Special Collection: Tractor ROPS and Stability Research

Development of an Open-Source Tractor Driving Simulator for Tractor Stability Tests

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ABSTRACT. *Developing devices for stability monitoring and rollover alerts is a promising possibility to prevent overturn events, which pose a severe risk to tractor operators. However, performing relevant tests with operators in the field is dangerous and impractical. As an alternative, this work identifies the challenges of simulating a tractor driving environment in a laboratory and details the solutions put in place to develop a tractor driving simulator at Penn State University. The simulator includes an instrumented tractor cab mounted on a custom motion base, a 2.43 m tall, 360° high-definition screen, a sound system, and a nine-computer network running open-source software that can be used to conduct experiments and simulate driving scenarios relevant to tractor instabilities. The system is used for an experiment that evaluates the driver's ability to perceive tilt angles at various tilt and roll combinations. Pilot-test results show that roll and pitch are systematically overestimated, producing perceptual errors that are unbiased, independent for roll and pitch, and typically have magnitudes of 4°. These results can aid the development of instability monitoring systems by considering human tilt perception to set alert thresholds. Future projects and applications of the tractor driving simulator are also discussed.*

Keywords. *Risk assessment, Rollover protective structure, Simulation, Stability, Tractors.*

Occupational safety statistics have shown for decades that tractor rollover remains one of the leading causes of fatalities and serious injuries in agriculture. Data from the National Institute for Occupational Safety and Health suggest that 1,412 workers on farms died from tractor overturns between 1992 and 2005 (NIOSH, 2009). Data from the U.S. Department of Labor's Census of Fatal Occupational Injuries (CFOI, 2015) indicate that, out of the 2,320 work-related deaths that occurred between 2003 and 2007 in the production agriculture sector, nearly 900 involved tractors, 43% of which were overturn incidents. While these fatalities have shown a decreasing trend over the last 20 years, the decline is not uniform across all demographic and geographical groups, many of which

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retain high risk indicators (Myers and Hendricks, 2010). Penn State University maintains a unique database of farm fatalities in Pennsylvania since 1980. In the latest five-year summary covering 2010 to 2014 (Görücü et al., 2015), 32 of the 141 recorded fatalities included vehicle rollover or overturn incidents.

The introduction of rollover protective structures (ROPS), via legislation or promotion and education programs, has sought to address rollover incidents; however, various characteristics of the agricultural sector can limit their impact (Pessina et al., 2010). The fleet of tractors currently in operation is heterogeneous; machines over 20 years old remain popular, and changing technologies in newer models impose challenges on current safety standards (Jarén et al., 2009). Foldable ROPS systems offer favorable solutions for retrofit installation and flexibility, but human factors interfere with their practical use: "the time, effort, and safety risks associated with operating foldable ROPS limits their effectiveness" (Ayers et al., 2012). In this context, there is a justifiable need to prevent rollover incidents from happening, as a complementary measure to the use of ROPS (Murphy et al., 2010).

While education programs (Cole and Myers, 2002) and ROPS retrofit programs (Tinc et al., 2015) have succeeded, another avenue is to provide in-vehicle technological assistance to operators. As an example, in the automobile industry, electronic stability control has been shown to reduce the odds of a single-vehicle crash by 30% in general and by 49% for sport utility vehicles in particular (Green and Woodroffe, 2006).

Similarly, intelligent vehicle systems can be brought into the agricultural sector for added safety and accident prevention. Tractor operators determine safe operational limits based on their experience, which is nearly always comprised of situations that did not involve rollover. Thus, alert systems can be used to indicate imminent rollover, but these alerts may be ignored if the operator's perception of the situation does not agree with the sensor data.

In this regard, Nichol et al. (2005) developed a compact, low-cost sensor unit that uses a microcomputer and a simplified mathematical model to inform the operator of potentially hazardous driving conditions through an LCD display. Furthermore, Tillapaugh et al. (2010) showed that adding a visual slope indicator in the tractor cab could help operators improve their accuracy in ranking the risk of simulated driving conditions.

Conducting real rollover experiments with an operator driving a tractor in the field is not feasible due to the high risk of injury. Every year, Penn State University holds Ag Progress Days, a three-day show with 500 exhibitors and 45,000 attendees that includes the latest technology, research, and education programs for the agricultural industry. Figure 1 shows the Penn State Agricultural Safety and Health group conducting experiments and demonstrations at Ag Progress Days using a remote-controlled tractor, which takes the driver out of danger. Nonetheless, to develop rollover alert systems that are practical and useful on the farm, human-factor testing is essential in situations that mimic rollover initiation.

Driving simulators are regularly used in vehicle studies, including vehicle and traffic control testing, driver performance testing, driver training under various circumstances, and in the development of realistic driving games (Hancock and Sheridan, 2011). In contrast to operation of actual vehicles, driving simulators allow high reproducibility of driving scenarios at the expense of realism (Olstam and Espié, 2007). Recently, simulators have moved beyond basic driver testing and training, and many simulators are now used for specialized purposes, such as testing hardware interfaces, allowing multiple drivers in

Figure 1. Outreach and training, such as these demonstrations of rollover events at Penn State University's Ag Progress Days, can be complemented with on-board stability monitoring systems to prevent this type of incident. These demonstrations illustrate the need to use a simulator environment for human testing.

the loop, interacting with real vehicles, and even remote tele-operation of vehicles (Swanson et al., 2013). The automotive sector regularly uses driving simulators for such hardware-in-the-loop (HIL) tests. According to Fathy et al. (2006), the advantages of an HIL system include higher fidelity, faster simulation speed than purely virtual systems, and greater comprehensiveness than purely physical systems. The state-of-the-art in driving simulations often uses HIL in combination with human-in-the-loop testing, sometimes called H^2iL, in which human operators interact with an HIL workbench. While this represents an extremely high fidelity yet highly safe testing environment, it is recognized that such H^2iL capability is generally underused in vehicle research and development (Onesti, 2009).

The use of driving simulators for tractor studies is in the very early stages compared to

automotive systems. Examples of research using tractor simulators include the state-of-the-art NADS system (Schwarz et al., 2003) and the Clinton County Farm Bureau's simulator (Farm Bureau, 2013). The rarity of simulated tractor testing environments is largely due to the high operating expense, combined with the limited funding available for tractor research relative to automotive systems; however, similar to automotive safety, the safety of tractor systems is unquestionably a concern.

One means to increase driving simulator usage among researchers is to reduce the significant financial and time costs associated with the construction, programming, maintenance, and operation of these systems. To this end, this research seeks to develop an open-source software and hardware testing environment for tractor driving simulation.

For this particular application, the simulator is used to study the behavior of tractor operators in rollover-prone situations. Initially, the focus is on evaluating human tilt perception at large roll and pitch angles to determine whether perceptual errors happen in protective or injurious directions. In ongoing work, the simulator is being used to test the operator's reactions to different alert interfaces that could promote safe driving practices and prevent tractor rollover incidents.

The following section identifies the unique design requirements of a driving simulator for tractor stability applications. This is followed by a description of the solutions put in place to develop the simulator, detailing the characteristics of the custom motion base, display screen, sound system, and computing network, as well as the open-source software that runs the simulator. Thereafter, an example application is shown through an experiment that evaluates the operator's ability to perceive tilt angles, and the results are discussed in light of their usefulness in designing rollover alert systems. Finally, conclusions are drawn regarding the capabilities and limitations of the simulator, as well as future testing and research projects that are ongoing or will be conducted.

Design Requirements

Tractor rollover events are uniquely different from passenger vehicle rollovers, as they occur at roll angles higher than common driving and driving-simulator practices (fig. 2). The American Association of State Highway and Transportation Officials (AASHTO) policy for highway design limits bank angles to 12° (AASHTO, 2011). In contrast, tests at Ag Progress Days have shown that tractors can drive stably on slopes steeper than 15°. This difference highlights the perceptual differences between tractor operators and typical vehicle operators and is of particular relevance in Pennsylvania and the northeastern U.S., as well as in many countries (e.g., Italy and Mexico, among others) where agriculture on hillslopes is common. Tractors routinely operate on surfaces that require steep bank angles despite flat surrounding terrain, such as mowing on highway medians and shoulders. Similar rollover concerns may occur in mountainous operations, such as with logging or mining equipment.

A challenge in designing rollover alert systems is that tractor operators spend most of their time not looking ahead but looking to the sides or rear of the tractor. This behavior was tested by the authors in a study conducted in 2015 in which videos of tractor operators were recorded during agricultural field operations at Penn State University (fig. 3). The data collection included nine experienced tractor operators who each had between 31 and 55 years of tractor driving experience (only two had completed formal training). The videos were reviewed and manually coded to determine the operator's gaze direction and duration,

Figure 2. Tractors frequently operate at bank angles that are not encountered in other driving scenarios, and rollover events occur at roll angles beyond the normal motion capabilities of driving simulators.

and these metrics were used to determine gaze-point statistics.

The resulting data (table 1) show that tractor operators look forward only about one-third to one-fifth of the time, depending on the operation being performed. Looking to the sides and backward was especially prominent during hay baling and manure spreading, while soybean harvesting required increased attention on the lower instrument panel, as opposed to the oncoming driving terrain. These results show that visual alert systems placed in the front of the operator, which is the natural position for visual alert systems in automobiles, may have limited utility for rollover alerts because the operator is often not facing the front panel and thus may not see such alerts in a timely manner.

Another commonly used alert method for vehicle safety systems is an audible alarm; however, in tractor operations, such alerts may not be practical due to the severe noise during typical tractor operations. To determine representative noise levels of agricultural equipment, and thus the sound environment necessary for testing auditory alerts within a simulated environment, sound measurements were conducted with a tractor in use. A sound level meter and datalogger (model 322, Center Technology Corp., Taipei, Taiwan) was used to measure sound levels for 5 s bursts while simultaneously recording the sound of a T7-270 New Holland tractor. The procedure followed recommendations from the OSHA Technical Manual's chapter on noise (OSHA, 2015). The meter was set up with A-weightings and fast response (0.125 s time constant). The meter was placed in four locations: inside the cab at operator head level (with all doors and windows closed), on the tractor's front fender, and on the stepladder directly below the cab doors on the left and right sides of the tractor. Measurements were conducted at a standstill at idle (850 rpm), mid-range

Figure 3. Still frames from video recorded during a hay-baling operation: (a) the operator looking backward while the tractor is moving forward and (b) the corresponding view from a GoPro camera mounted on the operator's head. This illustrates the importance of using a surround screen to simulate the tractor driving environment.

Table 1. Tractor operators' gaze direction during different farming operations.

	Percentage of Time Spent Looking…			
Operation	Forward	To the Side	Backward	At a Low Panel
Hay baling	30%	35%	35%	N/A
Manure spreading	20%	39%	39%	N/A
Soybean harvesting	34%	21%	2%	43%

(1650 rpm), and high (2250 rpm) engine speeds. Measurements were also conducted while driving on a grass field at middle (11 kph) and high (19 kph) speeds. All measurements were repeated three times, producing the average and peak noise levels shown in figure 4. The in-cab noise was consistent with the value of 71.0 dBA reported by the Nebraska Tractor Test Laboratory for the same tractor model (NTTL, 2012) (no outside-of-cab measurements were available for comparison). Considering the high noise levels, and that operators may work with the cab windows open, the efficacy of a sound alert should be subject to simulator testing to determine its viability for in-field operations.

Tractor Driving Simulator

The previous section described the unique considerations for meeting the requirements

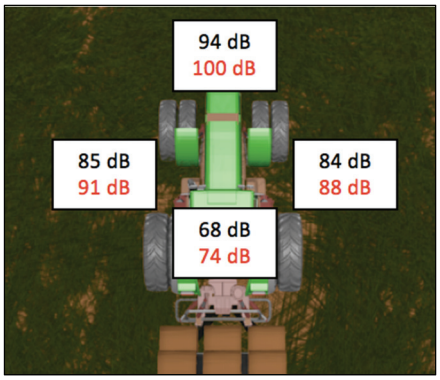


Figure 4. Noise level measurements (A-weightings) conducted on a T7-270 New Holland tractor at various engine speeds. Upper numbers (in black) are the amplitudes of typical noise, and lower numbers (in red) are the maximum noise levels to which drivers are exposed.

of simulated tractor operation and alert system testing at the onset of tractor rollover. This section describes the simulator's subsystems, specifically focusing on aspects unique to tractor simulation. These subsystems are presented in order from the most constraining factors for simulator design to the least constraining design factors. Due to the unique visual environment of a tractor simulator, the display screen presented the most restrictive design constraints, so it is described first. This is followed by the motion system, the software and computing system, and the cab controls for driver interaction. The section closes with a discussion of the safety aspects of building the tractor driving simulator.

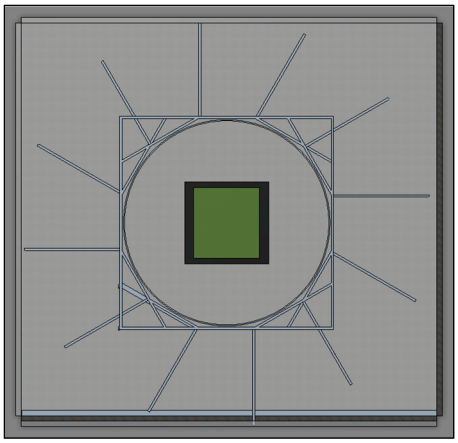
Display Screen

The display screen is responsible for some of the most vital cues in creating an immersive simulator experience. As described in the previous section, for tractor operation, a 360° visual presentation in a horizontal field-of-view (FOV) was considered a necessity, as routine tractor operations require this range of visibility. Maximizing the vertical FOV was also an objective, within the physical constrains of the room: 9.1 m × 8.5 m floor area and 3.6 m height. This resulted in a cylindrical screen, 2.44 m high and 4.66 m in diameter, with a 46° vertical FOV, which is greater than in other, larger driving simulator facilities.

The simplest setup for 360° projection is to mount the projectors in the center of the cylinder, projecting outward to the screen. Because of the motion of the tractor cab, the projectors would have to be placed above the cab. Due to the large motions of the cab required for rollover testing, the projectors would have to be mounted quite high. Although the building that houses the simulator has a high ceiling, it was not possible to mount the projectors in a way to ensure that the light from the projectors would not be blocked. Therefore, 12 short-throw projectors were arranged in a spoke pattern around the outside of the screen to provide a rear-projection image, as shown in figure 5a. Each short-throw projector creates a 2.43 m × 1.22 m image when placed as close as 2.14 m to the projection surface. The acrylic panels comprising the screen were fitted with a special film for rear-projection to enhance the contrast of the images, the results of which are shown in figure 5b.

Motion System

A custom-modified motion base was built for the simulator that enables ±28° of roll



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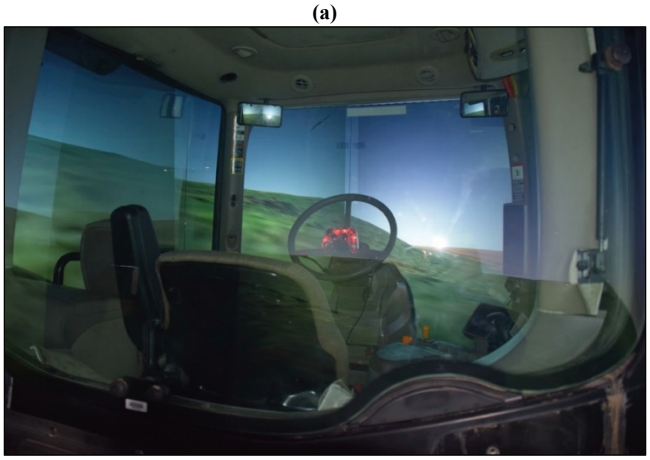


(b)

Figure 5. (a) Arrangement of the tractor cab, screen, and array of projectors inside the simulator room and (b) example of the immersive visual environment as seen from the cab.

motion and ±18° of pitch motion. The motion base is comprised of two parts. First, a commercial off-the-shelf industrial parallel robot with six degrees of freedom for 3D motion (model 6DOF2000E-170122A, Moog, Inc., Elma, N.Y.) provides up to ±18° of pitch and roll for a 1000 kg payload. The acceleration capabilities are 6.0 m s^{-2} in translation and 500° s^{-2} in rotation. Additionally, an inverted slider-crank mechanism was designed and installed between the Moog robot and the tractor cab, providing an additional 10° of roll in each direction, relative to the motion base's position. This mechanism was powered by a linear actuator from an electric trailer jack (Brute power jack model HB4500, Husky Towing Products, Wilsonville, Ore.).

The motion system was calibrated to verify the precision of its tilting motion. Total roll angles were measured using a digital slope meter (SmartTool GEN2, M-D Building Products, Inc., Oklahoma City, Okla.) with a resolution of 0.01% slope (equivalent to 0.06°). This was used to calibrate both the commands sent to the Moog motion base (the first stage) and to the custom-built roll-tilt mechanism (the second stage).

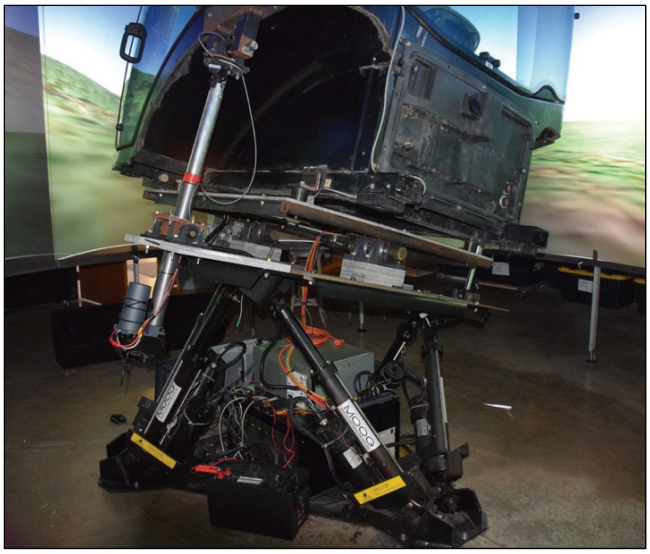


Figure 6. The motion system is comprised of two stages. The lower stage is an electrical, six-degrees-of-freedom Stewart platform (model 6DOF2000E-170122A, Moog, Inc.). On top of that, a custom-built, one-degree-of-freedom mechanism provides additional roll motion.

The secondary mechanism uses a linear actuator instrumented with a string potentiometer (model JX-PA, UniMeasure, Corvallis, Ore.) to control the cab's roll angle relative to the Moog motion base, as well as an encoder with 40,000 counts per revolution (model HD25, US Digital, Vancouver, Wash.) installed on the shaft around which the cab rotates. Both give precise relative control of the cab's motion and additionally allow control if there is an intermittent power failure in the system. During testing, the positioning errors of the custom motion base were found to be negligible: 0.07° ±0.28° (95% confidence). The complete system is shown in figure 6.

Software and Computing System

Because 12 screens of scene information must be registered in high definition (HD) resolution, the computing power necessary to drive the dynamic simulation and the visual rendering is considerable. A hub of nine computers running Linux was used for this project. Each computer has a quad-core 3.40 GHz CPU, 32 GB of RAM, and a 2 GB video card, capable of generating two HD outputs per computer. Six of the computers are used for generating the HD images for the 12 projectors; one computer runs the dynamic simulation, one serves as the input/output interface to the hardware (sensors, controls, and actuators), and one is used for data storage and processing.

The entire project was developed with open-source software. This was motivated not only by the ease of peer-sharing of code (and peer-review), but also because this drastically reduces the cost of licensing the software. Typically, commercial packages for driving simulators charge "by the screen," which considerably increases the costs of a 12-screen tractor simulator. Additionally, we desired the ability to add other human-driven vehicles that can interact with the primary user in the driving simulator, and each of these additional scenes added additional costs to commercial software packages. The use of open-source software allowed for significantly greater flexibility in multi-user/multi-input integration, as well as

enabling a larger range of simulation algorithms that can be implemented.

The core of the computing system, allowing it to work together in synchrony, is the Robot Operating System (ROS Indigo version, http://www.ros.org), a collection of libraries that allow various hardware and software elements to interact with each other and share information, creating a network as shown in figure 7. The ROS system can be interfaced with numerous physics engines to simulate tractor dynamics, and it supports a range of rendering packages to generate images for the projectors. The system is configured carefully to split the computational burden among the nine computers, as illustrated by the typical workflow for a driving simulation:

- The control CPU is the primary hardware interface to the user and receives data from the driver inputs (steering, throttle, brake, and gear).
- The inputs are shared through the ROS network to the host CPU.
- The host CPU uses the driver inputs to run a dynamic simulation of the tractor's motion in the simulated environment, computing the position and velocity of the tractor in the virtual world.
- The tractor's position is shared through the ROS network with the six image CPUs as well as with the control CPU.
- Each of the six image CPUs uses a camera model and independent duplicate models of the simulated physical environment to render an HD image for two 30° slices of the operator's field-of-view.
- The HD images are sent to the corresponding 12 projectors by each of the six image CPUs.
- Simultaneously, the control CPU sends the relevant motion commands to the motion base units, the steering actuator for any haptic feedback, and the sound system.
- Concurrent with the above processes, the data CPU collects and stores data for post-test analysis.

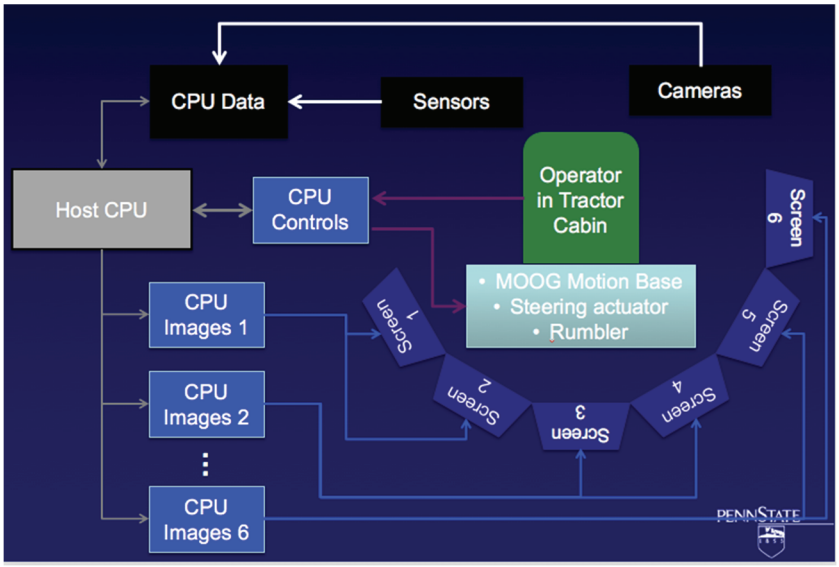


Figure 7. Nine computers work together to produce HD images for the screen, capture sensor data from the driver, and send commands to the actuation systems that produce motion and haptic feedback.

The current deployment of the simulator can use either version 2.2 of Gazebo (http://gazebosim.org) or version 2.69 of Blender (https://www.blender.org) as open-source rendering and environmental simulation software interfaced to ROS. The test results shown later in this article used Gazebo open-source software for the 3D simulation. Gazebo includes the Open Dynamics Engine physics engine (http://www.ode.org) and the OGRE 3D graphics engine (http://www.ogre3d.org) for rendering. Another simulation option uses Blender, a 3D modeling and rendering package that uses the Bullet Physics Library (http://bulletphysics.org/wordpress/). Blender is interfaced to ROS through version 1.3 of MORSE (https://www.openrobots.org/wiki/morse/), a robot simulation program.

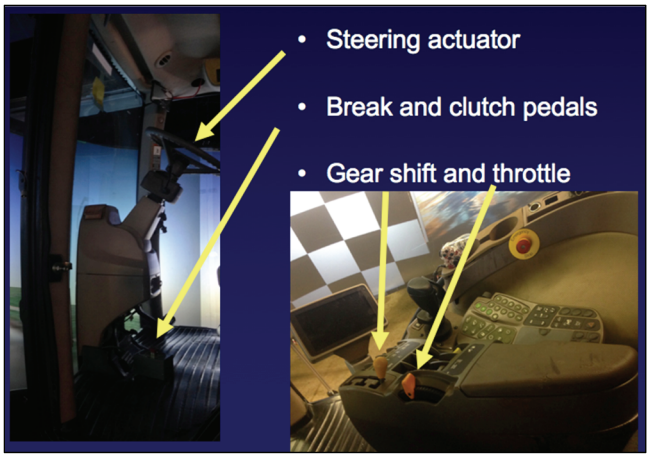
Cab Controls

A full tractor cab is used as the driver's interface to the virtual tractor. The cab's components were fitted with automotive-grade sensors and actuators. The resulting data are acquired through an Arduino UNO microcontroller (https://www.arduino.cc/en/Main/ArduinoBoardUno) that is hosted on the control CPU and the ROS network, as shown in figure 8. The brake and clutch pedals were instrumented with string potentiometers (model LX, UniMeasure, Corvallis, Ore.), while the manual throttle was fitted with a generic 5 kΩ rotary potentiometer. For the gear lever, a set of Hall-effect sensors detect the shift position (park, neutral, forward gear up/down, reverse gear up/down) and produce an output based on four digital signals.

The steering column has been fitted with an automotive-grade electric steering actuator manufactured by TRW (http://www.trw.com/steering_systems/steering/electrically_powered_steering) that is sized for commercial vehicles. The actuator communicates through a CAN interface with the ROS network and fulfills three needs: first, it serves as a sensor device because it is capable of measuring the steering angle and the driver's input steering torque. Second, it can output a commanded torque proportional to the tire/terrain aligning moment on the tractor, and thus it can simulate the sensation of steering a real vehicle over real terrain. Third, it allows a computer-commanded torque overlay such as a torque shudder, which can become a haptic interface to alert the driver of impending roll hazards. The latter functionality allows the steering wheel to vibrate to capture the driver's attention. This can be a valuable rollover alert, as tractor operators rarely let go of the steering wheel while in motion, even when their visual attention is directed away from the forward panels or the oncoming terrain.

The cab has also been fitted with a visual stability display (fig. 8b) that uses data from a three-axis accelerometer (model ADXL335, https://www.sparkfun.com/products/9269) in the tractor cab to estimate the pitch and roll angle of the cab. The display plots the tractor's roll angle in a bubble-type graphical display that shows a history of the tractor's motion over the past few seconds. The display can thus be configured to indicate different thresholds of rollover risk, the current inclination, and the time history of inclination (e.g., example from the past 0.3 to 1.0 s of driving). This display is extremely useful for training, as well as an alert or deterrent for hazardous driving situations.

The final element of the driver-simulator interaction is the sound environment. Tractor sound recordings made in the field (described in the previous section) have been incorporated into the simulation software. The sound can be changed depending on engine speed, and its loudness was calibrated to match the field measurements at the operator's head location. To reproduce the sound levels, a 2000 W, two-channel amplifier (model XTI-



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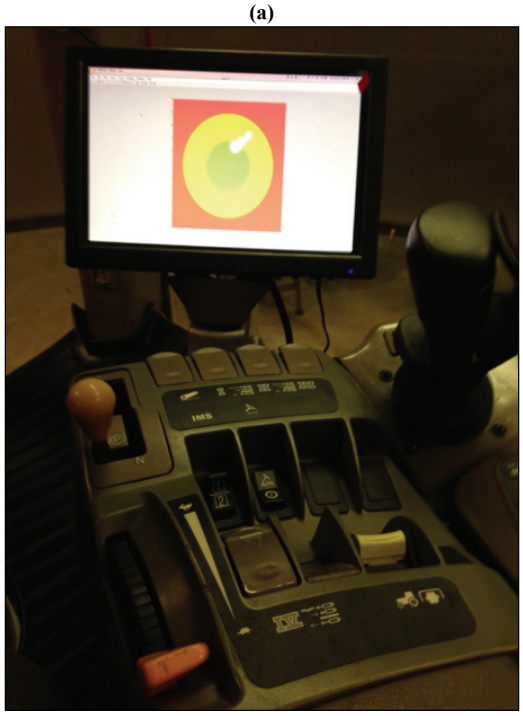

(b)

Figure 8. (a) The cab and its instrumented devices and (b) the tractor stability display.

2002, Crown Audio, Elkhart, Ind.) powers four speakers (model JRX212, JBL Professional, Northridge, Cal.), each with 250 W of rated power and 1000 W of peak power. The system easily reaches 105 dB outside the cab and can exceed 85 dB of in-cab noise, providing a suitable platform to test the effectiveness of auditory alerts.

Safety Emphasis

The construction of the simulator needed careful assessment of safety in various aspects.

First, the assembly of the robot with the additional roll mechanism and tractor cab put close to 1000 kg of payload on the Moog motion base. Therefore, the nuts, bolts, and welds are subject to periodic inspection.

Previous driving simulators developed by the team (Petersheim et al., 2006) used tilting of the visual environment to emulate vehicle roll or pitch, but it was found that this caused extreme motion sickness for the driver. An advantage of the extended motion range of the platform is that it allows large roll angles without using movements of the visual environment projected on the screen, thus reducing and generally eliminating the onset of motion sickness.

In addition to mechanical safety, electrical safety was also a vital factor. Because the simulator room is low-lit, laboratory safety rules do not permit any wiring on the floor, as this would present a tripping hazard as well as a risk of fire in case of a flood. All electrical power to the Moog motion base, actuators, control computers, and other simulator components is wired from the roof, through the cab, and from there to the underside of the simulator.

Next, a protocol for use of the simulator was developed to ensure that both the driver and the researchers operate the system under safe conditions. A key part of this safety protocol is for those involved to understand the system's fault management strategies, which have three levels: manually turning the simulator off at the software level, cutting off power to the simulator with manual switches (available in the cab and in the control room), and automatic safety procedures in the Moog software, which handle actuator overloads or electric supply failures, among others.

Finally, the acoustic testing necessitated a specific protocol due to the high sound levels in the simulator room (above 100 dB) and in the public areas around the simulator (around 80 dB). These sound levels outside the cab can violate OSHA rules for exposure if caution is not used, not only for the simulator driver but also for others in the building. Routine sound checks are performed in the simulator room and surrounding hallway areas to ensure that there is no exposure to unsafe sound levels.

As a whole, the simulator system, aided by the ROS software tools, represents an emphasis on safety. The goal of the system is to permit the recreation of dangerous tractor driving situations in a safe environment.

Operator Perception of Tractor Instability

This section shows an example of the testing capabilities of the simulator and how they can impact safety with regard to rollover events on farm tractors.

Testing Protocol

After the system was calibrated, tractor operators were tested on their ability to recreate various roll-pitch combinations. The test protocol consisted of the following steps:

1. The test subject boards the simulator, and the system is initialized.
2. The motion base moves the cab to a set roll-pitch combination and remains stationary for 5 s, after which it returns to level.
3. The subject is then instructed to operate the motion base using a videogame controller until it reaches what the subject believes is the same angle at which the motion base paused earlier.
4. Once the subject is satisfied with the position, a data point is recorded, registering both the original roll-pitch angles and the subject's attempt to reproduce that specific roll-pitch combination.

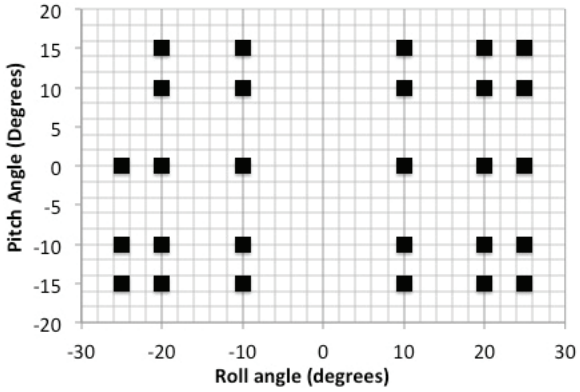

Figure 9. Subjects were exposed to 28 tilt angles of various roll-pitch combinations.

5. The platform is returned to level, and steps 2 through 4 are repeated for 28 tilt angles across a randomized pattern.

The set of tilt angles is shown in figure 9. The set is not symmetrical; two angles are missing in the top left corner. They were removed from the sequence because the Moog motion base can be overloaded when tilting the cab to these large angles. This happens because the mass of the cab at this severe roll-pitch combination is close to the maximum payload, and additional motion past this point has the potential to overload the motion base's actuators.

The sequence of tilt angles was presented in randomized order so that each subject reproduced the same angles in a different sequence. This was done to prevent skewing the results with learning or fatigue during the test, as measurement of all angles for a test subject required about 50 min to complete.

During the test, a fixed image with a virtual rural scene was projected on the screen. The subjects were instructed to look at the screen during the whole procedure. The intention was twofold: first, the horizon line is considered an important visual cue for tilt estimation in the open field; second, the subjects needed to avoid using visual cues that would be unavailable in a natural driving environment, such as the top or bottom edges of the screen or the screen structure, to aid in their tilt estimations.

Preliminary testing was done with pilot-test subjects in order to evaluate the system's performance and refine the software that controls the experimental protocol. During this process, full and consistent data were collected for four subjects, and the results and analysis are presented in the following section. Testing is ongoing at present using an identical protocol but with a deeper subject pool including up to 60 tractor operators, of varying levels of experience, age, and other demographic factors. These results will appear in a follow-up publication.

Results

The graphs in figure 10 plot the pilot-test subjects' reproduced tilt angles versus the angles to which they were exposed. The graphs show three types of information: first, the individual data points for all subjects (28 points per subject); second, a linear regression of these points (thick blue line) with its corresponding equation; and third, the ideal result for the regression if the subjects had perfect tilt angle estimation (i.e., slope equal to one, and

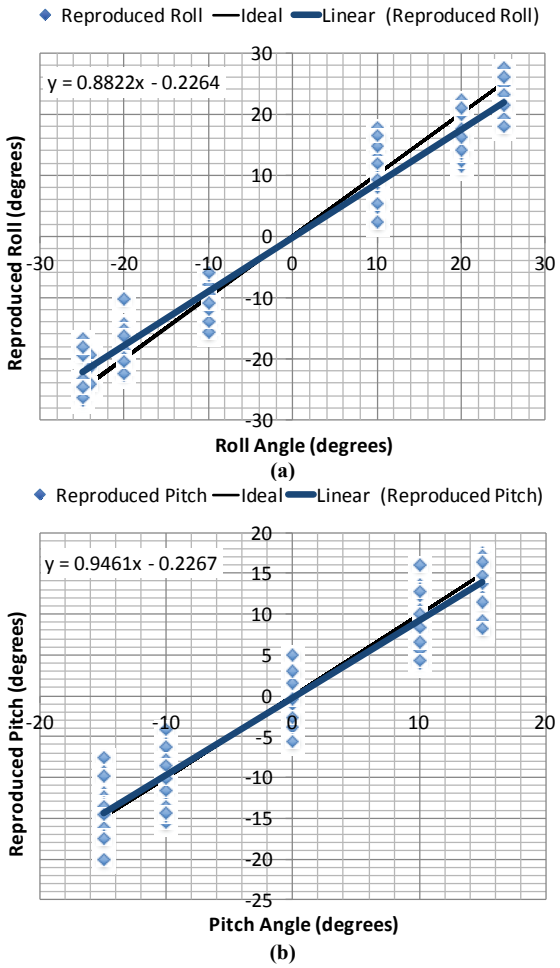

Figure 10. Plots of reproduced tilt angles showing that (a) roll and (b) pitch were systematically under-reproduced and unbiased.

intercept equal to zero).

The first notable result is that the roll angle was systematically under-reproduced (fig. 10a), having a slope of 0.88 with a 95% confidence interval of (0.85, 0.92), compared to the ideal value of 1.00. This means that the subjects overestimated the roll angle. For example, when exposed to an angle of 10°, the regression predicts that a subject would reproduce an angle of 8.6° while perceiving that angle to be 10°, thus overestimating the actual roll by 16%. The intercept is 0.23° with a 95% confidence interval of (-0.85°, 0.40°), meaning that the estimation can be assumed to be unbiased:

$$roll_{perceived} = 0.88 \cdot roll_{actual} + 0.23° \quad (1)$$

Similarly, pitch was also under-reproduced, with slope of 0.95 with a 95% confidence interval of (0.89, 1.00), and can be considered to be unbiased, with an intercept of -0.23°

with a 95% confidence interval of (-0.81°, 0.35°):

$$pitch_{perceived} = 0.95 \cdot pitch_{actual} + 0.23° \quad (2)$$

In this case, when exposed to a pitch of 10°, the regression predicts a reproduction of 9.7°, corresponding to 3% overestimation. Interestingly, roll perception has a bigger overestimation than pitch, meaning that roll perception errors have a dominant effect over those of pitch and thus would pose a larger threat during risky driving tasks at high tilt angles.

While these two regression models had good fit (R^2 values of 0.962 for roll and 0.923 for pitch), other regressions that were attempted showed poor goodness-of-fit values, which can be indicative of the independence of certain variables in the experiment. For example, from the current results, pitch angle does not appear to have an appreciable influence on roll estimation. For the following model:

$$roll_{perceived} = m_p \cdot pitch_{actual} + b_p \quad (3)$$

the regression results in a slope of 0.1503 (-0.1314, 0.432), which can be considered statistically insignificant, as it contains the zero-interaction hypothesis well within its 95% confidence interval. Moreover, the goodness-of-fit metric is negligible ($R^2 = 0.010$). For further confirmation, a two-factor model of roll estimation:

$$roll_{perceived} = m_1 \cdot roll_{actual} + m_2 \cdot pitch_{actual} + b_t \quad (4)$$

produced a good fit ($R^2 = 0.962$), with slope $m_1 = 0.88$ (0.85, 0.92), which is statistically significant and consistent with the regression model in figure 10a, while slope $m_2 = 0.004$ (-0.05, 0.06), which, like the pitch-only regression model, is not statistically significant. Similar results were obtained for the influence of roll angle on pitch estimation. The data set did not show a significant effect of pitch on the subject's roll perception, or vice versa.

Average Errors

Another issue that was examined was the possible influence of tilt angle magnitude on the subjects' estimation errors. Figure 11 shows the mean estimation errors, with corresponding 2-sigma error bars (for 95% confidence), at different roll and pitch magnitudes.

The mean of the roll estimation errors shows a slight tendency to slope downward as roll magnitude increases. However, the averages for all three cases are below 1.4° in magnitude, while the confidence intervals range between ±4.2° and ±7.8°. In that regard, any apparent pattern cannot be considered statistically significant. A larger sample would be required to draw a conclusion about this relationship, and tests with larger subject pools are ongoing. In similar fashion, the mean pitch errors have slightly smaller variability compared to roll (ranging between ±5.1° and ±6.9°) but again show small magnitudes (below 1.4°) and no statistically significant effect of pitch magnitude.

However, these plots both show that errors for both roll and pitch are centered close to zero, meaning that there is no clear bias toward positive or negative estimation errors. The two-variable relationships (i.e., roll error vs. pitch magnitude, and pitch error vs. roll magnitude) were also not statistically significant, and thus are omitted for brevity.

Absolute Errors

One final indicator that was analyzed was the absolute value of the estimation errors, or the distance-to-truth. This is a measure of how far the subject's perception is from the true

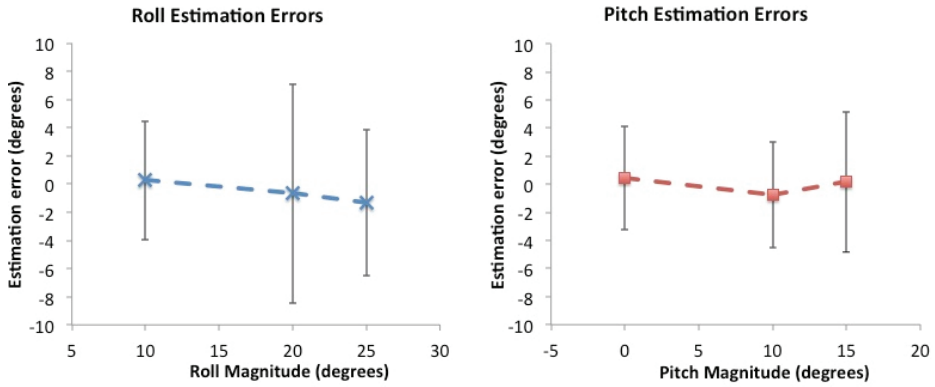

Figure 11. Estimation errors are not strongly influenced by angle magnitude.

tilt angle, irrespective of whether the error occurred as overestimation or underestimation. Figure 12 shows the average distance-to-truth for different angle magnitudes.

As was the case for the average errors, the distance-to-truth metric does not show a clear pattern or influence from tilt angle magnitude. However, it reveals three key trends:

- Pitch estimation has lower mean absolute errors than roll estimation (<2.7° for pitch vs. up to 4.0° for roll) and can thus be said to have higher estimation accuracy. Test subjects can apparently perceive pitch with more accuracy than roll.
- The variability of distance-to-truth for pitch increases with pitch magnitude, as shown by the error bars. At zero pitch, the 95% confidence interval is very small (±0.6°). It increases to ±1.6° at 10° and further increases to ±2.13° at 15°. Thus, the test subjects appear to become worse at perceiving pitch with larger pitch angles.
- For the pitch and roll angles of interest in this study (i.e., those that are near the rollover or skidding threshold of an agricultural tractor), absolute roll errors of up to 4° to 5° would be expected; for pitch, absolute errors of up to 3° to 4° would be expected.

This last observation can be a useful indicator for calibrating a rollover alert system: tractor operators on a 16° roll slope can commonly perceive this angle to be in the 20° to 21° range. While the perceptual errors tend to be in the protective direction, an alert system should intervene within 4° of a tractor's actual rollover threshold, as this is a common

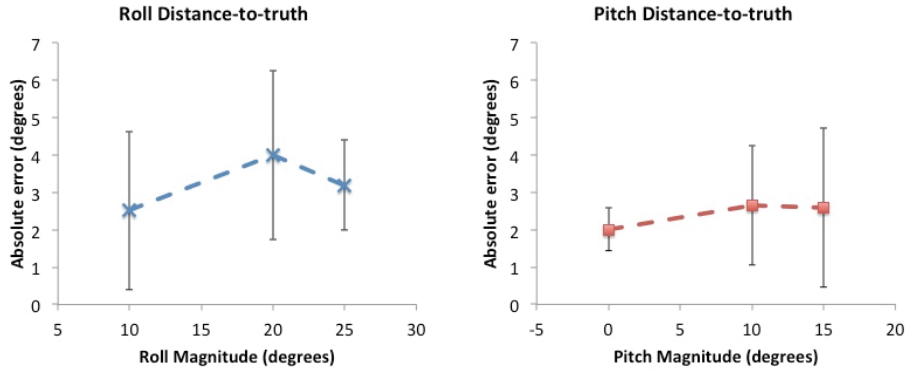

Figure 12. Distance-to-truth averages show magnitudes of typical perception errors.

magnitude for roll estimation errors.

Safety Emphasis

This study with pilot-test subjects provides insights that are useful for designing tractor alert systems. In particular, the subjects systematically overestimated roll but produced unbiased errors. Pitch was also systematically overestimated as well, but to a lesser degree, and was also unbiased.

The current data set showed no two-variable relationships between roll estimation and pitch angle, nor between pitch estimation and roll angle. While the expectation was that combined roll and pitch angles could be more difficult to estimate correctly, the results suggest that roll and pitch estimation are sufficiently independent in human perception to allow alert systems that are isolated by each behavior.

The estimation errors for both roll and pitch were centered close to zero, further evidence of the absence of bias, and did not exhibit a relevant relationship with tilt angle. Similarly, the mean absolute errors, or distance-to-truth, showed no influence from tilt angle magnitude but provided upper bounds for typical roll and pitch estimation errors. Such bounds can be useful in determining the threshold for a rollover alert system, as they offer a statistically supported worst-case scenario for roll perception errors, which can lead to dangerous tractor operation on steep hills.

These conclusions based on a preliminary data set are consistent with the literature in that roll tends to be overestimated (Tillapaugh et al., 2010; Görücü et al., 2014; Cavallo et al., 2015), but these conclusions have been enhanced by the use of combined pitch and roll angles. In this way, these conclusions serve as a starting point for ongoing testing using a wider subject pool (close to 60 subjects) that will include experienced and novice tractor operators of different ages. Additionally, these results are useful for developing prototype tractor rollover and pitch-based alert systems to be tested with the same subject pool.

Conclusion

This article identified the design requirements that are specific to tractor driving simulation and described the development of the Penn State University tractor driving simulator, with particular focus on testing the tractor operator's perception of rollover events. The tractor driving simulator has been fitted with an array of subsystems that provide an immersive experience for the tractor operator in a virtual environment. These include a 360° high-definition screen, a custom-built motion system, a haptic interface through the steering wheel, and a sound system that recreates realistic tractor noise levels. Most of these subsystems required considerations that are unique to tractor driving simulators, and these are explained in detail in this article.

The simulator, as currently constructed, was used in a pilot test of subjective perception of tilt. The preliminary data showed how subjects estimated tilt angles. This article quantified and described the characteristics of the subjects' perceptual errors, and the results were consistent with the literature. A replication of this experiment, with experienced and novice tractor drivers, is ongoing and will establish a sensible threshold for rollover alert systems. Future work on the simulator will evaluate the effectiveness of various mechanisms for alerting the operator in a timely manner to reduce or eliminate rollover incidents.

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