Development of Driving Simulator for Safety Training of Agricultural Tractor Operators

Yu-Yong Kim*, Byounggap Kim, Seung-yeoub Shin, Jinoh Kim, Sunghyun Yum

Department of Agricultural Engineering, National Academy of Agricultural Science, Rural Development Administration, Jeonju, Korea

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Abstract

Purpose: This study was aimed at developing a tractor-driving simulator for the safety training of agricultural tractor operators.

Methods: The developed simulator consists of five principal components: mock operator control devices, a data acquisition and processing device, a motion platform, a visual system that displays a computer model of the tractor, a motion platform, and a virtual environment. The control devices of a real tractor cabin were successfully converted into mock operator control devices in which sensors were used for relevant measurements. A 3D computer model of the tractor was also implemented using 3ds Max, tractor dynamics, and the physics of Unity 3D. The visual system consisted of two graphic cards and four monitors for the simultaneous display of the four different sides of a 3D object to the operator. The motion platform was designed with two rotational degrees of freedom to reduce cost, and inverse kinematics was used to calculate the required motor positions and to rotate the platform. The generated virtual environment consisted of roads, traffic signals, buildings, rice paddies, and fields.

Results: The effectiveness of the simulator was evaluated by a performance test survey administered to 128 agricultural machinery instructors, 116 of whom considered the simulator as having potential for improving safety training.

Conclusions: From the study results, it is concluded that the developed simulator can be effectively used for the safety training of agricultural tractor operators.

Keywords: Accident prevention, Agricultural tractor, Safety training, Simulator, Virtual reality

Introduction

Agricultural tractors have become part of the basic equipment used for crop production and transportation, and in recent times, the number of tractors in service has increased. In addition, rural-urban migration has resulted in an increase in the percentage of the aged population in agricultural areas, with an attendant increase in the average age of tractor operators. This in turn has led to an increase in accidents involving agricultural tractors in Korea. The Rural Development Administration (RDA) in Korea reported that 93% of tractor work accidents were due to operator errors such as neglect and inexperience, and 98% of tractor traffic accidents were due to operator neglect and violation of traffic regulations (Kim et al., 2012). It is therefore necessary to train tractor operators in safe operation. Moreover, empirical safety training is more effective than theoretical training. However, although the use of a real tractor for such training is highly effective, it is dangerous, especially on roads and slopes.

Driving simulation dates back to the 1970s, when General Motors developed one of the first driving simulators (Gruening et al., 1998). A driving simulator is used to create a virtual traffic environment, and it affords a realistic feeling of driving a real vehicle. Indeed, simulators are increasingly being used globally for diverse training purposes, such as aircraft piloting. A driving simulator can also be used for training tractor operators in the safe handling of real-life situations such as driving and farm work, with...
the advantage of an easily controllable environment (Lee et al., 1998). Although simulators have been extensively used in the automotive industry for many years, very few simulators of agricultural vehicles have been developed, an example being that developed by Wilkerson et al. (1993). Agricultural tractors and ordinary automobiles are similar in some ways with regard to road travel; nevertheless, the way they are driven is quite different owing to differences in their safety devices, operating devices, forward speeds, and the driving surfaces they were optimized for.

Therefore, the objective of the present study was to develop a driving simulator for the safety training of operators of agricultural tractors.

Materials and Methods

The effectiveness of a simulator depends on how well it mimics real-world conditions and the way in which it represents the physical elements of the real world that play active roles in the simulated scenario (Adler et al., 1993). As shown in Figure 1, the tractor simulator developed in this study includes five principal components: mock operator control devices, a data acquisition and processing device, a motion platform, a visual system that displays a computer model of the tractor, and a virtual environment.

Mock operator control devices

As shown in Figure 2, the operator control devices of the tractor simulator include the following: a steering wheel; a clutch pedal; two (left and right) brake pedals, which can be connected while traveling and operated separately while working; an accelerator pedal; a forward-reverse shuttle shift; a main-gear shift lever; a sub-gear shift lever; a 2W/4W driving selection pedal; a differential lock pedal; a power take-off (PTO)-gear shift lever; a position control lever; a parking brake; an ignition key; a directional signal switch; a controller for lighting devices such as the head lamps; and a PTO clutch switch. The operator control devices of the simulator were obtained from a real tractor (U43, LS Mtron, Korea).

Data acquisition and processing device

The operator control inputs were acquired through an A/D board (NI USB-6343, National Instruments, USA) and transmitted to a tablet PC (H160-GV3WK, LG Electronics, Korea), which functioned as a dashboard. An application for data acquisition was programmed using a visual programming language (LabVIEW 2010, National Instruments, USA). A local networking system communicating over the Ethernet was employed, and it consisted of the tablet PC, a controller for the motion platform, and a main PC that simulated the computer model of the tractor and the virtual environment.

Virtual environment and computer model of tractor

The virtual environment and the computer model of the tractor were developed using the game development tool Unity 3D, an open source project with some basic automobile physics, and Microsoft C#. Three-dimensional computer models representing a 3D object were developed from a collection of points in 3D space connected by various geometric entities such as triangles, lines, and curved surfaces.

The 3D computer model of the tractor was designed
using 3ds Max and was based on a real tractor (L7040, LS Mtron, Korea) inspected at the Foundation of Agricultural Technology Commercialization and Transfer (FACT) in 2010 (FACT, 2011). The modeled tractor was operated on the basis of the vehicle dynamics and the wheel collider of Unity 3D. The tractor had a direct injection diesel engine with a rated power of 73.53 kW and maximum power of 88.24 kW at 2200 rpm. The maximum torque of the engine was 478.77 Nm, and its idling speed and maximum idling speed were 800 rpm and 2900 rpm, respectively. It should be noted that the maximum attainable power of an internal combustion engine is a function of the engine speed. The governing function is known as the power performance function and is experimentally determined. However, because this function was not determined at FACT, it was estimated as a third-order polynomial (Reze, 2009) as follows:

$$P_e = P_1\omega_e + P_2\omega_e^2 + P_3\omega_e^3$$  \hspace{1cm} (1)

where $P_e$ is the engine power function (W), $\omega_e$ is the engine speed (radian/s), $P_1$, $P_2$, and $P_3$ are the engine power (W), the engine speed (radian/s), and the engine power (Nm) respectively. The available torque at the drive wheel ($T_w$) is given by

$$T_w = \frac{P_w}{\omega_w} = \eta_m \eta_g T_e$$  \hspace{1cm} (2)

where $\eta$ is the overall efficiency, $\eta_m = \eta_{mg} \times \eta_g$ is the transmission ratio of the gear box, $\eta_{mg} = 0.0235$, $G_g = 0.1465$, $G_m = 0.107$, $G_s = 2.112$ is the transmission ratio based on the rank of the main gear box ($G_m$), $\eta_g = -0.5947 G_c^3 + 6.7055 G_c^2 - 26.414 G_c + 37.434$ is the transmission ratio based on the rank of the sub-gear box ($G_s$), and $\eta_d = 19.273$ is the transmission ratio of the differential.

However, if the forward-reverse shuttle shift, main gear, or sub-gear is in neutral, the transmission ratio would be zero. The traveling speed was limited to 40 km/h.

The 3D model of the tractor was adjusted and refined using existing car physics for simulation based on the positions of the steering wheel, pedals, and levers. Dynamic objects in the implemented virtual environment consisted of buildings, roads, a rural landscape, autonomous vehicles, and pedestrians.

According to a 2010 survey of agricultural machinery accidents (RDA), 27.3% of farm work accidents occurred in rice paddies/fields, 18.2%, on farm roads; 18.2%; on access roads to rice paddies/fields; 18.2%, in farm houses; 9.1%, on village roads; 9.1%, on city streets. 40.4% of traffic accidents occurred on local roads, 27.7% on national roads; 7.4%, on farm roads; and 24.5% of the accidents were unclassified.

### Motion platform

The most advanced driving simulator in the world has a motion platform with more than six degrees of freedom (DOFs) and costs about 50 million USD. Parallel manipulators with less than six DOFs have recently been widely applied in the motion platforms of various simulators owing to their inherent advantage of parallel mechanisms and several other benefits including significantly lower production and operation costs (Wu et al., 2011). To reduce the cost of the presently developed simulator, the motion platform was designed with two rotational DOFs (pitch and roll), and inverse kinematics was used to determine the required motor positions and to rotate the platform.

### Visual system

To simultaneously display the four different sides of a 3D object on the screen for an operator, four different camera outputs are required, one each to show the front, back left, and right sides of the object. Hence, the visual system consisted of two graphic cards (AMD Radeon HD 7990, USA), four active mini displays ported to HDMI video converters (MDP2HDS, StarTech.com, USA), and four monitors (42LNS5400, LG Electronics, Korea) placed in the abovementioned four directions on the motion platform. The screen resolution was determined by the dimensions of the four monitors, namely, 7680 × 1080 pixels.
Results and Discussion

Operator control devices

As shown in Figure 3, the steering wheel was connected through a universal joint to the remodeled steering wheel of a PC game set (G27 Racing Wheel, Logitech, Swiss), which has a dual-motor force feedback mechanism with 900° wheel rotation. The value of the steering was acquired to be between -1 and 1 by the main PC through a USB. As shown in Figure 4, the existing forward-reverse shuttle shift was remodeled with three proximity sensors (PR08-2DN, Autonics Corporation, Korea) and three ball plungers, which were used to detect and select three gear positions (forward, neutral, and reverse).

As shown in Figure 5, the main gear box was developed using a ball joint, a linear motion guide, a shift lever, two ball plungers, four proximity sensors (PR12-4DN, Autonics Corporation, Korea), an H-shaped plate, a push-pull-type tubular solenoid (DS-1822A, DKC, Korea), two bars attached to the solenoid, and a timer controller to prevent overheating of the solenoid. The solenoid was operated by a switch attached to the clutch pedal. As shown in Figure 6, the sub-gear and PTO gear consisted of linear motion guides attached to their cases, as well as four ball plungers and five proximity sensors (PR08-2DN, Autonics Corporation, Korea). The gears were separately operated in four-speed gear boxes and moved in a straight line.

As shown in Figures 6, 7, and 8, the inputs of the four pedals (clutch, two brakes, and accelerator) were acquired by modifying each of the pedals with the installation of an
angle sensor (ST-350, Sensor Systems, Italy) with an input of 24 V and output of 0–10 V, two pulleys, and a timing belt. The outputs of the sensors were connected to the analog ports of the data acquisition device. A proximity sensor (PR08-2DN, Autonics Corporation, Korea) was fitted near a brake connection pin to detect the brake connection.

**Data acquisition device**

As shown in Figure 7, the position control device consisted of an angle sensor, a roller bearing, a sliding rail, a link, and an existing lock bolt. These were used to vary the length of the link and detect the angle of rotation. Further, a 2W/4W drive selection device (or differential lock device) was developed for use as a push button. If the pedal was pressed once, the position link bearing would be moved to the pressed position and 4W drive (or differential lock) would be selected. If the pedal was pressed twice, the position link bearing would be moved to the released position and 2W drive (or differential motion) would be selected.

As shown in Figure 9, a magnetic switch was set in the buckle housing of the seat belt to detect whether the seat belt was engaged. When the operator would insert the tongue into the buckle, the magnetic switch would be pressed and the seat belt would be engaged. As also shown in Figure 10, the parking brake was detected by installing a proximity sensor near the protrusion rotated by the parking brake.

A regulated voltage of 24 V was supplied to the angle sensors and proximity sensors, and a regulated voltage of 5 V was supplied to the contact switches, such as the ignition key, directional signal switch, and lighting system controller. The output signals from the angle sensors were connected to the analog ports of the data acquisition device; those from the proximity sensors were converted to a level of 5 V using photo-couplers; and those from the contact switches were connected to the digital ports of the data acquisition device. The application program was developed as an instrument panel for acquiring 6 analog and 32 digital channels, sending the acquired data, and receiving the simulation data at 50-ms intervals. As shown in Figure 14, the analog data could be calibrated to an acceptable value range of between 0 and 1 by clicking buttons on the screen and operating the controls two or three times.

**Tractor computer model and virtual environment**

The computer model of the tractor dynamics is part of the driving simulator software that determines the operator's perception and is used to evaluate the physics and motions of the real vehicle according to the operator inputs and environmental conditions.

The engine speed ($\omega_e$) was determined from the position...
of the accelerator pedal as follows:

$$\omega_c = \frac{2\pi(idling \ speed + S_c (no \ load \ maximum \ speed - idling \ speed))}{60}$$  \hspace{1cm} (3)

where $S_c$ is the position of the accelerator pedal ($0 \leq S_c \leq 1$).

The brake torque was set to 500 Nm to obtain a braking distance of 11 m when the brake pedals were pressed by more than 80% at a speed of 40 km/h. It was set to 0 Nm when the pedal was pressed by less than 25%, and it increased linearly from 25% to 80%. Each brake torque was divided equally.

The power transfer rate of the clutch was set to 100% when the clutch pedal was pressed by less than 45% and to 0% when the pedal was pressed by more than 95%. The other clutch transfer rate was set as follows:

$$\text{Transfer rate} (\%) = 100 + \frac{0.45 - S_c}{0.5} \times 100$$  \hspace{1cm} (4)

where $S_c$ is the position of the clutch pedal ($0.45 \leq S_c \leq 0.95$).

The acceleration ability of the tractor was calculated using equation (5), which is based on the schematics in Figures 11 and 12. Equation (5) was implemented using a Rigidbody3D-class physics component.

$$\begin{align*}
\ddot{X} &= \left( m + \frac{r_f^2 I_f + r_l^2 I_l}{r_f^2 (1 - s_I)} \right) \ddot{X} - \frac{r_f M_f + r_f M_s - (F_u e_f r_e + F_w e_r r_f)}{r_f r_f} - F_{ul} - m g \sin \gamma - P \cos \alpha \\
\end{align*}$$  \hspace{1cm} (5)

where $M_f$ is the front-wheel driving torque (0 in 2WD and $T_{w_f}(\omega)$ in 4WD) [Nm], $M_s$ is the rear-wheel driving torque ($T_{w_r}(\omega)$ in 2WD and $T_{w_r}(\omega)$ in 4WD) [Nm], $I_f$ is the polar moment of inertia of the front wheel [kg/m²], $I_l$ is the polar moment of inertia of the rear wheel [kg/m²], $r_f$ is the radius of the front wheel [m], $r_s$ is the radius of the rear wheel [m], $s_I$ is the slip rate, $F_u e_f r_e + F_w e_r r_f$ is the traction force and tillage resistance force. The traction force was automatically applied by the wheel collider of the Unity 3D engine, whereas the tillage resistance force varied with the depth of tillage, traveling speed, and soil condition. The resistance force of the rotavator was calculated by the following equation:

$$P \cos \alpha = -\tau \times F_{rot}$$  \hspace{1cm} (6)

where $\tau$ is the rotation angle of the three-point linkage $[(\tau = (70 \times h - 20)/20 \text{ if } \tau \geq 0)]$, $h$ is the position of the area of the tractor ($=0.8WH$; W: width, H: height) [m²]. $\gamma$ is the road slope angle, and $P \cos \alpha$ is the force applied on the implement [N].

The two external forces that acted on the implement were the traction force and tillage resistance force. The traction force was automatically applied by the wheel collider of the Unity 3D engine, whereas the tillage resistance force varied with the depth of tillage, traveling speed, and soil condition. The resistance force of the rotavator was calculated by the following equation:

$$P \cos \alpha = -\tau \times F_{rot}$$  \hspace{1cm} (6)

where $\tau$ is the rotation angle of the three-point linkage $[(\tau = (70 \times h - 20)/20 \text{ if } \tau \geq 0)]$, $h$ is the position of the implement.
position control lever (0–1), and $F_{act}$ is the maximum tillage resistance set by the operator.

The tractor-trailer system was implemented using a Hinge Joint 2D, in which two rigid bodies are grouped together and thus constrained to move as though connected by a hinge. The trailer was therefore spun in a manner similar to a real trailer.

As shown in Figures 13 and 14, the virtual environment consisted of four-lane roads with/without traffic signals, two-lane roads with/without traffic signals, farm roads, village roads, access roads into rice paddies/fields, rice paddies, and inclined fields.

The traffic signals were changed in the order shown in the Figures 15 and 16.

As shown in Figures 17 and 18, 40 autonomous vehicles were driven in the virtual environment in accordance with the traffic signals, set path, and speed of each vehicle. The maximum speed of the regular vehicles (buses, trucks, cars, and taxis) was set to 80 km/h, and those of the tractors, combines, and power tiller were set to 40, 10, and 15 km/h, respectively.

Accidental collision could not occur between the artificial intelligence (AI) vehicles, because each of them received information of the traffic signals and information on all vehicles approaching the intersection, with the exception of MyTractor, which was the tractor model driven by the operator in compliance with the following rules. 1) If the traffic signal of an AI vehicle approaching the cross street is green, it would enter the cross street at its normal speed, which is less than the set maximum speed. 2) If the traffic signal of an AI vehicle approaching the cross street is yellow, the distance from the point at which it receives information of the traffic signal to stop would be calculated to determine whether it would stop (set stopping distance ≥ calculated stopping distance). The set stopping distance was 0.125 m per 10 km/h. A right-turning vehicle enters the cross street unaffected by the traffic signal if it does not interfere with the flow of other vehicles and pedestrians.
Figure 17. Path of autonomous vehicles.

Figure 18. Autonomous vehicles at cross street.

Figure 19. Accident 1 at cross street.

Figure 20. Accident 2 at cross street.

Figure 21. Accident 3 at cross street.

Figure 22. Crash zone at cross street.
4) A pedestrian crosses the street at a crosswalk if his/her signal is green, and waits otherwise.

As shown in the following condition figures (Figures 19~22), when an AI vehicle enters the cross street or turns right, if the operator’s signal is yellow or green and the operator enters the cross street, an accident would occur between the AI vehicle and MyTractor in the crash zone of the cross street.

### Motion platform

As shown in Figure 23, the motion platform consisted of two servomotors, two 50:1 reducers, two four-bar linkages placed at $90^\circ$ to each other, a universal center joint, four rod end bearings, and four links. The rotation angle of the servomotor was determined by inverse kinematics using equation (7), which is based on the schematic in Figure 24. The subscripts $p$ and $r$ denote pitch and roll, respectively.

\[
\phi = \tan^{-1}\left(\frac{H + L \sin \theta - h}{L \cos \theta - 1}\right) - \cos^{-1}\left(\frac{QP^2 + b^2 - a^2}{2QPb}\right)
\]  

where $\phi$ is the rotation angle of the reducer (rad), $\theta$ is the roll or pitch angle of the tip plate (rad), $s = \sqrt{L^2 + (H-h)^2}$ ($s_p = 5780.138$ mm and $s_r = 565.0855$ mm), $QP = \sqrt{L^2 + s^2 - 2Ls \cos(\varphi + \theta)}$, $\varphi = \tan^{-1}\left(\frac{H-h}{1}\right)$ ($\varphi_p = 0.5256$ rad and $\varphi_r = 0.5359$ rad), $H$ is the vertical height from the bottom to point O ($H_p = H_r = 455$ mm), $L$ is the distance between points O and P ($L_p = L_r = 520$ mm), $b$ is the link distance between points Q and R ($b_p = b_r = 175$ mm), $a$ is the link distance between points P and R ($a_p = 320$ mm and $a_r = 315$ mm), $l$ is the horizontal distance between points O and Q ($l_p = 500$ mm and $l_r = 485$ mm), and $h$ is the vertical height from the bottom to point Q ($h_p = h_r = 165$ mm).

Figure 25 shows a comparison of values determined by AutoCAD with those calculated by the above equation, revealing good agreement between them. The above-derived equation was therefore used in the inverse kinematics for controlling the motion platform.

The two servomotors of the motion platform were controlled by a programmable logic controller (PLC). The PLC received the data (pitch and roll angles) through User Datagram Protocol (UDP) communication from the simulation computer at 50-ms intervals and transmitted the rotation angles of the two servomotors to each servomotor driver. These drivers controlled the rotation angles of the servomotors by proportional-integral-derivative (PID) control. The gains of the PID control were adjusted by autotuning, and each servomotor driver required a minimum command time of 100 ms. Each servomotor was controlled by step signals and not continuously, and a particular position control was implemented that performed control before completion of the previous position control. The minimum time for attaining a target position was therefore set at 120 ms.
Performance test by agricultural machinery instructors

A total of 128 agricultural machinery instructors trained at the human resource training center of RDA participated in the performance test survey of the developed simulator. They rode on the developed simulator and were then surveyed on its efficacy in terms of educational effectiveness in comparison to existing safety education and recommended improvements in the developed simulator. From the 128 instructors surveyed, 116 responded that the simulator would effectively improve the safety training of tractor operators, and 110 deemed it necessary for training in institutions. They, however, recommended improvements such as cost reduction, realistic visualization, and improved compactness.

The developed simulator can therefore be used for the safety training of agricultural tractor operators, although further study toward its improvement is required.

Conclusions

This study was aimed at developing a simulator for the safety training of agricultural tractor operators. The simulator consisted of five principal components: the operator control devices, a data acquisition and processing device, a motion platform, a visual system that displays the computer model of the tractor, and a virtual environment. To achieve good accuracy while maintaining low cost of the simulator, a developed inverse kinematics model was used for the 2-DOF control of the motion platform of the simulator. A total of 128 instructors of agricultural machinery operation participated in a performance test survey of the simulator, and the survey results demonstrated that the developed simulator was effective for the safety training of agricultural tractor operators. Further study is, however, required for improvement of the simulator in some aspects.

Conflict of Interest

The authors have no conflicting financial or other interests.

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