

Simplified Overturn Stability Monitoring of Agricultural Tractors

C. I. Nichol, H. J. Sommer III, D. J. Murphy

ABSTRACT. *Agricultural tractors are the most common source of farm work fatalities in the U.S., with overturns the most common type of incident. For the year 2001, there were 15 tractor-related fatalities in Pennsylvania, 9 of which were due to tractor rollover. A new device using low-cost sensors and microcomputers was developed around a simplified mathematical model of an agricultural tractor to inform the operator of potential tractor instability. This device communicates the current rollover potential, along with a recent history of rollover potential, to the operator of the tractor via a simple bar-graph display. The device uses a single-chip accelerometer to sense the current rollover potential and a small microprocessor to analyze the accelerometer data, compensate for variations due to temperature, and then send this information to a visual display. The use of these low-cost "off the shelf" components enabled the fabrication of a very inexpensive sensor system. Because agricultural tractors have a long service life, it was important to make the device low cost and flexible. This could enable it to be sold as an aftermarket add-on for a variety of tractor models. The device is also capable of interfacing with newer on-board tractor systems via a CAN bus to make it more attractive to tractor manufacturers who may want to incorporate this device into new models. Work is continuing on the development of an improved display to inform the tractor operator of possible instability, including display ergonomic studies, investigation of threshold levels for alerting an operator of potential instability, and investigation into audible warning signals.*

Keywords. *Accident prevention, Agricultural tractor, Tractor operator education, Tractor overturn, Tractor rollover.*

Agriculture is the second most dangerous industry in the U.S. after mining and quarrying. Tractors are the most common source of farm fatalities, accounting for just over one in every four (Myers, 2003; NSC, 2001). Every year in the U.S., tractor-related incidents kill approximately 210 farmers (Myers, 2003). In Pennsylvania from 1995 to 1999, there were 102 tractor-related fatalities. The tractor overturned in 60 (58.8%) of these cases (Murphy, 2001). For the year 2001, there were 15 tractor related fatalities, 9 of which were due to tractor rollover (Murphy, 2002).

While a more experienced tractor operator may have developed an intuitive feel for which situations are dangerous, or what terrain may be too steep at certain speeds, there is a large group of young and inexperienced farm workers who have no formal training in safe tractor operation. These inexperienced operators may be placing themselves in

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dangerous situations without fully understanding the inherent danger. The situation we are trying to avoid was described best by Murphy and Johnson (1984):

“As an example, a tractor operator is baling hay with a large round baler. He is operating the tractor at 6.4 km/h (4 mph) on ground that starts out with a 5% slope at the outer edges of the field. The windrows on the outside of the field are sufficiently rounded, so he hasn’t had to slow down to make turns. But as he moves toward the center of the field, the slope has gradually increased to 20% and the turns have grown slightly tighter.

“He hasn’t cut his speed yet, but he has noticed that there is less time to correct his steering after the turn to stay on the windrow. On the next round, a narrow rise, where the inside rear tire travels, raises the slope to 23% and the turning angle is tightened once again. Unbeknownst to the operator, the slight increase in slope, decrease in radius, and constant speed put his tractor right on the brink of overturn.

“As he starts into the turn of this new round, the operator, from previous experiences, senses that he needs to slow down. But just as he reaches for the throttle, his eye catches sight of a groundhog hole that the front wheel is about to drop into. The presentation of this new bit of stimuli causes the slightest hesitation as it is transmitted to the brain and analyzed. Almost instinctively, the operator quickly yanks the steering wheel tighter to avoid the hole. This final act results in the tractor rolling over” (p. 16).

The focus of this research is to develop a system capable of informing the tractor operator of the stability of the tractor as it is operated. In the situation above, if the operator had some feedback concerning instability, he could have corrected the situation before it became too late. Although situations may vary from that described above, if the operator knew the stability limits of the tractor during operation, then situations that are near the point of rollover, or that are inherently dangerous, could be avoided. In general, such a system would allow the operator to avoid dangerous situations, identify a potential or impending rollover, and return to safe operation. Most importantly, this stability monitoring system could teach the operator what situations are dangerous by presenting a visual measure of stability that the operator could internalize with his own perceptions.

Objectives

The objectives of this project were, first, to develop a low-cost device capable of sensing impending rollover and reporting this to the tractor operator. Because it must be inexpensive enough that it could be purchased as an aftermarket add-on device for an existing tractor, a target price was set at around \$50.

Second, because only approximately 50% of farm tractors are equipped with a ROPS, the sensing device should be flexible enough to accurately predict rollover potential for various tractor makes and models.

Third, the display should allow the tractor operator to learn from the device as the tractor is operated under different situations. This means that the display should be able to show the recent history of stability values encountered over the last few seconds of operation. Such a display should be intuitive, so that the information conveyed is easily understood to reinforce the potential severity of the current situation.

Last, the device should be able to communicate the rollover instability information over a controller area network (CAN) bus.

Device Design

Model Used

The majority of the mathematical models that have been developed for the prediction of farm tractor overturn are very complex. While these complex models have potential

application in tractor and ROPS design, they become unwieldy when the problem of real-time stability evaluation is considered.

In addition, as stated above, a major objective of this project was to develop a device that was low cost. Many of the existing mathematical models would have required a complex, high-level microprocessor and several instrument-grade measurement devices. This would have increased the cost considerably, which was deemed unacceptable for this project.

For this project, a simplified quasi-static model was used. The model used measures only acceleration near the CG in one direction, parallel to the rear axle. The arcsine of this acceleration is then compared to a static hill roll angle. The static hill roll angle is taken as the hill slope angle at which a tractor, placed on a hill with the rear axle parallel with the fall line, would experience zero force on the uphill tire. While this model is very simple, it takes into account any acceleration due to gravity and the centrifugal acceleration caused by turns. It also measures any lateral gravitational acceleration resulting from a dynamic increase in tractor roll angle due to large bumps. This is similar to the sensing method used by Powers et al. (2001) for an automatically deployable ROPS.

System Overview

Informing the tractor operator of impending rollover as described above requires a system that is capable of first sensing a potentially unstable attitude of the tractor and then conveying this information to the operator. These two parts of the system will be discussed separately.

Sensing Device

The sensing device incorporates an accelerometer to sense static and dynamic accelerations and compute the angle at which the tractor is operating. This information is then processed by a microprocessor, and an assessment of rollover potential is reported to the display device. Figure 1 is a block diagram (Jaar, 2002) showing the CAN bus, microcontroller, and other components.

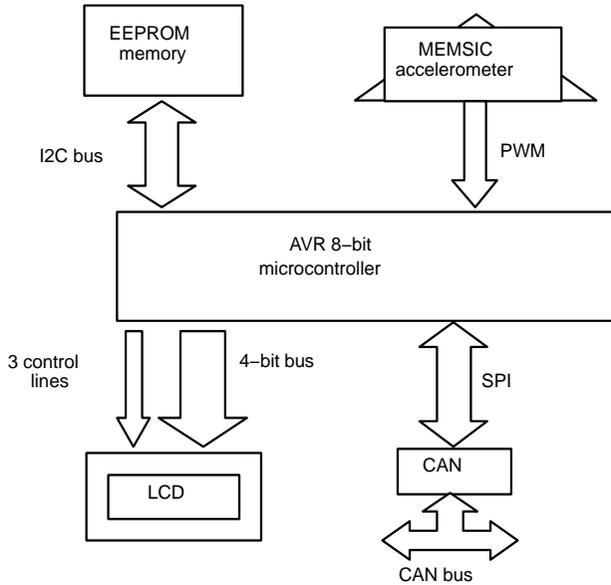


Figure 1. Block diagram of the third iteration of the sensing device.

For the purposes of testing and evaluation, the sensing device was also capable of storing information using an EEPROM chip. An LCD module was incorporated into the device to facilitate development.

A MEMSIC dual-axis thermal accelerometer (MXD2020U, MEMSIC, Inc., North Andover, Mass.) was selected for the project. This accelerometer is very small and is capable of sensing static and dynamic accelerations. It has an operating range of ± 2 G, and the manufacturer states sensitivities of up to 2 mG. This accelerometer is packaged in a very small, square, 8-pin TSSOP package. It retails for \$9.25 when purchased in quantities over 100. These features make it well suited for this application.

A microprocessor (AT Mega 163-10SI, Atmel Corp., San Jose, Cal.) was used to measure the signal from the accelerometer and process the information. Although the PIC microprocessor family from Microchip Technology, Inc., has a comparable processor that would have been equally capable of accomplishing the tasks, and at a comparable price, the Atmel microprocessor has many features that were more desirable. This microprocessor retails for \$11.29 in small quantities and for \$7.67 in quantities over 100.

The CAN controller (MCP2510, Microchip Technology, Inc., Chandler, Ariz.) monitors the CAN bus, filters incoming messages, and communicates these to the host microprocessor. It also receives messages from the host microprocessor, formats them for transmission, and transmits these on the CAN bus. The CAN transceiver (SN65LBC031D, Texas Instruments, Inc., Dallas, Texas) converts the two wire differential voltage levels on the CAN bus to TTL levels for the CAN controller, and vice versa.

A 128-kbit EEPROM chip was also included in the device for storing a small burst of data during testing. The microprocessor communicates to the EEPROM chip via the I2C serial data communication bus. After a tractor overturn test, the stored data is communicated to a PC. The information is downloaded over the CAN bus into the PC and stored in a text file for later evaluation.

Display Device

The display device presents a short-time history of roll angle encountered over the last 15 seconds to give the operator a chance to react and later inspect what level of potential instability was encountered. This task was accomplished with a matrix of tricolor LEDs. The relative stability state of the tractor is displayed as a bar of varying height and color, which moves from the left side of the display to the right as new values are acquired and placed on the left. When the state of the tractor passes a specified threshold, the bar turns yellow. The bar turns red to indicate a potential rollover situation. During operation, the tractor operator can monitor the state of tractor stability and learn what situations are near rollover. Because the tractor operator's attention is often diverted elsewhere, the display keeps a record of the last few seconds. When the operator again directs his attention to the display, he can see how near rollover the recent situation was. This enables the tractor operator to develop good judgment as to what situations are potentially dangerous.

There are many ergonomic, cognitive, and psychological aspects to this type of display. The tractor operator may disregard a display that too often indicates a near-rollover situation, while a display that does not allow enough advanced warning will not enable the operator to correct the situation. The threshold levels at which the display indicates a near-rollover condition must be evaluated by observing tractor operators in real or simulated situations to find the optimal values. This was beyond the scope of this project.

Future Production Iteration of the Sensor Device

A production model of the tractor stability monitoring system could be much simpler than specified above. Several of the parts listed above were used to facilitate testing and development. The actual production device need only consist of the sensor device and the display device. Both of these devices could be integrated into one unit to further reduce the cost and part count. Such a production iteration would only need to contain one accelerometer (or more if the mathematical model were expanded to include all of the parameters included by Johnson, 1983), one microprocessor, and the display components (LED matrix and latches). In addition, because the device is capable of being operated on a CAN bus, it is possible for a tractor manufacturer to incorporate it into the final design of the tractor. In such a case, the display device could be integrated into the existing tractor display, and the sensor device would need only consist of the microprocessor, accelerometer, and the CAN bus chip set.

Tractor Testing and Evaluation

Laboratory Validation

After the initial iteration of the device was completed, it was placed on a test fixture on which roll angle could be varied and measured with a SmartTool commercial digital level. The two readings were then compared, and the correctness of the output of the sensor device was confirmed.

Field Validation

For field validation, the box was mounted on a full-scale New Holland TN65 agricultural tractor (fig. 2). This tractor was modified to be completely radio controlled (R/C) and is equipped with a reinforced ROPS. This enables it to be remotely operated and rolled without damaging the tractor. It is also equipped with a separate radio-controlled dead man switch. This allows safer operation by requiring two operators to monitor operation and testing, and provides a failsafe in the event that one of the radio controls fails or one of the operators is hurt.

The R/C tractor was operated on an engineered test hill that was set up to have a slope of 20° and across which the tractor can be driven. The hill contains a bump so that during testing the uphill wheels of the tractor can be driven over the bump to cause rollover, as shown in figure 2. The hill and bump combination are such that the tractor will not roll over unless operated at speeds above 2.5 mph. Tractor speed was evaluated by timing the tractor as it crossed two lines spaced a known distance apart.

During testing, a sample burst of data was recorded. A wireless video camera was also mounted on the tractor to view the display. After field testing, the burst of data was analyzed for maximum roll angle. Figure 3 is a series of pictures showing a typical side overturn. Figure 4 shows the display and sensor devices, and a screen shot of the display. The bars of varying height and color, which represent potential roll angle, march to the right as new data is added on the left.

Results

The device was successfully constructed, as outlined above. It incorporates an Atmel ATMEGA163 microprocessor operating at 6 MHz, connected to a MEMSIC MXD2020UL dual-axis thermal accelerometer. A temperature compensation routine was successfully implemented to account for the sensitivity change and the zero shift with varying ambient temperatures. An EEPROM chip was used to collect the data during



Figure 2. Test hill with bump.

testing and hold it until the device could be interrogated by a PC. The device was originally interfaced with an RS-232 communication chip for interrogation. It is now interfaced with a Microchip Technology MCP2510 CAN controller and a Texas Instruments SN65LBC031D CAN transceiver. It is able to communicate with other devices and can be interrogated by the PC via the CAN bus.

The device is able to correctly measure accelerations in two directions: the “X angle,” defined as the angle between horizontal and the rear axle, and the “Y angle” (perpendicular to the X angle), defined as the angle between horizontal and the tractor chassis. The device is also able to save these measurements for display on the display device and for later evaluation. In laboratory testing, the measure of acceleration and roll angle corresponded very well to known angle values, as verified by in-lab comparisons with a commercial SmartTool digital level on an inclined surface. In field testing, the indications of rollover were found to be accurate.

An example set of data is presented in figure 5. The raw data were filtered by taking the average of six consecutive raw values. This was done to remove some of the noise in the data due to engine vibration.

Analysis of the video footage from the on-board camera revealed that, when the tractor was operated over the bump at a slow speed without rolling over, the display indicated a potential rollover situation by lighting one of the two red LEDs. This signifies a situation that almost resulted in rollover, where the peak angle was between 45° and 50° . In every testing situation that resulted in an overturn, the display indicated the condition by lighting both of the red LEDs, corresponding to an angle greater than 50° .

The device described here cannot prevent the tractor operator from encountering a potential rollover situation, but it can educate the operator as to how potentially unstable a situation is, and it can allow the operator to vary one of the three critical parameters under his control, i.e., speed, turning radius, and current side-hill operating angle.



Figure 3. Typical side overturn.

Conclusions

As stated by Murphy and Johnson (1984), one way to avoid critically dangerous situations is to present the operator with stability feedback before the critical moment arrives, allowing the operator enough time to react correctly to avoid the situation. The

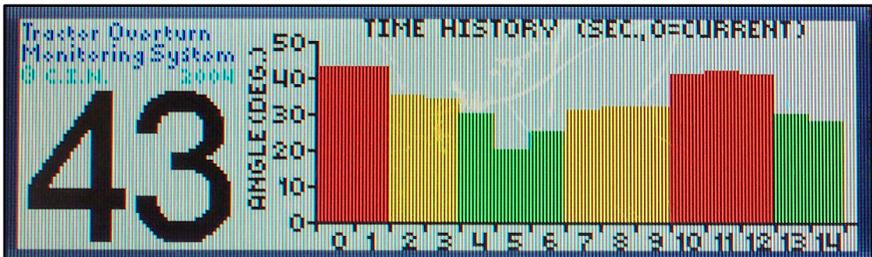
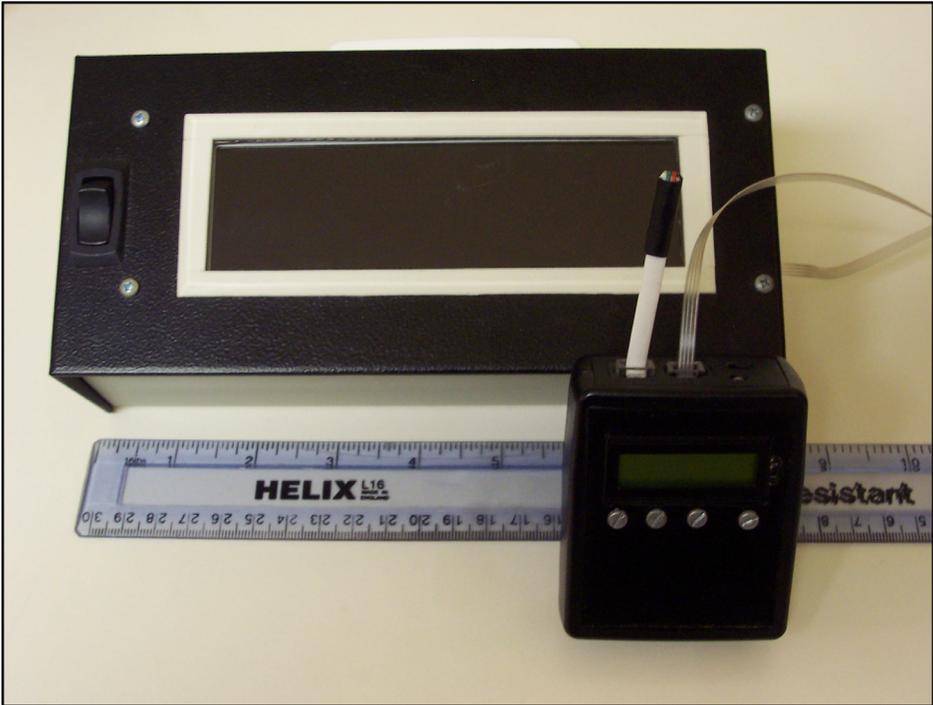


Figure 4. Display and sensor device and example display screen shot.

system developed and discussed in this article has the ability to provide critical information to the operator of a farm tractor about the tractor’s stability on a side hill. This will enable the operator to correct critical variables (such as speed or angle at which a hill is being traversed) before the tractor overturns, as well as teach the operator to recognize what situations are potentially unstable.

The system developed here meets the objectives stated above. The first objective was to develop a low-cost device capable of sensing potential rollover and reporting this to the operator. The system has a total projected cost of under \$50 when produced in large quantities.

The second objective was to develop a device that could be retrofitted to an existing tractor. It should be flexible enough to accurately predict rollover potential for various makes and models of tractors, and it should also be small, so as to not impede any of the function of the tractor on which it is used. The sensing device developed can be easily

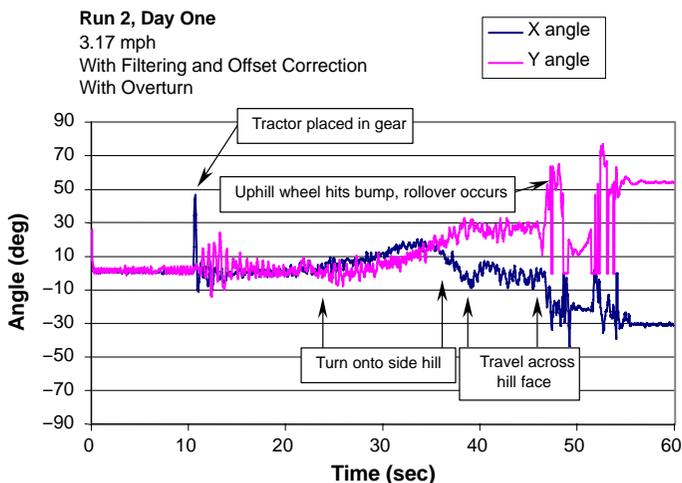


Figure 5. Example data set.

reprogrammed to predict rollover based on any range of critical quasi-static hill angles. Its dimensions are only $2.54 \times 7.62 \times 6.35$ cm ($1 \times 3 \times 2.5$ in.) including a 9 V battery. The actual device, if run on the existing tractor electrical circuit, could be packaged in roughly half the stated size.

The third objective was that the display should be such that the tractor operator can learn from the device as the tractor is operated in different situations. The display was designed to communicate in an easily understood format. It displays peak critical angles for the current situation as well as a short record of historical peak values, as described earlier and shown in figure 4.

The last stated objective was that the system should be able to communicate on a CAN bus. The system can communicate on a CAN bus, enabling it to communicate with other devices on the bus. This would enable tractor manufacturers to incorporate this device into new tractor designs as standard equipment. It could also be incorporated into other existing safety devices on the tractor or into an existing display module.

The system that has been developed is flexible. The technologies can be added to, and the system can be expanded to incorporate more measurements, utilize a more complicated mathematical model, or interface with an array of other devices.

Recommendations

Future research should focus on the following areas. First, work should be done to further develop the display and user interface. It is very common in farming operations for the tractor operator to focus on the implement being towed. This means that the operator is turned around, looking back at the implement, for a large portion of the time. Because the operator is not always looking forward, it is not possible to closely monitor the information presented on the display. This necessitates the addition of an audible signal that would alert the operator to a potential rollover situation, even when the operator is not paying attention to the stability indicator or when the display is not in the operator's field of vision.

The second area for future work concerns the effect of attaching a farm implement to the tractor. There has been little research done in this area. The work done by Spencer

(1978) showed that attaching an implement to a tractor has a significant effect on the tractor's stability. The device discussed in this article is incapable of adjusting to the changes in tractor handling and stability due to the addition of an implement. Research should focus on the effect of various implements on tractor stability and on how to detect the presence of different types of equipment. This information should be accessible to the sensor device, and the device should be able to use the information to adjust the critical parameters in its model to correctly predict overturn. In conjunction with this work, there needs to be an extended field evaluation. Such research would help to establish normal operating conditions for tractors as they are used with implements.

A third area for future work would be to integrate this device with a cell phone and other electronic devices, such as a GPS receiver. The purpose of this would be to contact emergency response personnel in the event of an overturn. This could result in a quicker and more efficient response by emergency personnel, which may save lives or improve the recovery time for non-fatally injured victims.

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