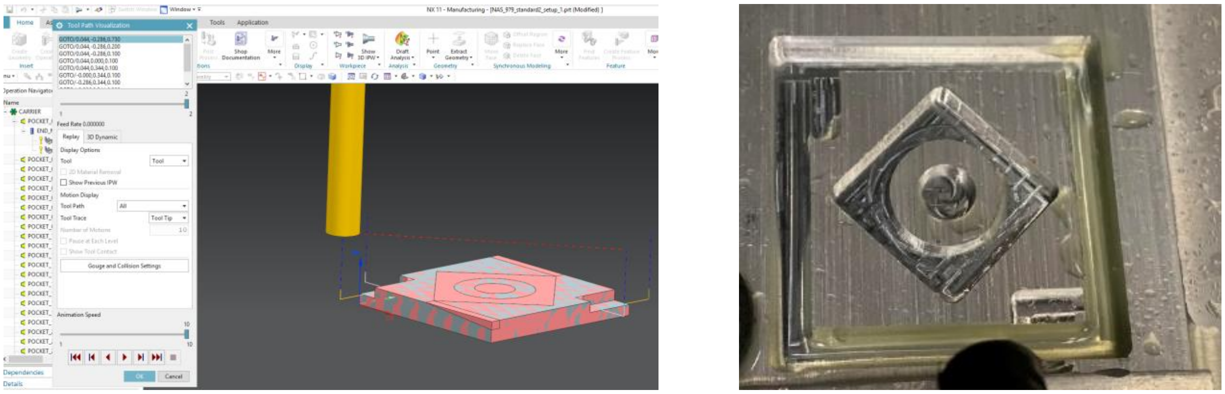

Figure 7. Toolpath simulation and finally machined part

4.2 Experiment Validation

The monitoring system was tested on machining the NAS 979 part with a Haas CNC mill. The test setup is provided in Figure 8.

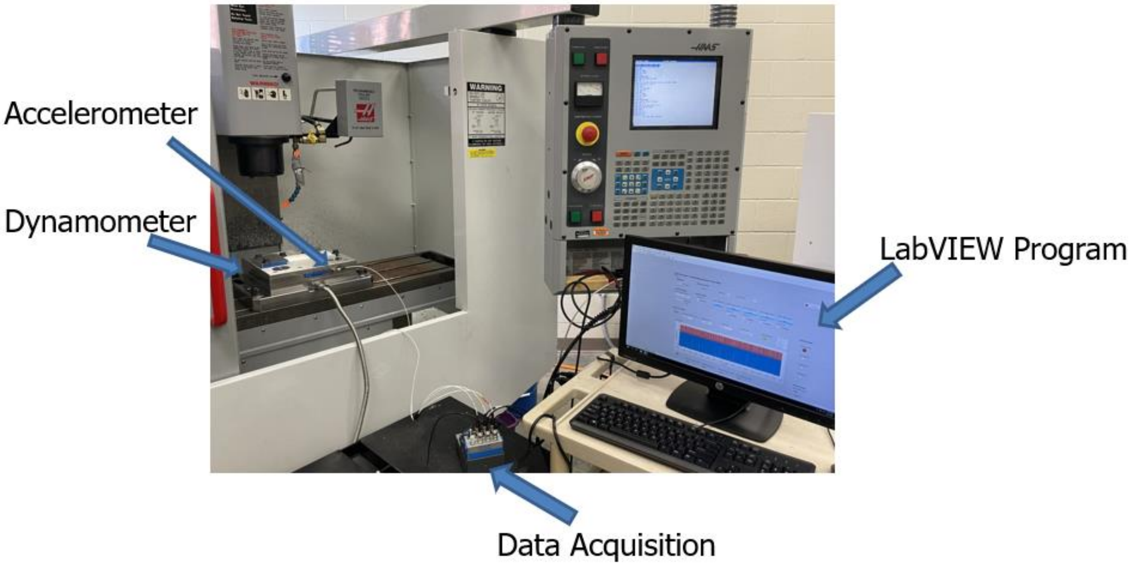

Figure 8. Experiment setup to test the monitoring system

The machining used an end mill with 4 mm diameter and 4 cutting flutes. The spindle speed was 5000 rpm. We selected conservative cutting parameters on the cutting depth and feed rate, so the cutting conditions are stable. An example on the vibration and force data acquired when cutting a corner is presented in Figure 9. An FFT analysis on these data is also presented in the figure. From the FFT, the peaks of the vibration and force do coincide with the cutting parameters: cutting rpm frequency (5000/60 = 83.3 Hz) and tooth pass frequency (5000/60x4 = 333.3 Hz). This validates the data acquired using this system.

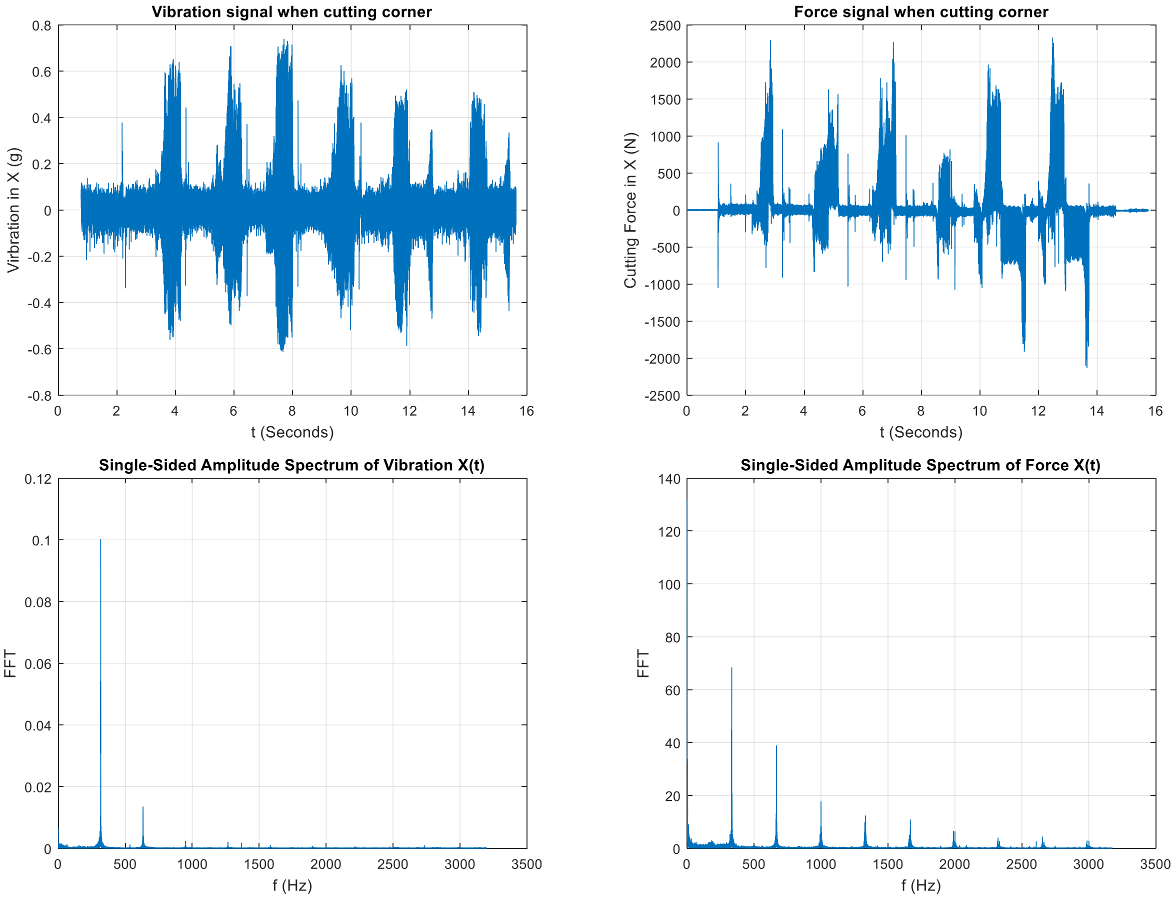

Figure 9. Acquired vibration, force data when cutting a corner and its FFT analysis

4.3 Curriculum Impact and Student Outcomes

The results from this project improve three courses in the Manufacturing Engineering program in particular, namely “Manufacturing Automation,” “CAD/CAM,” and “Manufacturing Processes.” The designed monitoring system can be applied to the laboratory apparatus in both “Manufacturing Processes” and “Manufacturing Automation.” Also, when applying the system to “Manufacturing Processes,” it potentially can be used for illustrating machining dynamics to students. Two such examples are: 1) how cutting force and vibration vary when changing the machining parameters, and 2) constructing a stability lobe diagram, which distinguishes stable and chattering cuts when varying the spindle speed (rpm) and cutting depth (mm). In addition, the students’ experience in designing a monitoring system tightly links ABET Student Outcome (SO) 6 (an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions) to "Manufacturing Automation," "CAD/CAM," and "Manufacturing Processes" where the SO is assessed or the courses contribute to Student Outcome.

Essential or professional skills are critically important in the engineering profession. In addition to the technical knowledge students acquired and applied, they also demonstrated an ability to function effectively on a team which is associated with ABET Student Outcome 5. In the Senior Design Project course, project advisors assess this ability through observation. The Course Coordinator/Instructor meets with teams frequently, and individual members, if deemed necessary, to query students about their team processes and progress. Moreover, team members formally assess themselves and well as they teammates about the processes as well. The team evolved over the one-year course sequence, and particularly during the implementation phase of this project. Having students design such a monitoring system has enriched Virginia State University's Manufacturing Engineering program's curriculum at Virginia State University, especially in laboratory settings through experiments, and has also enhanced students' readiness for the job market.

5. Conclusion and Future Work

This senior project was conducted during the pandemic year of 2021-2022. Students learned how to: 1) apply knowledge of sensors and sensing; 2) use LabVIEW programming to design the monitoring system; 3) apply CAD/CAM to design a test part and generate the G/M code for machining the part, then carried cutting experimentation on a CNC machine to test the monitoring system and CAD/CAM design; and 4) acquire the cutting force and vibration data from the experimentation. They finally analyzed the experiment data using an FFT. Students worked in a team to solve different project tasks. Sometimes team members did not have the prior technical knowledge required for a task, but they were able to look for solutions by having discussions with the project advisor and using learning strategies to find resources.

For future work, the capabilities of the system can be extended to online analysis. Currently, the FFT was analyzed off-line. The authors plan to perform online analysis using LabVIEW capability. In addition to this, the system can integrate with a more physical measurement for other advanced manufacturing processes. For example, the NI 9244 can be integrated for electrical power measurements, and the NI 9211 can be integrated for thermocouples. The power and temperature, as well as the aforementioned force and vibration measurements, are desired for monitoring the friction stir welding process.

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