The Impact Detector Project: Mechanical and electrical worlds collide

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Abstract

Mechanical engineering students at Penn State University, Berks campus, were tasked with designing and fabricating an impact detector to meet a detailed specification. The device was intended to be similar to that used to trigger the inflation of automobile airbags. The project was part of a third-year instrumentation and measurement theory course and was implemented to provide the students with exposure to mechanical and electrical design, fabrication, test, and documentation techniques and methods. Students worked in teams of two or three members. The device specification provided detailed electrical, mechanical, and physical requirements for the impact detector. A major requirement was the range of accelerations that *must* trigger the device and the range that must *not* cause the device to trigger. An acceleration greater than 35g for a duration of 1ms or longer *must* cause the device to trigger. Any duration of acceleration with an amplitude less than 25g must be ignored by the detector. Detector output for acceleration profiles between these two conditions is not defined. The detector output is a voltage pulse (logic high) with a nominal duration of one second when an appropriate impact event occurs. Otherwise, the output of the detector should be zero (logic low). Another important requirement of the detector is that it must fit inside a prescribed enclosure (1.25" x 1.25" x 1.10"). The enclosure is mounted to an impact sled for testing. The sled also contains a reference accelerometer to measure the actual profile of the impact during device testing. The sled is struck horizontally with a spring-loaded rod like that found in a pinball machine to launch the ball into play. The teams must develop a detailed test procedure to document the compliance of their design with the specification. Faculty and staff developed custom test apparatus for the project. Dynamic test data was captured with a USB data acquisition unit and LabVIEW software. This paper describes the lessons learned by the students and faculty during the project. Examples of impact detectors designed by the students are presented. The custom test apparatus and software are also presented and discussed.

Introduction

The motivation for this project came from observing the operation of a child's toy. The toy was a small stuffed likeness of an animated movie character. Embedded in the toy was a battery powered module which played a short clip of the character's voice when the toy was subjected to rough handling. Disassembly of the module revealed a simple spring trigger mechanism to sense the motion of the toy and cause it to activate the voice circuit when sufficient impact acceleration occurred.

Hands-on experience is a key part of effective undergraduate engineering education [1], [2]. Coupling hands-on experience with team project-based learning further benefits the students [3] – [5]. Instrumentation and measurement courses lend themselves to a variety of topics and physical devices that are suitable for team projects. The work presented here involves the design, development, and testing of an impact detecting device by students in a third-year mechanical engineering instrumentation and measurement theory course.

The overall intent of the project is to demonstrate to the students how various topics discussed throughout the semester can be combined and applied to produce the desired result. The project also gave the students exposure to reading and interpreting technical specification documents. Depending on the device for the project, the order of topics discussed during the semester may be modified. It is important that enough of the baseline material has been covered to allow the students to make informed choices and tradeoffs in their design process. Obviously, the design must start well before the end of the semester so some material may need to be supplemented by the students on their own, as needed.

For the impact detector project, students self-selected small teams of two or three members. Team members typically discuss their respective strengths and weaknesses which leads to a natural division of labor for the project. There are also some tasks, like soldering, that may be foreign to all team members so there is opportunity for learning.

- Impact acceleration measurement range: 0 - 40g
- Maximum total weight: 40 grams
- Maximum outside dimensions of enclosure: 1.25”W x 1.25”L x 1.1”H
- Device operating power supply voltage: +5 VDC ± 0.25 VDC
- Maximum power supply current: 25 mA
- Signal output resistance 50Ω ± 5Ω
- Output Signal
  - 0VDC ± 0.2VDC for acceleration less than 25g
  - 5VDC ± 0.5VDC pulse with duration of 1s ± 0.5s when acceleration greater than 35g for duration greater than 1ms
- Part marking to indicate “UP” and “IMPACT” directions
- Part marking to indicate team name
- External connection wires #26 - #22, 3 ± 0.5 inches long
  - +5V wire shall be red
  - GND wire shall be black or blue
  - Output Signal wire shall be white or yellow
- Mounting hole pattern must match provided drawing

Table 1. Summary of impact detector requirements

The teams are given a coarsely defined specification for the performance of the instrument to be produced. They are also given a small budget, preferred sources for parts, and list of milestones to help keep the projects moving. Table 1 shows a summary of the impact detector requirements.

Students were encouraged, but not required, to use a pre-designed printed circuit board (PCB) for a fixed-duration pulse generating circuit (one-shot). The one-shot could be triggered by some sort of custom impact detecting mechanism/device. Therefore, for most of the teams, the project became a matter of designing a triggering mechanism that responded to the specified impact acceleration profile. One team chose to use some extracurricular experience with microcontrollers together with an integrated circuit accelerometer to create a device to meet the required specifications.

One of the most imposing requirements of the specification was that of the maximum physical size constraints. All components of the impact detector must fit within a small plastic enclosure with inside dimensions of 1.25" W x 1.25" L x 1.10" H. The device must operate as specified with the enclosure closed. The design teams did have the option of either a horizontal or vertical mounting orientation for their device. Figure 1 shows photographs of a few of the teams' designs, with the enclosure lids removed.

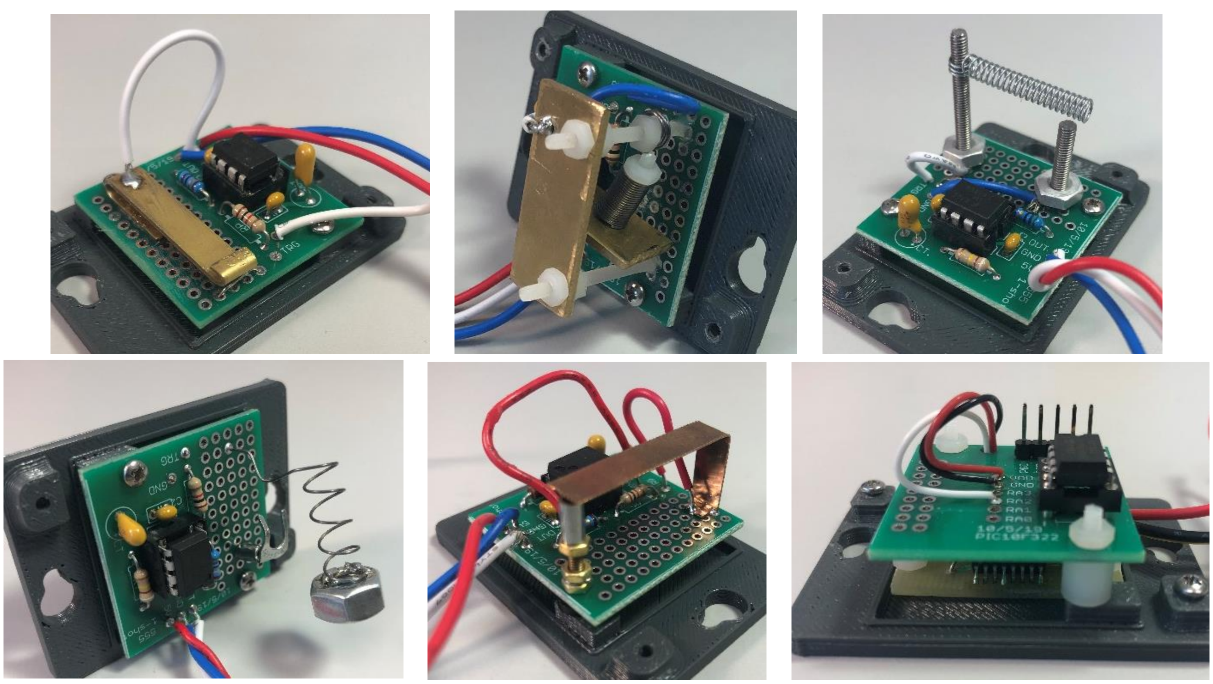

Figure 1. Photographs of several impact detector designs (enclosure lids removed)

The teams that used a mechanical triggering scheme needed to determine an appropriate combination of seismic mass, spring constant, and contact gap width. As diagramed in Figure 2, one end of the spring (either coil or leaf) is attached to the device housing while the free end has bonded to it the seismic mass. The metallic spring is used as a switch contact. An opposing metallic contact is placed on the housing at the point nearest the free end of the spring. During an impact acceleration event of the proper magnitude and direction, the second-order displacement response of the mass-spring system will allow the free end of the spring to collide with the housing and thus momentarily close the “switch” contacts.

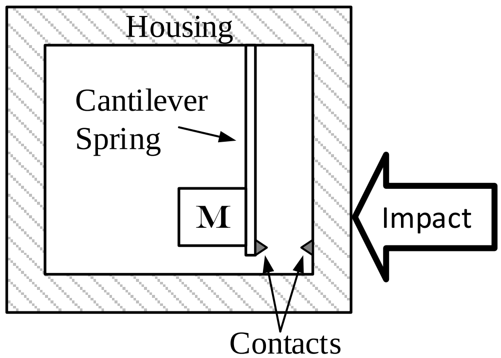

Figure 2. Impact detector trigger mechanism diagram.

The event-triggered, pulse-generating circuit was built by the students using a provided PCB. An LM555 (“555 Timer”) integrated circuit configured as a monostable multivibrator (one-shot) was used. The students determined the required timing components such that the specified pulse (1s ± 0.5s) was produced when a trigger (momentary switch closure) from the detector mechanism occurred. Figure 3 shows a schematic diagram of the one-shot circuit. Figure 4 shows a photograph of the one-shot PCB used by most of the teams.

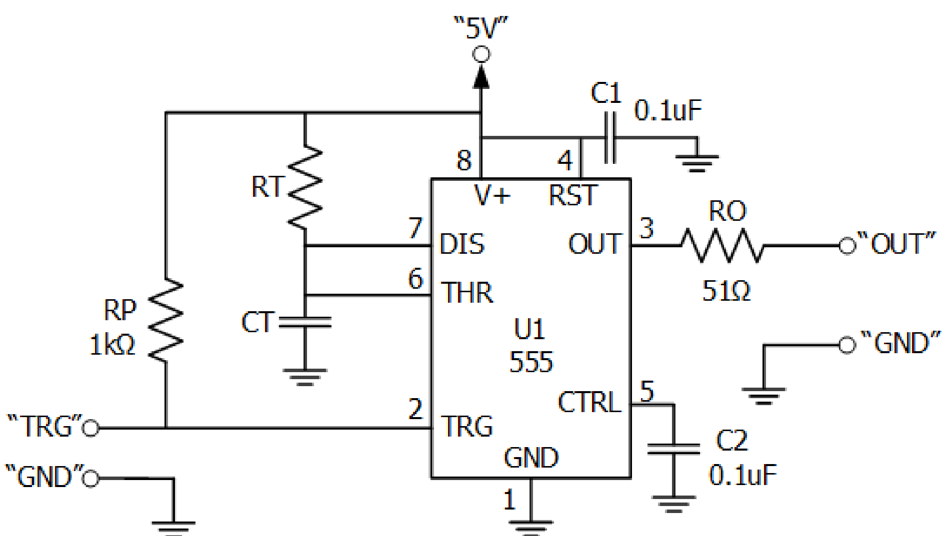

Figure 3. Schematic diagram of one-shot circuit

Figure 4. Photograph of one-shot PCB

The impact detectors were tested in several ways to determine compliance with the specifications. The dimensions and weight of each device were measured. The pulse-generating circuit was independently tested by manually forcing the spring to momentarily close the switch contacts. Finally, the sealed device was mounted to a test "sled," connected to the instrumentation, and subjected to various impact events.

The test sled was constructed by the campus machine shop using nylon (gray base) and polycarbonate (clear) materials. Figure 5 shows a photograph of the test sled. The sled also contained a reference accelerometer to measure the profile of each impact event. The device-under-test (DUT) could be mounted in the horizontal or vertical planes as shown in Figure 6 depending on the team's particular design.

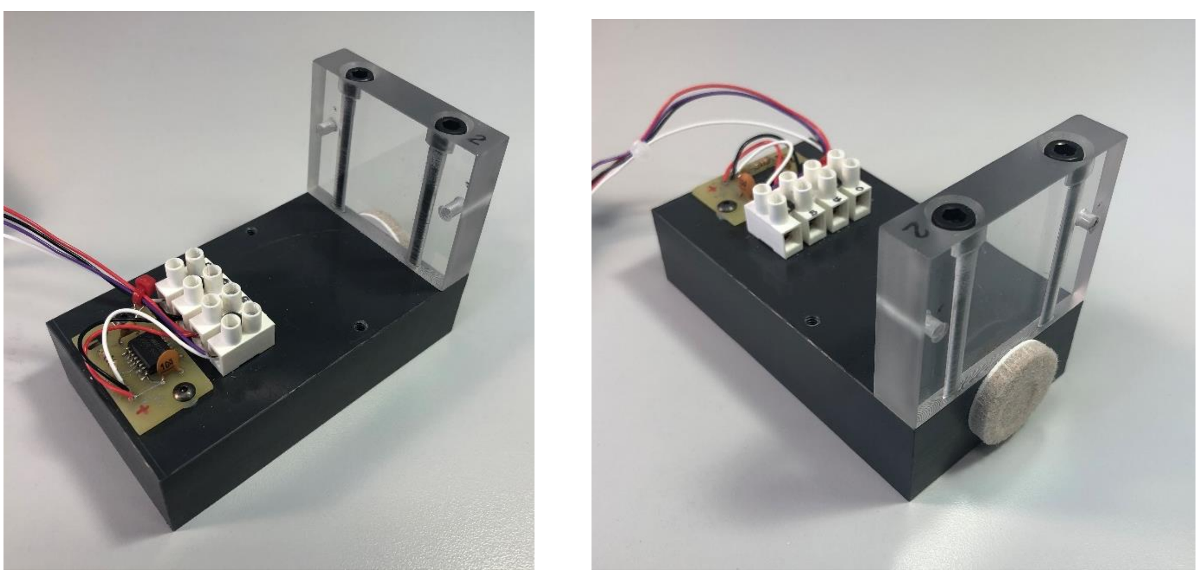

Figure 5. Photographs of impact test sled.

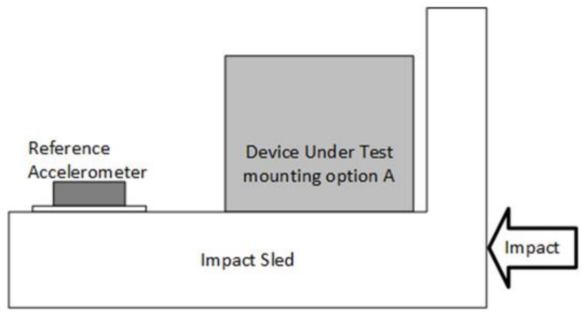

Figure 6. Impact test sled diagrams showing DUT mounting options.

Four impact test sleds were fabricated so that several groups could test their designs with minimal interference. To conduct a test, the impact test sled is placed onto a short, guided test track which contained a spring-loaded, horizontal impact driver (very similar to that used to launch a ball in a pinball machine). Figure 7 shows a photograph of the impact driver assembly. A felt bumper pad is located on the impact test sled where the impact driver strikes it. The thickness of the pad was selected to help shape the impact acceleration profile as needed.[6] A small foam bumper at the end of the test track is used to stop the sled.

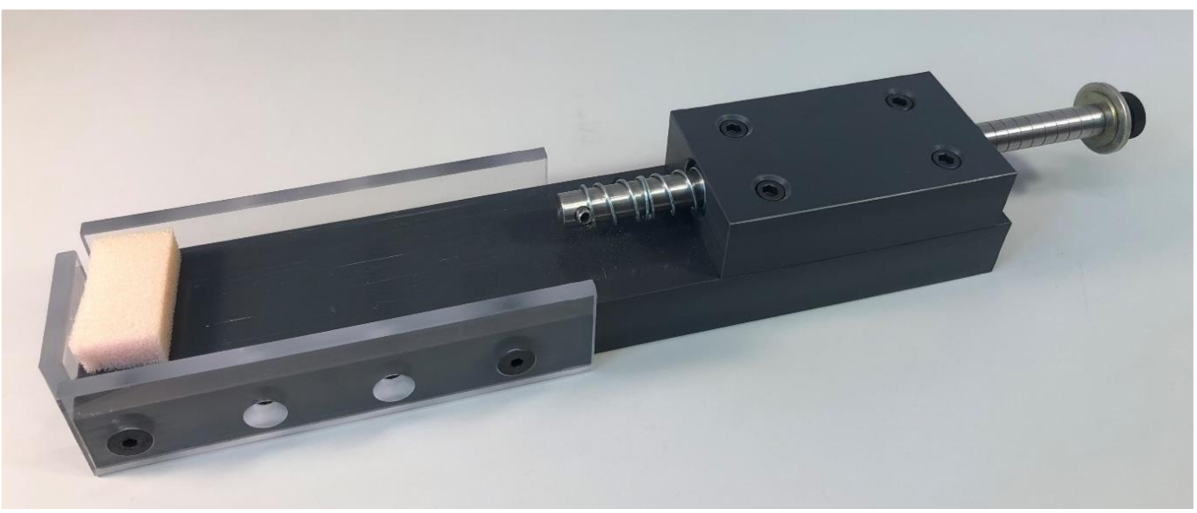

Figure 7. Photograph of impact driver assembly.

Pertinent Course Topics

The instrumentation and measurement theory course is typically taken by BSME students in the first semester of their third year. The course topics that were illustrated and emphasized by the accelerometer project include the following:

- Accelerometers
- Second-order response

        - Natural Frequency
        - Damping Ratio
        - Resonance
    - Pulse circuits
        - Timing component selection
    - Uncertainty Analysis
    - Test Equipment Setup and Use
    - Data Acquisition Hardware and Software

Impact Detector Construction

The majority of the sixteen teams used a custom triggering mechanism. A 40g MEMS accelerometer was also successfully used by one team. The spring component was implemented in many ways. Some teams used thin steel or brass cantilevers while others used steel coil springs to either swing or compress/expand during the impact. The seismic mass was realized using various arrangements of metal nuts and/or bolts connected to the spring. For some designs, the mass of the cantilever alone provided the desired performance. The fixed end of the spring was fastened to the PCB where it was also connected to the pulse circuit. The free end of the spring was then aligned over the opposing contact which was also on the PCB where it too was connected to the pulse circuit. The device enclosure was 3D printed on campus using ABS material and all teams chose to use the same design.

Calibration

For the design teams using a custom spring-mass mechanism, calibration involved adjusting the gap between the free end of the spring and the opposing electrical contact. For some teams, this was just a matter of bending the spring. For others, it required the adjustment of a screw or nut to raise or lower one of the contacts. The calibration was an iterative process using the impact test sled and impact driver assembly. A reference accelerometer on the test sled provided the known acceleration profile.[7] Various levels of impact acceleration were imposed on the DUT using a sled-mounted MEMS accelerometer (Freescale/NXP MMA2201D) as the governing reference device. During calibration, the DUT enclosure lids were removed to provide easier access to tweak the mechanism. The MEMS accelerometer impact detector design was also calibrated in an iterative manner, but the trigger threshold was adjusted in software rather than physically manipulating the hardware.

Size and Weight Testing

Each team’s impact detector was measured to determine conformance to the size and weight specifications. If a team used the provided 3D printed enclosure (which all teams did), the maximum size specification was satisfied without further testing required. Figure 8 shows a DUT during weight specification testing.

Figure 8 Photo of DUT weight testing.

Impact Testing

Using the impact driver required a bit of practice and finesse to obtain the desired impact acceleration profiles. Students used the impact driver as part of the calibration process. The impact driver was also used by the lab instructors as part of the customer acceptance test. Several trials were preformed to obtain impact acceleration profiles that demonstrated device performance in the three regions of operation: 1. Must not trigger (acceleration less than 25g). 2. Must trigger (acceleration greater than 35g for more than 1ms). 3. Triggering not required but okay if it does (acceleration greater than 25g but less than 35g for any duration). Note: The specification also required that if the acceleration was greater than 35g for longer than 1.5s, the detector output should be a constant logic high level. This requirement however was not tested during the final customer acceptance test. Figure 9 shows a DUT on the test rig.

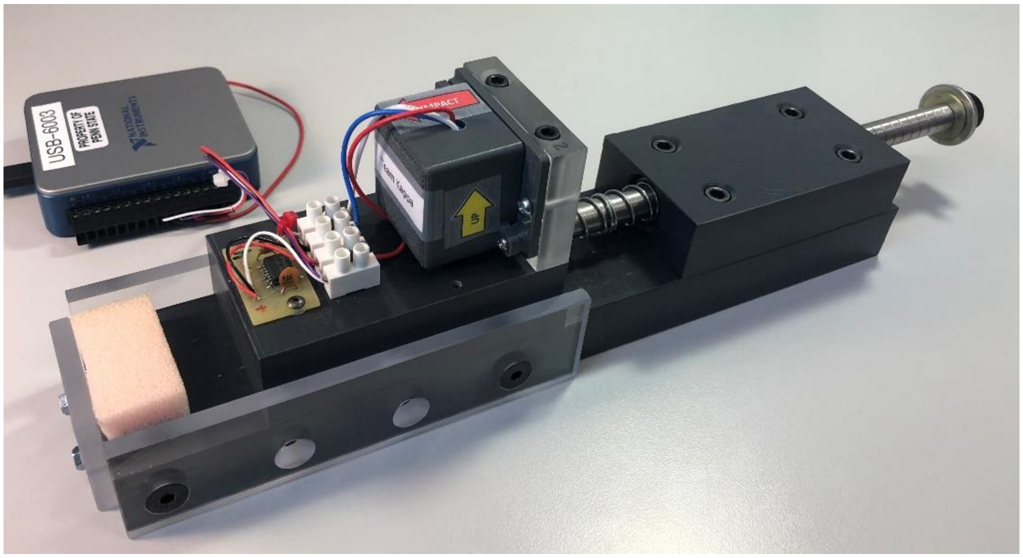

Figure 9. DUT in position on test rig

The output of the DUT and the reference accelerometer were measured during the impact testing with a USB data acquisition device controlled by custom LabVIEW software. Figure 10 shows a connection diagram for the impact test. Figures 11 and 12 show the front panel of the custom LabVIEW Virtual Instrument (VI) used to control the test data acquisition and displaying examples of measured data for various impact acceleration profiles.

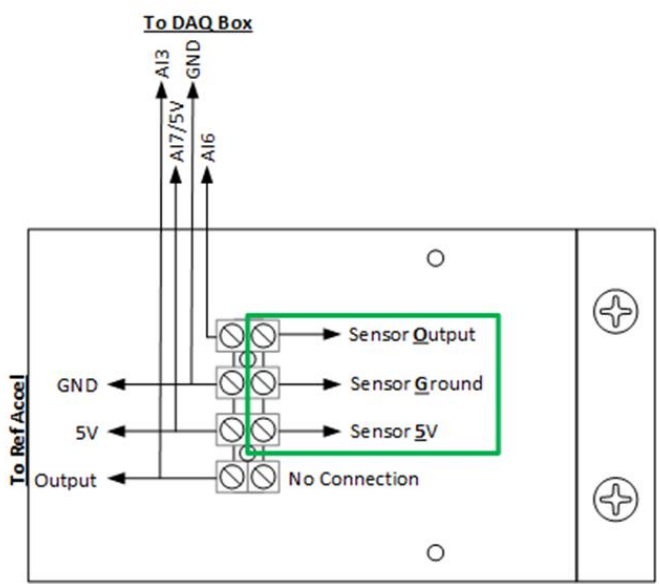

Figure 10. Impact test fixture connection diagram.

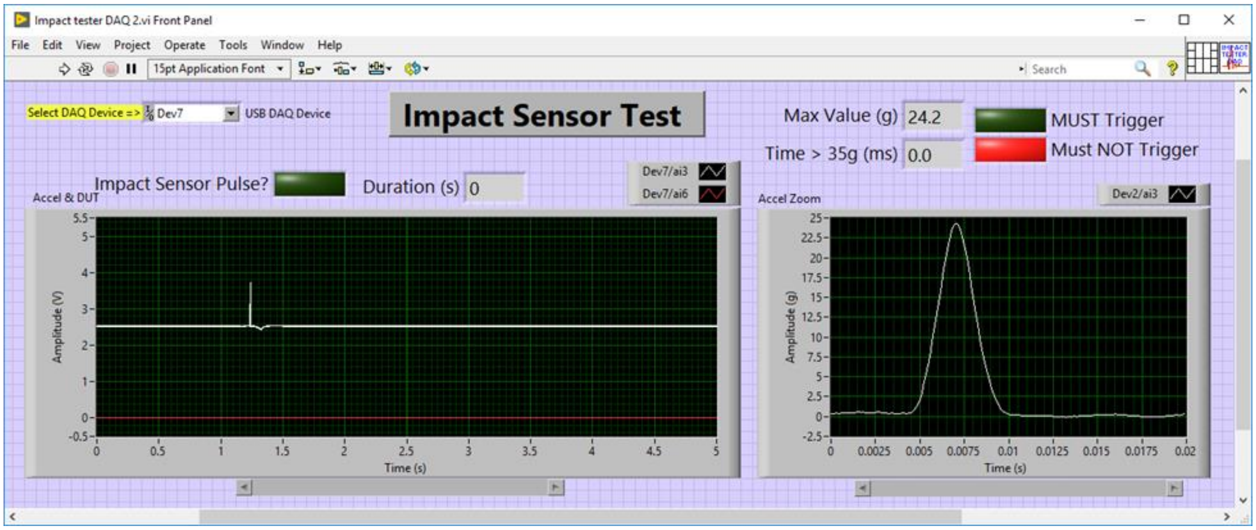

Figure 11. LabVIEW VI front panel for impact test showing "Must NOT Trigger" condition.

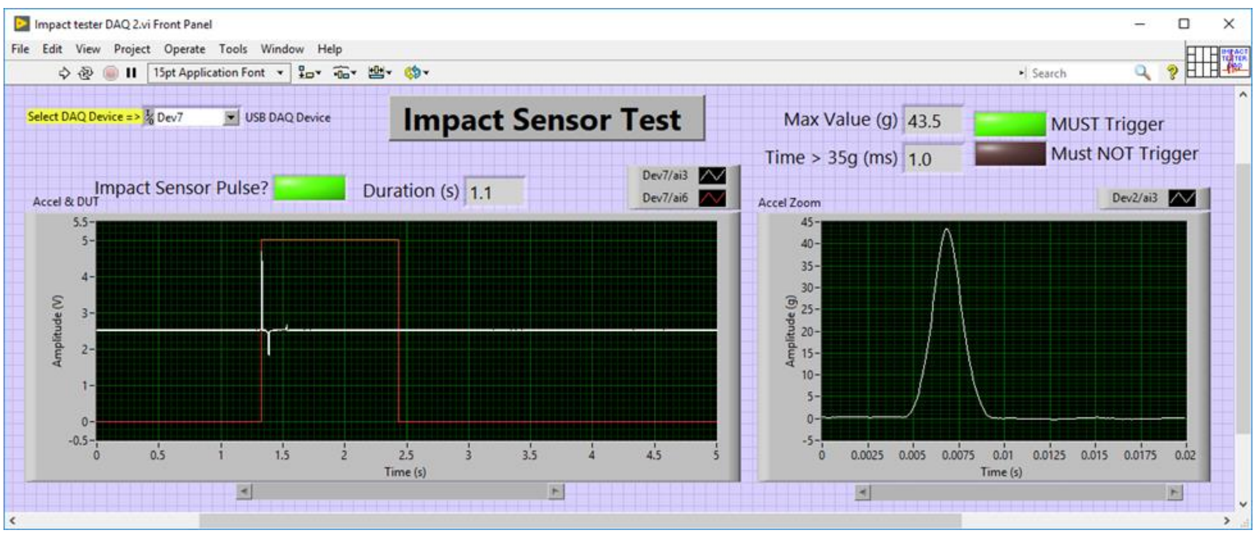

Figure 12. LabVIEW VI front panel for impact test showing "MUST Trigger" condition.

Conclusions

The impact detector project provided the mechanical engineering students with hands-on experience that they had not previously encountered. For some students, it was the first time they had used a hand drill or soldering iron. The project also served to highlight many aspects of the course and show how these concepts can be combined to create an actual useful device.

The instrumentation and measurement course supports the following student outcomes for the mechanical engineering program:

b. Students have an ability to design and conduct experiments, as well as to analyze and interpret data.
g. Students have an ability to communicate effectively.
j. Students have a knowledge of contemporary issues.

At the beginning of the semester it was stressed that part of the grade for the project requires that the team *must* produce a functional prototype. This requirement was certainly a factor in some of the risk-taking decisions made by the teams. Although there were several technical difficulties encountered throughout the semester, by the final week of class, *all teams* had produced a working prototype.

Although most of the prototypes were not suitable for manufacturing production, the project still provided valuable experience with the design process. The students became familiar with reading and interpreting a specification document which is very different from simply solving a homework problem on paper. The students also learned how to develop tests to show that their prototype met the specification.

The actual functional test using the impact driver provided a bit of a "wow factor" for the students in a few ways:

1. Seeing their design colliding with a spring-driven steel rod added a little excitement to the process.
2. Realizing that 40g, which may seem like a large acceleration, is really not that big.
3. The anticipation of the testing, and that part of the grade for the project relies on it working perfectly in the presence of the customer, created a level of real-world pressure followed by, hopefully, real-world relief.

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