Experimental determination of operator perception of tractor instability

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Abstract

Tractor instability is a major cause of serious injuries and fatalities in the agricultural industry. Thus, preventing tractor rollover can have a vital impact in reducing injury risk and saving lives of operators. This study presents preliminary experimental results on the perception of tilt angles. Using a novel tractor driving simulator developed at Penn State, a testing protocol was implemented in order to evaluate the ability of subjects to remember poses at various roll-pitch combinations. Results suggest that roll and pitch are both systematically underestimated, the former more severely than the latter. They also show no statistically significant correlation between the effect of pitch angles on the perception of roll, but do provide an upper bound on typical perceptual errors. These pilot-test results will serve as the basis of a comprehensive study with a wider subject pool. The bigger goal in this effort is to develop rollover alert systems that can prevent these accidents from happening. In that regard, the data obtained from this experiment can be useful in the design and tuning of predictive rollover alerts that promote safe operation of farm tractors, using human perception errors of roll and pitch to guide the thresholds at which warnings should be initiated in each of these directions.

Keywords: Rollover Protective Structure, Tractor Stability, Risk Perception, Stability Research

Introduction

Occupational safety statistics have shown for decades that tractor rollover remains one of the leading causes of fatalities and serious injuries in the agricultural industry. Data from the US Department of Labor's Census of Fatal Occupational Injuries (CFOI) indicate that, out of the 2,320 work deaths that occurred between 2003 and 2007 in the production agriculture sector, nearly 900 of them 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 retain high risk indicators (Myers 2009).

The introduction of Roll Over Protection Structure (ROPS) devices, via legislature or promotion and education programs, has sought to address rollover accidents but various characteristics of the agricultural sector can limit their impact across the industry (Pessina 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 also 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's a justifiable need to prevent rollover incidents from happening, as a complimentary measure to the use of ROPS (Murphy et al. 2010).

While training and education programs 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 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 past experience, which is nearly always comprised of situations that did not involve rollover. Thus, warning systems can be used to indicate imminent rollover, but these may be ignored if the driver’s perception of the situation does not agree with sensor data.

In this regard, (Nichol et al. 2005) developed a compact, low-cost sensor unit, which employs 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 cabin could help operators improve their accuracy in ranking the risk of simulated driving conditions. This experiment was conducted on a tractor simulator with a single degree-of-freedom motion base, setting a precedent for the work presented here.

The goal of this study is to evaluate a tractor operator’s nescient perception of vehicle stability, and whether confounding factors such as pitch-roll coupling affect this perception. This paper in particular examines the operator’s “memory” of pose, whether this memory is affected by pitch and roll, and how to use this information in the design of rollover alert systems.

The remainder of this paper is organized as follows: first, the Materials and Methods section describes the driving simulator that was used and the test protocol. The Results section summarizes the regression analysis on the data, analysis of regression error, and analysis of absolute error. The primary findings of this work are then summarized in a Conclusions section.

Materials and Methods

Tractor Driving Simulator

This study utilizes a novel tractor simulator shown in Figure 1 wherein a tractor cab is mounted on top of a custom-modified motion base that enables +/- 28 degrees of roll motion and +/- 18 degrees of pitch motion. The motion base is comprised of two parts. First, a commercial off-the-shelf industrial parallel robot manufactured by Moog, with 6 degrees-of-freedom for full 3D motion, which provides up to +/- 18º of pitch and roll for a 2,000 lb. payload. Additionally, an inverted slider-crank (IS-C) mechanism (detailed on the right in Figure 1) was designed and installed between the Moog robot and the tractor cabin, providing an additional 10º of roll in each direction, relative to the Moog’s motion base position.

The simulator also includes an 8 ft. tall, 360º surround screen with 12 High-Definition projectors for an immersive simulation environment. The whole system (Moog robot, IS-C mechanism, projectors and cabin sensors) is operated through a cluster of 9 Linux-based computers, networked with the Robot Operating System (ROS) and running the Gazebo simulation software, which are both open source.

Prior to conducting any tests, the motion system was calibrated to verify the precision of its tilting motion. Total roll angles were measured using a digital slope-meter, with resolution of 0.01% slope (equivalent to 0.06º) (Figure 1, right image). This was used to calibrate both the commands that are sent to the Moog robot, as well as the custom-built roll-tilt mechanism.

The mechanism employs a linear actuator instrumented with a string potentiometer to control the cabin's roll angle relative to the Moog, as well as an encoder with 40,000 counts-per-revolution 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 subject testing, the positioning errors of the custom motion base were recorded and found to be negligible: 0.07º +/- 0.28º (95% confidence).

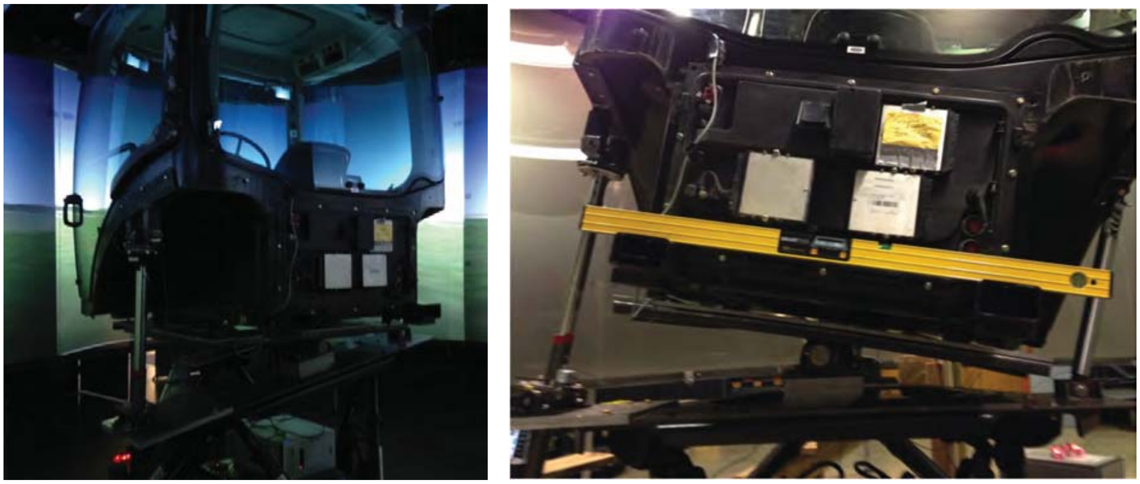

Figure 1. On the left, the tractor driving simulator; on the right, the IS-C mechanism fully extended for 10º of additional roll relative to the Moog robot.

Test Protocol

Once the system was calibrated, operators were tested on their ability to remember 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 cabin to a set roll-pitch combination, and remains stationary for 5 seconds, after which it returns to level.
3. The subject is then instructed to operate the motion base (using a videogame controller) until they reach what they believe is the same angle at which the motion base paused earlier.
4. Once the subject is satisfied with their position, a data point is recorded, registering the original roll-pitch angles and the subject's perceived roll-pitch.
5. The platform is returned to level, and steps 2-4 are repeated for the 28 tilt angles across a randomized pattern.

The set of tilt angles is shown in Figure 2. The reader may note that the set is not symmetric; two angles on the top left corner are missing. They were removed from the sequence because the Moog motion base can be overloaded in force when tilting the cabin to these large angles. This happens because the mass of the cabin in this severe roll-pitch combination is close to the maximum payload, and additional motion past this point has the potential of overloading the motion base's actuators.

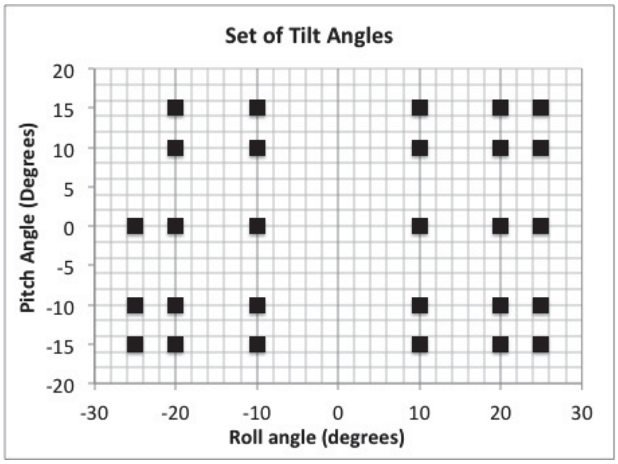

Figure 2. Subjects were exposed to 28 tilt angles of various roll-pitch combinations.

The sequence was presented in randomized order, so that every subject goes through the same angles, but in a different order. This was done to prevent skewing the results with fatigue during the test, as measurement of all angles for a test subject takes around 50 minutes to complete.

During the test, a fixed image with a virtual rural scene is projected on the screen. The subjects are instructed to look at the screen during the whole procedure. The intention here is twofold: first, observance of the horizon line is considered an important visual cue for tilt estimation in the open field; second, in order have the subjects refrain from using external visual cues –ones which would be unavailable in the natural driving environment, such as the top/bottom edges of the screen, or the screen structure– to aid in their tilt estimation task.

Preliminary testing was done with pilot test subjects in order to evaluate the system's performance and polish the software that controls the experimental protocol. During this process, full and consistent data was collected for four subjects, and its 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 degrees of experience, age and other demographic factors. These results will appear in a follow-up publication.

Results

The graphs in Figure 3 plot the pilot-testing subject pool's perceived tilt angles versus the angles they were exposed to. The figure on the left does so for roll, and the one on the right for pitch. The graphs show three types of information: first, the individual data points for all subjects (28 per subject); second, a linear regression of these points (in thick blue line) with its corresponding equation; and third, the ideal result for the regression if the subjects were to have perfect tilt angle estimation i.e., slope equal to one, and intercept equal to zero.

The first notable result is that the roll angle is systematically underestimated, having a slope of 0.88 with 95% confidence interval (0.85, 0.92), compared to the ideal value of 1.00. Meanwhile, the intercept is 0.23º –with 95% confidence interval (-0.85º, 0.40º), meaning that the estimation can be assumed to be unbiased:

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

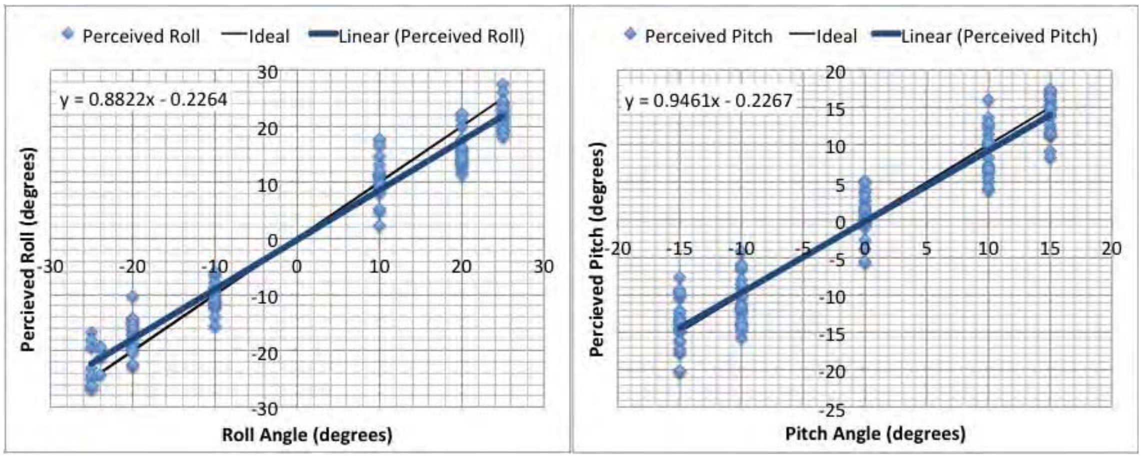

Figure 3. Tilt perception plots show that roll and pitch are systematically underestimated and unbiased. Roll on the left; pitch on the right.

Similarly, pitch is also underestimated, with slope of 0.95 with 95% confidence interval of (0.89, 1.00), and can be considered to be unbiased, with intercept of -0.23º with 95% confidence interval (-0.81º, 0.35º):

$$pitch_{perceived} = 0.95 \cdot pitch_{actual} + 0.23°. \tag{2}$$

Interestingly, roll perception has a bigger issue with underestimation than pitch, meaning that roll perception errors have a dominant effect over pitch perception errors, 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 current results, pitch angle does not appear to have an appreciable influence on roll estimation. For the model

$$roll_{perceived} = m_p \cdot pitch_{actual} + b_p, \tag{3}$$

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

$$roll_{perceived} = m_1 \cdot roll_{actual} + m_2 \cdot pitch_{actual} + b_t, \tag{4}$$

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 from Figure 3, while a slope $m_2 = 0.004$ (-0.05, 0.06) which, like the earlier pitch-only regression model, is not statistically significant. Similar results were obtained for the influence of roll angle on pitch estimation. The current data set does not show a significant effect of pitch affecting the subject's roll perception, or vice versa.

Average Errors

Another issue that was examined was the possible influence of tilt angle magnitudes on the subjects' estimation errors. Figure 4 shows the mean estimation error, with corresponding 2-σ error bars (for 95% confidence), at different roll and pitch magnitudes.

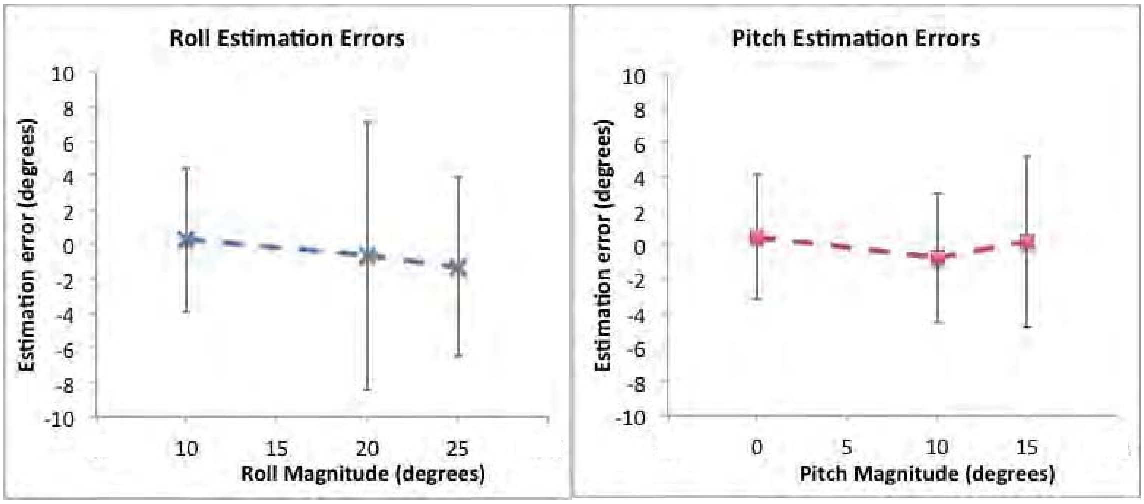

Figure 4. Estimation errors are not strongly influenced by angle magnitude. Roll is shown on the left; pitch on the right.

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

What these plots do show, however, is that errors for both roll and pitch are centered close to zero, meaning there's no clear bias towards positive or negative estimation errors. The two-variable relationships (roll error vs. pitch magnitude, and pitch error vs. roll magnitude) were also not statistically significant, and are 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 off the subject's perception is from the true tilt angle, irrespective of whether they incurred in over-estimation or under-estimation. Figure 5 shows the average distance-to-truth for different angle magnitudes.

As was the case for the error averages, the distance-to-mean metric does not show a clear pattern or influence from tilt angle magnitude. However, it does reveal three key trends:

- Pitch estimation has lower mean absolute errors than roll (below 2.7º vs. up to 4.0º in 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 does increase with pitch magnitude, as seen from the error bars. At zero pitch the 95% confidence interval is very small

+/- 0.6º, and it increases at 10º to +/- 1.6º, and further increases at 15º to +/- 2.13 º. Thus, test subjects appear to become worse at perceiving pitch with larger pitch angles.

- For the pitch and roll angles of interest in this study – namely those that are near the rollover or skidding threshold of an agricultural tractor, absolute roll errors of up to 4º-5º would be expected to be commonplace; for pitch, absolute errors up to 3º-4º would be widely expected.

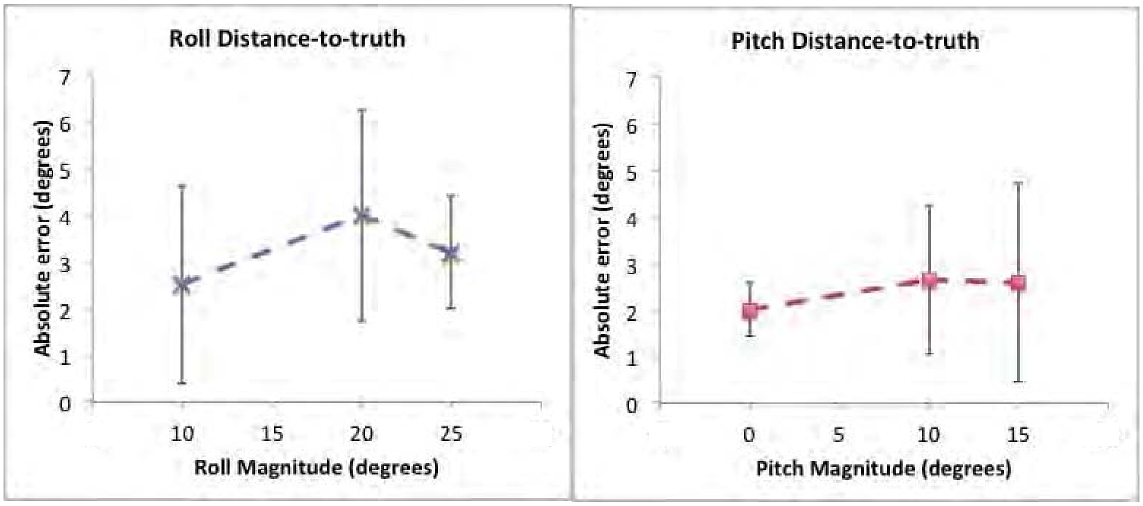

Figure 5. Distance-to-truth averages show the magnitude of typical perception errors.

This last observation can be a useful indicator in tuning a rollover alert system, knowing that a tractor operator driving on a 20º roll slope can commonly perceive this to be in the 15º-16º roll range, therefore underestimating the risk of a rollover accident. Any warning system for roll should therefore give a severe warning within 4 degrees of a tractor's actual rollover threshold.

Conclusions

This study on a pilot-test pool provides insights that are useful for tractor warning systems. In particular, subjects systematically underestimated roll, but produced unbiased errors. Pitch was also systematically underestimated, 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 one for pitch estimation and roll angle. While the expectation was that combined roll-pitch angles would prove to be more difficult to estimate correctly, the results suggest that roll and pitch estimation operate independently in terms of human perception.

Estimation errors for both roll and pitch are centered close to zero, further evidence of the absence of bias, and do not exhibit a relevant relationship with tilt angle magnitudes.

In similar fashion the mean absolute errors, or distance-to-truth, showed no influence from tilt angle magnitude, but do provide upper bounds on 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 underestimation, which can lead to dangerous tractor operation on steep hills.

These conclusions based on this preliminary data set have provided guidance on testing with a wider subject pool (close to 60 subjects), which will include experienced and novice tractor operators of different ages. Additionally, these results are useful to develop prototype tractor rollover and pitch-based warning systems to be tested with that same test pool.

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