Original Article Journal of Biosystems Engineering

J. of Biosystems Eng. 41(2):67-74. (2016. 6)
http://dx.doi.org/10.5307/JBE.2016.41.2.067

eISSN : 2234-1862
pISSN : 1738-1266

Performance Improvement of the Horizontal Control System for a Tractor Implement Using Sensor Signal from the Front Axle

Young-Min Ro[1], Jun-Hee Moon[2], Kyeong Uk Kim[3]*

[1]Department of Electrical and Computer Engineering, Seoul National University, Seoul, 00826, Korea
[2]Department of Mechatronics, Yuhan University, Bucheon-si, Gyeonggi-do, 14780, Korea
[3]Department of Biosystems & Biomaterials Science and Engineering, Seoul National University, Seoul, 00826, Korea

Received: March 16th, 2016; Revised: May 2nd, 2016; Accepted: May 16th, 2016

Abstract

Purpose: Many tractors have adopted the horizontal control system designed to maintain the three-point mounted implements in horizontal position when they are tilted sideways. The control system rotates the implement in the opposite direction to the inclination of rear axle of the tractor. However, the current control system was found to have poor performance in accuracy and response. A new control system was therefore developed to improve the performance. **Methods:** The new control system was designed to get the response of the implement to be started earlier by using the tilt information from the front axle of the tractor. By this approach, the rotation of the implement can be adjusted as required to make it horizontal at the expected time, even though the response is slow. The optimal values of the control parameters for the new system were determined by computer simulation and validated by a performance test conducted with an obstacle of 120 mm height on a flat concrete surface. The performance of the control system was evaluated by the root mean square error (RMSE) of the rotation angle of the implement with respect to the actual inclination of the rear axle. **Results:** The new control system reduced the RMSE of the current control system by 44.6% indicating a high performance improvement. The inclination of the front axle was easily obtained from a sensor mounted on the front axle of the tractor and used as input to the new control system. **Conclusions:** The method of getting the response of the implement to be started earlier by utilizing the inclination information of the front axle can be applied to improve the performance of the current control system at least cost.

Keywords: Horizontal control system, Implement, RMSE, Tractor

Introduction

Paddy fields pulverized with water before rice transplanting often consist of irregular soil surface that causes missing or floating hills when transplanting is conducted. To reduce this irregularity, leveling is usually performed before transplanting using a tractor equipped with a horizontal control system for the rotovator mounted on a three-point hitch. A control system is required to maintain the implement in level position regardless of the inclination of tractor. However, there have been many complaints regarding the domestic control system due to its poor performance. Results of a field survey conducted on the domestic control system and feedbacks from tractor operators and repair technicians indicated that the implement control responds too slowly and fails to make the implement horizontal at the expected time. In contrast, the control system of a foreign leading company is shown to work well by using an angular speed sensor to assess the precision of control (Kubota Corporation, 2004).

The purpose of this study was to investigate the causes of the slow response of the implement and to find a possible solution with least cost and without structural changes in the current control system. In other words, this study intended to develop a cost-effective control

---

***Corresponding author:** Kyeong Uk Kim
Tel: +82-2-880-4602; **Fax:** +82-2-873-2049
E-mail: kukim@snu.ac.kr

system to solve the problem of slow response of the implement without upgrading the capacities of the components of the current control system. In order to develop such control system, simulation and parameter optimization are important. There were previous studies such as simulation and verification with computer programing to estimate the control system (Kim et al., 1990), and a study in which the control algorithm was developed to utilize hydraulic valves at reasonable prices (Cha et al., 1997). In this study, the simulation model was designed by MATLAB/ Simulink and verification was implemented through a real-time running test.

Materials and Methods

Current horizontal control system

The current horizontal control system is a simple on-off type hydraulic control system comprising of a tilt sensor, hydraulic cylinder, on-off type hydraulic valve, and controller. The sensor is mounted on the rear axle of the tractor to detect its inclination. The hydraulic cylinder works as an actuator to control the rotation of the implement. The controller receives the input signal from the sensor and sends out a command signal to the hydraulic cylinder to rotate the implement in the direction opposite to the tilt angle of the rear axle. Figure 1 shows a tractor equipped with the current horizontal control system used in this study.

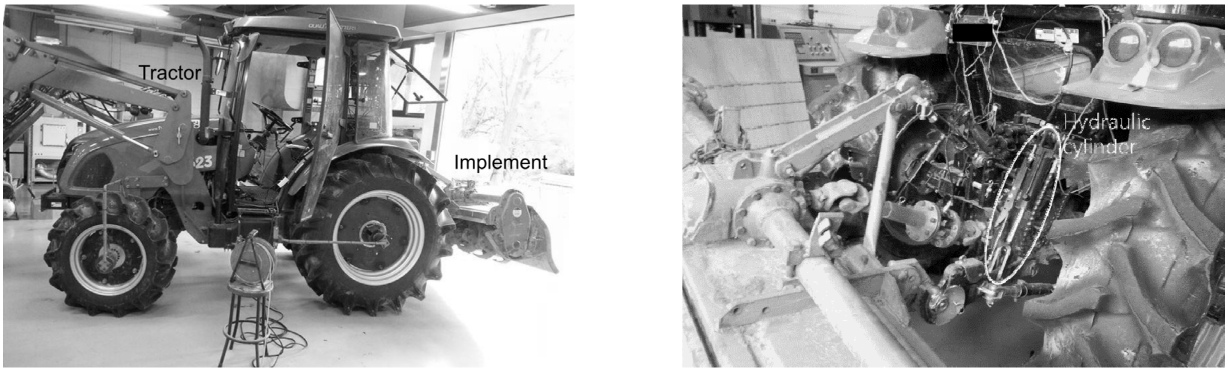
The performance of the current horizontal control system has been evaluated as poor in accuracy and response. The slow response causes the failure of the implement to make its position horizontal at the desired time so that the tractor bypasses the location where the leveling is required. The slow response appears to be caused by the low delivery rate of the hydraulic pump, whic h can be solved by upgrading the capacities of the hydraulic components of the control system. Such components include a high flow rate hydraulic pump and a high-speed proportional valve (Yoo et al., 1993; Lee et al., 2011). This approach is simple but may not be acceptable to tractor manufacturers because of high costs. In addition, since the other systems of the tractor such as wheel steering and three-point hitch need to share the same hydraulic pump, it may be impractical to customize the pump for the horizontal control system only.

Design of new control system

The idea of the new control system is to start the rotation of the implement as early as possible so that the implement reaches to horizontal position when the tractor passes over the area where leveling is required. This can be accomplished by detecting the irregularity of soil surface in advance before it is detected by the tilt sensor on the rear axle and providing this information to the controller to initiate a command signal to the hydraulic cylinder.

Since the front and rear tires of the tractor traverse over the same soil surface, it can be assumed that the inclination of the front axle occurs before the rear axle is inclined. This means that if the tilt angle of the front axle can be detected in advance, it can be used as additional information for the controller to generate the command signal earlier.

To validate this proposal, the response of the implement to an idealized square input was evaluated in terms of root mean square error (RMSE). RMSE is determined to be most suitable in evaluating the errors with respect to the horizontal position in real-time. In many studies,



(a) A rotovator (implement) attached to tractor (b) Hydraulic cylinder as an actuator of horizontal control system

Figure 1. A tractor equipped with the horizontal control system.

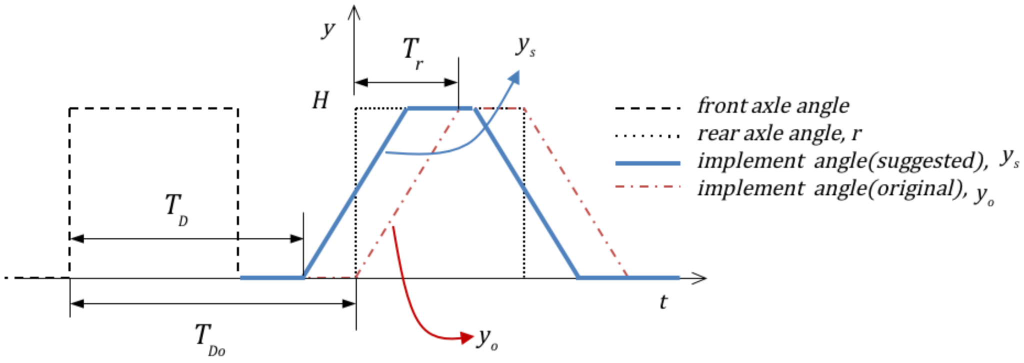


Figure 2. Responses of the implement to the idealized square inputs.

RMSE is solely used as the performance index (Karkee et al., 2011; Ishak et al., 2012; Ling et al., 2015). Figure 2 shows the responses of the implement to the square inputs representing the inclination of the front and rear axles. The best time to start the rotation of the implement in response to the inclination of the front axle can be found by adjusting the time delay T_D, while there should be no time delay in the response to the inclination of the rear axle to control the implement on time. In this study, RMSE represent the errors between tilt angles of rear axle and implement since the reference value is the angle of rear axle.

The implement rotation angle in response to the rear axle inclination as an input in the original system and the response to the front axle of the suggested strategy can be defined by Eq. (1) and (2) respectively.

$$y_o = \frac{H}{T_r} t \tag{1}$$

$$y_s = \frac{H}{T_r} t + \frac{H}{2} \tag{2}$$

where y_s = implement angle (suggested) [°]
y_o = implement angle (original) [°]
H = high value of angle [°]
T_r = rising time of implement response [s]
t = time [s]

The RMSE value between the tilt angles of the rear axle and implement of original system can be defined as

$$RMSE_o = \sqrt{\frac{\sum_i^N (r_i - y_i)^2}{N}} = \sqrt{\sum_i^N (r_i - y_i)^2 \frac{T_r}{N} \frac{1}{T_r}} \tag{3}$$

where r = the tilt angle of the rear axle [°]
y = the tilt angle of implement [°]
N = number of samples
H = high value of angle [°]
T_r = rising time of implement response [s]
t = time [s]

In continuous form, Eq. (3) can be written as

$$RMSE_o = \sqrt{\frac{1}{T_r} \int_0^{T_r} (H - \frac{H}{T_r} t)^2 dt} = \frac{H}{\sqrt{3}} \tag{4}$$

In a similar way, the RMSE of the implement rotation in response to the inclination of the front axle with a time delay T_D, i.e., RMSE of suggested strategy is defined as

$$RMSE_s = \sqrt{\frac{2}{T_r} \int_0^{\frac{T_r}{2}} (H - \frac{H}{T_r} t - \frac{H}{2})^2 dt} = \frac{H}{2\sqrt{3}} \tag{5}$$

which is 50% smaller than that generated by using the inclination of the rear axle. The time delay $T_D(t)$ can be defined as (Zhang et al., 2012)

$$T_D(t) = \frac{L}{v_m(t)} \tag{6}$$

where $v_m(t)$ = speed of tractor [m/s]
L = wheelbase [m]

As mentioned previously, the time delay should be adjusted to make the rotation of the implement on time. However, it was found that Eq. (6) did not yield the best time delay; it was smaller compared to the value determined by Eq. (6). This may be attributable to the errors in the measurement of wheelbase and tractor speed.

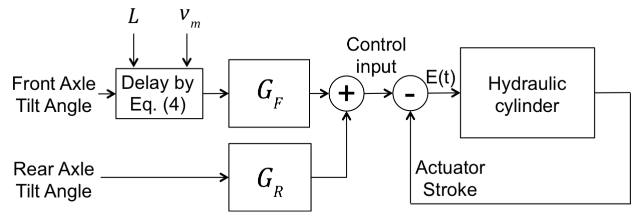


Figure 3. Input parameters for the new control system.

The new control system was developed on the basis of this idea of getting the response of the implement to be started earlier than in the current control system by using the inclination of the front axle as an input. Although the inclination information comes in advance from the front axle, the rear axle still has more accurate information about it. Thus, the new control system was designed to use the information from both the front and rear axles as shown in Figure 3. By doing this, the new control system is expected to perform better and more accurately than the current control system that uses information from the front axle only. The weightings for each information were then determined to minimize the RMSE.

Modeling of new control system

Hydraulic system

The main components of the hydraulic system for the new control system included a fixed-displacement pump, a three-way on-off spool valve, and a double acting cylinder. A simulation model of the system was developed using the commercially available software SimulationX (ITI, 2012) as shown in Figure 4. Specifications of each component were obtained from their manufacturers and are given in Table 1.

Tuning of Hydraulic System Parameters

Experiments were conducted to determine the parameter values of the simulation model, particularly the input flow of the pump and diameter of the throttle valve to make the simulated responses of the implement close enough to those obtained from the experiments. In the experiments, the sensor signal s_v was varied from 1 to 4 V corresponding to a tilt angle θ_v of-15 to 15°, which can be expressed as follows:

$$\theta_v = 10(s_v - 2.5) \qquad (7)$$

where θ_v = the tilt angle [°]
s_v= sensor signal [V]

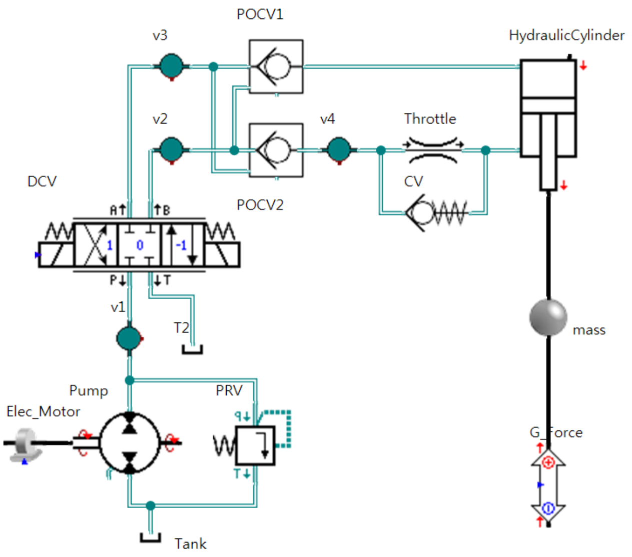


Figure 4. Simulation model of hydraulic system.

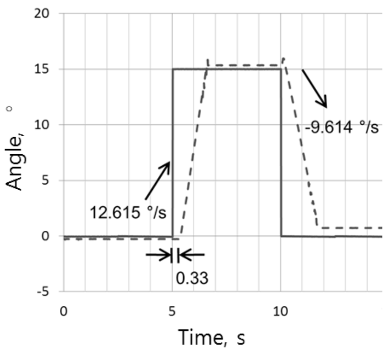
Table 1. Specifications of the hydraulic components

Directional control valve	Lap condition	-1.4 mm (underlap)
	Shape of edge	Sharp edge
	Spool diameter	10 mm
	Rod diameter	7 mm
	Solenoid ON	110 ms (delay:16)
	Solenoid OFF	65 ms (delay:12)
Double-acting cylinder	Maximum stroke	130 mm
	Piston diameter	50 mm
	Rod diameter	25 mm
Throttle valve	Cross section	Circular
	Bore diameter	0.9 mm
Pump	Flow rate	5 L/min

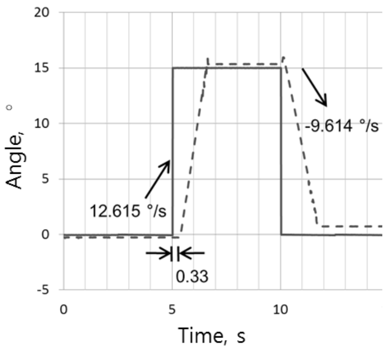
Figure 5(a) shows the experimental response of the implement to the square input signal in terms of its angular velocity. The rotating and reversing velocities were estimated to be 12.615 and 9.614 °/s respectively, and the response started 0.33 s after the input signal. On the other hand, the simulated response to the same input were 12.701 and 9.507 °/s respectively, and 0.29 s as shown in Figure 5(b) when the flow rate and the diameter of the throttle valve were set to 5.25 L/min and 1.3 mm, respectively which were considered as the optimum. The percentage errors of the simulated velocities were estimated to be 0.8% for the rotating and 1.0% for the reversing, which were considered as acceptable for simulation purpose.

Control System

Since the hydraulic system was based on the on-off



(a) Experimental response



(b) Simulated response

Figure 5. Response of the implement to an idealized square input.

type directional control valve, the type of the control system was chosen as the bang-bang type. A dead band was also introduced in the control system to avoid unstable oscillations. The range of the dead band was set from -0.05 to +0.05 V which is 0.5% of the input signals from -1 to 1 V. A functional block "variable transport delay" is used to calculate the time delay for appropriate response of the implement. The time delay needs to be considered because it changes depending on the speed of the tractor in real time. In other words, using this functional block, the situation in which the traveling speed when the front axle inclines differs from the traveling speed when the rear axle angle inclines can be considered. To attenuate its noise, the input signals were low-pass filtered with a cut-off frequency of 0.8 Hz. Figure 6 shows the simulation model of the control system developed using MATLAB/Simulink.

Optimization of Control Parameter by Simulation

To minimize the RMSE of the implement response to the inclinations of the front and rear axles, an optimization was performed by computer simulation on the three control parameters: weighting G_F for the input signal from the front axle, weighting G_R for the input signal from the rear axle, and the wheelbase of the tractor L. The optimization can be expressed in an equation form as follows:

$$\min_{G_F,\, G_R,\, L} RMSE, \text{ subject to } G_F,\ G_R,\ L \quad 0 \tag{8}$$

The input data for the simulation were taken from the field experiments and stored after being digitized with a

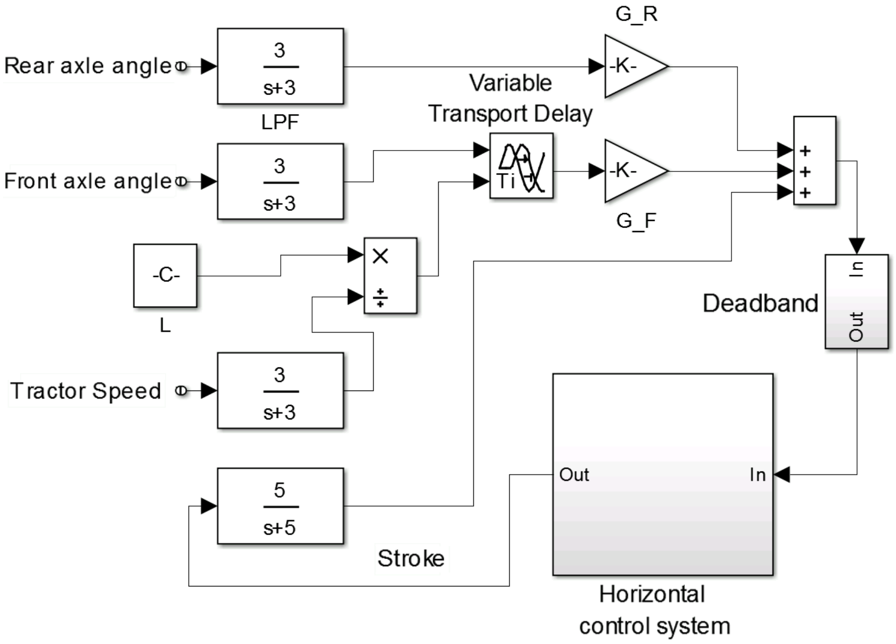
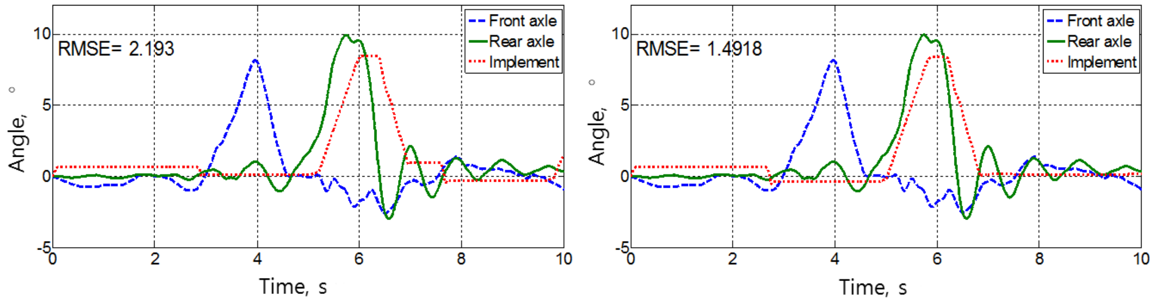
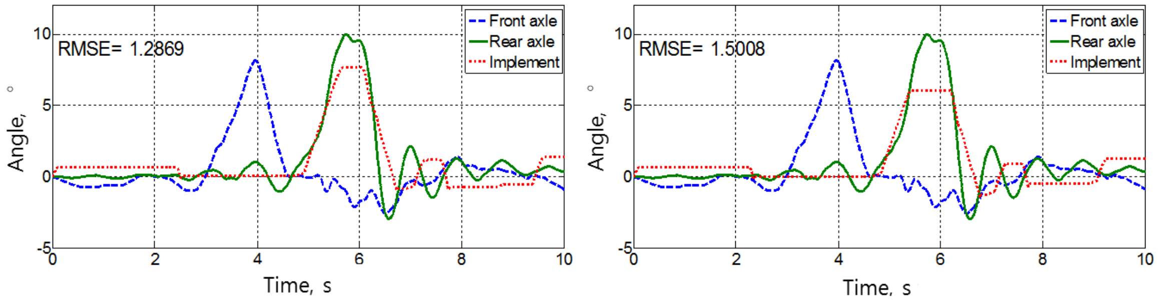


Figure 6. Block diagram of the new control system model.



(a) L = 2.0 (a) L = 1.8



(a) L = 1.6 (a) L = 1.4

Figure 7. Optimization of virtual wheelbase L at fixed axle signal weightings of 0.5.

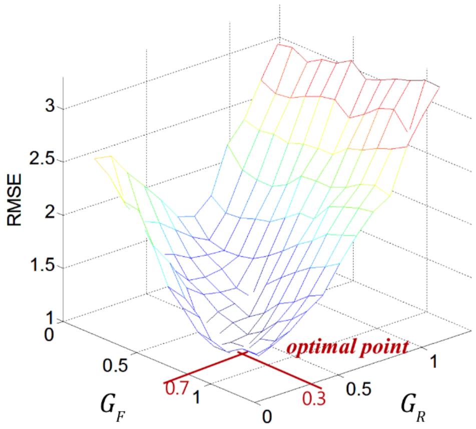


Figure 8. Optimization of signal weightings and with fixed to the optimized value of 1.6 m.

sampling time of 0.01 s. The data acquisition system "myDAQ" (National Instrument, 2010) was used in these experiments. This system can collect the data signal from the tilt sensors at the front and rear axle and the GPS sensor. The calculation solver simulation selected was ode23t (Mod. stiff/Trapezoidal), which is generally recommended in solving stiff systems such as hydraulic systems (Shampine et al., 1997; Shampine et al., 1999).

To begin with, the wheelbase was varied from 1.4 to 2.0 m with both weightings for the sensor signals fixed to 0.5. The simulation results are shown in Figure 7, where the response of the implement was plotted in the positive side to make a better comparison with the inclinations of the front and rear axles. It was noticed that the shorter the L, the earlier the start of the implement response. The value of L was optimized at 1.6 m by making the RMSE minimum.

With L fixed to an optimized value of 1.6 m, a total of 144 simulations were performed to determine the optimal weighting values. Figure 8 shows the results of the simulations in terms of RMSE plotted as a function of the weightings. The RMSE was minimized when G_F and G_R were 0.7 and 0.3, respectively. It was also noted that if the weighting for the inclination signal from the front axle is greater than that from the rear axle, the RMSE tends to decrease. This indicates that a more effective control of the implement can be achieved by using the inclination information from both the front and rear axles.

Hardware implementation for verification

Arduino MEGA2560 (Arduino) board was selected as a controller for the control system. The program for the control system was coded by using the automatic code generation in MATLAB/Simulink and uploaded to the controller. The Arduino board was connected directly to a laptop computer by the external mode of MATLAB/Simulink in which the target hardware can also be operated, and the real-time monitoring and collecting of data can be done simultaneously. The controller receives data from the sensor at a sampling time of 0.05 s and sends out the command signal to the directional control valve. The traveling speed data of the tractor was collected by GPS speed sensor (Racelogic, UK). The calculations to generate the command signal were performed using the ode3 (fixed-step and continuous solver).

Results and Discussion

Verification of performance improvement

The performance of the new control system was evaluated experimentally using a tractor with the new control system installed. The tractor was run over an obstacle of 120 mm height placed along its right side wheels on the flat concrete ground as shown in Figure 9. To recognize whether or not the optimized values determined by the simulation will properly work in the experiment, the neighborhood search (Arora, 2004) known as a non-gradient based optimization method was conducted as shown in Figure 10. Table 2 shows the RMSE determined from the experimental results. The minimum RMSE was obtained when the wheelbase was adjusted from 1.6 to 1.5 m, while the weightings for the front and rear sensor signals were maintained as determined by the simulation. It was noticed that the weightings and the value of wheelbase should be adjusted depending on the tractor to maximize the performance of the new control system.

Figure 9. A view of performance test for new control system.

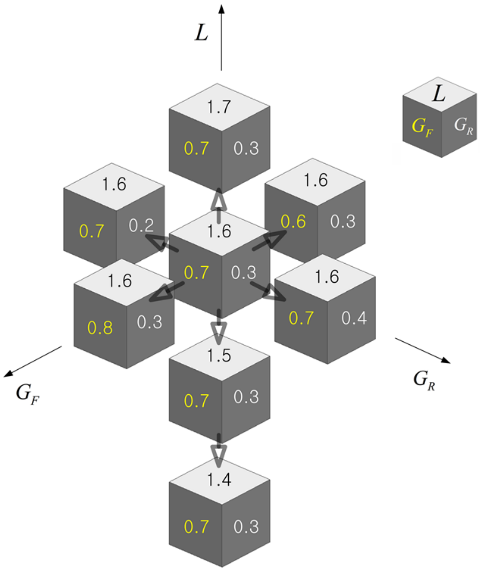


Figure 10. Optimization of control parameters by the neighborhood search.

Table 2. Experimental RMSE by different values of the control parameters

#	Rear	Front	Length, m	RMSE
1		Current system		2.8205
2	0.3	0.7	1.6	1.8853
3	**0.2**	0.7	1.6	1.9887
4	**0.4**	0.7	1.6	2.1960
5	0.3	**0.6**	1.6	2.1544
6	0.3	**0.8**	1.6	1.9616
7	0.3	0.7	**1.5**	1.5613
8	0.3	0.7	**1.7**	2.0489
9	0.3	0.7	**1.4**	1.6631

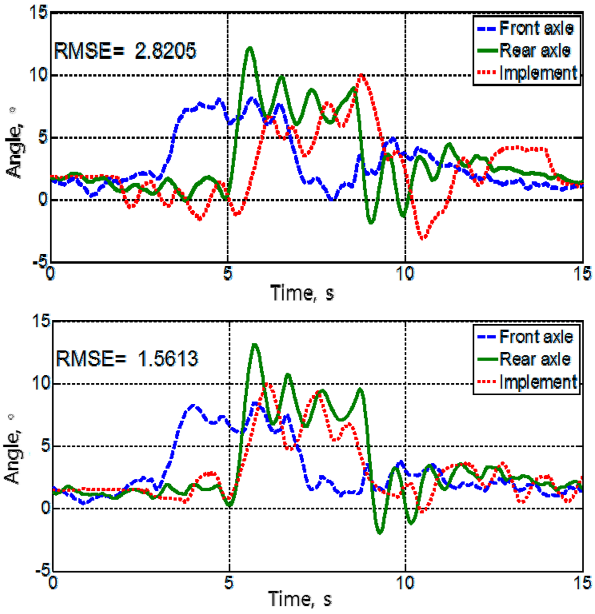


Figure 11. RMSE taken from the experiment with optimized values G_F= 0.7, G_R= 0.3, and L= 1.5 m of the control parameters.

Figure 11 shows the inclinations of the front and rear axles and the response of the implement when controlled by the current and new control systems with weightings for the sensor signals from the front and rear axles; the wheelbase set to 0.7, 0.3, and 1.5 m, respectively. The new control system reduced the RMSE of the current control system by 44.6%. In other words, the new control system showed much better performance than the current control system.

Conclusions

The horizontal control system for tractor implements mounted on the three-point hitch has been found to have poor performance in accuracy and response. To improve its performance, a new control system was developed at least cost and with no structural changes in the current control system. The purpose of the new control system was to make the response of the implement to be started earlier because the current control system fails to adjust the rotation of the implement at the required time to make it horizontal. The following summarizes the study.

1) A new control system was developed by installing an additional sensor to detect the inclination of the front axle and using it as an input to the current control system so that the response of the implement can be started earlier than expected.
2) The weightings for input signals from the front and rear axles were determined to be 0.7 and 0.3 respectively, and the value of the wheelbase was 1.5 m to make the performance of the control system optimal.
3) The new control system reduced the RMSE of the current control system by 44.6%, resulting to a 44.6% performance improvement.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

We wish to express our gratitude for the support from Tong Yang Moolsan Company, Ltd., Seoul, Korea. We are especially grateful to Dr. Jung Hoon Kim of Tong Yang Moolsan for his comments and suggestions provided during this study.

References

Arora, J. S. 2004. Introduction to Optimum Design, 2nd Ed., USA., Elsevier Academic Press.

Cha, J. P., W. P. Park, S. C. Kim, I. K. Jung and S. O. Chung, 1997. Development of Control Algorithm of Balancing Tractor Implement. In: *Proceedings of The KSAM 1997 Summer Conference*, 2(2):32-40 (In Korean).

Ishak, N., M. Tajjudin, H. Ismail, M. H. F. Rahiman, Y. M., Sam, and R. Adnan. 2012. PID studies on position tracking control of an electro-hydraulic actuator. International Journal of Control Science and Engineering 2(5):120-126.

Karkee, M. and B. L. Steward. 2011. Parameter estimation and validation of a tractor and single axle towed implement dynamic system model. Computers and electronics in agriculture 77(2):135-146.

Kim, K. Y., K. H. Ryu and S. N. Yoo. 1990. Electronic-Hydraulic Hitch Control System for Agricultural Tractors (III) -Computer Simulation- Journal of the Korean Society for Agricultural Machinery 15(4):290-297 (In Korean, with English abstract).

Kubota corporation. 2004. Rolling controller of working vehicle. Republic of Korea patent No. 1004366410000

Lee, S. S., W. Y. Park. 2011. Development of Tractor Three-point Hitch Control System using Proportional Valve. Journal of Biosystems Engineering 36(2):89-95 (In Korean, with English abstract).

Ling, T. G., M. F. Rahmat and A. R. Husain. 2015. A Comparative Study of Linear ARX and Nonlinear ANFIS Modeling of an Electro-Hydraulic Actuator System. Jurnal Teknologi 67(5):1-8.

Shampine, L. F. and M. W. Reichelt. 1997. The matlab ode suite. SIAM Journal on Scientific Computing 18(1):1-22.

Shampine, L. F., M. W. Reichelt and J. A. Kierzenka. 1999. Solving index-1 DAEs in MATLAB and Simulink. SIAM review 41(3):538-552.

Yoo, S. N., S. R. Suh and D. J. Kim. 1993. Tractor Implement Attitude Control System Using Microcomputer. Journal of the Korean Society for Agricultural Machinery 18(3):199-208 (In Korean, with English abstract).

Zhang, F., M. Yeddanapudi. 2012. Modeling and simulation of time-varying delays, In: *Proc. of the Symposium on Theory of Modeling and Simulation - DEVS Integrative M&S Symposium*. Society for Computer Simulation International, 34.