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Demonstrating Tractor Rollover Stability Using Lego Mindstorms and Smartphones

A. Bulent Koc[1], Bo Liu[2]

[1] Assistant Professor, Agricultural Systems Management Department, Division of Food Systems and Bioengineering, University of Missouri, 211 Agricultural Engineering Building, Columbia, MO 65211, USA. Email: koca@missouri.edu

[2] Graduate Research Assistant, Bioengineering Department, Division of Food Systems and Bioengineering, University of Missouri, 222 Agricultural Engineering Building, Columbia, MO 65211, USA. Email: bl2cf@mail.missouri.edu

Abstract

Lego RCX Mindstorms kits have been used for teaching traction and ballasting of tractors in the Agricultural Equipment and Machinery course at the University of Missouri for several years. Students design and program autonomous model tractors and observe their performance in a competition involving a simulated tractor pulling a set of weights. With this activity, students observe the effects of drive mechanisms and ballasting on the amount of weight a tractor can pull. In addition to tractor performance activities, we developed a methodology to demonstrate the instabilities taking place during tractor operation on uneven terrain. We used the sensors of a smartphone to monitor the tractor stability on sloping ground. A smartphone application transmitted the data from its inbuilt sensors to a computer over a Wi-Fi network. The physical dimensions of the tractor and the data from the smartphone were used in a mathematical model to determine a stability index value for the tractor operation. The laboratory experiments indicated that the inbuilt sensors of smartphones can be used to wirelessly collect information regarding a tractor's stability. The developed methodology is suitable for teaching rollover prevention of tractors.

Keywords**:** tractor; stability; rollover; iOS; Lego Mindstorms; curriculum

Introduction

LEGO Mindstorms RCX and NXT bricks and software are increasingly used in education. Computer science, math, engineering, robotics and mechatronics disciplines benefit from the LEGO Mindstorms education kits that contain several sensors, actuators and building blocks. LEGO NXT bricks contain powerful 32 bit microcontrollers and have Bluetooth capability making them suitable for various programming and wireless applications. Cruz-Martín et al. (2012) used LEGO NXT bricks for teaching the concepts of data acquisition, control systems and real-time systems. Wang, LaCombe, and Rogers (2004) used LEGO RCX bricks to conduct engineering experiments for teaching fundamental engineering concepts. Benefits of using LEGO bricks in engineering education include exposure of students to data acquisition and analysis, graphical programming, freedom in design of the experiments and increased learning and interest (Wang et al., 2004). Gawthrop and McGookin (n.d.) and Kim (2011) used LEGO Mindstorms NXT in laboratory activities of control systems engineering. While the majority of the applications of LEGO Mindstorms robots were related to science and engineering (Benitti, 2012), Whittier and Robinson (2007) used LEGO kits for teaching the basic principles of evolution and Owens, Granader, Humphrey, and Baron-Cohen (2008) used LEGO kits for social communication skills in individuals with autism.

Grift and Hansen (2003) used LEGO Mindstorms robots as a teaching tool in a Technical Systems Management course. Student projects reported by Grift and Hansen (2003) included self-guided model tractor, variable rate applicator, optimization of turning an offset harvester through 90 degrees and automated farm concepts. Razali, Noor, and Othman (2011) used LEGO robot tractors to analyze the effects of machine weight on soil compaction. While there are several applications of LEGO Mindstorms in education and research in the literature, the intention in this paper is not to provide a detailed survey on the applications of LEGO Mindstorms, but to discuss the development and the use of a smartphone application with LEGO Mindstorms robots to demonstrate tractor rollover stability issues at University of Missouri.

Agricultural equipment and machinery is one of the required courses in the Agricultural Systems Management program at the University of Missouri. It is an undergraduate/graduate level course with two lectures and two laboratory hours per week. Students taking this course come with a background in operating various agricultural machinery and equipment and they often indicate their interest in hands-on activities to improve their mechanical skills. The majority of the students in the class are knowledgeable in corn and soybean production.

The laboratory activities on power performance involve demonstrating traction, weight transfer and ballasting during a tractor operation. For this activity, Lego Mindstorms RCX kits have been used for several years. Following the lectures on traction and ballasting, the students work in groups of three or four to build and program model tractors. With these activities, students learn to program a microcontroller to receive data from the sensors, process the data and generate control signals for the actuators. Four lab sessions are reserved for the model tractor building and programming. During the first lab session, the operation of RCX and its programming with Robolab graphical programming concepts are discussed. The second lab session involves collection and recording data from the RCX sensors. The third and fourth lab sessions involve building and fine-tuning a model tractor, programming and preparing for a simulated tractor pull competition. The details of the lab activities on tractor ballasting and traction using Lego Mindstorms were presented in an earlier report by Adams and Keene (2005).

By observing several tractors built by the students over the years, we realized that the model tractors may not be very stable on uneven terrains because of their narrow tracks, high center of gravity, uneven weight distributions and triaxial structures (Figure 1). To demonstrate the significant factors affecting the stability of a tractor and to emphasize tractor safety issues, we investigated new experiments that involve smartphones and wireless data collection.

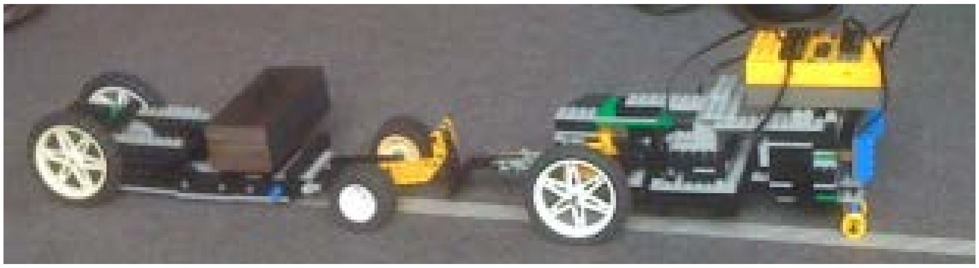


Figure 1. A model tractor pulling a simulated sled on an even surface.

Objective

The objective of this study was to develop experiments to monitor and demonstrate the important parameters affecting the stability of a tractor operating on an uneven terrain using a smartphone and a computer.

Tractor rollover model

Tractor stability is affected by several factors. While complicated modeling methods are able to cover the half or full overturns and multi-body problems, simplified models can also be used to conduct stability analyses to predict vehicle rollovers (Eger and Kiencke, 2003). In this study, a simplified tractor rollover model was used. In the model, the deflections of tires and suspension of the tractor, road conditions, and environmental factors were not considered. Overall, the stability of the vehicle was calculated based on the lateral and longitudinal stability of the tractor. A rigid tractor model on a horizontal surface is shown in Figure 2.

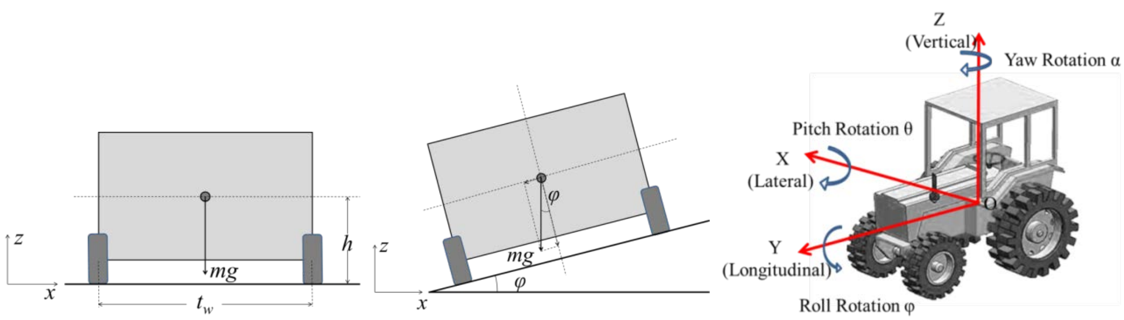


Figure 2. A rigid vehicle model and the roll, pitch and yaw rotations of a tractor.

The track width (t_w) of the vehicle is measured from the center of the right tire to the center of the left tire and wheelbase (w_b) is the distance between the centers of the front and rear wheels. The center-of-gravity (CG) is a theoretical critical design point in the vehicle's mass where the vehicle can be balanced in every direction. The height of the CG is h, mass of the vehicle is m, and the acceleration due to the gravity is *g*. The static stability of a tractor can be described by static stability ratio (SR) along the longitudinal and lateral directions using Eq. 1:

$$\begin{bmatrix} SR_x \\ SR_y \end{bmatrix} = \frac{1}{2h} \begin{bmatrix} w_b \\ t_w \end{bmatrix} \tag{1}$$

Typically, a higher SR indicates a more stable vehicle (Dirk, Tilman, & Jürgen, 1999). In the real world, many moving vehicles are operated on uneven surfaces with varying slopes. The actual status of a vehicle can be simplified into stationary models with dynamic actions considered. To analyze the vehicle kinetics and dynamics, the vehicle's static and dynamic stability indices were used (Liu, 1999). The static stability index in x and y directions indicating the lateral and longitudinal overturns can be defined using Eq. 2 (Liu & Ayers, 1999). The stability index (SI) values range between 0 (least stable) and 100 (most stable).

$$\begin{bmatrix} SI_x \\ SI_y \end{bmatrix} = 100 \begin{bmatrix} 1 - \dfrac{\theta}{\theta_{cri}} \\ 1 - \dfrac{\varphi}{\varphi_{cri}} \end{bmatrix} \tag{2}$$

Where, φ and θ are the roll angle and pitch angle of the vehicle and φ_{cri} and θ_{cri} are the critical roll angle and critical pitch angle, at which lateral or longitudinal overturning is about to happen. The critical pitch and roll angles in Eq. 2 are defined by Eq. 3 (Liu & Ayers, 1999):

$$\begin{bmatrix} \theta_{cri} \\ \varphi_{cri} \end{bmatrix} = \begin{bmatrix} \arctan\left(\dfrac{w_b}{2h}\right) \\ \arctan\left(\dfrac{t_w}{2h}\right) \end{bmatrix} = \begin{bmatrix} \arctan\left(SR_x\right) \\ \arctan\left(SR_y\right) \end{bmatrix} \tag{3}$$

The dynamic stability index is defined by Eq. 4 (Liu & Ayers, 1999):

$$\begin{bmatrix} SI_x(t) \\ SI_y(t) \end{bmatrix} = 100 \begin{bmatrix} \left(1 - \dfrac{\theta}{\theta_{cri}}\right)\left[1 - \left(\dfrac{\dot{\theta}}{\dot{\theta}_{cri}}\right)^2\right] \\ \left(1 - \dfrac{\varphi}{\varphi_{cri}}\right)\left[1 - \left(\dfrac{\dot{\varphi}}{\dot{\varphi}_{cri}}\right)^2\right] \end{bmatrix} \tag{4}$$

Where $\dot{\theta}$ is the pitch rate and $\dot{\theta}_{cri}$ is the critical pitch angle of the vehicle, $\dot{\varphi}$ is the actual roll rate, and $\dot{\varphi}_{cri}$ is the critical roll rate of the vehicle which are defined by Eq. 5 (Ertlmeier, Faaist, Spannaus, & Brandmeier, 2012):

$$\begin{bmatrix} \dot{\theta}_{cri} \\ \dot{\varphi}_{cri} \end{bmatrix} = \sqrt{2mg} \begin{bmatrix} \sqrt{\dfrac{r_x\left[1-\cos(\theta_{cri}-\theta)\right]}{J_x + m{r_x}^2}} \\ \sqrt{\dfrac{r_y\left[1-\cos(\varphi_{cri}-\varphi)\right]}{J_y + m{r_y}^2}} \end{bmatrix} \quad (5)$$

Where m is the vehicle mass, g is gravity, J_x and J_y are moments of inertia along the x and y axes, and r_x and r_y are defined by Eq. 6.

$$\begin{bmatrix} r_x \\ r_y \end{bmatrix} = \begin{bmatrix} \left(\dfrac{w_b}{2}\right)^2 + h^2 \\ \left(\dfrac{t_w}{2}\right)^2 + h^2 \end{bmatrix} \quad (6)$$

In dynamic situations, the vehicle is statically placed on a slope and a dynamic action is added. The dynamic roll and pitch stability indices are calculated using Eq. 7:

$$\begin{bmatrix} SI(t)_{roll} \\ SI(t)_{pitch} \end{bmatrix} = 100 \begin{bmatrix} \left(1-\left(\dfrac{\varphi}{\varphi_{cri}}\right)\right) * \left[1-\left(\dfrac{\dot{\varphi}}{\dot{\varphi}_{cri}}\right)^2\right] \\ \left(1-\left(\dfrac{\theta}{\theta_{cri}}\right)\right) * \left[1-\left(\dfrac{\dot{\theta}}{\dot{\theta}_{cri}}\right)^2\right] \end{bmatrix} \quad (7)$$

An overall stability index value from the dynamic roll and pitch stability indices is calculated using Eq. 8:

$$SI_{overall}(t) = \left(1-\sqrt{\left(\dfrac{\varphi}{\varphi_{cri}}\right)^2 + \left(\dfrac{\theta}{\theta_{cri}}\right)^2}\right) * \left[1-\sqrt{\left(\dfrac{\dot{\varphi}}{\dot{\varphi}_{cri}}\right)^4 + \left(\dfrac{\dot{\theta}}{\dot{\theta}_{cri}}\right)^4}\right] * 100 \quad (8)$$

To calculate these parameters in determining the stability index in real-time, the data from a smartphone's inbuilt sensors and the physical dimensions of the tractor were used.

Model tractor and test platform

We updated the Lego Mindstorms kits at the beginning of the fall 2012 semester. The new kits come with an intelligent NXT 2.0 Lego brick, which contains a 32-bit ARM 7 microcontroller, a large matrix display, four input ports and three output ports. NXT 2.0 brick also has Bluetooth and USB communication links to a computer. Each kit has three interactive servo motors, an ultrasonic range sensor, two touch sensors and a color sensor. NXT 2.0 microcontroller is programmed using drag and drop icon-based programming using a PC or a MAC computer.

A model tractor (Figure 3) was built to travel on a test platform with increasing slopes (Figure 4). An iPhone application program was developed in XCode to transmit the sensors data to a computer. XCode is an Integrated Development Environment (IDE) containing software development tools to create apps for OS X and iOS (Apple Inc., CA, USA). A user datagram protocol (UDP) was developed in Labview (National Instruments, Austin, TX) to receive the data from the iPhone. The accelerometer sensor data was used to estimate the roll and pitch angles, while the gyroscope sensor data was used to measure the roll and pitch rates. The Labview program opens a UDP connection between the phone and the computer which are on the same Wi-Fi network. Once the connection is made, comma delimited data streams from the iPhone were separated into columns and recorded as a text file on the computer. The graphic panel of the Labview program is shown in Figure 5.

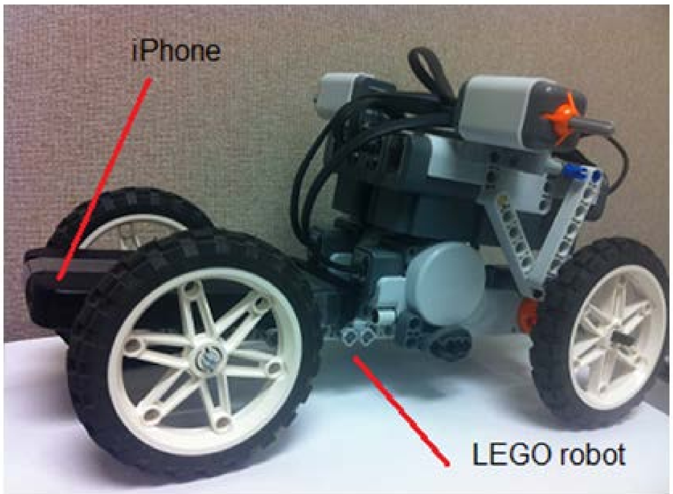


Figure 3. The location of the phone on the model tractor.

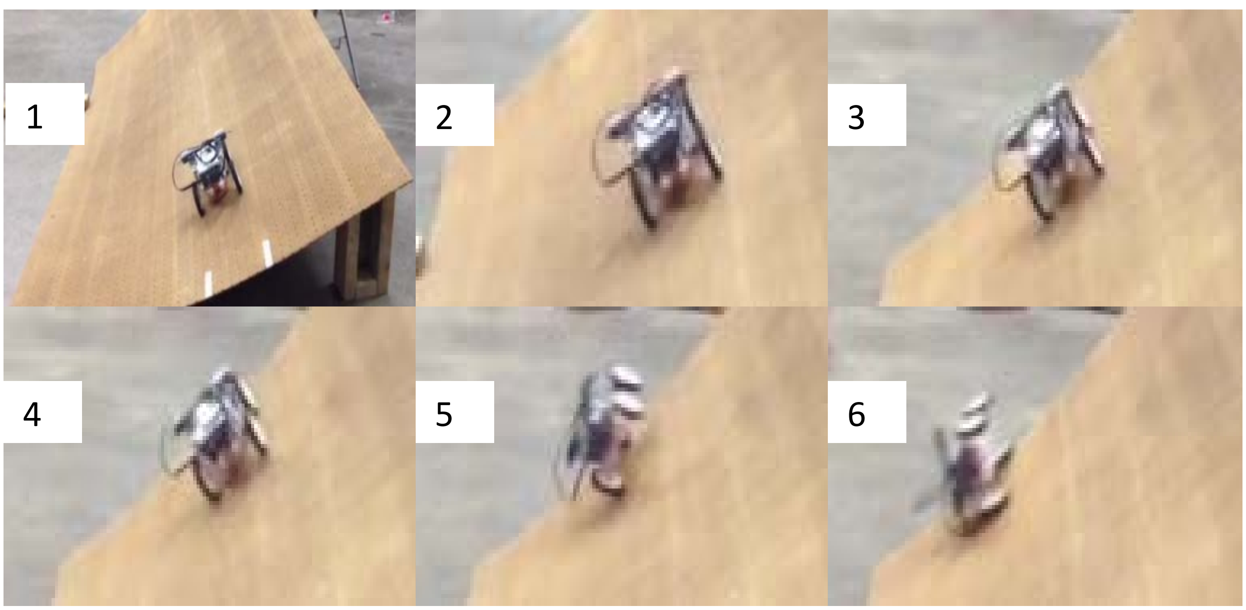
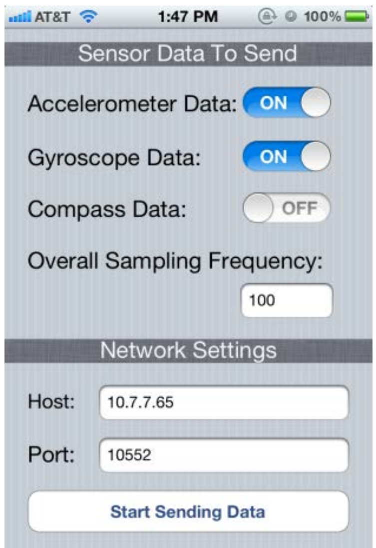


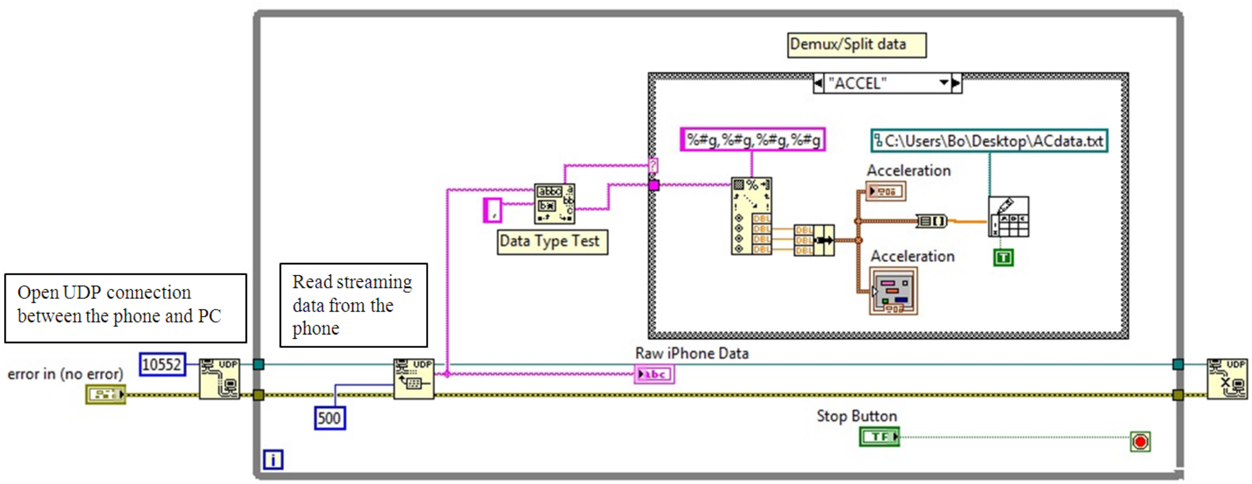
Figure 4. The video frames captured at different times during a rollover test (frame 4: the start of the rollover, frame 5: rolling tractor and frame 6: overturned model tractor).

Results of Experiments

During the tests, the iPhone was placed on the front axle of the tractor and the iPhone app was activated. The track width of the model tractor was 13 cm, the height of tractor's center of gravity was 7.2 cm, and the mass of the tractor with the iPhone was 1.019 kg. The rollover experiments were conducted at three speeds (0.25m/s, 0.33m/s, 0.5m/s) on the same path as shown in Figure 4. The changes of roll angle and stability index values with time at each speed are shown in Figures 6, 7 and 8. Figure 6 shows the model tractor moving on the platform with a varying slope at a speed of 0.25 m/s. The roll angle increased as the slope of the platform was increasing and the stability index decreased with increasing slope. Beyond the critical roll angle, which was 42.1° for this model tractor, the roll angle increased suddenly and rollover took place. Rollover started when the stability index value approached zero.



(a)



(b)

Figure 5. a) The screenshot of the iPhone app for collecting and transmitting inbuilt sensor data and b) the Labview program to record the streaming data from the phone to a computer.

Results of Experiments

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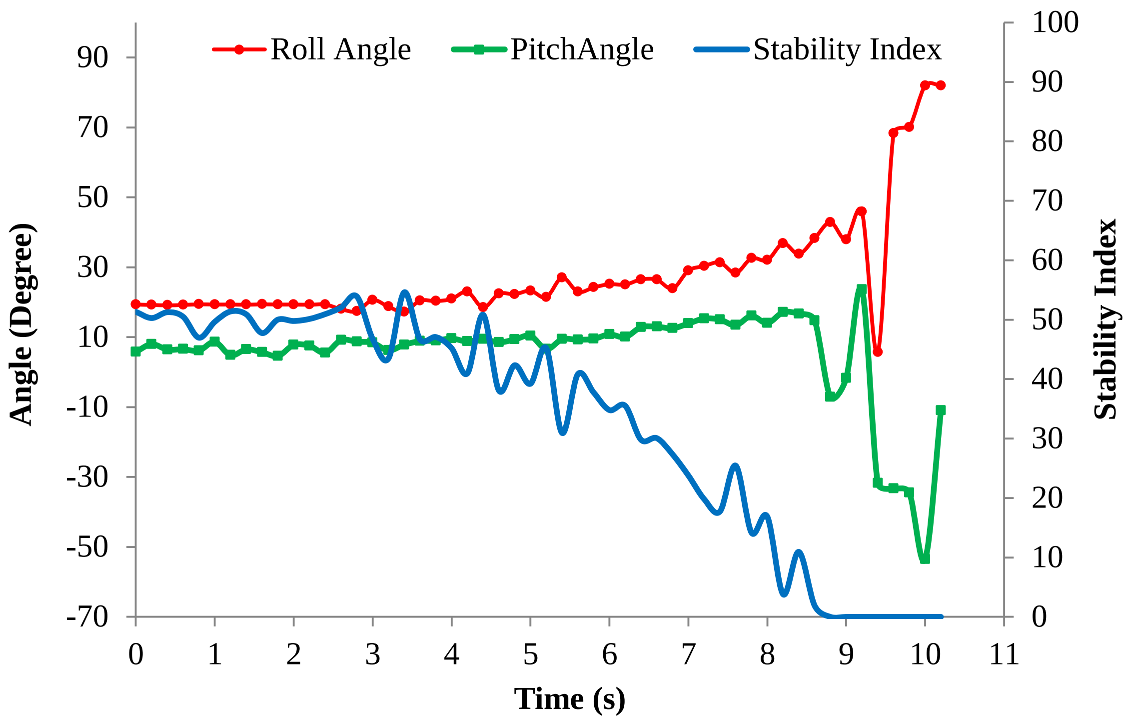

Figure 6. Change of roll angle, pitch angle and roll stability index value with time at a speed of 0.25 m/s.

The model tractor was operated on the same platform at a speed of 0.33 m/s under the same conditions as before (Figure 7). When the roll angle value became close to the critical roll angle, the stability index values began to oscillate. Rollover occurred when the measured roll angle became greater than the critical roll angle at the stability index value of zero. Figure 8 shows the model tractor was moving at a speed of 0.5 m/s under the same conditions as previous tests. As the roll angle increased, the stability index value became unstable and dropped below zero beyond the critical roll angle value.

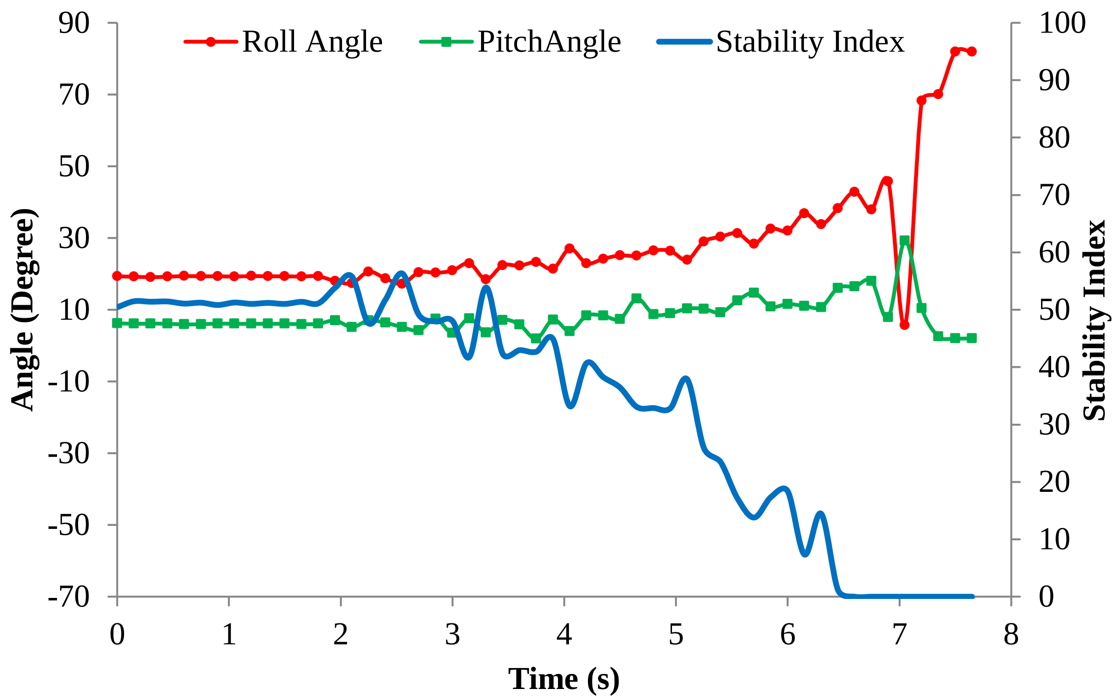

Figure 7. Change in roll angle, pitch angle and roll stability index value with time at a speed of 0.33 m/s.

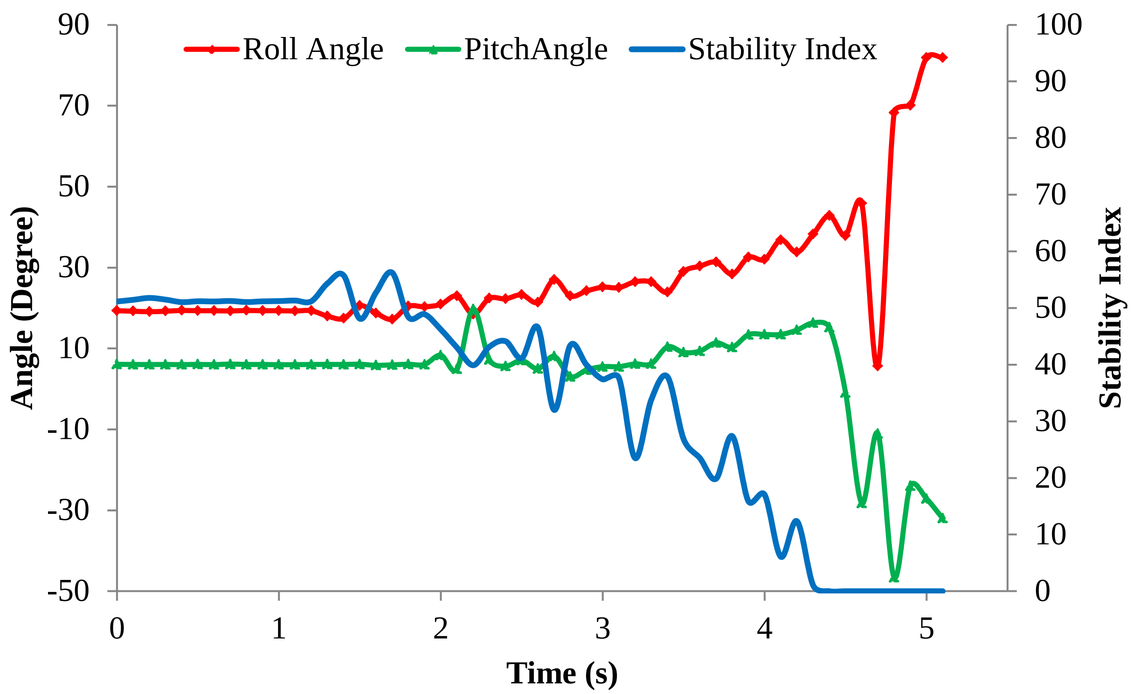

Figure 8. Change in roll angle, pitch angle and roll stability index value with time at a speed of 0.5 m/s.

The method developed and presented in this paper will be integrated with the laboratory activities for the topics of tractor performance, traction and ballasting in the agricultural equipment and machinery course. Once mounted securely on the model vehicle, smartphones with their miniaturized microelectromechanical systems (MEMS) provide important information about the stability of a vehicle. The precision, accuracy and variety of sensors in smartphones provide several opportunities in the measurement of motion, capturing images with their cameras and determining the location of an object on earth. The wireless communication and telephone functions of these phones allow for the building of low cost applications which can be integrated into the teaching of important parameters affecting the stability of a vehicle.

Conclusions

A method was developed to monitor the stability of a tractor on sloping surfaces using the sensors of a smartphone. A simplified mathematical model was implemented to indicate the stability of the tractor operation. The stability of the vehicle was represented with a stability index (SI) value. The SI value was calculated based on the sensor data from a smartphone and the physical dimensions of the tractor. The experiment results showed that the proposed method can successfully predict a possible tractor rollover. The developed method of monitoring tractor stability will be integrated into the laboratory activities in the agricultural equipment and machinery course at the University of Missouri. The future research on tractor stability monitoring will include developing and testing a smartphone app to monitor the stability of other motorized vehicles. Once the app is completed and tested on real size vehicles, it will be a low cost tool for teaching vehicle rollover prevention.

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