The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #43091

Tilt Sensor Design Project Raises Awareness of Rollover Accidents and their Prevention

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Abstract

Mechanical engineering students at Penn State Berks were tasked with designing and fabricating a single-axis tilt sensor to meet a detailed specification. The device was intended to be used in a system to alert an operator or automatically intervene to prevent an impending rollover condition of farm and garden equipment such as tractors and riding lawnmowers. 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 tilt sensor. A major requirement was the tilt angle limits that *must* trigger the device and the range of angles that must *not* cause the device to trigger. The device must also ignore short duration tilt transients to avoid nuisance alerts. Another important requirement of the sensor is that it must fit inside a prescribed plastic box enclosure. The enclosure is mounted to a rotating fixture for testing. The fixture is driven by a stepper motor to produce the required static and transient tilt angles. The teams must develop a detailed test procedure to document the compliance of their design with the specification. Faculty and staff developed the custom test fixture 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 tilt sensors designed by the students are presented. The custom test hardware and software are also presented and discussed.

Motivation and Introduction

Riding lawn mower rollover accidents, commercial and residential, cause many injuries and deaths each year in the United States. [1-3]. The rural student demographic of the campus is an appropriate cohort for a project to raise awareness of this real hazard. Devising a solution for the problem serves as motivation for the project.

Passive indicators are commercially available for installation on landscaping, recreational, and off-road equipment. [4] Figure 1 shows a simple rolling ball inclinometer mounted to the dashboard of a garden tractor.

Figure 1. A passive inclinometer installed on a garden tractor.

A passive inclinometer can provide valuable feedback to the equipment operator if they are actually looking at it. In this student project, an *active* tilt sensor is required such that action can be taken to help *prevent* a rollover condition. The sensor would provide tilt limit threshold information to a monitoring system that could be used to stop the motion of the equipment or at least provide an alarm, perhaps aural, visual, or both, to the operator.

The tilt sensor project was part of a third-year instrumentation and measurement theory course in a Bachelor of Science in mechanical engineering program. The project was implemented to provide the students with exposure to mechanical and electrical design, fabrication, and test. The benefits of which are well known [5], [6]. It also introduced documentation techniques and methods used in industry.

The salient requirements of the tilt sensor are as follows: 1. Provide an output that causes a switch closure to ground when subjected to one-axis tilt angles in the range of 15 to 25 degrees with respect to horizontal in either direction (must not be active at 15° and must be active at 25°). 2. The output must be an open circuit for tilt angles up to 15 degrees in either direction. The state of the output is not defined for angles exceeding 25 degrees in either direction (just to simplify the design). Note: these ranges and limits are typical but are not specific to any particular application or equipment. Figure 2 shows the tilt angle definitions with respect to the project enclosure.

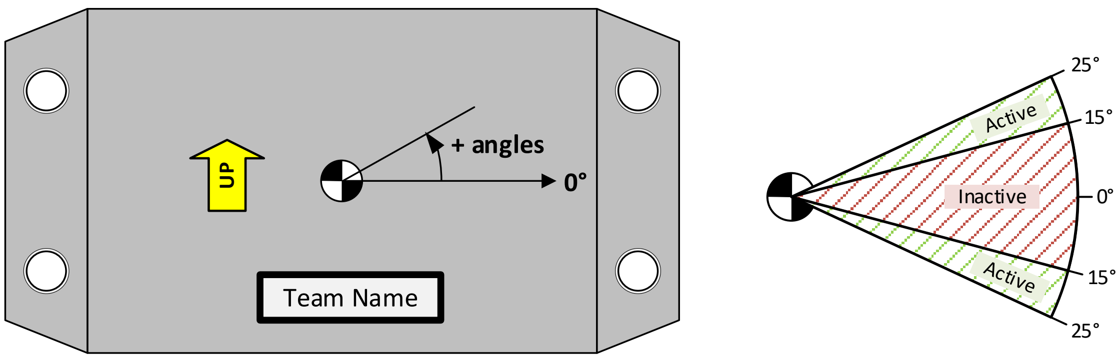

Figure 2. Project enclosure drawing and tilt angle definitions.

To also include some realistic aspects associated with this application, a transient performance requirement was imposed. This requirement was to simulate normal rocking and bouncing of the equipment that would be encountered even on flat terrain. These transients should be masked to help eliminate nuisance false triggering of the rollover avoidance system. The transient tilt profile is shown in Figure 3.

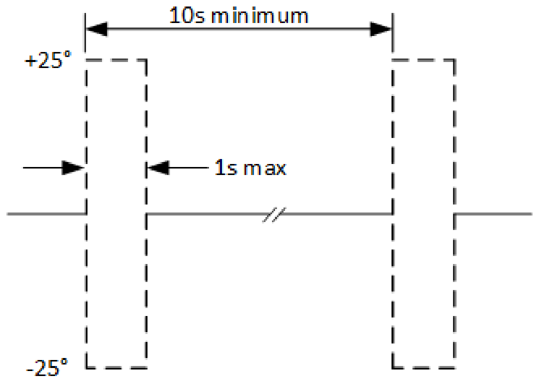

Figure 3. Tilt angle transient timing and magnitude profile.

The students were given a specification document that detailed each aspect of the device they were to design and build. The document is written in much that same manner as would be found in industry with each aspect of the device described by a numbered paragraph and/or subparagraph. A summary of the specifications is given in Table 1.

- Tilt angle limits for active output (must be active): -25° and +25°
  - Active output is ground closure (less than 0.5V when connected to 5V source through 1kΩ)
- Tilt angle range for inactive output: -15° to +15°
  - Inactive output is open circuit (greater than 4.5V when connected to 5V source through 1kΩ)
- Output state is undefined for all other tilt angles.
- Active mounting direction provided via drawing.
- Maximum total weight: 90 grams
- Must fit inside enclosure: 3.1” x 2.1” x 1.2”
- Device operating power supply voltage: +5 VDC ± 0.25 VDC
- Maximum power supply current: 50 mA
- Transient Test
  - Output signal must remain inactive for transient tilt up to 1s in duration and up to 25° in either direction. The transient may repeat every 10s.
- Part marking to indicate “UP” direction.
- Part marking to indicate team name.
- External connection wires #26 - #22, 6 ± 0.5 inches long
  - +5V wire shall be red.
  - GND wire shall be black or blue.
  - Output Signal wire shall be white or yellow.

Table 1. Summary of tilt sensor requirements

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 tilt sensor project include the following:

- First-Order Transient Response
- Second-Order Transient Response
- Essential Electronic Components
- Uncertainty Analysis
- Test Equipment Setup and Use
- Standard Test Methods
- Data Acquisition Hardware and Software

Methods

Students worked on the project in teams of three. Each team received a modest budget of $30 not including the prototype enclosure which was provided. Milestones were set throughout the semester to help keep them on track for success. The following milestones were set:

- Preliminary sketch and bill of materials.
    - Preliminary submissions were reviewed by faculty and the teams were given feedback to improve their design or methods.
- Refined design and detailed bill of materials.
    - Teams were required to select parts from limited sources.
        - Newark
        - Digi-Key
        - Amazon
    - Department staff ordered parts and prepared kits
- Demonstration of prototype operation
- Submission of final report

The teams selected a variety of designs to implement the tilt sensor function. Examples of the designs are shown in Figure 4. Some teams opted to try a pendulous magnet with Hall sensors to detect the angle of swing (Figure 4a) Other designs implemented a rolling metal ball in a clear plastic tube with photo-interrupters at either end of the ball travel (Figure 4b). Other teams selected a pendulous mass with electrical travel-stop contacts at the appropriate angles (Figure 4c and 4d). Still other teams elected to use an accelerometer and a microcontroller to achieve the design requirements (Figure 4e).

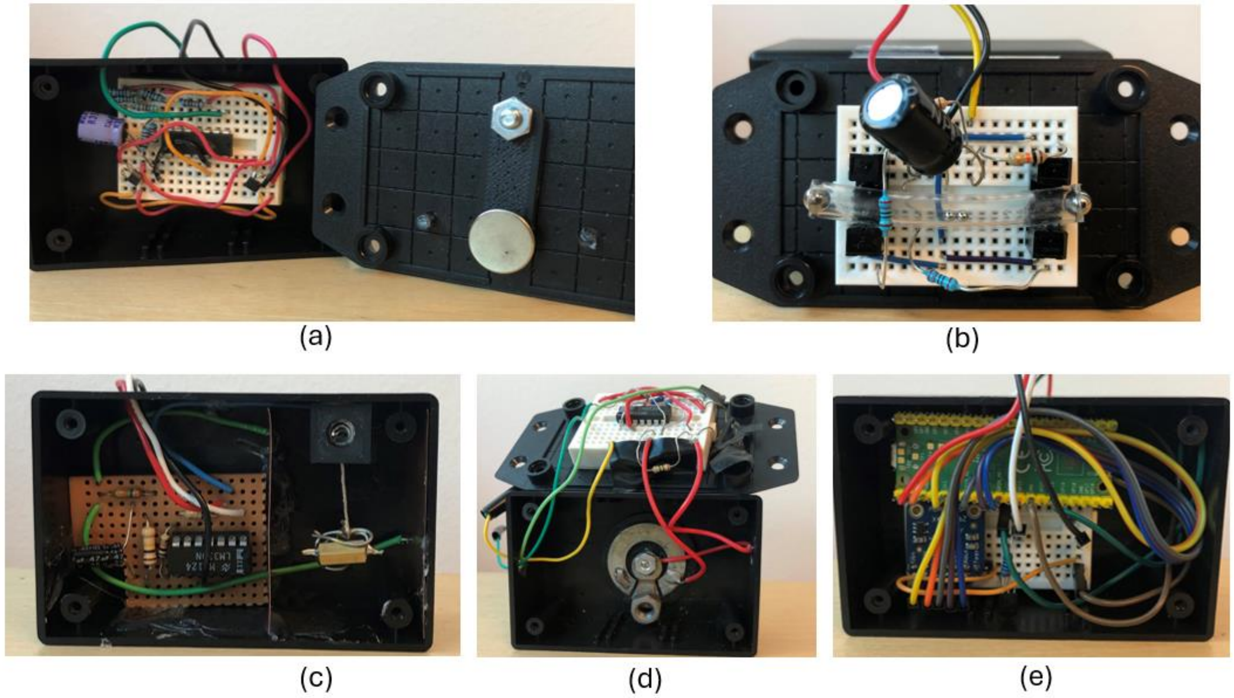

Figure 4. Examples of tilt sensor design methods.

To meet the transient performance requirements, the action of the tilt angle sensing or its output needed to be delayed. Some teams were hoping that the combination of pivot friction and inertia of their swinging mass would be sufficient to meet the transient tilt suppression. Some teams using swinging magnets were able to implement a copper sheet to provide eddy current damping to slow the motion enough to meet the specification. Teams with rolling balls in tubes attempted to use damping fluid with some success.

Several teams, however, opted to use an electronic circuit to delay the output response. The integration of electronics into sensors such as this provides valuable cross-discipline experience [7]. Figure 5 shows a simple resistor-capacitor charging circuit with a comparator that some teams used to achieve the desired delay. R1 and C1 were chosen such that it took about one second to charge from zero to the reference voltage. R2 was chosen much larger (about x10) than R1 such that C1 could discharge in order to reset for the next event. The circuit was assembled using a solderless board that fit into the enclosure.

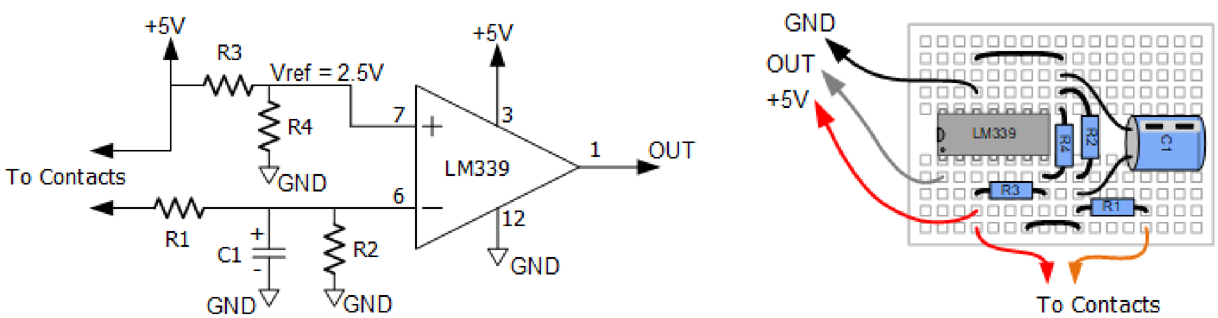

Figure 5. Suggested circuit and layout for electronic delay of sensor output signal.

Testing and Calibration

The teams were able to test and calibrate the static performance of their designs using a simple digital “bubble” level. The accuracy of these instruments was more than sufficient for the tilt sensor testing and calibration. Figure 6 shows a student prototype being tested on a digital level.

Figure 6. Static testing of tilt sensor using a digital level as tilt angle reference

The sensor electrical interface for initial static testing was realized using a lab power supply and a terminal block to hold the discrete components. An LED was used to indicate the state of the sensor output signal. The test circuit connection diagram is shown in Figure 7.

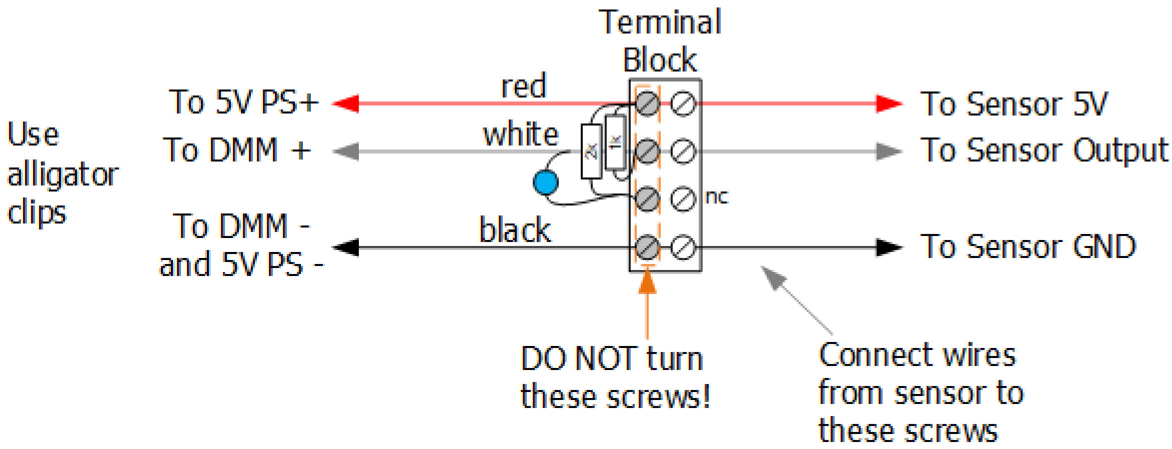

Figure 7. Tilt sensor manual test connection diagram.

If the prototype performed satisfactorily using the manual test setup, the teams could then use the transient test fixture to test the transient performance of their design. The transient test fixture utilized a stepper motor (0.9°/step) to produce a reliable and repeatable transient angle profile. The stepper motor and associated motor driver are housed in a metal enclosure as shown in Figure 8. The enclosure is positioned such that the motor shaft protrudes horizontally. An aluminum mounting bar was fabricated and attached to the shaft. Five duplicate test fixtures were fabricated.

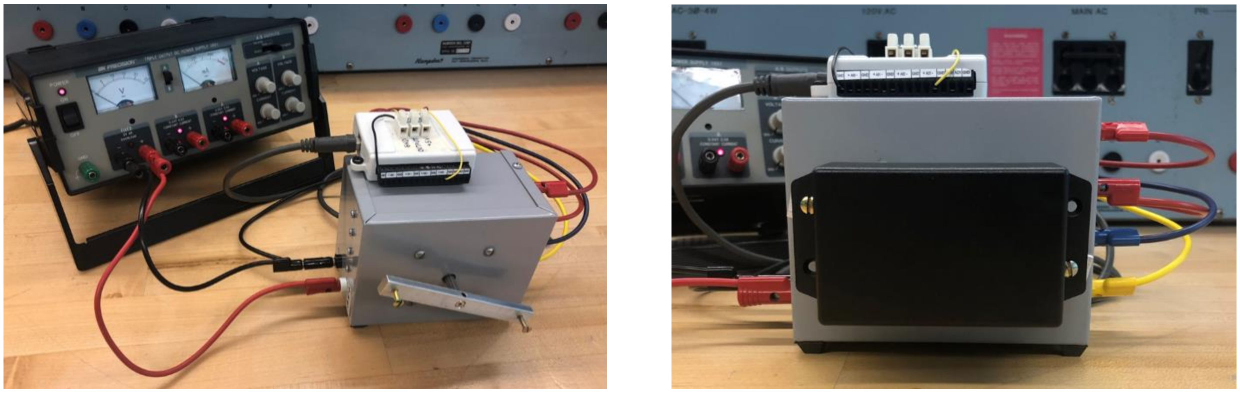

Figure 8. Transient test fixture with and without a unit under test connected.

The stepper motor drive signals originate from an NI USB-6009 data acquisition (DAQ) unit. The timing of the signals is sufficiently slow that it can be generated in computer software. NI LabVIEW was used as the controlling software. For the transient tilt test, the software generates 27 steps of 15ms each, pauses 190ms, then generates 27 steps of 15ms each to return to zero tilt. The DAQ unit also simultaneously measures the output signal from the unit under test looking for any glitches to occur (glitch = fail). Figure 9 shows the LabVIEW user interface (front panel) created for controlling and monitoring the test setup. The connection diagram for the DAQ unit, stepper motor, and the device under test (DUT) is shown in Figure 10.

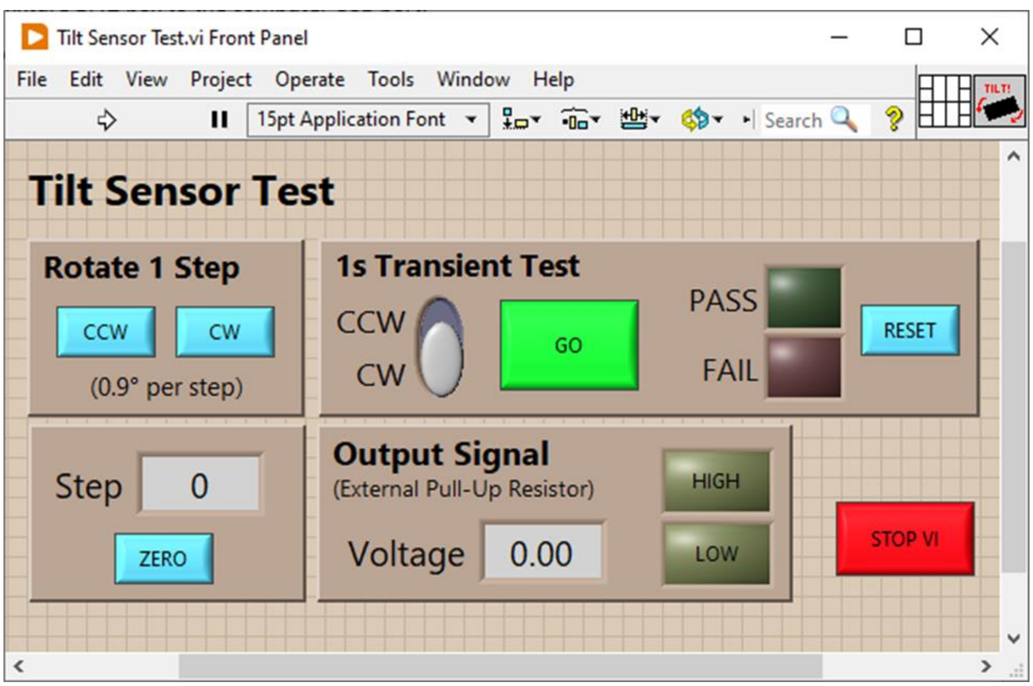

Figure 9. LabVIEW user interface for the tilt sensor test setup.

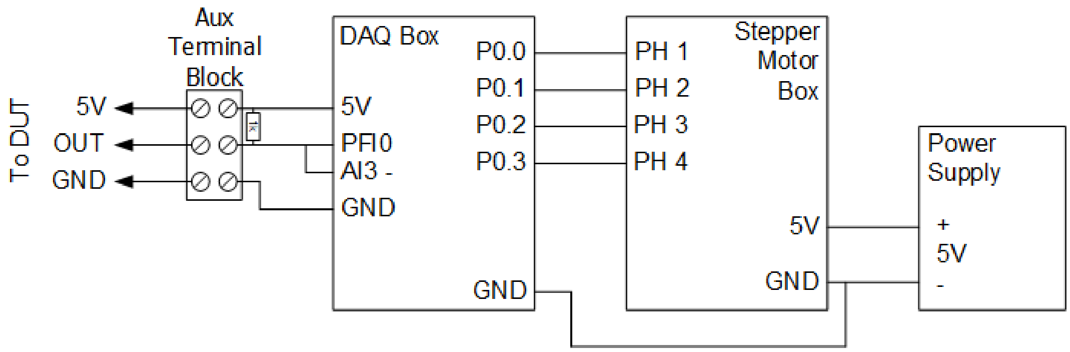

Figure 10. Connection diagram for the stepper motor - driven test fixture.

Customer Acceptance Testing

Each team was required to demonstrate the performance of their design for the “customer.” Course faculty played the role of the customer. The faculty emphasized that it does not matter if the prototype worked previously, it must work at the time of the demonstration.

Customer acceptance testing was performed with the protype mounted to the computer-controlled test fixture that was used to test both static and transient performance. The fixture could be driven one step at a time (0.9°) to test the static performance of the tilt sensors.

Stations were set up in the laboratory for various other required tests to be witnessed by the customer. The prototypes were each weighed as shown in Figure 11. The input current drawn from the 5V power supply was measured. Connecting wires were inspected for proper color length. The prototype part marking was also inspected for specification compliance.

Figure 11. Prototype tilt sensor being weighed.

Results

Twelve teams created a prototype tilt sensor. The sensor produced by eleven of the teams successfully passed the static angle tests. Of these eleven teams, only one team's device did not pass the transient tests. Some of the designs exceeded the maximum weight requirement due to excessively large pendulums or copper eddy current plates. All of the working prototypes passed the maximum input current test. Part marking and wire requirements were met by most of the teams although neatness was a recurring problem. The documentation produced by the teams showed a fairly good attention to detail.

The design teams were all aware of the requirement to produce a *working* prototype. Despite allowing a very conservative timeline, some teams delayed beginning construction of their device, including the team that did not produce a working prototype.

During the customer acceptance testing, the laboratory was alive with student activity. Students made last minute adjustments to their designs. Teams shared equipment, materials, and ideas as they scrambled to meet the deadline. There was a great deal of anticipation and excitement as each device was tested.

Conclusions

The tilt sensor project provided hands-on experience for mechanical engineering students that they had not previously encountered in college. For some students, it was their first experience with hand tools. 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. Working in a team of three students also presented communication and negotiation challenges.

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.

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.

Farm and lawn equipment rollover accidents are a serious problem. Equipment operator awareness of the potential for a rollover may help to prevent some accidents. The tilt sensor project exposed a small group of future mechanical engineers to the accident threat. Widespread adoption of tilt sensing and rollover avoidance systems may never happen, but the problem does present a suitable motivation for inspiring new ideas to be explored.

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