Electrical Engineering Technology Undergraduate Research Experience: Phase Torque™ —A Design for Real-Time Monitoring of Torque Applied to a Rotating Shaft

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Abstract

As part of the continuous effort in developing industry partnerships that will lead to priority consideration of graduates from The School of Technology, an industrial partner collaborated with The Electrical Engineering Technology (EET) Program at Michigan Technological University to engage an EET student in researching Engineering problems. This undergraduate research experience is offered through an independent-study course and is used to fulfill the degree program requirements. This research project is a continuation of work originally conducted by the industrial partner. The project makes use of high-speed, field-programmable-gate-array-based data acquisition to monitor the relative positions of two cogged wheels spaced out on a rotating shaft that is powered on one end and loaded on the other. Once the twist in the shaft is measured, the applied torque can be calculated mathematically allowing for real-time monitoring of loads with minimally invasive setup. The goal was to take the initial research by the industrial partner and advance it as far as possible within the limited time frame of a single fourteen-week semester, while focusing on areas relevant to an Electrical Engineering Technology degree such as signal acquisition, data processing and Field Programmable Gate Array (FPGA) hardware design.

This paper details the undergraduate research experience, an independent-study project, for the Electrical Engineering Technology program at Michigan Technological University conducted with the industrial partner. The project consisted of further development of a data-acquisition system that can monitor the amount of torque applied to a rotating shaft in real time. The design focuses on software and FPGA hardware development for real-time data acquisition and processing.

Introduction

Usually, academic institutions teach students in a traditional environment composed of traditional lectures and laboratories—the lack of engaging students in solving real-world engineering problems reflects negatively on students' ability to compete in a global market. A strong link between academia and industry must be established. This partnership is a two-way street with advantages for both parties [1]. Today's students need both perspectives if they are going to be able to compete in the highly competitive global economy. They need to be more job-ready and know more than just theories [2]. Industry demands for ready-to-contribute graduates continue to rise; they are looking for graduates who can contribute on day one rather than a graduate who will need further training. To respond to industry's needs, academia and industry have been exploring possibilities of working together, either informally or formally, including student internships, faculty exchanges and industry-sponsored capstone projects. Collaboration between academia and industry is a two-way street, where both parties enjoy many advantages of this collaboration. Academia will benefit from this collaboration by providing students with marketable skills, securing additional funding for possible research and accessing state-of-the-art technology. On the other hand, industrial organizations will benefit from this collaboration by having access to academia's talent provided by both faculty and students at a reduced rate, and access to a common pool of talented students for a possible hire. The goals are always to bridge the gap between academic programs and industry demands, the needs and challenges of the industry had to be transformed to the classroom to make sure that the graduates compete in a challenging marketplace.

Industrial collaboration can be represented in many different forms. One form of industrial collaboration can be done by utilizing an effective Industrial Advisory Board (IAB). The IAB usually helps to keep the program current and relevant to industry needs; help from the IAB can be used in assessing academic programs' student outcomes to meet accreditation requirements [3]. Second, industrial collaborations can be established through a possible internship program, where industry partners hire students for their company as interns on a try-before-you-buy basis [2], [4]. The third possible collaboration is through sponsoring possible capstone projects or undergraduate research experiences, where students work on a real-world engineering problem, which eventually will result in a full-time employment opportunity for the students. Earlier research [5], [6] showed the importance of industrial involvement in the capstone environment, which became more than just the financial support. However, support in the form of equipment, materials and technical consulting is common and, in most cases, necessary [6-8]. Other forms of industrial support include providing awards for meritorious designs and assisting in the evaluation of teams and projects [9].

Each of these forms has the elements of bringing real-world problem-solving skills to the student and at the same time helping the industrial partner. Many academic institutions manage to establish a strong collaboration with local and regional industrial partners; Morehead State University represents an example of how a strong relationship with local industrial partners helped the department of Industrial and Engineering Technology program survived and to become one of the most successful departments at the university [10].

The undergraduate research Experience is a reflection of quality education. Academic institutions aim to integrate research experiences in their curricula by establishing a partnership with both local and regional industry [11]. The Electrical Engineering Technology program at Michigan Technological University established a relationship with possible industrial partners to provide students the opportunity to work on real-world engineering design problems with possible industry supervisors in which the student establishes a working relationship with an industrial supervisor who works with them to develop a project and to prepare a work plan. The industry supervisor evaluates the student's performance and work closely with the student's academic advisor on monitoring the progress the student makes towards achieving the project's goals.

This project was conducted with the industrial partner as an Electrical Engineering Technology undergraduate independent-study course for the spring, 2012, semester under the direction of a faculty member at Michigan Technological University. The project consisted of a continuation of work originally conducted by the industrial partner. Specifically, the project made use of high-speed FPGA-based data acquisition to monitor the relative positions of two cogged wheels spaced out on a rotating shaft that was powered on one end and loaded on the other. Once the twist in the shaft is measured, the applied torque can be calculated mathematically allowing for real-time monitoring of loads with minimally invasive setup. The goal was to build upon the initial research done by the industrial partner, progressing it as far as possible within the limited time frame of a single fourteen-week semester, while focusing on areas relevant to an Electrical Engineering Technology degree such as signal acquisition and conditioning, data processing and FPGA hardware design.

Electrical Engineering Technology Program

The EET program offers a Bachelor of Science in Electrical Engineering Technology and is designed to train the future workforce directly in response to industry needs. The EET program is application-oriented and focuses on preparing graduates for entry into the workforce upon graduation. Graduates of the program are electrical engineering technologists with career options in micro-controller applications, robotics, industrial automation, instrumentation and control.

A major strength of the EET program in attracting and retaining interested students is the emphasis on applied laboratory experience. The program has a solid record of career placement among employers seeking graduates that are productive upon entering the workforce. The university as a whole has maintained a placement rate of over 95% in recent years, in spite of the difficult economic times. All School of Technology faculty members have a minimum of three years of industrial experience, which enhances the ability of the School to access industry support and place engineering technology graduates. The faculty members have a strong commitment to the integration of practical laboratory experience with engineering technology fundamentals.

Electrical Engineering Technology Undergraduate Research Experience

Course Objectives

The course places an emphasis on the importance of integrating undergraduate experience in the Electrical Engineering Technology curriculum through partnership with local and regional industry. This research experience consists of part-time employment (8-10 hrs/week) at Industrial Partner campus that specializes in engineering wireless telemetry systems. A large portion of the work was focused on the engineering and design of the electrical components used for sensing, transmitting and receiving data as well as powering the devices. Upon successful completion of this course, students will be able to:

- Prepare background research on applied electrical engineering technology;

- Organize research and data for synthesis;
- Prepare written reports;
- Prepare and present oral reports;
- Coordinate and work to meet scheduled deadlines and facilities, manage resources, etc.; and,
- Consider non-engineering considerations in your work (e.g., economic issues, marketing issues, esthetics).

Course Structure

The undergraduate research experience course is three credit hours. Students will meet with their instructors weekly to discuss progress to date. The entire grade is based on the satisfactory completion of the project and the presentation of the final results in an appropriate engineering report at the end of the semester. The final grade is based on student performance throughout the semester. The timeline for submitting these materials will be as follows:

1. Final Report (due 2 weeks before final exams start)
2. Poster (due 1 week before final exams start)
3. Prototype (due 3 weeks before final exams)
4. Final and midterm presentations
5. Project proposal and portfolio (by the end of the 3rd week)
6. Bi-weekly progress report

Engineering Design System Description

The following sections cover the specific design choices and theory behind each major sub-section of this design. Concepts that will be covered include both hardware and software design components of the FPGA real-time data acquisition and processing system.

System Overview

The project design requirement was to outfit a piston pin from a diesel engine with an array of seven thermocouples to monitor piston pin temperature and an optical transducer to observe the relative rotation of the piston pin. Figure 1 is an image of the telemetry setup that shows the cogged wheel on the end piston pin and the optical transducer mounted on the piston that is used to monitor pin rotation during engine operation.

The purpose of the Phase Torque™ system is to monitor the torque applied to a rotating shaft. This has many potential applications including monitoring of industrial equipment, or use in research and design of automotive drivetrain systems. The Phase Torque™ system has many benefits over conventional torque monitoring systems that are currently in place. The system is designed to be as unobtrusive as possible, leading to simpler installations and greater ease-of-use.

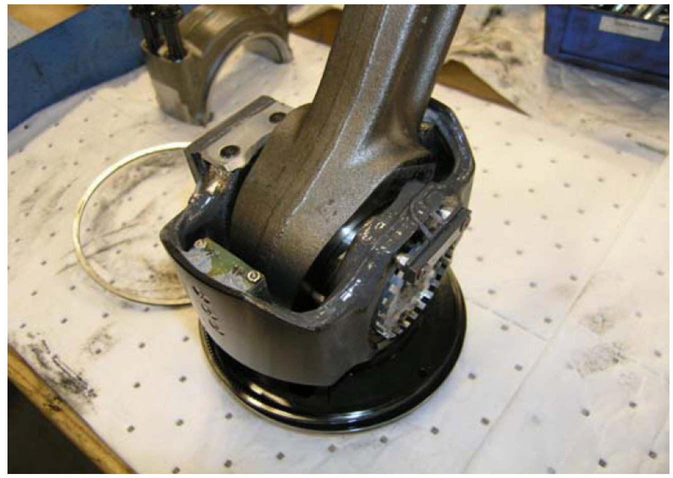

Figure 1. Piston and Rod Combination Outfitted with Pin Temperature and Rotation Sensors [12]

The concept of the new design is based on the idea that it would be possible to monitor the amount of torsion in a rotating shaft and, therefore, the applied torque, using two cogged wheels whose position relative to each other would change due to the twisting of the shaft as the applied torque changed [12].

Figure 2 is a block diagram of the Phase Torque™ system. For the initial tests, an electric motor was used to turn a shaft connected to an alternator. The alternator had a load that could be varied from 0 to 900 watts. Three cogged wheels were attached on the shaft, two with 36 teeth and one with only one tooth. The wheel with one tooth was used as a reference pulse to synchronize data readings. The two wheels with 36 teeth were used to measure the rotational displacement along the shaft due to the load torque. Optical interrupters were used to sense the passing of the teeth and to trigger the FPGA-based data-acquisition hardware. The data from the data-acquisition hardware were sent to a computer where they were analyzed.

FPGA-Based Data-Acquisition Circuit Design

The data-acquisition system was an FPGA-based device with six digital and six analog inputs that operates at a high frequency. The design also requires applying data-processing routines written in Visual Basic (VB) for post-processing the data and implementing them on the FPGA for real-time data processing. The goal was to produce a self-contained unit that can acquire, process and output all of the relevant data needed for monitoring shaft torque.

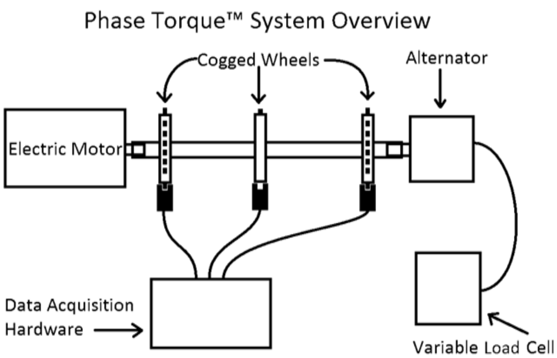

Figure 2. Block Diagram of the Phase Torque™ System

Hardware Circuit Description

Figure 3 is a block diagram of the FPGA data-acquisition and processing system. There are four input signals, the signals from each of the optical interrupters and a push-button signal used for calibrating the system. The time between successive pulses from wheel0 and wheel1 will be used to calculate the angle of twist in the shaft. This value will be corrected by reading that tooth's calibration value from a calibration register. A counter will keep track of the current tooth number and will use the wheel with only one tooth, shown as wheel2 in the block diagram, as a reference. After the correction factor is applied to the angle value, this will then pass through the averaging filter, which will then pass this data on to the USB interface controls so that the data can be sent via USB or other communication interface technology. There are seven major components in the FPGA design, the rising edge detector, the tooth number counter, the RPM counters, the tooth event timer, the calibration register memory interface, the correction factor application block and the averaging filter block.

Rising Edge Detector: The rising edge detector is fairly straightforward and similar to many examples of rising edge detectors seen elsewhere and implemented in VHDL. It ensures that the system always triggers off of the rising edge of a signal so that the timing is as accurate as possible.

Tooth Number Counter: The tooth number counter consists of two 8-bit counters that increment with the tooth pulses of each wheel. The block diagram for the tooth number counter can be seen in Figure 4. The counters are reset by a high signal on the wheel2 input, which is the reference pulse. This signal is also used as the clock input to the output registers, which hold the values for the number of teeth on each wheel. The value of the current tooth is also output from this block for use by various other components in the design. Due to the register size of the counter (eight bits), wheels with up to 256 teeth can be used.

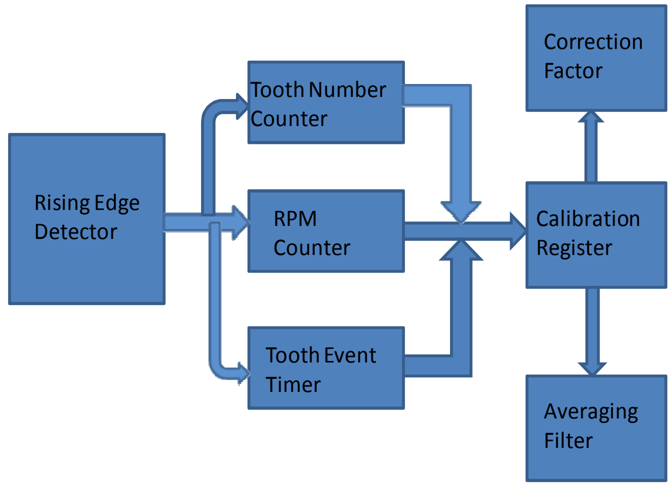

Figure 3. Circuit Block Diagram

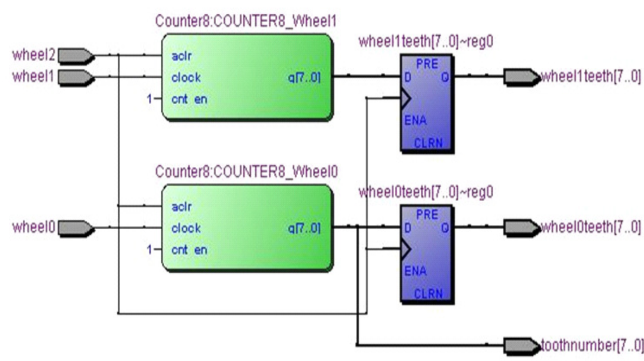

Figure 4. Tooth Number Counter Block Diagram

RPM Counter: The RPM counter is a simple, 32-bit interval counter that records the amount of time between pulses on the single-toothed wheel. Acquiring the RPM signal is important because it allows for the horsepower of the system being monitored to be calculated by using the measured torque.

Tooth Event Timer: The tooth event timer is what tracks the amount of time that has passed between successive teeth on the two wheels. It uses a 32-bit counter to keep track of the number of clock ticks between inputs. The counter starts in the middle of its 32-bit range and, depending on which tooth crosses first, it either counts up or down. This allows for negative values to be handled by the hardware as well.

Calibration Register: The calibration register memory interface utilizes the 8 kb of User Flash Memory (UFM) available on the Altera MAX II FPGA used in the design. However, the UFM utilizes 16-bit registers, and the timer used in the tooth event timer uses 32-bit values. In order to store these 32-bit values into the 16-bit registers of the UFM, each 32-bit value is first separated into two 16-bit values, one corresponding to the first 16 bits and the other corresponding to the second 16 bits. So for each read/write operation from the UFM to read/write a calibration value, two reads or two writes need to take place. A state machine was created which first reads/writes the low bits then reads/writes the high bits. In the case of a read operation, the high and low bits are then concatenated to create the desired 32-bit output. The 8 kb size of the UFM allows storage of 256 32-bit values, which is just the right size for storing calibration data for the maximum number of teeth dictated by the 8 -bit counters used in the tooth-number counter block.

Correction Factor Circuit: The correction-factor application block is used to apply the appropriate correction factor to the value from the tooth event timer. When the calibration data for the current tooth is successfully read from the UFM, the correction-factor application block subtracts this calibration value from the output of the tooth event timer. The output from this goes to the averaging filter block.

Averaging Filter: The averaging filter block is where the averaging routine, developed first in software, is implemented. The averaging filter consists of a state machine that steps through the averaging process.

As it currently stands, the output from this circuit is an average value given in a number of clock cycles. Additional logic blocks will need to be added to convert this time-based value into a torque value. The design was coded using VHDL and compiled with Altera's Quartus II software [13]. Also, all current testing of the design was done solely with simulations. In order to implement the FPGA design in hardware, the USB interface and controls will need to be implemented within the design to be able to send the data to a computer for storage and analysis.

Software Design

The software was written in Microsoft Visual Basic to provide an easy environment to analyze and record the data and visually compare the results. The two main parts of the software written for this project focused on calibrating the system and processing the data recorded by the data-acquisition system, specifically the averaging algorithm.

Due to the need for high resolution for measuring angle variations, the system had to be calibrated to eliminate as many variables as possible. The calibration processes used effectively eliminate any erroneous readings due to machine tolerance variations in the width of the teeth. This was done by running the setup with no load applied to the shaft and taking the average angle value read for corresponding teeth between the two wheels with 36 teeth. The wheel with one tooth was used to maintain synchronism in the data, to ensure that the corresponding teeth between each wheel were counted correctly. After calibration was complete, the amount of noise in the data was greatly reduced. Without this calibration, the noise present would be greater than any desired reading you would want to get and, therefore, the system would not work. The raw data from this run varied by about 0.45°. After the calibration was applied, the data variation was reduced to about 0.16°. Figure 5 shows the impact of the calibration process on data captured for 30 seconds and compares the raw data with the calibrated data. Initially, the raw data varied from approximately 5.85° to 6.3°. With the calibration process applied, the data changed to vary from 0.1° to -0.05°. The blue trace in the graph represents the raw data with the left vertical scale. The red trace represents the calibrated data with the right vertical scale.

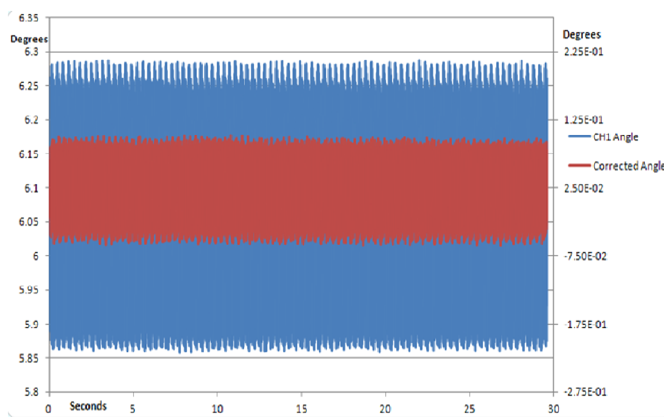

Figure 5. Overlay of Raw and Corrected Data

To decrease the noise in the data even further, an averaging filter was used. The averaging filter uses a running weighted average. This is better than a traditional average because as each new piece of data is acquired, it can be combined with the current average and the average value can be updated immediately, rather than accumulating a set number of data points then dividing the sum by the number of data points, and updating the average. The depth of the averaging filter was used to add weighting to the data so that more recent data had a greater effect on the average than old data. This filter depth is selectable and effectively alters the smoothing of the data. A higher filter depth puts more weighting on older data so the average value is slower to react to changes in the raw data, which smoothes out the average value. A compromise between smoothness and reaction time must be reached in order to provide a stable reading that accurately reflects the current state of the device being measured. Figure 6 shows the average value. It can be seen that the range in values is now much lower. The initial ramp up is due to the averaging function and the weighting values used.

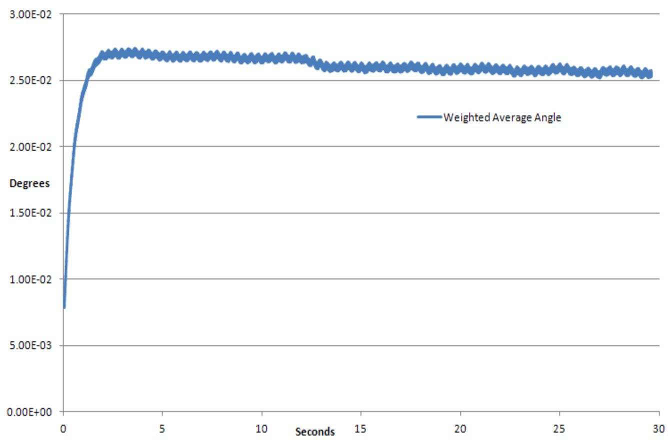

Figure 6. Weighted Average Angle Separation Data

In addition to measuring the angle between corresponding teeth on the two wheels, the software can also count the number of revolutions, identify each individual tooth for each wheel and monitor the rotational speed of the shaft. The rotational speed of the shaft allows for a real-time power reading in addition to the real-time torque reading.

System Verification

The mechanical layout of the test bed essentially follows the system block diagram. The electric motor spins the shaft that turns the alternator. The shaft has the three-cogged wheels on it and the alternator is loaded down with a variable load. The load-bank consisted of nine 100-watt, 12-volt light bulbs. It also had an aluminum heat sink and a large fan to keep it cool. Each of the cogged wheels had one optical interrupter switch mounted below it. The signals from the optical interrupter switches were fed to the FPGA-based data-acquisition system, which was connected to the computer. The end of the shaft that the alternator threads into was mounted on a pillow-block bearing. This was done so that the alternator could be free-floating. With the alternator free to rotate, an analog load cell was mounted to the alternator. The data from this analog load cell was fed to one of the analog input ports of the data-acquisition system and was then used to verify the torque readings obtained from the optical interrupter switches. The load cell reading was used purely for testing, comparison and validation of results during the development of this project.

The limitations that were encountered during the development of the system were simply due to the setup being used. One of the problems identified through the use of the current setup was the lack of alignment between the motor, the pillow-block bearing and the alternator. This caused the shaft to bind and bend ever so slightly each time it turned over, which added to the noise and vibrations seen in the data. The motor used was simply spot-welded to a stamped steel bracket bolted to the base of the test bed. Even if the motor were perfectly aligned with the pillow-block bearing while resting, under load this stamped-steel bracket would bend and twist causing the motor to move out of alignment, resulting in the same vibrations and unwanted bending forces on the shaft.

Conclusion

The Undergraduate Research Experience is directly related to and a reflection of quality education. Academic institutions aim to integrate research experience in their curricula by establishing a strong partnership with both local and regional industry. The Electrical Engineering Technology program at Michigan Technological University established a relationship with industrial partners to provide students with the opportunity to work on real-world engineering design problems. This project was conducted with the industrial partner as an Electrical Engineering Technology undergraduate independent study course for the spring, 2012, semester under the direction of a faculty member at Michigan Technological University.

The project consisted of the development of a data-acquisition system that can monitor the amount of torque applied to a rotating shaft in real time. The design was focused on software and Field Programmable Gate Array hardware development for real-time data acquisition and processing. This Electrical Engineering Technology Undergraduate Research opportunity will advance undergraduate research within the School of Technology, fostering enhanced real-world engineering design projects and enhancing the students' classroom experience using undergraduate research. Such an approach to the education of engineering technology students meets the expectations of ABET accreditation standards [14] by connecting students to the solution of real problems.

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