AGRICULTURAL TRACTOR OVERTURN MITIGATION VIA AN OPERATOR ALERTING SYSTEM AND ACTIVE INTERVENTION

A Thesis in
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by
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Abstract

A system was developed to sense proximity to side overturn for an agricultural tractor. This system was tested, and a statistical analysis was performed on the collected data.

The system was augmented with the addition of rate gyros and the augmented system was able to intervene and prevent simple rearward overturn events.

A display was also developed to communicate information to tractor operators. The development of this display included a study of existing display technologies, recent research into automobile collision avoidance systems, and a survey of agricultural tractor operators.

The results of the research show that this system can correctly predict side overturn, and can sense and intervene to prevent rearward overturn. It is found that this information is best communicated to the operator by means of an audible alarm and a visual display.

Work is also presented on development of a similar system for four-wheel all-terrain vehicles (ATV). Proposals are made in regard to the development of a future device for ATVs.
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Introduction

Agriculture is one of the most dangerous occupations in the United States. In 2002, 730 of the 4,900 workplace fatalities (roughly 15%) were in agriculture [Hal05]. In the state of Pennsylvania from 2000 to 2004 there were 135 farm-related fatality incidents, roughly 4.6 fatalities per 10,000 farms [MK05]. Records show that in roughly 40 of these, a tractor was the primary cause of the fatality, and the tractor overturned in roughly 23 of the cited fatalities [MK05].

As agriculture continues to expand, new marginal terrain that is now being farmed is becoming steeper and steeper. 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. Concomitantly, these inexperienced operators may be placing themselves in situations that are dangerous without any way of knowing the inherent danger.

Efforts to reduce the number of tractor related fatalities have been widely varied, from educational programs to government mandated safety equipment. Beginning in 1975, OSHA adopted a regulation to require a Roll Over Protection Structure (ROPS) on any tractor manufactured after 1976, and operated by a farm employee. The effect of this regulation was limited, and OSHA was prevented from enforcing it on farms with less than 11 employees [Mye04]. In 1985 tractor manufacturers agreed to sell only tractors equipped with a ROPS. As of 2002 roughly 50% of tractors in use on farms were equiped with a ROPS. These structures have been proven effective in preventing injury and fatalities in the event of overturns.
Given that such technology exists and is effective, E. Hallman [Hal05] discusses why so few older tractors are equipped with ROPS.

Because agricultural tractors are designed to have a long service life, there are and will continue to be a large number of farm tractors that are simply too old to be equipped with a ROPS. Tractors designed and built prior to the 1960’s were not designed with sufficient strength in the chasis and axles to allow effective retrofitting with a ROPS [Hal05]. Cost is also a concern with ROPS retrofitting. A ROPS retrofit for a tractor can vary from around $400 to $3,500. A majority of farms (59%) report annual sales of less than $10,000 [Hal05], and for farm owners in such situations, a ROPS retrofit is often seen as simply too expensive.

Hallman went on to attempt to determine what level of subsidy would be necessary to provide sufficient incentive for a farm owner to retrofit a tractor with a ROPS [Hal05]. Participants in the study were offered varying levels of subsidy to retrofit tractors with a ROPS. Of those who chose not to participate, 27% stated that it was too much trouble to retrofit their tractors, while only 13% stated that it was too expensive. Of those who chose to participate, the researchers noted several ”stumbling points” that were encountered in retrofitting a tractor with a ROPS. Many found the price for a ROPS varied widely by dealer for the same model of tractor. While some participants were able to retrofit the tractor themselves, many could not, and then had to transport the tractor to the dealer for installation, resulting in further cost and the loss of the use of a tractor for a period of time. For some of the participants, the process took several months to get the ROPS in stock because the factory would often hold orders until a sufficient number were needed before manufacturing the ROPS. Because of these and other factors, many found the trouble to be greater than the perceived benefit of having a ROPS on their tractors. [Hal05]

A further limitation to the use of ROPS is that while ROPS can be effective, it cannot prevent a rollover. This presents a problem for four reasons. First, if the operator does not wear a seatbelt, the tractor operator may still be injured or killed. A survey of New York farmers showed that seat belts were used for only 33% of operating hours [MC00]. Second, if the tractor does roll, it can damage the tractor or the implement attached to the tractor. Thirdly, overturn can result in lost working hours due to injury to the farmer, and can require the farmer to
hire employees to make up for temporary, or permanent disability. Lastly, tractor manufacturers also recommend that ROPS be replaced in the event of rollover. The end result is that a rollover event is costly and dangerous even with a ROPS in place. One situation we are trying to avoid, or correct was described best by Murphy et al. [MJ84]:

“As an example, a tractor operator is baling hay with a large round baler. He is operating the tractor at 6.4 km/hr (4 mi/hr) 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 puts 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.” (pp. 188)

The continuing focus of this research is to develop a system capable of informing the operator of an impending side overturn, and to intervene in some cases to prevent rear overturn. In the situation described above, if the operator had some monitor of stability to inform him that he was nearing a potentially unstable operating condition, he could have corrected the situation before it became too late. In general, such a system would allow the operator to avoid dangerous situa-

tions, identify a potential or impending side overturn situation and return to safe
operation, and could intervene in rear overturn situations.

This system could also teach the operator to understand which situations are
dangerous by presenting a measure of stability external to the operator’s percep-
tions that the operator could compare to his or her own perception of how steep
the slope is, or how near overturn the tractor is.

Rear overturn events are often triggered by improper hitching, and may be ex-
acerbated by ground roughness, or slope. Because rear overturns are driven by the
tractor wheel torque, they are most often very fast occurrences. Consequently once
an event begins and is recognized by the operator, it is difficult, if not impossible,
for the tractor operator to then take corrective action to stop the tractor from
overturning. Because of this it is important to further develop a sensor system to
be able to sense the tractor’s instability state, and effect intervention to prevent
overturn.

Recent developments in sensor and microprocessor technologies have made
available a wide range of inexpensive sensors and processors that can be utilized
for the purpose of mitigating events such as the one described above.

In conjunction with this research, data was collected during the annual Ag
Progress Days at the Penn State Larsen Agricultural Facility. This is an annual
exhibition at which recent innovations in agricultural equipment are showcased,
along with an emphasis on safety, and community life in agriculture. Part of this
exhibition has included demonstrations on tractor and other agriculture equipment
safety. Actual side and rear overturns of full size remote control tractors have
been demonstrated to the public. Most recently, this demonstration has included
overturn involving a 4 wheel all-terrain vehicle (ATV).

These demonstrations often prompt viewers to approach the demonstrators
and share their experiences with similar circumstances. Although many statistics
are presented above on injury and death resulting from overturn type accidents,
there are surely many such accidents which involve only minor or no injury to
the operator of the tractor, and so are not reported. Evidence of this is provided
by the anecdotal accounts shared by attendees of Ag Progress Days. The most
striking examples of such anecdotes were shared during the 2005 Ag Progress Days
by several people (many under the age of 18) after watching the 4-wheel ATV
demonstrations. Several people approached the booth to share experiences that they had had or witnessed where similar overturn accidents had occurred, some involving injury, but many in which the operator was thrown from the vehicle, or otherwise survived the incident relatively unscathed. While this information is not supported by hard data, it further suggests that there is a great deal that could, and should be done to improve safety for the operators of farm tractors and ATV’s.
2.1 Tractor Stability

Research on the dynamics and stability of farm tractors has been conducted since the 1920’s. McKibben published a series of articles in 1927 entitled “The Kinematics and Dynamics of the Wheel Type Farm Tractor” [McK27]. The focus of his early work was to understand the dynamic response of the farm tractor to external loads, and to develop some tools for tractor design that would result in a more stable agricultural machine. He also analyzed stability against rearward overturn due to fast clutch engagement and high draw-bar location, in which he proposed a device that could stop the tractor from overturning by disabling its vital systems when a specified inclination was reached.

McCormick [McC41] was the first to publish data with respect to side overturn in which he shows the smallest turning radius at a given speed without causing side overturn. His calculations were based on a simple free body and vector sums to find the point at which the inside wheel lifts off the ground.

More recently several mathematical models have been proposed to describe the behavior of a farm tractor. The following is a brief survey of that work.

Koch et al. [KBM70] developed and verified a mathematical model of a farm tractor to predict rearward tipping behavior. In their work they instrumented a farm tractor, and ballasted it such that rearward tipping was easily caused. They showed very good correlation between the predictions of the mathematical model, and the actual field measurements.
Mitchell et al. [MZL72] proposed a method for prediction and control of a tractor during rear overturning. In their paper the stability of the tractor is presented in phase portrait plots where angle vs. angular rate are plotted against each other. In these plots, the delineation between initial conditions resulting in a stable condition and an unstable condition is noted as the separatrix, or the line of minimal stability. This information was then used to construct an analog computer which was given control authority over clutch disengagement via a solenoid and hydraulic actuator. This arrangement and control system was found to be successful in preventing rearward overturning for a variety of scenarios, with the limitation that the model was developed for one specific tractor.

Smith et al. [SPL74] developed a model for describing the kinematics of tractor side overturn. In their paper two tipping axes are described. The first tipping axis connects the hinge point of the front axle to the contact point of the rear tire. The initial tipping motion of the tractor is about this axis. After the tractor contacts the front axle stop a second tipping axis is employed connecting the contact point of the front tire with the contact point of the rear tire. The focus of the paper is to describe the motion of the center of gravity with respect to these two tipping axes. Based on the position of the center of gravity, a stability index is obtained.

Davis et al. [DR74a] developed a very exhaustive mathematical model of the wide front end farm tractor. The model was developed to be able to study a rollover event from the stable operating state, through the point of instability, up to the point when the ROPS strikes the ground. This model has 10 degrees of freedom, and requires the solution of 20 differential equations [DR74a]. This model was then verified and the results of the verification using scale models was presented in a later paper [DR74b].

Spencer and Gilfillan [SG76] developed a statistical method to evaluate tractor stability on rough ground. The proposed method is based on the kinetic energy imparted to the tractor by the roughness of the ground upon which it is traveling. The method used an analysis of static stability, coupled with a statistical probability based on the current ground roughness, that a tractor will be imparted sufficient energy to roll over.

Spencer [Spe78] then went on to consider the problem of stability and control of tractors on sloping ground in connection with a towed implement from another
viewpoint. He contended that in many situations loss of wheel to ground adhesion and not the likelihood of overturn are the limiting factors in the maximum safe slope of tractor operation. In his paper he noted that rollover often occurs as a secondary event, one that is caused by an initial loss of control, followed by an increase of speed of the tractor and implement combination. He then created a model to predict the safe operating slope and cross-hill angle combination. The results predicted by the model were plotted on a polar chart and compared to values obtained from a scale model study. In the conclusions he noted that control loss may not occur before stability loss if the tractor is operated with an implement with a sufficiently high center of gravity.

Chisholm was the next to develop a mathematical model to further study the energy absorbed by the ROPS during impact. His model considered the primary forces that cause roll of a farm tractor as acting in a plane parallel with the rear axles, and perpendicular with the ground. [Chi79b] This model was then verified by full-size tractor testing. The tractor tested was equipped with a safety frame that was instrumented to analyze its overturn and impact behavior. The tractor was remotely driven on a ramp, and rolled onto a surface of known hardness. Although the model was very simplified, he reported good correlation between predicted and observed values. [Chi79a]

Johnson [Joh83] proposed a simplified model in his masters thesis. This model considered the static hill angle, centrifugal acceleration, and ground roughness to generate stability information. Because the three were considered independently, it was possible to report to the tractor operator the relative contribution of each, and hence, the root cause of the impending instability.

Spencer [SOG85] later presented a method for measuring the stability limit of a tractor on site. The method is very simple, and requires that the normal to ground force of the tractor wheels be measured at a few angles. This information is then extrapolated to define the limit of the tractor’s stability. Spencer acknowledged that this method is only valid for a static stability limit, and should serve as an upper bound on the maximum safe operating slope. Experiments were then carried out with tractors and trailers to validate the prediction technique.

Kim et al. [KR87] presented a review of the majority of the mathematical models proposed to date in their paper published in 1987. They point out that
there are several mathematical models that have been developed for prediction of tractor rollover, but note that there exists a lack of experimental data pertinent to these models. They further propose that if automatic safety devices are to be implemented in the future, the results of simulations must be presented in forms that are acceptable for practical use.

Most recently, Liu and Ayers [LA96] proposed the development of stability indices. In their work the effect of static stability and forces resulting from turning are separated, calculated, and then combined into an overall stability index. Their work showed that the stability indices indeed predicted instability at the times of overturn for both side and rear overturn.

2.2 Human Factors

2.2.1 Ergonomics and Warning Systems

Because the system proposed in this thesis is to inform the operator of impending instability, consideration of tractor operators is also important.

Murphy et al. [MJ84] proposed a sensor and information display system for farm tractor overturn mitigation that presented a general relative measure of stability, along with relative levels of several factors that contributed to instability such as steepness of a hill, ground roughness, speed, and turning radius.

Goldberg et al. [GP89] studied the abilities of a tractor operator in dangerous situations. In his paper he discussed operator response times to given external stimuli. These times were found to be too long to provide any real corrective action to prevent a tractor from rolling over once the tractor reaches the critical angle. He also stated that often an operator’s perceptions of the current situation are inaccurate, and are incapable of correctly assessing the proximity to impending overturn. Such factors as fatigue, tractor motion, and the orientation of the tractor operator (rearward facing, watching equipment, or forward facing) play a large role in the operator’s ability to correctly assess safe operating conditions.

Murphy states that the key problem is not that the operator uses poor judgment, but rather, that the operator is unable to properly handle all the pieces of information that are presented at the critical moment. He concludes by stat-
ing that if the tractor were equipped with an information processing system that could constantly monitor the stability of the machine, the operator could respond in advance by slowing the tractor down before it is too late to make a correction. [MJ84]

More recently there have been many papers published in the area of collision avoidance in automobiles. Faciane [Fac93] conducted a general survey of technologies that were in existence for collision avoidance, blindspot monitoring, and driver alertness monitoring. In this paper the author states that in all such warning systems, the key issue is often creating a system that will not present false positives, and that must also be accurate so that the end result is not that the driver simply alters driving behavior to avoid alarms (effectively capitalizing on system weaknesses), rather than simply driving in a safer manner.

In the area of vehicle collision avoidance, there has been a great deal of work done with Autonomous Cruise Control (ACC) in which the standard cruise control system is augmented with sensor systems and actuators to enable the system to consider following distance and avoid collision through brake actuation. One such system is proposed and analyzed by Fancher et al. [FBE01]. In this article the authors state, among other things that the variability from person to person in stress threshold levels for a given situation vary widely, however for a given person the threshold is rather constant. They then state that if a system does not produce a warning before the driver’s stress level boundary is crossed, the driver may not be satisfied with the warning system. This provides an interesting contrast to the considerations stated above that a system that is overactive and provides too many warnings will also be seen as ineffective or useless. Fancher et al. then go on to state that based on their results, a successful warning algorithm will consider both driver actions and current state of the vehicle and its surroundings, and they point out that in situations where the driver’s attention is completely dedicated to vehicular control, a warning system can be more disruptive than helpful. Because their system is concerned only with longitudinal control of a vehicle, it is stated that one method for avoiding a large portion of such disruptive warnings is to monitor whether the driver is currently braking, i.e. whether the driver is currently involved in mitigating the condition being warned.

Gupta et al. [GBS02] studied the effects of adverse condition warning system
characteristics on driver performance. They summarized work that was done in aircraft cockpits and in other transportation sectors on the most effective configurations of alarm and warning systems in triggering operators to take the right corrective action for a given situation. They then performed a study utilizing an audible alarm and a driving simulator to test the effectiveness of both binary and ramp style alarm systems that alert the driver of the simulator as to the traction state of the vehicle. They showed that for a binary on-off signal the participants were often startled by the signal and actually took actions to further increase risk of loss of control before being able to correct the situation. The ramp type alarm, in contrast, was much more effective in alerting the driver and invoking the appropriate corrective action from the driver. Overall the study showed that the presence of the warning system had a positive effect on performance in the simulator, as compared to the performance of the drivers in the control group. They also showed that alarm sensitivity level had a strong effect on participant’s trust in the system’s ability to provide useful information on the current state of the vehicle as discussed above. They concluded by noting that further research into alarm modalities, or combinations of alarm modalities, such as an audible alarm combined with a visual display would be needed to determine the most effective alarm modality for a given situation. They further stated that while the auditory alarm is recommended for urgent situations, to attract attention quickly, one major drawback is that they may startle the driver. This may cause the driver to inadvertently take incorrect action, and so they recommended that a combination of alarm modalities may aid in eliciting the appropriate corrective action from the driver, resulting in the most effective warning system.

Work on display arrangement conducted by Shiki et al. [SSD+04] showed that a more intuitive display arrangement resulted in better cognition of information being communicated. Specifically, in a driving simulator the blind-spot and headway warning systems were most effective when arranged in the vehicle to correspond with the location of hazards. The blind-spot warning systems were most effective when positioned at locations near the side mirrors where drivers check first before making a lane change, and the headway warning system was most effective when placed centrally on the dash board, where the driver was already looking during straight forward driving.
In a study conducted by Haas and Edworthy [HE96] the urgency perceived by an operator as a function of input pitch, speed and loudness was studied. They state the following in their conclusion. “These findings lead to design recommendations for auditory warnings. Those who wish to obtain signals containing the highest level of perceived urgency and the shortest response time without regard to sound pressure level above ambient would employ signals with the highest fundamental frequency (800 Hz), the shortest time between pulses (0 ms), and the highest sound pressure level above ambient (40 dB SPL). Designers who wished to follow signal design recommendations of 15 to 30 dB SPL above ambient could use signals with a fundamental frequency of 500 Hz or greater, and a 0 ms inter-pulse interval.” (pg. 198)

Sanders and McCormick’s [SM93] further state that alarms consisting of three to four frequencies are less easily masked by ambient noise. They also recommend frequencies between 1000 Hz and 4000 Hz for maximum cognition.

Holt et al. [HBH93] studied the ambient noise of 155 tractors and found that the average noise level for an enclosed cab tractor was between 78-103 dB. They also found that 75% of tractors with no cab, and 18% of tractors with a cab had noise levels above 90 dB.

Bean [Bea90] also compiled information on tractor noise, and states that tractors without a cab have approximate noise levels of 100 dB, while tractors equipped with soundproof cabs have typical noise levels of 85 dB.

2.2.2 Verbal Reports

In order to better understand how to most effectively communicate current vehicle overturn potential to the operator, it was necessary to interview tractor operators. Asking an operator to verbalize what sort of cognitive and sensory processes are used during operation is commonly referred to as “retrospective verbal reporting”, and a discussion of the treatment of such reports as data follows.

Ericsson and Simon [ES84] studied the viability of using verbal reports as data in studies in their book, *Protocol Analysis*. The practice of using verbal reports as reliable data has limitations. As is described in the introduction of their book, modern psychology has been dubious about verbalizations of subjects in regard
to their process of arriving at a response, and “Even more dubious has been the status of responses to experimenter probes or retrospective answers to questions about prior behavior.” (pg. 2) Chapter 2 deals primarily with verbalization. When a subject is asked to verbalize a process in a thinking aloud activity, the act of asking a subject to verbalize their thought processes may alter the process itself. The collection of data via verbalization as it relates to retrospective verbalization of a cognitive process is summarized as follows:

“From our review of the evidence, we conclude that the processes subjects use to verbalize while thinking are neither illusory nor elusive, but can be understood and modeled. The processes associated with verbalization should be treated as an integral part of any model of the cognitive processes for a given task whenever the articulation takes the form of direct verbalization (i.e., vocalization of heeded information). The model should also include the processes for storing information at the end of experimental trials. The gross model we have proposed is focused on the verbalization of ongoing cognitive processes, but the postulated close link between information attended to and information stored should make it a relatively straightforward matter to model retrospective verbalization.” (ppg. 106-7)

In chapter 3 of their book, Ericsson and Simon cite a study in which subjects were unexpectedly asked to give retrospective reports of what they remembered experiencing and thinking during such events as traveling to work. From page 151,

“Summarizing the reports of all subjects, Smirnov notes that virtually all the recalled information referred to experiences related to walking to the office. However, subjects were subjectively certain that they must have thought about other things, yet only thought related to walking to the office could be retrieved. Such a selective retrieval can be easily understood from the assumption that subjects could only access retrieval cues related to the walking and the physical environment traversed.”

This suggests that the recall of processes connected with external cues, particularly
those related to events that are not relegated to nearly automatic processes are better recalled later.

In the summary of chapter 3 (pg. 168), Ericsson and Simon state the following:

“Many of the other claimed gaps in verbal reports are attributable to memory failures or confusions, especially when subjects are asked to make general retrospective reports, rather than to report specific recent information that has been requested of them, they may reason about the situation and report the results of their inferences instead of memories.

“With this baseline hypothesis in hand, we are now in a position to discuss the kinds of inferences that experimenters are justified in making from verbal protocols taken concurrently with performance of a task.”

Further discussion on the superiority of concurrent verbal protocols follows in the next few chapters of Ericsson and Simon’s book. Much of this is in relation to verbal reports on cognitive processes. The primary interests in this phase of the research project are related to actual physical processes, particularly as they relate to what the operator of a tractor is doing physically, i.e. where the operator’s attentions are focused during certain phases of operation. It is also of interest to know how an operator senses hill steepness, etc., in order to discover what sensory channels will be most effectively utilized for communication of impending overturn.

In the appendix of their book, Ericsson and Simon include some practical advice for collection of data via verbal reports.

From page 375,

“In many studies we want to collect verbal reports for cognitive processes that are no different from those occurring in traditional experiments. Apart from the instruction to verbalize and the production of the verbalization, the only differences are the presence of the monitoring experimenters and of the tape recorder. “After a short time subjects become accustomed to both the experimenter and tape-recorder. In many tasks, especially problem-solving tasks, subjects get so involved in the task that little notice is taken of the environment,
and situational factors have no real effect. For other cases, we have found it better to keep the tape-recorder and experimenter outside the view of the subject... The number of verbalizations that are social and directed to the experimenter may be used to evaluate how much the experimenter has intruded...”

They then suggest that experimenters may help subjects become accustomed to talking aloud by giving them some warm-up type exercises, such as asking the subjects to perform mental multiplication, addition, spelling exercises during which the subjects vocalize their cognitive processes during the activity.

In regard to think-aloud and retrospective reports:

“Rather than considering think-aloud and retrospective reports separately, we will discuss them as parts of a more general procedure, which we recommend be used whether think-aloud or retrospective reports, or both be given for the same cognitive process. The main reason for combining them in a common warm-up procedure is that for cognitive processes of intermediate duration we expect the “think-aloud” protocol and the retrospective report to contain basically the same information. Hence by having the subject give both reports for the same cognitive process we are in a position to assess completeness of the think-aloud protocol and assure that the retrospective report contains an actual record of the cognitive process.”

A description of a suggested warm up procedure follows, and then in conclusion, they state the following:

“The over-all idea is to present the subject with warm-up tasks until he or she is comfortable in thinking aloud and provides reports of the same information in both retrospective and concurrent reports. Occasionally the experimenter may be required to point out differences between information reported during think-aloud and retrospectively reported information. Also, subjects may use a more retrospective mode of reporting during think-aloud, or during the retrospective report engage in analysis of why they thought in a certain way, especially
if they recognize making errors. Most of these deviations can be set straight by simply repeating key phrases of the general instruction. Some subjects may be benefited by interspersing silent trials, for which the solution time is recorded, to assure that they are not changing their mode of thought to accommodate verbalization.

“During the actual experiment we recommend that both think-aloud and retrospective reports be recorded. Even for cognitive processes of long duration, where we know that the retrospective report will be incomplete, it will be quite useful. In this case, it will more clearly convey the general structure of the process, as most of the detailed information will not be retrieved, and retrieval will use the higher-level organizational cues, like subgoals, or recall cues.” (ppg. 378-9)

### 2.2.3 Alarm Modality and Reaction Times

Sanders and McCormick’s [SM93] textbook entitled *Human Factors in Engineering and Design* addresses many issues relating to designing for human use and interaction.

In chapter 3 of their book, Sanders and McCormick discuss in detail the issues related to “information input and processing”. They discuss the selection criteria for various communication modalities based on the type of information presented and the environment in which the information is to be conveyed. They also discuss maximum absolute discriminations a person can make between information transmitted by certain stimuli.

They also discuss guidelines for conveying information based on the type of task being performed, and discuss issues related to tasks which involve competition for the operator’s attention.

In chapter 5 they discuss visual displays of dynamic information, and make a comparison with altimeters in airplanes. They discuss the utility of scale markers and information presentation in such displays. They also discuss coding of qualitative information in displays involving red, yellow and green sections to communicate readings of relative qualitative information.

In chapter 9 they present a summary of human motor skills and reaction time.
They present a summary of a study in which tractor operators were tested to determine reaction time to actuate four possible emergency cutoff devices as they might be used on an agricultural tractor. This study found that the average time to actuate the clutch on a tractor was 613 milli-seconds.

In chapter 21 Sanders and McCormick also discuss human factors related to the automobile. In one study cited they present information on drivers reaction time to an unexpected stimulus. In this study the door of a car parked on the side of the road was opened. “The evasive response started in no case until more than 1 s had passed from the onset of the stimulus. The halfway point of the steering response was reached at about 2.5 s, and maximum steering deflection occurred between 3 and 4 s.” [SM93] pg. 703.

### 2.3 The Kalman Filter

The Kalman filter is a set of mathematical equations that provide an optimal means of estimating the state of a process such that the error is minimized.

In their paper, Welch and Bishop introduce the fundamentals of the Kalman filter [WB04]. They begin with a short treatment of the computational origins of the filter, and discuss in general terms what is gained by using multiple estimates of a single state.

They then discuss the discrete Kalman filter. They present the equations governing the Kalman filter at each time step, and discuss their solution. These equations are the basis for the C/C++ implementation of the Kalman filtering algorithm which was used in this thesis for tractor overturn state estimation.

Welch and Bishop then discuss the implementation of the extended Kalman filter for estimation of problems involving a non-linear relationship between the measurement and process to be estimated, or for the estimation of a non-linear process itself.

They then conclude with a presentation of simulation results for the estimation capability of the Kalman filter in the presence of noise.
Chapter 3

Objectives

The objectives of this research were first, to focus on validating and improving a sensor developed previously, second, further develop a display to more effectively convey critical overturn information to the operator, and third, develop the sensor device to enable it to intervene in rear overturn situations and prevent rear overturn. Capabilities to notify emergency personnel when a rollover event has occurred were also proposed, as well as a preliminary investigation on using the sensor device on a four wheel ATV, such as the kind commonly used for farm work and sport.

The timeline in Figure 3.1 illustrates the three main phases of a rollover event. Attached to the timeline are events or situations where this research will focus.

![Figure 3.1. Tractor Overturn Timeline.](image-url)
3.1 Pre-Event Tractor State

The first portion of research will focus on the pre-event state of the vehicle. The focus of previous research has been to develop a system that is capable of tracking the state of the vehicle in real time directly before the rollover event. The sensor device that has been developed has shown favorable results in testing. It is now necessary to validate the current sensor statistically. This will require a large number of data sets to be analyzed, and filtered in an optimal manner such that the critical data is preserved, while eliminating tractor engine noise and other vibration. These filtered data sets will then be analyzed, and the data will be used to attempt to predict the outcome of the test run. This prediction will be compared to the observed result of the overturn, i.e. whether the result of the test run was an overturn, or a near miss. The results of this analysis will then be evaluated to determine the efficacy of the sensor in predicting overturn.

The second portion of the pre-event research will be to expand the current sensor device to implement both accelerometers and angular rate gyros. This will enable real-time access to an unbiased current angle at which the tractor is operating independent of dynamic acceleration effects, a value of current acceleration to include centrifugal acceleration effects, and an unbiased angular rate in both the roll and pitch directions.

The third portion of pre-event research will be to attempt active intervention in a rear overturn situation. The expanded set of data available from the new sensor system will allow a more detailed description of the current tractor state. This more detailed information on the tractor state will be analyzed to predict rear overturn potential, and to intervene before overturn occurs by disengaging the tractor clutch, or by some other means.

3.2 Pre-Event Operator State

Before a rollover event it is necessary to convey the information collected by the sensor to the operator of the tractor, with the intent that it will educate the operator for safer future tractor operation, and allow the operator to correct the current situation to avoid rollover. To accomplish this, a display has been developed that
incorporates a color LCD display. Work will focus on design of the displayed information.

This work will also include a study of the current state of the art in display cognition. This will focus on conveying information to the operator in such a way that the operator is able to learn from and correct near-overturn situations, and will include research into alarm modalities. In order to better facilitate the communication of this data to the operator, this portion of the research will include a small survey of agricultural tractor operators in an attempt to determine what sensory paths are currently being used during regular tractor operation. This study will guide the further development of the display and communication device in an effort to both augment the sensory channels used naturally by a tractor operator to comprehend vehicle state while not overloading those channels, and to introduce stimuli via alternate sensory channels to inform the operator of the vehicle’s nearness to overturn.

This portion of the research will draw heavily on research that has been conducted in collision avoidance systems for road vehicles.

3.3 Post-Event Issues

After the tractor has overturned it is important that the victim receive medical attention as soon as possible. Timely response from Emergency Medical Service (EMS) professionals is critical to shorter recovery time, and is often lifesaving. However, it may well be the case that the rollover event occurs in a remote area of a farmer’s field, and/or the operator will simply be expected to be out in the field for a long period of time and may not immediately be missed. Although beyond the scope of the current research project, the expanded sensor system could correctly identify an overturn event, and if integrated with a cell phone or other broadband wireless communication device, could enable more rapid response time from EMS personnel. The device could be further refined with the inclusion of Global Positioning System (GPS) sensing capability to enable the device to transmit the exact GPS coordinates of the victim of an overturn event. The device could then either communicate directly with EMS personnel or could inform someone at home, or some combination of both.
This would be similar in concept to the GM OnStar® system commercially available in road vehicles.
Chapter 4

Procedure and Methodology

This chapter is divided into two basic parts. The first part deals with statistical data collected using an earlier, simpler design of the sensor device. This device incorporated only an accelerometer to sense roll and pitch angle, resulting in the measurement of a “dynamic angle,” which includes the effect of dynamic accelerations encountered by the tractor.

The remaining portion of this chapter deals with the results of development and testing of the expanded sensor device which incorporates both accelerometers and angular rate gyros.

4.1 Statistical Analysis of Pre-Event State of Vehicle

As previously stated, it was necessary to characterize the pre-overturn vehicle state and to validate the capability of the sensor previously developed in reporting the vehicle state in regards to potential overturn. In order to validate the sensor, a large group of data sets had to be collected that represent both typical side overturn and near miss conditions. The raw data sets, as collected by the simple sensors are inherently noisy, and so it was necessary to design a filter that will remove the noise from the data sets. Then the filtered data were analyzed to determine if the data predicts an overturn as described below.

The prediction criterion used for side overturn involving only the measure of a
“dynamic angle” (an angle calculated based on acceleration values which include dynamic effects as well as static gravitational acceleration) involves comparing the measured dynamic angle with some “static instability angle.” Static instability angle is defined to be the static angle of inclination at which a stationary tractor will have zero force on the uphill tire. This can be measured by placing the tractor on a large plate, and increasing the angle of the plate until the tractor overturns. Alternatively, it can be mathematically modeled as follows. Note, however, that this model assumes a purely rigid body, and makes no accounting for deformation of the tires under side load, nor does it include any effect that may arise from deflection of the front wheel assembly about the king pin.

Figure 4.1 is a diagram of the simplified model used to calculate static instability angle. The height (h) of the center of gravity must be known for the tractor, as well as the track width (W). The Static hill angle is illustrated in Figure 4.1 as $\theta$, and is the angle for which the center of mass is directly above the point of ground contact of the downhill wheel.

![Figure 4.1. Model for Calculating Static Hill Angle.](image)

The static instability angle ($\theta$) is then calculated using the following formula:

$$\theta = \arctan \left( \frac{W}{2 \cdot h} \right)$$  \hspace{1cm} (4.1)

For a measured data set, the peak angle encountered by the device during the test run will be compared to the static instability angle. The data will result in
a prediction of overturn for any case where the peak angle exceeded the static instability angle. The predicted results will then be compared to the observed overturn condition and evaluated as described below.

### 4.1.1 Filter Design

Because of tractor engine vibration and vibration of the tractor due to ground irregularities the collected data sets, which represent raw acceleration values, must be filtered to eliminate noise. In commercial applications of this technology, the data will be filtered in real time, so the filter used here must be designed in such a way that it could be implemented in the sensor device. This requires that the filter must only consider current and past values in the filtering algorithm, and that the order of the filter is small enough that the phase lag due to the filtering is not so large that it renders the presented information useless to the operator.

During the design and development stage, to facilitate both data filtering and data reduction, a MATLAB® m-file (Appendix A.3) was written which opens the raw data text files, extracts the desired acceleration values, and filters the data using a 4th order Butterworth digital filter. This filter was designed using the MATLAB® digital signal processing toolbox and filter design tool. The filter was designed to have a cutoff frequency of 1 Hz. This filter requires eight Floating Point Operations (FLOPs), (i.e. a floating point multiplication and addition) for each data point collected and could be easily implemented in the data collection device developed for the project. The cutoff frequency was chosen as 1 Hz based on comparisons of various filter cutoff frequencies on collected data. A cutoff frequency of 1 Hz results in good noise reduction in the signal without excessive attenuation of the desired signal. Hitting a bump has frequency content slightly faster than 1 Hz, but is slow enough that it is not significantly attenuated by the filter. This filtered data was then used to calculate the roll angle of the tractor during a run. The peak angle value for each run was then collected and compiled for further data processing.
4.1.2 Statistical Comparison and Analysis

After filtering the data and extracting the peak acceleration value, the peak angle was calculated by taking the arcsine of the peak acceleration value in G’s. This was then converted to degrees for more intuitive readability. These were then placed in a matrix and compared with observations recorded during testing, which consisted of both a binary roll/no roll observation and also a somewhat more qualitative description of how fast the event occurred, and what other conditions were observed during testing. The predicted overturn critical angle was selected based on the prediction of the algorithm, in comparison with the observed results. This angle is valid only for the Ford 1900 tractor that was used during the testing because this is a property of the tractor itself. For implementation on other tractors this would be the only side-overturn parameter that would have to be adjusted.

Based on the outcome of the comparison of the prediction algorithm and the observed results it is possible to draw conclusions as to the viability of the sensor system. A statistical analysis of the roughly 60 data points collected was conducted to calculate the sensitivity and the specificity of the sensor system.

Because the object of the statistical analysis is to evaluate the accuracy of the predictions of the sensing device it is also good to limit the total data points to those data points near the point of overturn. This will prevent a large number of tests that were not near overturn from skewing the data and making it appear better than it actually is. It can be concluded that the sensor device will correctly predict a no overturn condition for a tractor that is operating on flat ground. For this reason, a range of acceptable peak angle values was selected around the mean value and values found to be excessively low will be excluded from the following analysis. This is discussed in more detail in the Results section.

The terms “Sensitivity” and “Specificity” are used in the following sections and in the following chapters of this thesis to refer to statistical parameters [Kut05]. These should not be confused with the engineering definition of sensitivity, which is often used to describe the effect of variations of input parameters on the output of a system.
4.1.2.1 Sensitivity

The sensitivity of the sensor system is a way to characterize the system’s ability to correctly predict conditions which result in an overturn ([Kut05] pg. 606). Sensitivity is calculated by considering only those test runs which resulted in tractor overturn. The predicted outcome of these runs is based on the sensor systems measurement of vehicle state, and its comparison of this measurement with the critical angle as described above. The number of correct predictions are counted and divided by the total number of runs which resulted in overturn, and this percentage is taken as the measure of sensitivity.

\[
Sensitivity = \frac{\text{# Correct}}{\text{# Overturn Runs}}
\]  
(4.2)

Because of the inherent risk (both monetary cost of equipment damage and risk of operator injury or death) it is critical that every situation that results in overturn is correctly predicted, and the operator is informed of the condition. Because of this, it is important to absorb any noise in the data, or any uncertainty in prediction of overturn into the specificity.

4.1.2.2 Specificity

The specificity of the system is a measure of the predictive power of the system in regards to events that did not result in an overturn, and is calculated in much the same way as the sensitivity ([Kut05] pg. 607). Specificity is a measure of the portion of the runs that did not result in overturn that were correctly predicted as no overturn.

\[
Specificity = \frac{\text{# Correct}}{\text{# No Overturn Runs}}
\]  
(4.3)

The utility of this measurement of predictive power of the sensor device is that it provides a measure of how frequently the device gave a “false alarm”. An ideal sensor device would predict every situation exactly correctly. If there is some uncertainty in the prediction from the device, it is preferred that this uncertainty manifest itself here, where the safety of the tractor and operator are not at risk.

Given the above, it is important that the specificity of the sensor system be
high. The result of low specificity for a system is a system that is prone to false positives. The obvious result of this situation is that the operator would soon learn to distrust the information supplied from the device. A greater consideration of the operator/device interaction will be discussed in a later section.

4.1.2.3 Error Rate

It is also useful to consider an overall measure of the accuracy of the sensing device in predicting overturn. The error rate is simply a measure of the total number of correct predictions divided by the total number of test runs conducted.

\[
Error\ Rate = \frac{\#\ Incorrect\ Predictions}{\#\ Total\ Runs}
\]  

(4.4)

4.2 Sensor Device Expansion

A sensor device that was developed previously was able to report a “dynamic angle”. The dynamic angle was calculated based on acceleration values that included both static acceleration due to gravity (because the tractor was operating on a side hill) and dynamic acceleration (resulting from turning a corner, ground roughness, etc.) To facilitate further testing and development of the device to prevent rear overturn, it was necessary to expand the sensor device to include rate gyros, enabling the direct measurement of both angle and angular rate.

4.2.1 Hardware

A new sensor device was designed with accelerometers to measure accelerations in each of the three principal axes, and rate gyros to measure the roll and pitch rates, as shown in Figures 4.2 and 4.3.

A close up view of the actual MEMS fabricated accelerometer (Analog Devices ADXL 311J) and rate gyro (Analog Devices ADXRS 300ABG) modules can be seen in Figure 4.4. This figure shows the two axis accelerometer on the left, and the single axis rate gyro on the right. The sensitive axes of the accelerometer are aligned left to right, and up and down on the page. The sensitive axis for the rate gyro is the axis perpendicular to the page.
As can be seen in the figure 4.4 the new sensor device incorporates both angular rate gyro's and accelerometers. These are oriented orthogonally to allow sensing of both roll and pitch. The accelerometer and rate gyro outputs were monitored using an eight bit microcontroller. Values were stored in small EEPROM chips for later extraction and analysis.

A CAN bus interface was included for communication between the sensor and the display device. In this iteration, a USB interface was also included, and was used to interrogate the device and collect stored data after testing, as well as serving as a way to set and fine-tune rear overturn parameters during testing.

This device also incorporates a small optically isolated solid state relay. This relay was used to open a hydraulic valve connected to an actuator on the tractors clutch during testing and operation. This enabled the device to disengage the clutch in the event that the device sensed a rearward overturn condition.


4.2.2 Kalman Filter Implementation

The sensor devices listed above were validated as potential candidates by construction of a two wheel inverted pendulum mobile robot. The nature of the inverted pendulum is such that it is statically unstable, i.e. it will fall over if not supported. The accelerometer and rate gyro were used to measure the state of the inverted pendulum, and the measured values were then used in a digital linear quadratic regulator (DLQR) control routine to both stabilize the inverted pendulum, and to allow control of the robot platform. Because this application requires both an unbiased angular rate, and a measure of the vehicle pitch angle which is independent of the lateral accelerations of the robot platform, it was necessary to combine both
raw signals using a Kalman filter that would then report an unbiased measure of current angle and angular rate.

In the inverted pendulum robot application the rate gyro was oriented with its sensitive axis aligned with the axle of the vehicle. The accelerometer was oriented such that its two sensitive axes were perpendicular to the sensitive axis of the rate gyro. This arrangement provides a measurement of acceleration for which the static component always points down (due to the acceleration of gravity), and provides a measure of angular rate for the axis of interest. Figure 4.5 shows the pendulum robot balancing, and figure 4.6 shows the layout of the sensors, microprocessor, and other components inside the robot.

Figure 4.5. Inverted Pendulum Mobile Robotic Platform.

For the specific problem of sensing the angle of the inverted pendulum robot, there are two separate measures of the actual angle. The first measure of current angle is computed from measured acceleration values. The second is computed by integration of the measured angular rate. Both signals have noise inherent in them, resulting from vehicle vibration, electrical noise, etc. Also, by nature of a moving vehicle, the angle measured based on acceleration values will be coupled to the lateral (dynamic) acceleration of the vehicle itself. Because the second measure of angle is based on an integration of a somewhat noisy rate gyro signal which
may also have some steady state bias, it will tend to drift over time. A possible combination of the two would be to implement a low pass filter on the acceleration signal, and a high pass filter on the angular rate signal, and in fact, the Kalman filter accomplishes this in an optimal manner, and returns both an unbiased angle and angular rate for further processing.

The functional operation of the Kalman filter was presented in a diagram in a paper by Welch and Bishop [WB04] and is reproduced here as Figure 4.7. They note that for actual implementation, the measurement noise covariance $R$ is needed. This can be measured, and is explained below.

The Kalman filter requires that two estimates of expected measurement noise covariance be provided as denoted by the vector $R$. These values can be measured experimentally in the lab for the sensors, and an estimate of these was used in the implementation of the Kalman filter.

The remaining factor that must be estimated is denoted as $Q$ in Figure 4.7. This
is the measure of actual process noise covariance (i.e., unwanted higher frequency variation in the actual process being measured). It is difficult to separate this quantity from the measurement noise covariance because only one set of sensors was used. This quantity was assumed small, and was estimated for the implementation of the Kalman filter. This provides a sufficient characterization of sensor noise for the inverted pendulum robotic platform because the platform is operated primarily on smooth ground, and encounters little external vibration. When the sensor device was placed on the tractor the vibrations as listed above caused much more noise in the signal. This can be represented as process noise, as it represents spurious noise on the signal that is not related to the process being measured, i.e. the angle of the hill upon which the tractor is operating. To correct for this a digital filter was added to the Kalman filter routine to refine the signal. Further investigation into the noise levels of the signals from both the accelerometers and rate gyros in actual operation of the tractor on flat ground would provide a better estimate of the process noise covariance during actual operation. This could then be used in the Kalman filter to account for both the sensor device noise (measurement noise), and the noise resulting from operation of the tractor over rough ground (process noise).

The C/C++ Kalman filter implementation for the two wheel inverted pen-
dulum robot platform was initially developed by the SourceForge Autopilot group (www.sourceforge.net). This group makes such code openly available to the public. This specific implementation was particularly well suited to the inverted pendulum robot because it was initially developed on an Atmel eight bit microcontroller similar to the one used in the robot and in the tractor sensor device. This greatly simplified implementation, although some changes and adaptations were necessary.

Ideally the signals provided from both axes of the accelerometer are used to calculate the angle using the atan2 function. This was used very successfully for the inverted pendulum platform largely because variation in roll angle was ignored. This was possible for the inverted pendulum because it primarily operates on a flat plane, and so it typically only encounters variation in pitch. For application of this angle calculation for two angles simultaneously the problem becomes more difficult. For the purpose of this application, however, the angles of operation encountered by the tractor prior to overturn are below roughly 50 degrees for side hill operation, and below roughly 70 degrees for rear overturn operation. Because of this, and because both angles are calculated via the combination of an angle and an angular rate (thereby giving sufficient accuracy for quick deviations into the regions of larger angles) it was decided that the coarse measurement of angles due to a simplified arcsine calculation (based solely on measured accelerations) at angles above these values was acceptable.

4.2.3 Computational Time and Execution on Atmel® Microprocessor

Because the Kalman filter estimates angle based on an integration of a rate signal, it is necessary to execute the filter update code on a fixed time interval. This was accomplished on the Atmel® microprocessor by the use of an internal timer and interrupt. The measurement update code executes at 60 Hz. This leaves roughly 17 milli-seconds for each execution of the code. The microprocessor is running at 16 MHz, so there are 267,000 clock cycles per execution. The program was simulated without the write and read functions on an emulator provided by Atmel, and it was found that the extent of the interrupt code calculations requires 138,000 clock cycles, or roughly half the time available for each execution of the interrupt. This
allows some time for saving values to the EEPROM chip, and for sending values via the CAN bus to the display device.

4.3 Active Intervention - Energy Calculations

In order to effectively intervene in rear overturn situations it was necessary to model the system and predict the values for angle and angular rate that would result in instability. This gave a standard that was compared to the current vehicle state during operation. When this comparison indicated a condition near instability the device would intervene to avoid instability.

4.3.1 Derivation of Stability Criterion

For rear overturn minimum stability criterion the tractor was modeled as a rigid body pivoting about the rear axle as shown in Figure 4.8.

The point of minimum stability, or the threshold of stability was defined as the configuration where the center of mass of the tractor is directly above the rear axles, and the angular velocity is zero (see figure 4.8.C.) If the potential
energy in this configuration is equated to the kinetic energy of the tractor as it is rotating upwards under free rotation (i.e. when the clutch has been disengaged), a continuum of initial conditions for angle and angular rate that will cause the tractor to reach this unstable equilibrium configuration can be calculated. If the tractor is then restricted to conditions where the kinetic energy in pitch is always too low for the tractor to reach this point, the following inequality must hold for stability to be maintained.

\[ mgr \cdot \sin(\theta + \phi) + 0.5(mr^2 + J)\dot{\theta}^2 < mgr \]  \hspace{1cm} (4.5)

Where \( r \) is the distance from the rear axle to the center of mass of the tractor, and \( \phi \) is the static angle between horizontal and the line \( r \) when the tractor is on level ground. Angle \( \phi \) is constant for a given tractor. \( J \) and \( m \) in the above equation are the mass properties of the tractor, where \( J \) is the rotational moment of inertia of the tractor about its mass center, and \( m \) is the total mass of the tractor. This inequality can then be simplified as follows:

\[ \sin(\theta + \phi) < 1 - \frac{1}{2} \left( \frac{r}{g} + \frac{J}{mgr} \right) \dot{\theta}^2 \]  \hspace{1cm} (4.6)

\[ \theta + \phi < \arcsin \left( 1 - \frac{1}{2} \left( \frac{r}{g} + \frac{J}{mgr} \right) \dot{\theta}^2 \right) \]  \hspace{1cm} (4.7)

Here, a simplification for the arcsine function is substituted as follows.

\[ \arcsin(1 - u) \approx \frac{\pi}{2} (1 - \sqrt{u}) \]  \hspace{1cm} (4.8)

This function was compared to the arcsine function and a graph of its relative performance showed that at most the difference in the values of the two functions was 4.2%.

Substitution of this function into the above equation yields the following inequality.

\[ \theta + \phi < \frac{\pi}{2} - \frac{\pi}{2} \sqrt{1 - \frac{1}{2} \left( \frac{r}{g} + \frac{J}{mgr} \right) \dot{\theta}^2} \]  \hspace{1cm} (4.9)
Which simplifies as follows.

\[
\theta + \phi + \frac{\pi}{2} \sqrt{\frac{1}{2} \left( \frac{r}{g} + \frac{J}{mgr} \right) \dot{\theta}} < \frac{\pi}{2}
\]

(4.10)

This expression is then used to evaluate the relative stability of the tractor for a given set of operating conditions \(\theta\) and \(\dot{\theta}\) as collected by the sensor box.

The end result of the above equation is very intuitive. After linearization, the above equation shows that there are essentially two factors that will determine the relative stability at any given configuration. The first is the final angle that the tractor will reach before the system intervenes. This angle in the above analysis is assumed to be 90 degrees. The second factor that will be used to impose stability is the term associated with the angular rate term. A dimensional analysis of this term shows that it is simply a time delay. This implies that for a given initial angular rate, the power to the rear axle must be cut some time prior to the system reaching the instability condition or it will continue past the angular limit and overturn.

Mitchell et al. [MZL72] conducted an analysis of the same situation in which he derived a second order nonlinear differential equation. This equation described the motion of a tractor for any given set of initial angle, initial angular velocity, drawbar pull, engine torque, and drawbar hitching location. He then simulated the response of the tractor for a given set of initial conditions to determine for which initial conditions the tractor became unstable. The separation of stable and unstable initial condition regimes was separated by a minimum stability line called the separatrix. This is illustrated in Figure 4.9 below.

Mitchell et al. then went on to fit simplified lines to the simulations to define a regime for stable and unstable initial conditions. The simplest stability criterion used was a linear equation very similar to the equation above, in which \(x_1\) is pitch angle and \(x_2\) is pitch rate.

\[
x_2 = -2.98 \cdot x_1 + 2.75
\]

(4.11)

This can be rearranged as follows:
Figure 4.9. Derivation of the Separatrix [MZL72]

\[ 2.75 = x_2 + 2.98 \cdot x_1 \]  \hspace{1cm} (4.12)

For use in the automatic control device later proposed, Mitchell et al. triggered the disengagement of the clutch when the right hand side of the equation is greater than the left hand side, i.e. when the initial conditions pass outside the stable regime in state space defined by the original equation. This is illustrated by Mitchell et al. [MZL72] in figure 4.10.

Mitchell et al. [MZL72] then noted that this results in a much more conservative condition than is predicted by the solution of the differential equation, and proposed a further refinement by defining the stability boundary as a quadratic equation as follows. This is shown in the graph from Mitchell et al. shown in figure
Figure 4.10. Initial Cutoff Line and Separatrices [MZL72].

4.11.

\[ x_2 = 4.16 \cdot x_1^2 - x_1 + 4.6 \]  \hspace{1cm} (4.13)

The assumptions used for the above equations to work required that the clutch actuation time be on the order of 0.2 seconds. This necessitated that Mitchell et al. change actuation method from a hydraulic actuator to a spring loaded device.

These cutoff criterion were derived for an International Harvester Farmall 656 diesel row crop tractor. The mass properties for this tractor show that it is significantly larger than the Ford 2080 used for testing in this research project. The weight of the tractor listed by Mitchell et al. [MZL72] was 8,234 lb. whereas the weight of the Ford tractor tested for this research project was 3,900 lb.

The strategies employed by Mitchell et al. are very similar to the strategy outlined above. The results of the two independent analysis strategies both yield a linear equation that divides the state space into two areas of initial conditions, those that will result in overturn, and those that will not. Rearrangement of equation 4.10 and substitution of time delay values and mass properties yields the following.
This is similar both in form and in magnitude to the equation Mitchell used. Because Mitchell’s original model included an in-depth consideration of forces on a tractor, including drawbar pull, etc., he was able to include a more involved definition of stability criterion, whereas one of the simplifying assumptions used for the calculation of stability criterion for our model was that the drawbar force was zero. This assumption holds for many situations because if the tractor’s clutch is disengaged, and the brakes are not applied, the pull on the drawbar would diminish and would only consist of the dynamic loading due to the rotation of the tractor itself.

4.3.2 Angular Rate Signal Filter

Although the angular rate signal is given by the Kalman filter routine, and is therefore already optimally filtered as discussed above, it was noted in lab testing that the signal was still be too sensitive to small vibrations, and so it was necessary
to further filter the angular rate signal. As discussed above, refinement of the process noise covariance estimate that was used as an input to the Kalman filter would allow the attenuation of this noise to be handled by the Kalman filter itself. Access to better estimates of the noise covariances of the signals and process were not available at the time of the development of the filter, however, so the decision was made to simply further filter the data in the way described below.

A 2nd order Butterworth digital IIR filter was implemented in the box to further smooth the angular rate signal to avoid false positives during testing. The cutoff frequency of this filter was set to be 0.5 Hz based on a qualitative analysis of angular rate as calculated based on previous tractor rear overturn testing. The cutoff frequency of this filter was set at 0.5 Hz where the cutoff frequency selected as appropriate for the side overturn estimator is discussed below.

Because the mass arrangement of the tractor is different about the roll and pitch axes, the motion about each axis is expected to be different. The rotational moment of inertia about the roll axis is much smaller than the rotational moment of inertia about the rear axles. The even greater variation in input torques for each axis further changes the speed at which events occur about each axis, and was the reason that the filtering for each axis was treated separately.

4.3.3 Clutch Actuation

As stated above, after derivation of the stability criterion it was noted that the factors to be adjusted for a given tractor were the static cut-off angle and the time delay term for the angular rate. This is useful to note because on the tractor the actuation of the clutch (the proposed intervention method) requires a finite amount of time. The clutch on the tractor was retrofitted for remote operation, and controlled by a hydraulic actuator which was actuated by electronically controlled valves. The total time for the clutch actuator to travel the full distance from fully engaged to fully disengaged was just under one second. The clutch plates inside the tractors transmission actually contact and engage somewhere between these two extremes, so further evaluation will be necessary to pinpoint the exact clutch actuation time necessary for successful intervention.
4.4 Operator State and Display Ergonomics

In conjunction with previous research for side overturn mitigation it is necessary to communicate the current relative stability state of the vehicle to the operator.

4.4.1 Display Device Redesign

In order to effectively communicate current overturn potential to the operator, as well as a short time history, it is necessary to present a large amount of information to the operator in such a way that it can quickly be accessed. This necessitated the redesign of the display device to incorporate an LCD screen on which a significant amount of information could be displayed simultaneously, and to which the operator could glance periodically during operation of the tractor.

The LCD screen selected is equipped with a 40 pin parallel data interface. This data interface was attached to the output pins of a 52 I/O pin ATMEL MEGA 128 microcontroller. This microcontroller was also connected to a CAN bus controller chip. The previous iterations of the device included a CAN bus for data transfer from the sensor device to a laptop computer. The CAN bus was a logical choice for data transfer from the sensor device to the display device because the final design concept would include the ability to incorporate the sensor on a new tractor that is equipped with a CAN bus. It would then be able to communicate through the tractors’ existing CAN bus with the display on the tractor.

Information is updated via the CAN bus to the display device at roughly 30 Hz and is stored in the display device for roughly 15 seconds, resulting in a short time history. A picture of the display device with LCD screen is shown in Figure 4.12.

The display device requires a 12 volt supply for the LCD module. This was supplied by ten 1.2 volt AA NiMH rechargeable batteries. The batteries and the ATMEL Mega128 microcontroller are visible in Figure 4.13.

4.4.2 Display Design

The display design shown in Figure 4.14 provides the current angle in degrees in large numerals on the far left of the display. This is also provided in the left most
position on the time history bar graph. The bar graph then updates by shifting all values to the right every second. The bars also change color in relation to potential overturn: Green indicates low overturn potential; yellow indicates intermediate overturn potential; and red indicates the highest level of overturn potential.
4.4.3 Display Redesign or Justification

The display was designed in an intuitive manner, but little research was done initially to determine its configuration. In order to guide further redesign of the display and communication device it was necessary to better understand what sensory paths are used by a tractor operator to sense hill angle. This was accomplished by means of interviewing tractor operators and collecting retrospective reports on what cognitive processes were used by these operators during tractor operation.

Because the research involves human subjects it was conducted under Institutional Review Board (IRB) exemption approval through the Penn State Office of Research Protections, IRB #22221.

Subjects for the research were selected from a list of names provided by Mr. Bill Harshman, a former agricultural extension agent and high school agriculture instructor. Participants in the research were recruited by means of the telephone script included in Appendix C.

During meetings, the subjects were required to sign an informed consent form and information was collected for disbursement of money to the subjects for their participation.

No personally identifiable information was connected to the information shared by the subjects during the interviews. All subjects were later randomly assigned a subject number as a means of identifying responses that were shared by an individual research participant.

All interviews were tape recorded. The recordings will be retained for the mandatory minimum of 3 years by Dr. H. J. Sommer III in his office.
Tape recordings of the interviews were transcribed and aggregate data, as well as individual quotations were included in the results section below.

During the interview sessions, the subjects were asked to answer the following questions, and to discuss their experiences while driving an agricultural tractor. As was stated by Ericsson and Simon [ES84], retrospective reports are most reliable when accompanied by think-aloud exercises conducted while the subject is performing the task of interest. For the purposes of this research, such activities were outside the scope of the research, as it would have required a tractor equipped with a second instructor seat, a safe test course, and further IRB approval. Ericsson and Simon do note, however, that use of data from retrospective reports is valid if the researcher is mindful of the limitations of such data. These limitations include the realization that such data may contain information that the subject constructs based on cognitive processes and ideas about what the subject thinks should have happened.

The main purpose of interviewing tractor operators was to first, gain a basic understanding of what sensory paths are typically used by an agricultural tractor operator for sensing hill steepness, and second, to gain a basic idea of the process of operating an agricultural tractor in order to understand what alarm modalities and means of alerting the operator might be effective (i.e. understanding where an operator is looking during operation to know if a visual display is feasible). It was concluded that this information could be inferred in general terms based on the information provided from retrospective verbal reports.

The actual questions asked during the interview sessions are listed below.

---

**Farm Tractor Operator Stability Awareness Assessment Instrument**

The following was discussed verbally with all subjects. The sessions were recorded, and transcribed for use in the research project.

**Introduction:**

We are developing an instrument that would be used on a farm tractor to sense the stability of the tractor. It uses some electronic measuring devices that sense the angle that the tractor is operating on, and it then lets the operator know if the tractor is getting close to rolling over. The reason we have asked to talk to you is that as we have been developing the display device you see here (demonstrate
We have been trying to design it to help the operator of a tractor get the most information possible from the display while also making it easy to read. What we are now doing is investigating how a tractor operator, such as you, knows when a hill is too steep, or when their current situation is getting near rollover.

When I ask you questions, I want you to try and think of what you do, or what you feel or sense, rather than what you think you should do, or what you think you should feel or sense.

Do you have any questions before we get started?

1. I will now ask some questions about who you are.

   (a) How old are you?
   (b) How long have you been driving a tractor?
   (c) What training did you receive on driving a tractor?

2. I will now ask you some questions in regards to the area you farm.

   (a) Are the fields where you operate a tractor flat?
   (b) Do you operate a tractor on roads?
   (c) Do you operate a tractor at speeds above 15 mph?

3. I will now ask you some questions in regards to on-tractor experiences.

   (a) Have you ever been in a tractor that rolled over?
   (b) Did you know it was going to roll over or was it a complete surprise?
   (c) Have you ever been in a situation where you thought the tractor almost rolled over?
   (d) If you have, how recently did this happen?
   (e) What were you doing at the time? (Plowing, baling, just driving)
   (f) Have you ever been on a side slope that you thought was too steep?
   (g) Have you ever turned a corner and thought that you might have taken it too fast, or too sharp?
If any items in section three were answered in the affirmative, ask the subject to think about that experience specifically, and talk through that experience specifically, describing in sequential order what took place.

1. Now, based on the experiences you have had, I have some other questions for you.

   (a) How do you know if a hill is too steep to drive the tractor across?
   (b) How do you know how much to slow down for a turn?

2. General operating condition questions.

   (a) During operation with an implement (like a baler, mower, etc.), where do you typically look?
   (b) During operation with an implement, how do you know if things are working the way they are supposed to? If something goes wrong, how do you know it?
   (c) Tell me step by step what you do when you plow/mow/bale? Walk me step by step through what you do, what you think, and where you are looking during a typical operation.

Information collected from tractor operators will guide the further redesign of the display and communication device by highlighting where the operators attentions are during operation, and what senses are used to determine hill steepness, etc. The redesigned display will then augment the operators perceptions of hill steepness, and will present measured steepness information in a location and alarm mode that will communicate most effectively with the operator.
Chapter 5

Results

This chapter is divided into two basic parts. The first part, comprising Section 1, deals with statistical data collected using an early and simplified design of the sensor device.

The remaining portion of this chapter deals with the results of development and testing of the expanded sensor device which incorporates both accelerometers and angular rate gyros.

5.1 Statistical Analysis

The purpose of the statistical analysis was to determine whether the sensor device is reliable in predicting side overturn. If it was found to be reliable in at least some, or most situations, how reliable was it?

These questions required that a filter be designed and used to filter the raw data. The key considerations for filtering the data are described below. After the filter was designed, the overall reliability of the device was considered.

Data for this portion of the research was collected, as described previously, by measuring accelerations and taking the arcsine of these accelerations to find a current “dynamic angle” at which the tractor is operating. For these tests, only the data associated with side overturn was considered. It was postulated that if the dynamic angle angle exceeds some “static instability angle” the tractor will overturn. This was taken to be the prediction criterion for the statistical analysis portion of the testing.
The tractor used during the statistical analysis was a remotely operated Ford 2080 tractor. The mass properties of this tractor were measured and found to be as follows. The track width (W) is roughly 57 inches (this value is somewhat approximate, given that the rear tires deflect under side loading), and the center of mass is roughly 25 inches off the ground (h=25). Using these values, and the formula presented in chapter 4, the static instability angle predicted for the tractor was roughly 49 degrees.

5.1.1 Overall Filter Viability/Appropriateness

Data collected during testing was examined to determine some starting value for the cutoff frequency of the filter to be designed. It was noted that the events of interest as contained in the data seem to occur on the order of 1 Hz. This is a rough approximation based on an examination of a plot of the data. The entire run during data collection consists of starting the data collection, driving the tractor onto and across a 20 degree side hill, and impacting a bump with the uphill tire. The entire run usually occurs within roughly 60 seconds. The fastest item of interest occurs when the uphill tire hits the bump. This event in the data resembles a half sine wave pulse, and typically occurs in roughly one half to one second, and therefore, 1 Hz was selected as the starting point, and lowest viable cutoff frequency for the filter.

The next question for a starting point on filter design was to decide on the order for the filter. The primary concern when selecting filter order in a real time monitoring situation requires finding a balance between phase lag and noise attenuation. While a higher order filter will result in better attenuation in frequencies above the cutoff frequency, it can result in significant phase lag.

A comparison of three filters is presented below based on the set of data collected August 11th, 2004. First, the data was filtered with a 2nd order Butterworth filter with a 1.5 Hz cutoff frequency. The results are presented in Figure 5.1. The graph presents each run as a separate line, those for which overturn was predicted are displayed in red, and those for which no overturn was predicted are displayed in blue.

As is seen in this graph, there is still a great deal of noise present in the signal.
This results in peaks in the data that are higher than the actual value. This would lead to indicated values that are much higher than those actually encountered, and would cause an operator to soon lose confidence in the device.

The filter was then refined by lowering the cutoff frequency to 1 Hz as shown in Figure 5.2. As is seen in the figure, the data is significantly smoothed but evidence of noise still exists in the data.

One further step was taken and a 1 Hz., 4th order Butterworth filter was applied to this data set. This is presented in Figure 5.3. As is seen in the graph, the noise is nearly attenuated. The phase lag for a 4th order filter with an input at the cutoff frequency is 360 degrees. This would result in a full second of lag time for such signals.

Because of the phase lag issues discussed above, the data, although much smoother, now has too large a phase lag to be utilized in a real-time sensing device.

5.1.2 Overall Sensor Device Reliability

After defining a suitable filter for use in processing the data, it was applied to all datasets collected on the Ford tractor. This information is summarized in
Table 5.1. Data in this table are sorted according to the observed outcome of the test, i.e. whether the tractor actually rolled. The data sets for each run were filtered with the filter listed in the header rows, and the peak angle value was then extracted from each dataset. The peak angle was compared to the calculated static instability angle as discussed in chapter 4. The data extraction program
then predicted an outcome for the tests based on the comparison of the peak angle and the static instability angle. Peak angles greater than the static instability angle were flagged with a 1, meaning a predicted overturn, and peak angles less than the static instability angle were flagged with a zero, indicating no predicted overturn.

It is worth noting that the data associated with run 5 on the 16 July, 2003, predicts correct overturn state for the 4th order filter, but predicts incorrectly for the two other filters. This would suggest that the 4th order filter would be a better choice were it not for the limitations discussed previously.

As stated in section 4.1.2, the data needs to be reduced to a meaningful range about the static instability angle to determine the overall device reliability in predicting overturn about this point. The data was analyzed and found to have a mean value of around 47 degrees for each filter used, with a standard deviation of around 15 degrees. This was used to define the boundaries for acceptable data as being peak angles between 34 and 64 degrees. This selection eliminates the first eight data points representing test runs that were not close enough to overturn to be considered potential overturn candidates.

The data for runs that result in overturn have a range of values. In actuality, all runs that result in overturn have associated peak angle values greater than 90 degrees. The variation in this is an illustration of the limitation of the sensor system. This data was collected with a sensor device that relied solely on measurements of acceleration (without the gyros that were added to the later revision of the device) to formulate a measure of peak angle. The result of this is in part that the angle measured drops off as the tractor accelerates as it rotates toward the ground in near free fall. This results in a peak angle that varies between 52 and 63 degrees, but this angle has little meaning once the tractor passes the point of no return.

5.1.2.1 Sensitivity, Specificity, and Error Rate

Based on the reduced data set filtered with the 2nd order filter at 1 Hz., and the equation for sensitivity given in section 4.1.2, the sensitivity of the tractor was found to be 100%. This means that every test run that resulted in overturn was correctly predicted.

Specificity was also calculated for the reduced data set. There were 50 test
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<td>roll</td>
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<td>70.02</td>
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</table>

**Table 5.1.** Summary of Statistical Analysis and Extraction.
runs that fell within the range specified. Of these, 28 resulted in overturn, and 29 were flagged as a predicted overturn. This results in a specificity of 95.6%.

The error rate for the sensor system was calculated and found to be 2%.

As was discussed previously, the sensitivity of the system provides a measure of whether the system correctly predicts an overturn event. It is critical that such a device correctly predict every situation that results in overturn as discussed in chapter 4. If the device does not predict overturn in an overturn situation, thereby giving the operator the opportunity to correct the situation, the results could include the death or injury of the operator, as well as damage to the tractor and implement. It is also important to avoid incorrectly predicting an overturn event that does not result in overturn to avoid causing the operator to lose confidence in the device. However, the cost of an error in specificity (loss of confidence in the device) is lower than the cost of an error in sensitivity (injury, death, damage to equipment).

Overall, the device functioned very well, correctly predicting 98% of every test run studied.

5.1.2.2 The Rear-Deck Mower

As is noted in Table 5.1 testing for the statistical analysis involved a rear deck type mower attachment. It was theorized that the attachment of a significant amount of mass low to the ground on the back of the tractor would result in a more stable tractor. This was borne out during testing when it was discovered that it was more difficult to cause overturn with the mower attached.

An analysis of this data presented above is presented in table 5.2. These values are based on the reduced data set, filtered with the 2nd order 1 Hz filter used and recommended above. It is interesting to note that those test runs with the mower have lower average peak values than the runs without the mower. This is also shown in table 5.1 in which the values centered around the static hill angle all correspond to tests without the mower. While the reason for this is unclear, it is possible that the addition of the rear deck mower resulted in test runs for which the tractor bounced less on the bump, or it is also possible that the stabilizing effect of the mower deck was sufficient to cause the tractor to remain at lower peak angle values (i.e. that it may simply have been harder to cause the tractor
to approach its new static hill angle with the given test setup).

<table>
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<td>Roll</td>
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Table 5.2. Comparison of Mean Peak Angle With and Without Mower.

Further testing is necessary to determine the location of the center of mass of the tractor with the mower deck attached, and to evaluate the actual effect of this shift in center of mass on the overall performance of the tractor in side overturn testing.

5.2 Rate Gyro Device

5.2.1 Tractor Rear Overturn Testing

The sensor device with rate gyros as described in chapter 4.2 was tested in rear overturn testing on June 13, 2005. Overall, 21 data sets were collected. The device measured those parameters described in section 4.3, and disengaged the clutch based on the comparison criterion listed there. As was described in section 4.3, the comparison used to determine when to disengage the clutch of the tractor results in a value that is simply a time shift. This means that the power must be disengaged at a certain point during rearward overturn. This ensures that the momentum of the tractor will not carry it past the stability point. Implicit in this is that the tractor’s clutch, which takes a finite amount of time to disengage, must be triggered sufficiently early that it will be fully disengaged by the time the tractor reaches the predicted point of instability.

The hydraulic actuator on the tractor’s clutch takes approximately 1.5 seconds to travel from one limit to the other. However, the clutch actually engages at some point between stops. The point at which the clutch disengages is difficult to measure safely a priori. The determination was made to program the sensor device in such a way that this value could be adjusted and fine tuned during testing.

Seven of the data sets were collected with the sensor device intervention disabled. These represent a standard rear overturn scenario. For ten of the data sets collected, the device was activated and disengaged the clutch of the tractor. Five
of these test runs were used to determine an optimal value for clutch disengagement time, i.e. the time required under most circumstances for the clutch to fully disengage once triggered. Once a value was roughly determined, the device was able to prevent 4 of the 5 test runs from resulting in overturn. The fifth test run, based on the selected values, resulted in overturn. This dataset is presented and discussed below.

Several tests were also conducted to determine the propensity of the device to trigger under normal operation on sloping ground, and to determine if the device would trigger for short hops that were initiated and stopped by the tractor operator. Analysis of the latter tests, involving short hops, revealed a flaw with the implementation of the device. The tractor’s clutch was actuated by means of a hydraulic cylinder. This cylinder was controlled by an electrically operated hydraulic valve. While the device was able to disengage the clutch by energizing an electromagnet on one side of the valve, it did not disable the electromagnet on the engage side of the valve. The design of the valve is such that when both electromagnets are engaged simultaneously, the valve will engage the clutch. The result was that the operator of the tractor was able to override the sensor device, and force the tractor clutch to engage regardless of the state of the sensor device. The end result was that for two of the tests in which short hops were attempted, unbeknownst to the operator of the tractor, the device triggered disengagement of the clutch but the test proceeded as the operator overrode the device as described above.

Lastly, the device was programmed in such a way that after triggering the clutch disengagement, it would not reset until the manual reset button was pressed, effectively leaving the clutch disengagement coil energized until manually reset. This is shown in the data presented below.

The plot in Figure 5.4 shows a typical rear overturn. The two values collected represent the angle as filtered and estimated by the Kalman filter, and the angular rate, which was returned by the Kalman filter, and then further filtered by a second order, 0.5 Hz Butterworth digital filter. As discussed previously, this could be included in the Kalman filter by proper selection of the process and sensor noise covariances.

The plot in Figure 5.5 represents another typical rear overturn. On this test
run, as sometimes occurs, the tractor had sufficient energy that it reared up, landed on the roll bar, and then bounced back down.

The plot in Figure 5.6 shows a successful test run in which the device intervened and prevented rear overturn. Note that the state of the clutch switch is indicated as a binary state, scaled to be more visible on the plots. From this, it can be seen that the clutch actually takes some time to disengage, and the actual point of disengagement is characterized by the peak in the angular rate.
The plot in Figure 5.7 shows a data set for which the tractor was slowed down significantly. The overturn event takes significantly longer in this plot than in others. This was another test for which the device successfully intervened and prevented rear overturn. As was shown in the previous plot, the clutch valve was triggered to disengage the engine and a significant period of time elapsed before the engine actually disengaged, and the tractor began to slow down. It should also be mentioned that this time is slightly different for both plots. This suggests that the disengagement time may vary based on relative load. It is quite possible that the tractor clutch begins to slip sooner for cases where the load on the engine is higher.

The final test run is shown in Figure 5.8 and resulted in overturn. It shows that the tractor just coasted up to the final position. The angular velocity had slowed significantly at the apex. This shows that the parameters for clutch actuation are well tuned, and a small final adjustment would be sufficient to prevent nearly all rear overturns.

Interestingly, the angle takes some time to register the full 90 degrees expected after tipping up and resting on the roll bar as was seen during testing. This is most likely a result of poor resolution of the accelerometer at these angles. As was discussed in previous sections, the angle measurement from the accelerometers is calculated from only one of the axes of the accelerometers. This results in very
poor resolution at higher angles. This is compensated for somewhat by the Kalman filtering algorithm because the resolution of the angular rate sensor has no such limitations. Future iterations of the sensor device should focus on eliminating this limitation by using the extra axes of the accelerometers to calculate the two desired angles (roll and pitch).

Further testing conducted with the new iteration of the sensor device included a test of driving the tractor on sloping ground to test for false positives. The graph of this data is seen in figure 5.9. The yellow line is included to show that during
operation of the tractor on moderately sloping ground, the device never disengaged the clutch.

![Graph showing tractor operation on normal ground.](image)

**Figure 5.9.** Tractor Operation on Normal Ground.

In this graph it is also apparent that there appears to be some periodic noise on the angle measurement. This is also apparent on Figure 5.7. The source of this periodic disturbance is unknown, and should be investigated.

As was also discussed previously, two tests were conducted to determine if the device would trigger for short hops initiated and controlled by the tractor operator. Figure 5.10 shows one such test. The device triggered the clutch disengagement on the first hop. Note, however, that the device triggers near the top of the peak for the short hop. Because of the time needed to actuate the clutch, it is apparent that the operator had already triggered the clutch to disengage some time before the device triggered. Further hops were forced by the operator and as was stated above, the control input from the device to disengage the clutch was simply overridden by the hydraulic valve.

### 5.2.2 ATV Overturn Testing

The device used above for tractor overturn testing was used during the 2005 Ag Progress Days demonstrations to collect data on a four wheel ATV used in overturn demonstrations.
The rear overturn datasets were roughly the same as those collected for the tractor rear overturn testing in which a strap was attached to the rear rack of the ATV. The ATV then reared up, and settled down onto the rear rack and the tires. Testing was accomplished during demonstrations, and because the ATV leaked fuel from the cap on the fuel tank, the data sets include the righting of the device after testing, i.e. the ATV was quickly set down on its wheels while the device continued to record data. This can be seen in most test runs.

The side overturn data was collected somewhat differently for the ATV than for the tractor. The testing on the agricultural tractor always involved a tripped overturn scenario, in which the tractor was operated on a side hill, and the uphill wheel hit a bump. For the ATV, untripped overturn was tested. The ATV was operated on primarily flat ground at a sufficient speed, and the wheels were turned sharply, causing the ATV to roll.

The first dataset is shown in Figure 5.11 for a typical rear overturn. Note that the ATV was righted only a few seconds after causing rear overturn.

The next dataset shows a more atypical rear overturn. The ATV had more of a tendency to bounce and loose traction as it rotated up in rear overturn than did the tractor. This can be seen in figure 5.12. As the angle increases, the ATV looses traction and the angle decreases, the ATV regains traction, and the ATV rotates up past -80 degrees before slowly coming to rest at around -65 degrees.
Untripped side overturn was more difficult to distinguish in plots of the data. Possible reasons for this include the limitation of the angle sensing based on a single accelerometer reading, and possible sample time and filtering issues. During tractor overturn, the typical outcome resulted in little more than 90 degrees rotation, and the sensor arrangement was acceptable for such situations. Also, the tractor has much more mass than the ATV, and so rotation is much slower during overturn.

Figure 5.13 shows a typical side overturn dataset. The limitation of the sensing device is shown in that the device is unable to distinguish angles greater than 90
degrees, and so these angles are mirrored about the 90 degree line. Observations from the overturn describe the event as the overturn occurred. The ATV rotated up and landed on the handle bars, and returned to its position roughly 15-20 degrees past 90. This was mirrored by the device to appear that the device settled at roughly 70-75 degrees.

A slower event of this type shows similar characteristics. Figure 5.14 shows this test run, in which the overturn occurred relatively more slowly than during the above test.

It appears that the device simply gets confused during overturn involving rotations much past 90 degrees, and the Kalman filtering algorithm attempts to piece these into some continuous measure of angle and angular rate, although the information being passed to the filter is not accurate.

A further discussion on the conclusions drawn based on the results presented above will be handled in chapter 6.

5.3 Human Factors and Perception Augmentation

The interviewing process as discussed in chapter four was completed for a total of four participants. The participants ranged in age from 27 to 47 years old. The
number of years experience of those surveyed ranged from 21 to 37 years. The age at which each participant reported to have started driving an agricultural tractor was between 6 and 10 years old.

In the study cited by Ericsson [ES84] in which people were asked to report what they remember thinking on their way to work, most people were only able to recall what they were thinking when connected to some physical event that had occurred on their way to work. It is postulated that people only have access to memories or cognitive processes which have some link to a specific event in time, while the thoughts that were not as overtly connected to outside temporal events were difficult to recall. They reinforce this idea by citing the example of people who get “road hypnosis” in which while driving, particularly on long trips, people often suddenly realize that they have no recall of what transpired for the last 20 miles. This phenomenon has bearing on the retrospective verbal reports collected in connection to the operation of agricultural tractors. For almost all participants, it was very difficult for them to verbalize anything relating to the process of operation of the tractor. When asked questions in category 2, particularly 2c “Tell me step by step what you do when you mow/bale...” (see chapter 4.4.3), subjects most often shared information on how they planned to cover the field in which they were working, rather than explaining specifically what steps were taken during operation. It appears from this that the participants

![Graph of ATV Side Overturn, August 18, Run 3.](image)

**Figure 5.14.** ATV Side Overturn, August 18, Run 3.
were not necessarily aware of those events with no specific temporal link, such as the normal tasks involved in operating the tractor, where the temporal event of starting work in a field provided a solid link for the participants to begin recalling what they thought and did. When prompted further with such follow-up questions as “Where are you looking during operation?”, or “So, once you start operation, what do you do?” the participants would either repeat some of the information already shared, or add some insight as to what things were checked, or where they were looking.

It is probable that most of the subjects have been operating agricultural tractors for a sufficiently long period of time that they have little conscious access to the details of the processes involved. With this in mind, however, the reports shared by the research participants were insightful, and provided solid direction for the design of the display device.

5.3.1 Visual Data Presentation

Because of the versatility of the modern agricultural tractor, the operator needs to continually change their method of operation to correctly suit the implement being pulled. Participants 3 and 4 both stated that during a season they will typically cover the same field three or four times. This may involve plowing, planting, mowing, and harvesting. These participants both mentioned that particularly during harvesting, after a couple passes on the field, they have learned where potential obstacles are, (such as rocks and groundhog holes) and are able to plan future passes on the field accordingly. Participant 3 stated that “I’m usually the one that would mow the hay, and rake the hay, so if I notice a new groundhog hole, I know that when I raked it, I either raked hay over the hole so I don’t have to worry about it, or I have to make sure... I don’t drop the guide wheel on the baler in that hole, or if it’s on the other side, you make sure... you don’t want to be driving your tractor in that hole either.” He later stated, “From going over the field from mowing and raking I usually know where I am in the field... and if I know there is a hill or a rock coming up, I’ll look ahead and quit looking at the back, but when I’m baling, for the most part, I am watching the equipment.”

The result is that for those interviewed, the first run through a field may
require a great deal more visual scanning outside, and in front of the tractor, while subsequent runs, such as baling may result in the operator focusing almost exclusively on the windrow and baler behind the tractor.

One of the participants reported in answer to question 2b that he relies primarily on visual inspection of the implement to make sure things are going well. “[I’m looking] back and forth. The tractors we have, the seats swivel, from side to side, so whenever I’m sitting in a machine, the seat is turned so I can look both ways [in front and behind]. That’s the way I sit in the seat all the time. It doesn’t matter if I’m driving down the highway or if I’m actually working a piece of equipment.”

He also stated in response to further inquiry into question 2b, “99% is visual... sometimes you can feel it in the way the tractor’s working, if the tractor’s working smooth, most of the time, things are going smooth behind you. If you start to feel an increase of power, where it’s trying to pull itself, that’s a good indication that something’s wrong.”

The reports of all the participants show that the tractor operator is presented with such a large amount of visual stimulation, all of which must be correctly and quickly processed, that the addition of another display in the tractor would either present a distraction, or would not be heeded. One of the study participants demonstrated his modern tractor cab environment, complete with three sets of visual displays for monitoring the round baler he typically uses, along with the instrument panel of the tractor itself which includes all the displays for the tractor engine and hydraulic system. This response was roughly the same for the other participant who reported driving a tractor with a cab, and one other of the participants.

This same idea was also stated by Murphy et al. [MJ84] where he concluded that often times, when the operator of a tractor encounters a situation that is near overturn they are simply unable to properly handle all of the pieces of information that are presented to them at the critical moment.

At the conclusion of the interview three of the participants responded that while they did not feel the need to have a device as presented in figures 4.12 and 4.14 (the function of which was demonstrated to them during the interview sessions) in their own tractor, they would like to have access to it particularly for those times when their employees or children were operating the tractor.
5.3.2 Auditory Information Presentation

Two of the participants reported primarily operating a tractor with no cab. These two participants also stated in answer to question 2b that they typically listen to the sound that the implement makes as an indicator of whether things are working properly. Participant 3 stated in regard to this, “... You can tell by hearing [the implement] if it's working, so if the hay is getting too tough, then you can hear it straining harder, and the tractor straining harder, and you should maybe wait to bale it.”

Participant 1 reported in response to question 2b, “... I was born and raised in an open tractor, so you listen to the equipment. You can hear the equipment operating.”

These statements show that at least some operators are accustomed to receiving auditory feedback as a means of assessing whether the tractor and implement are operating properly.

Participant 1 went on to say: “I don’t think we need the bar-light scenario. I think you could have a sensor on there that would tell [with] a bell or a whistle, something to tell you that you are in the danger area, or the caution area... that would be something that wouldn’t distract you...” This opinion was shared by one other of the participants who also stated that he would prefer an auditory signal indicating entering a potentially unsafe condition.

Past discussion and research into the use of an auditory signal for indication of overturn potential has been limited primarily under the assumption that the tractor environment is too loud for such a system to be effective. The above statements suggest that those operators on open tractors (for which the operating environment is louder than with an enclosed cab) may actually be more in tune to the sounds made by the tractor and implement, and so may be better able to internalize information from an auditory system.

This is further reinforced by Sanders et al. [SM93] on page 53 of their book. They include a table of selection criterion for selecting appropriate presentation modes for information. The table summarizes the situation suggested by the interviews discussed above, and reinforced by the examination of the number of displays in a modern agricultural tractor. The following items in the table seem to apply to the current situation: 1) the visual system of the person is overburdened; 2) the
message deals with events over time; 3) The message calls for immediate attention; 4) The person’s job requires moving about continually.

The table [SM93] also describes situations where a visual presentation of information is desirable. Those items relating directly to the research are listed as follows: 1) The message will be referred to later; 2) the message is complex.

The goal of the project is to define a display that satisfies both sets of criterion. This suggests the necessity of a device with the ability to present both auditory and visual information.

This is further reinforced and the design is further guided by Sanders [SM93] where he proposes guidelines for “Divided-Attention Tasks.” From page 74, “...we can offer a few guidelines gleaned from the research evidence... that should improve performance in a time-sharing or divided-attention situation.” He then states the following. “Where possible, the number of potential sources of information should be minimized.” This suggests that the visual display should attempt to present the minimal amount of data necessary to communicate that which is necessary.

5.3.3 Human Factors Display Issues

In connection with the investigation into alarm modalities, a further investigation into some of the other questions on the display was conducted. This included an investigation into visual data communication.

Sanders and McCormick [SM93] discuss this topic in great detail in chapter 5 of their book. The selection of display type is determined by, and determines what the operator needs, or gets from the display. When considering the question of a display to inform a tractor operator of relative overturn potential, it is important for the operator to know or have access to some key pieces of information. First, the operator needs to know how near the current situation is to the absolute limit of overturn. This would enable the operator to connect their perceptions to some quantity. This is particularly useful information if the operator is able to stop and spend some time consulting the display of recent overturn potential. The second piece of information that should be communicated to the operator is the current trend of overturn potential. Ideally, the operator should be able to discern whether a current situation is becoming more stable or less stable.
Sanders and McCormick [SM93] (pg. 132) give some guidelines on selection of an appropriate display type for a given communication goal. They suggest four types of information communication devices that may be considered. Based on the above statements, it appears that a quantitative display may be necessary. This is based on the assumption that while it may not be absolutely necessary for an operator to know at any given moment exactly at what angle the tractor is operating, it is necessary that the operator know how stable their current situation is relative to overturn. It is also important that some information be communicated as to whether the current situation is becoming more stable or less stable. Both of these pieces of information are communicated very effectively by means of a quantitative display.

They also state that “If numerical increase is typically related to some other natural interpretation, such as more more or less or up or down, it is easier to interpret a straight-line or thermometer scale with a moving pointer... because of the added cue of pointer position relative to zero, or null, condition.” (pg. 135) In this case, relative stability relative to the maximum position is desired, and so this type of display is desired.

Sanders and McCormick [SM93] then discuss the design of a qualitative scale. “Many qualitative scales represent a continuum of values that are sliced into a limited number of ranges (such as cold, normal, and hot); in other instances, specific ranges have particular importance to the user (such as representing the danger zone). In such cases, perception of the correct reading is aided by some method of coding the separate ranges. One way to do this is to use color codes.” The display designed and discussed previously takes advantage of this by the addition of a color code to the quantitative digital readout and quantitative moving bar arrangement. The green zone represents low overturn potential, yellow represents somewhat higher overturn potential, and red indicates the necessity for immediate action to avoid overturn.

5.3.3.1 Reaction Time Considerations

The initial design of the displayed information involves a scrolling bar graph of recent peak angle values. This display indicates the relative proximity to overturn by changing color from green to yellow to red. The central idea between these
transitions is to alert the operator of the agricultural tractor with sufficient time to allow some corrective action to be taken to avoid an overturn. This necessitates an investigation into the times required to respond to a presented stimulus.

Goldberg et al. [GP89] investigated response times for tractors in imminent overturn situations. One study cited reveals that the operators required about 500 ms. to initiate a response at the start of rollover. They then considered the time required to effect corrective steering changes, and reported on a study by Rehkugler which showed that without power steering, a 55 degree steering change was possible in under one second.

In studying possible corrective actions for rear overturn, Goldberg et al. found that a minimum of 500-600 ms was required for an operator, upon sensing overturn, to take corrective action, either by actuating the clutch or some other dash mounted cutoff switch.

These results represent a very best case scenario. Further discussion by Goldberg [GP89] shows that reaction times are significantly increased by the addition of such outside factors as ground vibration and operator focus on the implement behind the tractor.

These findings are further reinforced by a study cited by Sanders et al. [SM93] (pg. 703) in which unsuspecting drivers were driving past a car on the side of the road. The car door was opened in front of the drivers and the time to response was measured. The results of the study show that a full second elapses before the steering response is initiated by the driver of the car, and a further 2-3 seconds elapsed before full steering angle was achieved.

The result of the studies presented above shows that the minimum reaction time for an operator to sense that corrective action is necessary, and then effect the corrective action is on the order of at least 1-1.5 seconds.

5.3.3.2 Display Type and Modality

An investigation into different stimulus modality for information communication requires some characterization of the amount of information that can be reliably communicated by various stimulus dimensions. Sanders and McCormick [SM93] state the following “Given that we [people] are not very good at making absolute judgements of stimuli, how can we identify such a wide variety of stimuli in our
everyday experience? The answer is that most stimuli differ in more than one dimension. Two sounds may differ in terms of both pitch and loudness; two symbols may differ in terms of size and shape.” (pg. 55) This is further stated in a table in which the average number of absolute discriminations that can be made for various stimulus dimensions. On average, people are able to make 5 discriminations of pure tones, and 4-5 discriminations of loudness. This limits the amount of data that can be reliably communicated by such dimensions. However, if the stimulus is varied on two dimensions, the number of discriminations increases. These numbers as presented by Sanders and McCormick represent averages across people in optimal environments. It is reasonable to conclude that in a noisy environment the discrimination of signal loudness would be adversely affected because the levels of loudness above the ambient noise that are discriminable would decrease corresponding to the loudness of the ambient noise.

This indicates that for the case of the relative overturn proximity, if an auditory signal is to be used, the amount of information communicated must be appropriately restricted. For the current iteration of the visual display, the display changes from green to yellow to red. The auditory coding of this information would then need only two discriminations, assuming the device was quiet when the display indicated green. These two discriminations could be coded using a combination of redundant dimensions as suggested by Sanders and McCormick [SM93] (pg. 56). This could take the form of a tonal signal that for the yellow level switches on and off at a specific frequency and loudness, at a specific tonal frequency. In the red zone of the display this tonal signal could then be made louder, slightly higher in pitch, and the signal could be left on, instead of turning on and off. This would result in an auditory signal for which the two levels to be discriminated were triple-redundantly coded.

Sanders and McCormick [SM93] also demonstrate similar conclusions for visually coded data. They state that the average number of absolute discriminations that can be transmitted via the size of viewed objects is from 5 to 7. They later discuss the use of visual displays of dynamic information in terms of qualitative vs. quantitative displays. A quantitative display in the case of an overturn proximity indicator, however, may be inappropriate in terms of one of the goals of the project, which is to allow the operator to effect some change in behavior to avoid
impending overturn. In such situations it is unlikely that the operator of a tractor would be interested in focusing enough attention on a display to register a numerical value of current angle, and then convert this to some meaningful understanding of overturn proximity. In this case, it would most likely be more useful to have some presentation of current state that involved sparse encoding of data, perhaps in the form of a qualitative display for which only the 3 states of green, yellow and red are indicated.

A consideration of another of the project goals, namely that the device would serve as a learning tool with which operators could connect their perceptions with some absolute measure of stability, would seem to suggest that given the chance to consider a recently past situation, an operator may indeed wish to stop and consider actual numerical data, or relative magnitudes of overturn proximity presented for the recent situation in an attempt to evaluate their perceptions.

5.3.3.3 Automobile In-Vehicle Information Systems

A great deal of work has been conducted on automobile in-vehicle information systems. These systems have also been integrated into automated cruise control systems, and the interaction between humans and such systems have been studied. The end goal of these systems is primarily to alert drivers of a situation that may require intervention, not at all unlike the proposed farm tractor overturn system.

It has been stated previously that the visual channel for operators of agricultural tractors are heavily loaded. Gupta et al. [GBS02] stated the following. “If the visual channel is overloaded, there are obvious advantages in allocating some task to other sensory channels.” This is particularly true for the agricultural tractor. They then cite a study performed by Dingus, and quote as follows. “A combined visual and auditory system provided some advantages in terms of increasing following distance over a solely visual or auditory display, under certain traffic systems.” These statements both reinforce the information provided by the interviews of tractor operators cited above. In support of the statements presented above in regards to the sensitivity and selectivity of the sensor device, Gupta further states, “If the criterion for the alarm activation is set at too low a threshold (e.g. when probability of an accident is low), the alarm may conflict with other cues available to the drivers... and they may learn to ignore, discount,
and possibly disengage the alerting system.”

During interviews of tractor subjects it became apparent that because the participants had no outside measure of hill steepness, all of their judgment as to whether a particular hill was too steep were based on past experience of their own, or from watching someone else perform operations on a specific hill. Because every operator has different experiences, and very few actually result in overturn, every operator will have a different level of comfort with a given hill, regardless of what information is presented to them. Fancher [FBE01] expressed the importance of this difference in relation to the effectiveness of a collision avoidance system. “Experience with this type of warning system indicates that different drivers will prefer different thresholds... Once a driver’s stress level boundary is crossed, that person will feel the need to brake. If drivers are not warned by the time their stress reaches an unacceptable level, they may not be satisfied with the warning system” pg. 212. This can lead to distrust and discounting of the information presented as stated above. While these conclusions have bearing on this research into alerting an agricultural tractor operator of impending overturn situations, there are some fundamental differences in the situations to which they are applied. In the case of a system to warn of following distances that are too close, drivers already have some sense of how near they are to collision. This information is used by the drivers to judge how close they feel comfortable. In the state of an agricultural tractor operator, the operators have no way of knowing where the limit is. There is some amorphous limit that they know exists somewhere beyond their comfort level, but its exact location is not known.

Fancher [FBE01] later states, “Based on the results of this section it seems likely that any successful warning algorithm will have to consider actions by the driver along with the kinematics and inter-vehicular relationships of the current situation when deciding whether to warn or not. Certainly, there are situations when the driver’s attention is completely dedicated to the task of longitudinal control, and in those situations, sounding a warning may be more disruptive than helpful” pg. 219. The assumption made during the development of the device presented previously has been that the system would present information from the recent past to allow the operator to consult the display after correcting a potentially unstable condition, while also providing a visual measure of current overturn potential. The addition
of an auditory signal may pose a distinct challenge. The balance that must be found is the point where operators will not distrust the information presented, but will also not find themselves in situations of high stress when the device alerts them of an impending overturn. For this reason, it is important to include a visual information display, as well as a two level auditory signal. This would allow instruction from the device to be acknowledged in relatively lower stress situations via the first auditory signal, and the second auditory signal could then be used to alert of impending overturn, and the need for immediate action.
Conclusions and Recommendations

As was stated in the objectives section, the major goals of this project were to: 1) validate and improve the sensor developed previously; 2) further develop the display to more effectively communicate information to the operator; 3) develop a sensor device that would be able to actively intervene in rearward overturn situations; and 4) conduct a preliminary investigation of the sensor for sensing overturn of a 4-wheel ATV.

6.1 The Sensor Device

As stated in previous chapters, the sensor device developed previously included only an accelerometer for measuring a dynamic acceleration and converting this into a “dynamic hill angle.” The sensor device was then expanded to include angular rate gyroscopes and an optically isolated relay for actuation of the tractor’s clutch.

6.1.1 Statistical Analysis of Simplified Device

As was stated in chapter 5, the statistical analysis of the device showed very good results. The device was found to have an error rate of only 2% for the 50 test runs included in the analysis. The only test run resulting in an erroneous reading was for a test run that was incorrectly predicted as overturn. As was stated in chapter 5, this was very encouraging given that if there is any uncertainty in the prediction
of the sensor device, it is better that the error be on the side of the specificity. This means that if the device is to make an error due to any sources of uncertainty, it is better that it predicts overturn for a set of data that does not result in overturn, rather than not predicting overturn for a data set that does. In the latter case, the operator of the agricultural tractor may not know that the tractor is about to overturn, and would, therefore, not be able to correct the situation.

The results of the statistical analysis show that the sensor device, filter, and method for predicting overturn based on a comparison to the static instability angle, is capable of correctly measuring and predicting overturn potential.

### 6.1.2 Performance of Rate Gyro Augmented Device

The addition of rate gyros to the sensor device greatly improved its measurement capability. This enabled further research to be done in preventing rearward overturn. As has been stated, rearward overturn events typically involve improper hitching of a load to some point on the tractor above the rear axle. The result is that the overturn event is very fast and the unsuspecting operator is often unable to prevent overturn once it has begun.

The redesigned sensor device was able to measure both the angle and angular rate for the tractor under rearward overturn conditions, and based on the comparison of the current conditions measured, was able to disengage the clutch of the tractor and prevent rearward overturn. This was shown in detail in chapter 5.

As was stated in chapter 5, after selecting appropriate values for clutch disengagement time, the device was able to successfully prevent overturn in 4 out of 5 test runs. The selection of slightly more conservative values for clutch actuation time would further reduce the number of rear overturns. It should also be noted that in those cases for which the device triggered prematurely, the tractor reached peak angles around 50 degrees. While this is a more qualitative assessment and is not backed by hard statistical data, it is fair to say that the average operator of a tractor that encountered such a severe angle would not care if the device disengaged the clutch prematurely as such a severe angle would likely be rather nerve wracking.

The device did show favorable results as stated above and for operation on hills
with angle values around 20 to 30 degrees the device did not falsely trigger clutch disengagement. Further testing should now be conducted to limit premature clutch disengagement.

It was also noted in chapter 5 that the actuation time of the clutch is significant. The result of this is that the time delay parameters required to prevent overturn also result in situations, such as those shown in figure 5.10, in which the device triggered prematurely. This was a problem faced by Mitchell [MZL72]. Because of this problem, Mitchell found it necessary to actuate the clutch via a spring loaded release device. This resulted in clutch disengagement times on the order of 0.2 seconds.

It was also conjectured that the actual clutch disengagement may vary somewhat with load. A clutch that releases slowly will begin to slip at some different point for varying loads. If the clutch actuation time is slow, the time variation for clutch deactivation will be more significant.

It was also shown in chapter 5 that for certain conditions, it was possible to force the clutch of the tractor to engage even if the device had activated the disengage side of the hydraulic valve. The result was that for some of the testing it was not immediately clear if the device had triggered clutch deactivation or not. One solution for this would be to have the tractor disable the engage side of the valve when it disengages the clutch. This would only require the inclusion of another relay to disable this switch.

Another solution for the slow actuation times, and for the forced clutch engagement problems, is to follow the work of Mitchell [MZL72] and redesign the clutch such that it could be deactivated by means of some spring loaded device. The device would allow for much faster clutch disengagement times, and could also be made non-resettable so as to disable any engagement of the clutch for further operation. This would also reduce the magnitude of the time variation for clutch actuation due to varying load on the clutch by simply reducing the overall time of clutch actuation. However, this would require significant effort for the operator of a tractor to reengage the device and regain control of the clutch of the tractor. It could also cause the operator of a tractor to lose control of the tractor after encountering a near overturn event, and may cause greater problems for the operator.
6.2 The Display Device

Research cited in previous chapters shows that the overall design of the display is good, but could be improved with some refinements.

6.2.1 Current Visual Display

The current visual display was analyzed and compared to existing devices and research. The following is proposed for the revised display device.

First, as cited previously, Sanders and McCormick [SM93] state that for deriving quantitative values from displays, and for the communication of trends in information, a display which incorporates a moving pointer is preferred. They also state that a qualitative display is good to communicate information quickly. The display proposed previously incorporates a series of moving bars. These bars act as quantitative moving pointers. Angle value can be extracted from the plot of data by comparing the relative height of the bars to the scale at the left. The display was further augmented with a qualitative feature. The bars themselves change color to indicate relative stability, green being stable, yellow intermediate overturn potential, and red being imminent overturn.

Second, the inclusion of the digital readout of current angle seems to be less effective when investigated in the literature. While it does provide a quick reference to current angle, it takes longer to read than a qualitative display, and stores no information for use later. If this is to be included in the further revision of the device, it should be accompanied by some sort of qualitative feedback, such as changing color with the bars on the graph. One limitation of this information coding strategy is discussed below.

Because agricultural tractors have different static hill angle values depending on the location of their center of mass, it is important to present the operator with some value that is relative to the state of overturn. While an angle measurement communicates current vehicle state, it is necessary to consider the current angle relative to the known angle of overturn. It is proposed that this be replaced with some measure of stability, or stability margin where the measure of zero equates to overturn. This was stated by Sanders and McCormick [SM93] (pg. 135) and was cited earlier. It is important to provide some limit on the display to which the
current condition is compared. This could be accomplished in two ways. Either the “static instability angle” could be marked by a line on the scrolling bar graph portion (effectively presenting the limit of stability relative to the moving height of the bars), or the measure of angle could be replaced with a percentage indication. If zones were included in the scrolling bar graph, indicating the green, yellow and red zones, the operators would be able to compare their current situation with the relative overturn potential indicated on the display. The percentage indication could show that for a given indication on the display, the operator was some percentage away from overturn. This would effectively put the red line at the top of the bar graph. This could be further reinforced with a labeled red line, and possibly a yellow zone on the bar graph.

6.2.2 Proposed Communication System

The proposed display should incorporate an auditory two level signal, and a visual bar graph arrangement discussed above.

The auditory signal would be triple redundantly coded as stated earlier, the first level being a pulsing tone of four different frequencies (800 Hz, 1000 Hz, 1500 Hz, and 2200 Hz) and set to roughly 15 dB SPL above ambient, corresponding to the yellow region on the bar graph. The second level would be a solid tone of a higher set of frequencies and roughly 20 dB SPL above ambient. These should then be evaluated for effectiveness and fine tuned for maximum cognition. The actual volume level must be selectable (by the distributor, not the tractor operator) to accommodate tractors both with and without a cab. Based on the information cited previously by Bean [Bea90] the auditory signal should initially be set to roughly 90-95 dB for tractors with a cab, and 105-110 dB for tractors without a cab, corresponding to the yellow region on the bar graph. The signal level for the red region on the graph should initially be set to 95-100 dB for tractors with a cab, and 110-115 dB for tractors without a cab. These values should then be evaluated for communication effectiveness, and consideration should also be made to prevent damage to the hearing of the operator of such tractors, given the high level of ambient noise, and the addition of an even louder auditory signal.

The coded information could be further reinforced by changing the color of the
digital portion of the display as stated above. The idea being that the change in color of such a large portion of the display would call the operator’s attention to the device in an imminent overturn condition.

6.2.3 Transition Angles

The addition of a qualitative feature to show state relative to the limit of stability, i.e. the change from green to yellow to red, is desirable for communication of current stability state. The question of where these transitions should occur will now be discussed.

An inspection of side hill overturn data such as is presented in Figure 5.1 shows one possible side overturn scenario. The operator is operating on a side hill, hits a bump, and the tractor overturns. In this case, the size of the bump is significant, but illustrates some of the timing of an overturn event.

A closer analysis of side overturn data shows that the time for the tractor to overturn after the front tire hits the bump is roughly 3-4 seconds. If the operator of the tractor has not taken action before this time, the tractor will overturn. Goldberg et al. [GP89] showed that an operator would need roughly 1-1.5 seconds to initiate some response (depending of course on the desired response), and as was shown by Sanders et al. [SM93] (pg. 703), the time for an unsuspecting driver to achieve full steering angle was around 2-3 seconds.

Given the realization that the situation presented in testing represents a rather severe case, it is instructive as to the timing of an overturn event. If the data collected during testing is used as a rough baseline, and the above reaction times are used as indications for when the display should change from green to yellow to red, the data shows that the display should turn yellow at around 25 degrees, and that it should turn red at roughly 35 degrees, assuming that the 1-1.5 seconds would be sufficient for the operator to see the change in the display color and begin to affect the correct change in operation to avoid overturn.

The assumption that is key to the above times is that the operator, once notified, will immediately know what corrective action to take, and will initiate that action. In cases for which the bump is less severe, the operator would be given more time than the minimum times listed above. This means that the angles
listed above are conservative. Further work could be done to include statistical considerations for ground roughness as proposed by Spencer and Gilfillan [SG76].

6.3 Four-Wheel ATV Device

The device functioned only marginally for the ATV. The primary difficulty in interpreting the data is that the device was only capable of measuring angles of at most 90 degrees, with decreases in resolution as the angle approaches the extreme values.

Some information can be gleaned from the plots. Figure 5.12 shows a typical rear overturn. The device was able to measure angles and rates for the device as it rotated up, but the limited resolution of the sensor at angles near 90 made it difficult to distinguish exactly what was occurring as the vehicle approached these values.

Figure 5.14 shows a side overturn. Similar problems exist for this data set, particularly because the ATV rolled completely over during these tests. Further refinement of the sensing device is necessary to reliably interpret data from such events.

For prediction of untripped overturn, the inclusion of a third rate gyro to collect yaw rate would be helpful. The accelerometer arrangement already allows the ability to sense acceleration in each of the principal axes, and the addition of the yaw rate sensor would allow a better characterization of the vehicles state.

6.4 Inclusion of Post-Event Notification

Chapter 3 also mentions the possibility of enabling the device to interface with a remote communication device. This would allow the device to sense overturn and signal for help, not unlike the emergency location transmitters (ELT) used in aircraft, or similar to the GM OnStar® system. The work done to prevent rearward overturn shows that the device could recognize a side overturn event, and could then trigger a communication device to aid in rescue efforts.
Proposed Future Work

7.1 Addition of an Implement

As stated in chapter 5, the addition of an implement, namely the rear deck mower, showed interesting results upon analysis of the data. It was shown in table 5.1 that the overturn tests with the mower attached showed lower peak angles for near misses. The data presented seems to suggest that for the testing scenario selected, the rear deck mower actually tends to reduce the stability of the tractor. Simple analysis of the tractor as a free body diagram shows that the addition of mass below the tractor’s center of mass will stabilize the tractor, so it is probable that the data presented is skewed by large numbers of tests with the mower that were not near overturn.

This was discussed in detail in chapter 5, and it was surmised that the test setup made it difficult to get the tractor with mower up to angles nearer the critical angle. Future work should focus on reexamining the test setup to determine how appropriate it is for this type of testing. Further work should be done to show how the mower affects static instability angle, and overall overturn stability. This could include testing on a steeper hill, or at a higher speed to try to bring the tractor to a higher angle before overturn is initiated.
7.2 Improved Rear Overturn Testing

There was some ambiguity in the rear overturn testing that arose from the ability of the tractor operator to force the clutch to engage regardless of the state of the sensor or disengagement side of the valve. As was proposed in chapter 6, the ability to force the clutch to engage once the device has disengaged should be interrupted by means of a relay. This would enable a more rigorous testing scenario for false positive tests by making it more obvious when the sensor device had disengaged the tractor’s clutch.

It was also proposed in chapter 6 that a faster method of clutch actuation be employed to further refine the selectivity of the rear overturn intervention. This would reduce the number of times the device disengages the tractor unnecessarily.

If a spring loaded device were used for clutch actuation, and were set to function in only one direction, it could also eliminate any ambiguity in the testing that may result from the ability of the operator to force clutch engagement.

It was also stated previously that the Kalman filter and post filter should be combined by measuring process noise covariance for operation on flat ground. This should then be used in the Kalman filter to account for this noise and eliminate the need for a post-filter.

7.3 Improved ATV Testing

The results of the preliminary testing of the use of the sensor device to sense overturn for a 4-wheel ATV showed that the device should be developed further. The angle sensing must include measurements of two axes of the accelerometers to place the angle in the correct quadrant, and to give better resolution for angles measured near 90 degrees.

The current data sampling rate is 60 Hz. The mass properties of the ATV are much different from those of the tractor, resulting in much faster events on the ATV than on the tractor. The filtering algorithms were set for the tractor and are probably not appropriate for the ATV and should be redesigned.
Further work should also be done to develop an algorithm for sensing untripped overturn potential. This could then be incorporated into a display suited for the ATV.
Appendix A

Listing of C/C++ Code

A.1 Sensor Device Code

Rather than providing an exhaustive listing of all code, a program flow chart A.1 was provided with rough indications of what program modules were created and used for the sensor device. The code for the Kalman filtering routine code is listed in full. Note that the Kalman filtering routine is listed as an interrupt service routine. It was executed at roughly 60 Hz. and the processor enabled or disabled the interrupt service routine to begin and end data collection.
Figure A.1. Flow Chart for Sensor System Code.

// Timer 0 overflow interrupt service routine
interrupt [TIM0_OVF] void timer0_ovf_isr(void)
{
    // declaration of function variables
    char c;
    float qx_m, qy_m, qx, qy,
        Pxdot[2*2], Pydot[2*2],
        anglex_m, angley_m,
        anglex_err, angley_err,
        C_0,
        // C_1,
        PCtx_0, PCtx_1,
        PCtx_y_0, PCtx_y_1,
Ex,
Ey,
Kx_0,
Kx_1,
Ky_0,
Ky_1,
tx_0,
tx_1,
ty_0,
ty_1,
tempfloat,
B[3] = \{0.0021,0.0042,0.0021\},
A[3] = \{1.0000,-1.8669,0.8752\};

long ax_m,
ay_m,
az_m;

// State Update

//read gyro, and accel values
qy_m=read_adc(3); //read the y-axis angular rate from the adc
qx_m=read_adc(7); //read the x-axis angular rate from the adc
ax_m=read_adc(4); //read the x-axis acceleration
ay_m=read_adc(0); //read the y-axis acceleration
az_m=read_adc(1); //read the z-axis acceleration

//convert gyro to units of rad/sec.
qx_m=-(qx_m-zeroxr)*.01745328*.99; //The gyro outputs 5mv/deg/sec, the ADC is 5mv/count.
qy_m=(qy_m-zeroyr)*.01745328*.99;

//Zero the acceleration values.
ax_m=ax_m-zerox;
ay_m=ay_m-zeroy;
az_m=az_m-zeroz;
qx = qx_m - qx_bias;
qy = qy_m - qy_bias;

/*
 * Compute the derivative of the covariance matrix
 * 
Pdot = A*P + P*A' + Q
 *
 * We've hand computed the expansion of A = \[ 0 -1, 0 0 \] multiplied
 * by P and P multiplied by A' = \[ 0 0, -1, 0 \]. This is then added
 * to the diagonal elements of Q, which are Q_angle and Q_gyro.
 */
Pxdot[0] = Qx_angle - Px[0][1] - Px[1][0]; /* 0,0 */
Pxdot[1] = - Px[1][1]; /* 0,1 */
Pxdot[2] = - Px[1][1]; /* 1,0 */
Pxdot[3] = Qx_gyro; /* 1,1 */

Pydot[0] = Qy_angle - Py[0][1] - Py[1][0]; /* 0,0 */
Pydot[1] = - Py[1][1]; /* 0,1 */
Pydot[2] = - Py[1][1]; /* 1,0 */
Pydot[3] = Qy_gyro; /* 1,1 */

/* Store our unbiased gyro estimate */
xrate = qx;
yrate = qy;

/*
 * Update our angle estimate
 * angle += angle_dot * dt
 * += (gyro - gyro_bias) * dt
 * += q * dt
 */
xangle = xangle + qx * dt;
yangle = yangle + qy * dt;

/* Update the covariance matrix */
Px[0][0] = Px[0][0] + Pxdot[0] * dt;
Px[0][1] = Px[0][1] + Pxdot[1] * dt;
Px[1][0] = Px[1][0] + Pxdot[2] * dt;
Px[1][1] = Px[1][1] + Pxdot[3] * dt;

Py[0][0] = Py[0][0] + Pydot[0] * dt;
Py[0][1] = Py[0][1] + Pydot[1] * dt;
Py[1][0] = Py[1][0] + Pydot[2] * dt;

// Kalman Update

//angle_x_m = atan2( ax_m, -az_m );
tempfloat=ax_m;
tempfloat=tempfloat/(30*2);//convert to G's
if (tempfloat>1){tempfloat=1;}
if (tempfloat<-1){tempfloat=-1;}
angle_x_m = asin( tempfloat );
angle_x_err = angle_x_m - xangle;
//angle_y_m = atan2( ay_m, -az_m );
tempfloat=ay_m;
tempfloat=tempfloat/(29*2);//convert to G's
if (tempfloat>1){tempfloat=1;}}
if (tempfloat<-1){tempfloat=-1;}
angley_m = -asin( tempfloat );
angley_err = (angley_m - yangle);

/*
 * C_0 shows how the state measurement directly relates to
 * the state estimate.
 * The C_1 shows that the state measurement does not relate
 * to the gyro bias estimate. We don't actually use this, so
 * we comment it out.
 */
C_0 = 1;
/* C_1 = 0; */

/*
 * PCt<2,1> = P<2,2> * C'<2,1>', which we use twice. This makes
 * it worthwhile to precompute and store the two values.
 * Note that C[0,1] = C_1 is zero, so we do not compute that
 * term.
 */
PCtx_0 = C_0 * Px[0][0]; /* + C_1 * P[0][1] = 0 */
PCtx_1 = C_0 * Px[1][0]; /* + C_1 * P[1][1] = 0 */
PCty_0 = C_0 * Py[0][0]; /* + C_1 * P[0][1] = 0 */
PCty_1 = C_0 * Py[1][0]; /* + C_1 * P[1][1] = 0 */

/*
 * Compute the error estimate. From the Kalman filter paper:
 * E = C P C' + R
 * Dimensionally,
 * E<1,1> = C<1,2> P<2,2> C'<2,1> + R<1,1>
 * Again, note that C_1 is zero, so we do not compute the term.
 */
Ex = R_xangle + C_0 * PCtx_0; /* + C_1 * PCtx_1 = 0 */
Ey = R_yangle + C_0 * PCty_0; /* + C_1 * PCty_1 = 0 */

/*
 * Compute the Kalman filter gains. From the Kalman paper:
 * K = P C' inv(E)
 * Dimensionally:
 * K<2,1> = P<2,2> C'<2,1> inv(E)<1,1>
 * Luckily, E is <1,1>, so the inverse of E is just 1/E.
Kx_0 = Pctx_0 / Ex;
Kx_1 = Pctx_1 / Ex;
Ky_0 = Pcty_0 / Ey;
Ky_1 = Pcty_1 / Ey;

/*
*  Update covariance matrix. Again, from the Kalman filter paper:
*  *
*  * P = P - K C P
*  *
*  * Dimensionally:
*  *
*  * P<2,2> -= K<2,1> C<1,2> P<2,2>
*  *
*  * We first compute t<1,2> = C P. Note that:
*  *
*  * t[0,0] = C[0,0] * P[0,0] + C[0,1] * P[1,0]
*  *
*  * But, since C_1 is zero, we have:
*  *
*  * t[0,0] = C[0,0] * P[0,0] = PCt[0,0]
*  *
*  * This saves us a floating point multiply.
*/
tx_0 = Pctx_0; /* C_0 * P[0][0] + C_1 * P[1][0] */
tx_1 = C_0 * Px[0][1]; /* + C_1 * P[1][1] = 0 */
ty_0 = Pcty_0; /* C_0 * P[0][0] + C_1 * P[1][0] */
ty_1 = C_0 * Py[0][1]; /* + C_1 * P[1][1] = 0 */

Px[0][0] = Px[0][0] - Kx_0 * tx_0;
Px[0][1] = Px[0][1] - Kx_0 * tx_1;
Px[1][0] = Px[1][0] - Kx_1 * tx_0;
Px[1][1] = Px[1][1] - Kx_1 * tx_1;

Py[0][0] = Py[0][0] - Ky_0 * ty_0;
Py[0][1] = Py[0][1] - Ky_0 * ty_1;
Py[1][0] = Py[1][0] - Ky_1 * ty_0;
Py[1][1] = Py[1][1] - Ky_1 * ty_1;

/* Update our state estimate. Again, from the Kalman paper:
*  *
*  * X += K * err
*  *
*  * And, dimensionally,
*  *
*  * X<2> = X<2> + K<2,1> * err<1,1>
*  *
*  * err is a measurement of the difference in the measured state
*  * and the estimate state. In our case, it is just the difference
between the two accelerometer measured angle and our estimated angle.*

\[ xangle = xangle + Kx_0 \cdot \text{anglex}_{\text{err}}; \]
\[ qx\_bias = qx\_bias + Kx_1 \cdot \text{anglex}_{\text{err}}; \]
\[ yangle = yangle + Ky_0 \cdot \text{angley}_{\text{err}}; \]
\[ qy\_bias = qy\_bias + Ky_1 \cdot \text{angley}_{\text{err}}; \]

//xangle=ax_m;
//yangle=sy_m;

// Write x and y angle and rate values to the eeprom via the i2c bus
\[
\text{tempfloat} = xangle \cdot 1000;
\text{xangleint} = \text{tempfloat} + 16000;
\text{tempfloat} = xrate \cdot 1000;
\text{xrateint} = \text{tempfloat} + 16000;
\text{tempfloat} = yangle \cdot 1000;
\text{yangleint} = \text{tempfloat} + 16000;
\text{tempfloat} = yrate \cdot 1000;
\text{yrateint} = \text{tempfloat} + 16000;
\text{eeprom_write}((\text{ramspot} \cdot 8), \text{xangleint}, \text{xrateint}, \text{yangleint}, \text{yrateint});
\text{ramspot} = \text{ramspot} + 1; // increment the ramspot memory pointer
// add 16000 so the value stored is never negative,
// this is subtracted off in the PC download program

// Tractor Cutoff Switch Actuation

/* Filter the angular rate with a .5Hz cutoff frequency digital IIR Butterworth Filter
\[ B = 0.0021 \quad 0.0042 \quad 0.0021 \]
\[ A = 1.0000 \quad -1.8669 \quad 0.8752 \]
\text{unfiltyrate}[2] = \text{unfiltyrate}[1];
\text{unfiltyrate}[1] = \text{unfiltyrate}[0];
\text{unfiltyrate}[0] = yrate;
\text{filtyrate}[2] = \text{filtyrate}[1];
\text{filtyrate}[1] = \text{filtyrate}[0];
*/

// PORTA.6 = 1; deltatime cutangle
\text{tempfloat} = (yangle) + (12.64 \cdot 3.14159/180) \cdot \text{(deltatime)} \cdot \text{(yrate)} // \text{filtyrate}[0];
\text{if (tempfloat} > \text{cutangle}{

PORTA.6 = (!\text{normswitchstate});
}

// Send Collected Data
if (\text{ramspot} > \text{samplenun}){
// Timer/Counter 0 initialization
   // Clock value: off
TCCR0=0x00;
collect=1;
//Upload the stored data.
lcd_clear();
lcd_gotoxy(0,0);
lcd_putsf("Upload Data?");
lcd_gotoxy(0,1);
lcd_putsf("1-NO 2-USB 3-CAN");

c=1;
while (c==1){
    if(PIND.4==0){
        collect=0;
        // Timer/Counter 0 initialization
        // Clock value: 15.625 kHz
        // Set to overflow at 60 Hz to initiate the
        // Kalman filter routine.
        //TCCR0=0x05;
        c=0;
    }
    if(PIND.5==0){
        transfer_data_usb(samplenum);
        c=0;
    }
    if(PIND.6==0){
        transfer_data(samplenum);
        c=0;
    }
};//end send saved data while loop

//transfer_data_usb(samplenum);

} //timetest=timetest+1;
}
A.2 Inverted Pendulum Mobile Robot Code

The Inverted Pendulum Mobile Robot uses the same Kalman filtering routine discussed above, but the output of the filtering routine is then used to calculate duty cycle output for the motors according to a control law. This is described in the flow chart, figure A.2.

![Flow Chart for Inverted Pendulum Mobile Robot](image)

**Figure A.2.** Flow Chart for Inverted Pendulum Mobile Robot.
This program was produced by the
CodeWizardAVR V1.24.1 Evaluation
Automatic Program Generator
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http://www.hpinfotech.ro
e-mail:office@hpinfotech.ro

Project : Pendulum Program
Version : 1.0
Date : 3/4/2004
Author : Corrie Nichol
Company :
Comments:

Chip type : ATmega32
Program type : Application
Clock frequency : 16.000000 MHz
Memory model : Small
External SRAM size : 0
Data Stack size : 512

*******************************************************************************/

#include <mega32.h>
#include <delay.h>
#include <math.h>
#include <stdio.h>

// Alphanumeric LCD Module functions
#asm
   .equ __lcd_port=0x15
#endasm
#include <lcd.h>

#define ADC_VREF_TYPE 0x40
// Read the AD conversion result
unsigned int read_adc(unsigned char adc_input)
{
   ADMUX=adc_input|ADC_VREF_TYPE;
   // Start the AD conversion
   ADCSRA|=0x40;
   // Wait for the AD conversion to complete
   while ((ADCSRA & 0x10)==0);
   ADCSRA|=0x10;
   return ADCW;
}

// Global variable declaration
float R_angle=.3,
Q_angle=.001,
Q_gyro=.003,
dt=.01632,
angle,
qu_bias,
rate,
P[2][2] = {
    1, 0

}.
position,
velocity,
tempvar1,
tempvar2,
enc1,
enc2,
cmdvelms,
cmdturnms;
int cmdvel,
cmdturn,
thumbsw,
rsdrive,
lsdrive;

//Read the encoder position
int read_enc(char encoder)
{
    int tempvar=0;
    if (encoder==1){
        PORTD.0=0;//enable output on quadrature chip encoder 1
    }
    else {PORTD.1=0;}//enable output on quadrature chip encoder 2

    PORTD.6=0;//select high byte on encoder
delay_ms(.1);
tempvar=PINB;//output for quadrature chips is on PINB
    tempvar=tempvar<<8;
    PORTD.6=1;//select low byte on encoder
delay_ms(.1);
tempvar=tempvar|PINB;
    PORTD.0=1;//disable output on quadrature chip encoder 1
    PORTD.1=1;//disable output on quadrature chip encoder 2

    return tempvar;
}

// Timer 0 overflow interrupt service routine
interrupt [TIM0_OVF] void timer0_ovf_isr(void)
{
// declaration of function variables
float  q_m,
q,
Pdot[2*2],
angle_m,
angle_err,
C_0,
// C_1,
Pct_0,
Pct_1,
E,
K_0,
K_1,
t_0,
t_1;

    long ax_m,
az_m;

// State Update

// read gyro, and accel values
q_m=read_adc(2); // read the y-axis angular rate from the adc
ax_m=read_adc(1); // read the x-axis acceleration
az_m=read_adc(0); // read the z-axis acceleration

// convert gyro to units of rad/sec.
q_m=-(q_m-512)*0.01745328;///2.5; // The gyro outputs 5mv/deg/sec, the ADC is 5mv/count.
// If using 150 deg/sec uncomment the 2.5
//(the 150 is 12.5mv/deg/sec)

// Zero the acceleration values.
ax_m=ax_m-512;
az_m=az_m-512;

q = q_m - q_bias;

/*
    * Compute the derivative of the covariance matrix
    *
    * Pdot = A*P + P*A' + Q
    *
    * We've hand computed the expansion of A = [ 0 -1, 0 0 ] multiplied
    * by P and P multiplied by A' = [ 0 0, -1, 0 ]. This is then added
    * to the diagonal elements of Q, which are Q_angle and Q_gyro.
    */
Pdot[0] = Q_angle - P[0][1] - P[1][0]; /* 0,0 */
Pdot[1] = -P[1][1]; /* 0,1 */
Pdot[2] = - P[1][1]; /* 1,0 */
Pdot[3] = Q_gyro; /* 1,1 */

/* Store our unbiased gyro estimate */
rate = q;

/* Update our angle estimate */
angle += angle_dot * dt
++ (gyro - gyro_bias) * dt
++ q * dt
*/
angle = angle + q * dt;

/* Update the covariance matrix */
P[0][0] = P[0][0] + Pdot[0] * dt;
P[0][1] = P[0][1] + Pdot[1] * dt;
P[1][0] = P[1][0] + Pdot[2] * dt;

// Kalman Update
angle_m = atan2(-ax_m, az_m); //for the 150, make az_m negative
angle_err = angle_m - angle;

/*
 * C_0 shows how the state measurement directly relates to
 * the state estimate.
 * The C_1 shows that the state measurement does not relate
 * to the gyro bias estimate. We don’t actually use this, so
 * we comment it out.
 */
C_0 = 1;
/* C_1 = 0; */

/*
 * PCt<2,1> = P<2,2> + C’<2,1>, which we use twice. This makes
 * it worthwhile to precompute and store the two values.
 * Note that C[0,1] = C_1 is zero, so we do not compute that
 * term.
 */
PCt_0 = C_0 * P[0][0]; /* * + C_1 * P[0][1] = 0 */
PCt_1 = C_0 * P[1][0]; /* * + C_1 * P[1][1] = 0 */

/*
 * Compute the error estimate. From the Kalman filter paper:
 * E = C P C’ + R
*/
* Dimensionally,
*  
* \( E_{1,1} = C_{1,2} P_{2,2} C'_{2,1} + R_{1,1} \)
*  
* Again, note that \( C_1 \) is zero, so we do not compute the term.
*/
E = R_angle + C_0 * PCt_0; /* + C_1 * PCt_1 = 0 */

/*
* Compute the Kalman filter gains. From the Kalman paper:
*  
* \( K = P C' \text{ inv}(E) \)
*  
* Dimensionally:
*  
* \( K_{2,1} = P_{2,2} C'_{2,1} \text{ inv}(E)_{1,1} \)
*  
* Luckily, \( E \) is \( <1,1> \), so the inverse of \( E \) is just \( 1/E \).
*/
K_0 = PCt_0 / E;
K_1 = PCt_1 / E;

/*
* Update covariance matrix. Again, from the Kalman filter paper:
*  
* \( P = P - K C P \)
*  
* Dimensionally:
*  
* \( P_{2,2} -= K_{2,1} C_{1,2} P_{2,2} \)
*  
* We first compute \( t_{1,2} = C P \). Note that:
*  
* \( t[0,0] = C[0,0] \cdot P[0,0] + C[0,1] \cdot P[1,0] \)
*  
* But, since \( C_1 \) is zero, we have:
*  
* \( t[0,0] = C[0,0] \cdot P[0,0] = PCt[0,0] \)
*  
* This saves us a floating point multiply.
*/
t_0 = PCt_0; /* C_0 * P[0][0] + C_1 * P[1][0] */
t_1 = C_0 * P[0][1]; /* + C_1 * P[1][1] = 0 */
P[0][0] = P[0][0] - K_0 * t_0;
P[0][1] = P[0][1] - K_0 * t_1;
P[1][0] = P[1][0] - K_1 * t_0;
P[1][1] = P[1][1] - K_1 * t_1;
/* Update our state estimate. Again, from the Kalman paper:
*  X += K * err
* And, dimensionally,
*  X<2> = X<2> + K<2,1> * err<1,1>
* err is a measurement of the difference in the measured state
* and the estimate state. In our case, it is just the difference
* between the two accelerometer measured angle and our estimated
* angle. */

angle = angle + K_0 * angle_err;
q_bias = q_bias + K_1 * angle_err;

// Control Routine
cmdvelms=.1*((cmdvel-125)*.4/125)+.9*cmdvelms;//max safe velocity is .4 m/s
tempvar1=cmdturn-100;
    cmdturnms=.1*(tempvar1)+.9*cmdturnms;

enc1=read_enc(1);
enc2=read_enc(2);
tempvar1=-(enc2+enc1)/2;
PORTC.3=0;//low will reset quadrature chips, high will not.
delay_ms(.01);
PORTC.3=1;

velocity=(tempvar1)/(dt*83545.97);//83545.97 ticks per meter
    //if (abs(velocity)>.5){cmdvelms=.5;}
velocity=cmdvelms+velocity;
    //velocity=0;
    //position=position+tempvar1;
    //K=[-31.6728 110.7064 12.9966]
    //K=[-7.7112 52.9525 5.2509]
tempvar2=velocity*(-7.7112)+(angle/*.211/)*(52.9525)+rate*(5.2509);
    //for the 150, add .211 to angle
    tempvar2=(tempvar2)*85;
    rsdrive=tempvar2-cmdturnms*6;
    lsdrive=tempvar2+cmdturnms*6;

if (rsdrive>0){
    PORTD.3=1;//Motor 1 Direction
}
else{ PORTD.3=0;
}
if (lsdrive>0){
PORTD.2=0;//Motor 2 Direction
}
else{ PORTD.2=1;
}

rsdrive=abs(rsdrive);
if (rsdrive>1023){
    rsdrive=1023;
}
lsdrive=abs(lsdrive);
if (lsdrive>1023){
    lsdrive=1023;
}

OCR1A=rsdrive;//Motor 1 Duty Cycle
OCR1B=lsdrive;//Motor 2 Duty Cycle

void read_data(void){
    //cmdturn, cmdvel, thumbsw
    int i,
    tempvar;
    cmdturn=0;
    for (i=0;i<8;i++){
        while(!PINA.6);
        tempvar=PINA.4;
        cmdturn=cmdturn|(tempvar<<i);
        PORTA.5=0;
        while(PINA.6);
        PORTA.5=1;
    } //end for loop
    cmdvel=0;
    for (i=0;i<8;i++){
        while(!PINA.6);
        tempvar=PINA.4;
        cmdvel=cmdvel|(tempvar<<i);
        PORTA.5=0;
        while(PINA.6);
        PORTA.5=1;
    } //end for loop
    thumbsw=0;
    for (i=0;i<8;i++){
        while(!PINA.6);
        tempvar=PINA.4;
        thumbsw=thumbsw|(tempvar<<i);
        PORTA.5=0;
        while(PINA.6);
        PORTA.5=1;
    } //end for loop
}
void main(void)
{
    // Local variables declaration
    int tempvar1, tempvar2, tempvar3, tempvar4, tempvar5;
    char line1[16], line2[16];

    // Input/Output Ports initialization
    // Port A initialization
    // Func7=In Func6=In Func5=Out Func4=In Func3=In Func2=In Func1=In Func0=In
    // State7=T State6=P State5=0 State4=P State3=T State2=T State1=T State0=T
    PORTA=0x50;
    DDRA=0x20;

    // Port B initialization
    // Func7=In Func6=In Func5=In Func4=In Func3=In Func2=In Func1=In Func0=In
    // State7=P State6=P State5=P State4=P State3=P State2=P State1=P State0=P
    PORTB=0xFF;
    DDRB=0x00;

    // Port C initialization
    // Func7=Out Func6=Out Func5=Out Func4=Out Func3=Out Func2=Out Func1=Out Func0=Out
    // State7=0 State6=0 State5=0 State4=0 State3=0 State2=0 State1=0 State0=0
    PORTC=0x00;
    DDRC=0xFF;

    // Port D initialization
    // Func7=Out Func6=Out Func5=Out Func4=Out Func3=Out Func2=Out Func1=Out Func0=Out
    // State7=0 State6=0 State5=0 State4=0 State3=0 State2=0 State1=0 State0=0
    PORTD=0x00;
    DDRD=0xFF;

    // Timer/Counter 0 initialization
    // Clock source: System Clock
    // Clock value: 15.625 kHz
    // Mode: Normal top=FFh
    // OC0 output: Disconnected
    // Set to overflow at 60 Hz to initiate the
    // Kalman filter routine.
    TCCRO=0x05;
    TCNTO=0x00;
    OCR0=0x00;

    // Timer/Counter 1 initialization
    // Clock source: System Clock
    // Clock value: 2000.000 kHz
// Mode: Ph. correct PWM top=03FFh
// OC1A output: Non-Inv.
// OC1B output: Non-Inv.
// Noise Canceler: Off
// Input Capture on Falling Edge
TCCR1A=0xA3;
TCCR1B=0x02;
TCNT1H=0x00;
TCNT1L=0x00;
ICR1H=0x00;
ICR1L=0x00;
OCR1AH=0x00;
OCR1AL=0x00;
OCR1BH=0x00;
OCR1BL=0x00;

// Timer/Counter 2 initialization
// Clock source: System Clock
// Clock value: 16000.000 kHz
// Mode: CTC top=OCR2
// OC2 output: Toggle on compare match
ASSR=0x00;
TCCR2=0x19;
TCNT2=0x00;
OCR2=0x01;

// External Interrupt(s) initialization
// INTO: Off
// INT1: Off
// INT2: Off
MCUCR=0x00;
MCUCSR=0x00;

// Timer(s)/Counter(s) Interrupt(s) initialization
TIMSK=0x01;

// Analog Comparator initialization
// Analog Comparator: Off
// Analog Comparator Input Capture by Timer/Counter 1: Off
// Analog Comparator Output: Off
ACSR=0x80;
SFIOR=0x00;

// ADC initialization
// ADC Clock frequency: 125.000 kHz
// ADC Voltage Reference: AVCC pin
ADMUX=ADC_VREF_TYPE;
ADCSRA=0x87;

// LCD module initialization
lcd_init(16);

// Global enable interrupts
#asm("sei")

// Watchdog Timer initialization
// Watchdog Timer Prescaler: OSC/1024k
// WDT CR=0x0E;

while (1)
{
//read in remote data
PORTA.5=1;//signal other microproc. - ready for data
read_data();
PORTA.5=0;

sprintf(line1,"%i:%i",cmdvel,cmdturn);
lcd_clear();
lcd_puts(line1);
delay_ms(10);
}
}
%Corrie Nichol
%Tractor Overturn Project
%Data Filtering and Extraction
%January 26, 2005

clear all
clc

%Set i for the number of files to be examined, files were all saved with
%the name "runX.txt" where X is the run number.
startnumber=1;
endnumber=8;
maxdatapoints=2048*2;

runmatrix=zeros(maxdatapoints,1);

%Change the directory to reflect the location of the run files to be
%evaluated.
%Don't forget to change the rollflag save path at the bottom of this file.
plottitle=sprintf('Ford 1900 Side Roll Angle Testing 16 July 2003');
for i=startnumber:endnumber
    if i==6
        i=7;
    end
    filename=sprintf('run%d.txt',i);
    temp=load(filename);
    [row,col]=size(temp);
    if row<maxdatapoints
        temp=[temp,zeros(maxdatapoints-row,2)];
    end
    runmatrix=[runmatrix,temp];
clear temp;
end

data=runmatrix(:,2:endnumber*2+1);
clear runmatrix row col filename startnumber i

% Now analyze the data stored
% Data was originally collected with pitch in column 1, roll in column 2.
% (The data in column 2 are of most interest.)
% So now in the data matrix, the odd columns contain the pitch data, and the
% even columns contain the pitch data.

% Filter the data with a butterworth filter
% The cutoff natural frequency is wc where 0.033=(wc/ws). The
% sampling frequency was ws=33Hz, giving a cutoff frequency of 1Hz.
[B,A] = BUTTER(2,.033,'low');
for i=1:endnumber*2
    filtdata(:,i)=filter(B,A,data(:,i));
end

% Calculate roll and pitch angles in radians by taking the arcsin of the
% acceleration values in milli-g's.
% Convert to degrees.
filtdata=asin(filtdata/1000); filtdata=filtdata.*(180/pi());

% Take the maximum angle values.
% maxangle is the angle value vector, maxangleindex is the index of where
% the max values occurred.
[maxangle,maxangleindex]=max(real(filtdata));

% Plot the data to get a comparison between the shape of each run, and flag
% angle values greater than staticrollangle with a 1 in the rollflag vector,
% and make their lines red.
staticrollangle=50; % Angle for NewHolland TN65
staticrollangle=49; % Angle for Ford 1900

for i=1:maxdatapoints%2048
    time(i)=i*(1/33);
end

figure(1)
for i=2:2:endnumber*2
    color=sprintf('b-');
    rollflag(i/2,:)=[i/2,0,maxangle(i)];
    if maxangle(i)>staticrollangle
        color=sprintf('r-');
    end
    plot(time(1:i),rollflag(i,:));
end
rollflag(i/2,:)=[i/2,1,maxangle(i)];
end
plot(time,filtdata(:,i),color)
hold on
end
hold off
xlabel('Time(sec)')
ylabel('Angle (deg)')
title(plottitle)
axis([0 70 -10 60])

%Save roll flag information in a .txt file where column 1 is the run
%number, and column 2 is the roll flag, 1 if the data predicts a roll, 0 if
%the data predicts no roll.
save sideoverturnflag.txt rollflag -ASCII -TABS
Telephone Recruitment Script

Agricultural Tractor Overturn Mitigation: Operator Stability Perception Study Telephone Recruitment Script

“Hello. My name is Corrie Nichol. I am a graduate student here at Penn State. In my research work, I have had the opportunity to work with Mr. Bill Harshman, whom you have known as your Vocational Agriculture teacher or the Ag Teacher in your community. Bill suggested that you may be willing to answer a few questions which will help me in my research.”

“I am conducting a study to help develop a measurement device that would warn a tractor driver when their tractor is close to rolling over (for example, when the tractor is driven on a side hill, or when a turn is taken too sharp).

Do you drive a tractor in your farm work?”

If the answer is “No,“:

“Thank you for your time. Because we are developing this device for tractors, we need to interview people with experience driving a tractor. Thanks, and have a nice day.”

If the answer is “Yes,“:

“I would like to meet with you either here on campus, or at a location convenient to you, and ask some questions. I would guess that the interview will take about 45 minutes, and I am prepared to pay you $25 for your participation. Are you interested in participating?”

If the answer is “No,“:
“Thanks for your time, and have a nice day.”
If the answer is “Yes,”:
Set up a meeting time, and date. Give directions to campus and to my office, as well as for parking, or get directions to a convenient meeting location.
Bibliography


[GBS02] N. Gupta, A. Bisantz, and T. Singh. The effects of adverse condition warning system characteristics on driver performance: an investigation


Vita
Corrie Ian Nichol

Corrie Ian Nichol was born on August 14, 1976, in Heber City, Utah. After graduating High School in Provo, Utah he began attending Brigham Young University where he earned a B.S. in Mechanical Engineering. After completing his undergraduate work, Mr. Nichol was accepted to the Mechanical Engineering graduate program at The Pennsylvania State University where he earned his M.S. and Ph.D., both in Mechanical Engineering.

During his graduate work at Penn State, Mr. Nichol developed an inertial sensor system which uses a Kalman filter to estimate the orientation of a vehicle. This device was successfully validated as an appropriate angular state sensor for a two-wheel dynamically stabilized inverted pendulum mobile robot which Mr. Nichol designed and built. The sensor device was then used to collect data on the current orientation of an agricultural tractor. This information was processed in real time and the sensor device was able to actively intervene to prevent rearward overturn. This device was also incorporated with a custom made display device to communicate information to an operator for education purposes.

While completing his research, Mr. Nichol accepted a Graduate Teaching Fellowship, for which he taught a junior level machine dynamics class. During this time, Mr. Nichol also developed and twice taught a three dimensional CAD class at a local community college.