Development of a Blade Lifting Control Assist System for a Motor Grader

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Abstract –

Precise blade control is a central task when automating the operation of motor graders. This paper focuses on the parallel lifting movement using a combination of feedforward and feedback control for controlling the respective lifting cylinders. To this end, the paper first examines the blade mechanism of a motor grader and defines its blade movements. Specifically, the mathematical relationship between the edge points of the blade and the lifting cylinders were obtained using 3D CAD data. Then, the hydraulic behavior of the system was analysed in a test environment with wire encoders that are embedded in the lifting cylinders of the real mechanism. Using the input/output relationship between the 'Desired Stroke' and the 'Actual Stroke' values in different experiments, system identification was applied and the system transfer functions were obtained. Then, a combination of feedforward and feedback control enables moving to desired positions fast while applying precise blade control.

Keywords – motor grader; automatic blade function control; system control algorithm

1 Introduction

Motor graders are construction machines used in specific works such as road construction and leveling/grading. Motor graders can reach high driving speeds. Since they perform machine functions while traveling, their operation can be challenging. Issues such as accidents that may occur at work sites, the accuracy of the levelling, fuel consumption and time have paved the way for studies on assistive systems to help operators [1-4].

Automatic function control from these systems is not only in demand in motor graders but also in other construction machines such as excavators and wheel loaders. GPS, laser, ultrasonic, and distance sensors are used in such assist systems. The aforementioned system items can be mounted outside of the vehicles. In this study, a control system was developed to assist the parallel lifting movement of the blade during fine grading by using the data obtain from the sensors mounted in the lifting cylinders.

2 Background

Hashimoto and Fujino [5], pointed out that the number of experienced operators will decrease in the near future and the results of this will negatively affect the construction industry. They compared experienced and inexperienced motor grader operators with reference to working time, working efficiency and work quality. Then, both operators tested the automatic control system for the blade control. The study showed that inexperienced operators had better results in terms of work when they have used machine control systems. The shortage of experienced operators foreseen in the near future can be substituted by using automatic control systems.

Sobczyk et al. [6] stated in their studies that the leveling errors created by the motor graders were also caused by the positioning of the front wheels. They aimed to prevent the errors with the stabilization system presented in their study. The model they created serves to determine the position of the blade during movement of the front frame. The position of the blade is constantly compared with the selected reference point in the working area. Accordingly, the cylinder stroke values are recalculated and the blade is positioned correctly.

Felas et al. [7], developed a detailed nonlinear dynamic model using hydraulic system equations and the wheel loader mechanism analysis. The machine they have used in their study is equipped with a load-sensing hydraulic pump, various cylinders and electro-hydraulic valves. While obtaining the hydraulic equations in the study, it is necessary to know the parameters of the elements from which the system is formed.

Shevchenko and Beztsennaya [8] mentioned in their study that the loads on the motor grader lifting cylinders have a significant effect on the mechanism design. To express the changes in the loads on the axes occurring at the connection points of the lifting cylinders, the reference coordinate frame is positioned at the connection point of the blade with the front chassis. As a result of the movement of the cylinders, it has been observed that the loads vary according to the axes.

3 Methodology and Development

In this section, first, all mechanism movements are defined. Then, analysis was made within the necessary mechanism constraints for parallel lifting and the equations required for mechanism analysis are obtained using least squares regression using Matlab [11]. In the last chapter of Section 3, the obtained equations are verified on the real mechanism.

3.1 Blade Mechanism

The motor grader blade mechanism consists of six hydraulic cylinders and one hydraulic motor. Figure 1 and Figure 2 show the mechanism components. The Right and Left Lifting Cylinders move the blade upwards and downwards. The Right and Left Tilting Cylinders create a different soil cutting angle on the blade edge concerning the working terrain. The side shift cylinder moves the blade in sidewise right and left directions. Finally, the hydraulic motor mounted in the circle rotates the mechanism clockwise or counter-clockwise [10]. See Figure 1 and Figure 2.

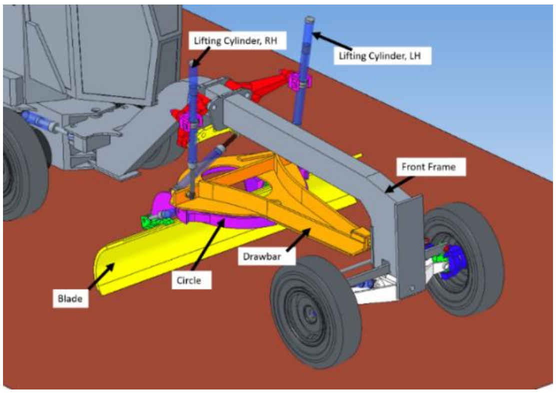

Figure 1. Blade Mechanism-Front View

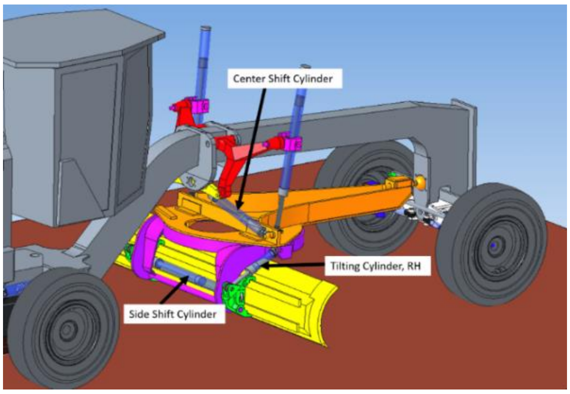

Figure 2. Blade Mechanism-Rear View

3.2 Mechanism Analysis

The motor grader blade mechanism analysis is very challenging since the mechanism has many different combinations of positions [9]. In this study, the main coordinate frame is placed on the grader's front frame and is taken as a reference while the blade edge position values are recorded. The points at the right and left sides of the blade edge are named B1 and B2, respectively.

3.2.1 Collecting Data Using CAD Model

The drawbar and front chassis connection is provided by a spherical joint as pointed out in Figure 1. The position of this connection point is not affected by blade mechanism movements. Only the tire size can change the ground clearance of this anchor point. This connection point on the vehicle is suitable for positioning the XYZ reference coordinate system. In the neutral position defined in Figure 3, XYZ coordinate systems are placed on the right and left edges of the blade. The X-axis represents the vehicle's driving direction, and the Z-axis represents the vertical axis of the machine itself as indicated in Figure 4.

The mechanism tool of PTC Creo 7.0.1.0 [12] was used to find the positions of the cutting edge of the blade in 3-axes concerning a fixed point on the machine at various stroke values of the lifting cylinders. Values were recorded at 1 mm intervals.

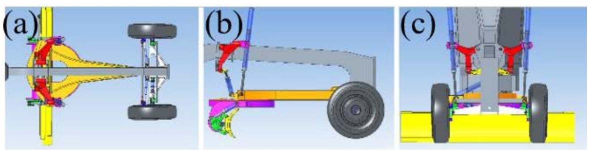

Figure 3. Restriction of Blade Mechanism:
(a) 0º Circle Rotation, (b) 0º Blade Cutting Edge Angle, (c) Side Shift Cylinder is Centered

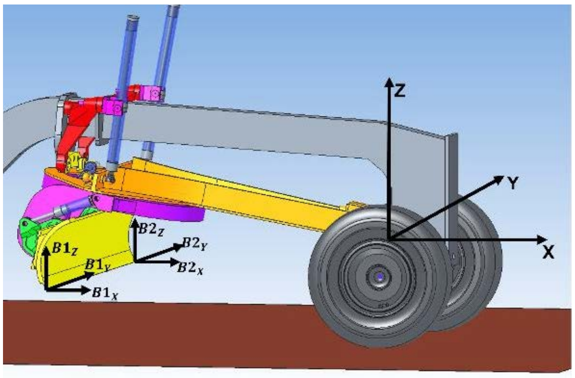

Figure 4. Edge Points B1 and B2 and Coordinate Frames XYZ

3.2.2 Mechanism Equations Using Basic Fitting Method

Considering the limitations in Figure 3, parallel lifting is used to determine the height of the blade from the ground. In other words, the z-axis values from the data collected for the cutting edges of the blade will be sufficient to describe the parallel lifting. The least squares regression method was used to express the relations between the stroke values of the lifting cylinders and the edge points of the blade. For parallel lifting, the right lifting cylinder affects the right edge, and the left lifting cylinder affects the left edge of the blade. Figure 5 and Figure 6 show the basic fitting results for both edges.

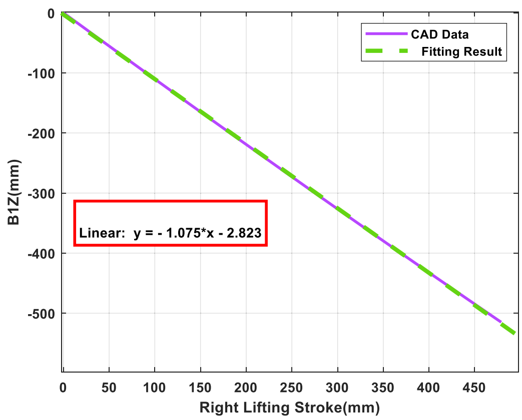

Figure 5. Right Lifting Stroke vs B1Z

The resulting equations (1) and (2) characterize the mathematical relation between the respective lifting stroke and z-coordinate of B1 and B2.

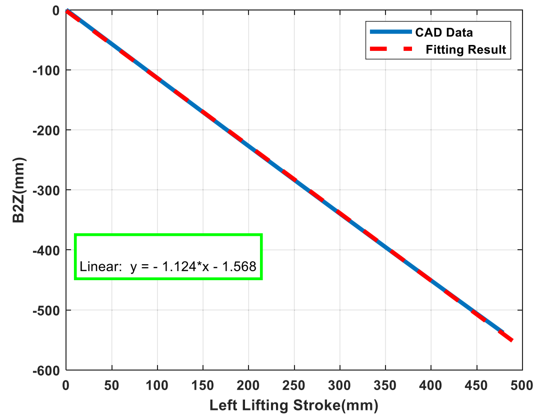

Figure 6. Left Lifting Stroke vs B2Z

$$B1_Z = -1.075(RightLiftingStroke) \tag{1}$$

$$B2_Z = -1.124(LeftLiftingStroke) \tag{2}$$

3.3 Implementation and Verification

A test environment was set up to test the accuracy of the equations obtained in Section 3.2.2 on the machine. Wire encoders are mounted inside the right and left cylinders to measure their stroke value (See Figure 7 and Figure 8). The wire is attached to the cylinder's rod, and it lengthens or shortens during the movement of the cylinder. The sensor calculates the length of the wire from each turn of its mechanism with the movement of the cylinder rod. Thus, the stroke values can be read.

During the test, the system is given a value for the movement of the blade on the z-axis. The system converts this height value to stroke value and the cylinders start to move. Wire encoders [13] measure stroke values. Then, the initial and final positions of the edge points of the blade are compared.

Figure 7. Draw-wire Encoder

Figure 8. Sensor-Cylinder Integration

The machine is positioned on a flat ground to examine the initial and final positions of the blade cutting edge. The mechanism is placed on the neutral position. The distance of the blade's cutting edge from the ground is measured. Then, the 'Desired Height' value is entered into the system and the lifting cylinders start to move. When the movement is complete, the distance from the ground for the new position of the blade is re-measured and the 'Desired Height' value is compared with the 'Actual Height'. As a result of the comparisons, it has been revealed that (1) and (2) are applicable equations for the real mechanism.

4 Controller Design

The flow generated by the hydraulic pump drives the cylinders through electro-hydraulic valves. The joystick movements provide the amount of flow that will pass through the valve. When the joystick moves forward or backward on the x and y axes, it generates a current for each movement on the axis (See Figure 9). These movements in the joystick axes are expressed as percentages. The rest position of the joystick is called the zero position, and it takes 0% of joystick value (JV). This generated joystick value is converted into a PWM signal with a PID controller, and the valve spool is energized by the generated PWM (See Figure 10). The higher the joystick value, the more flow passes through the electro-hydraulic valve.

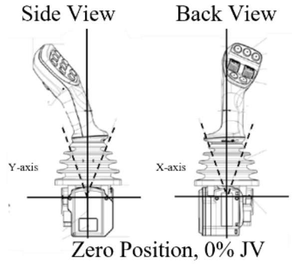

Figure 9. Joystick Representation

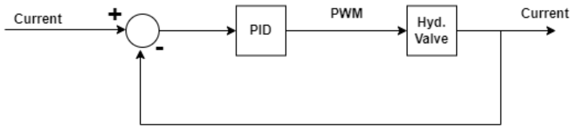

Figure 10. Electro-hydraulic Valve Working Principle

Draw-wire sensor data obtained from the machine can be used to describe the behavior of the hydraulic system. Using equations (1) and (2), the stroke values of the right and left cylinders are calculated from the 'Desired Height' value entered in the system. These values are hereafter referred to as 'Calculated Stroke'. By using the input/output relationship of the 'Actual Stroke' values coming from the sensor denoted as $y(t)$ in (4) and 'Calculated Stroke' values denoted as $u(t)$ in (5), the transfer function $G(s)$ can be calculated with reference to certain joystick values of the hydraulic system by system identification. Joystick values can range from 0% to 100%. To define the system behavior, three different joystick values have been selected for the first tests. These values represent slow, medium, and fast cylinder speeds. (See Figure 11). When tests were performed, the machine was in parking mode and had an engine speed of 800 RPM. Data were taken at 100 ms (10 Hz) intervals (see sampling time Ts in (5)).

$$u(t) = [u(Ts), u(2Ts), \dots, u(NTs)] \tag{3}$$

$$y(t) = [y(Ts), y(2Ts), \dots, y(NTs)] \tag{4}$$

$$Ts = 0.1\ sec \tag{5}$$

$$G(s) = \frac{y(s)}{u(s)} \tag{6}$$

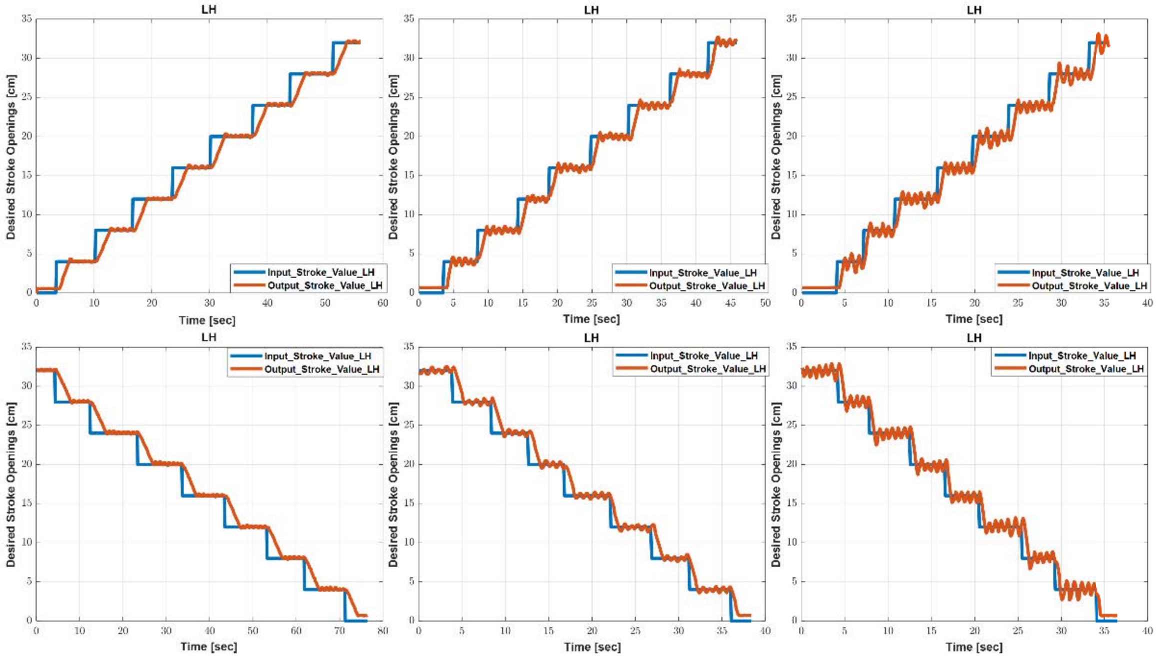

Figure 11. JV Effects with Desired and Actual Stroke Openings

The following relation is shown to exemplify the transfer functions obtained.

$$TFLH = e^{-0.214s}\frac{0.1453s + 1.5471}{s^2 + 1.7544s + 1.5467} \quad (7)$$

$$TFRH = e^{-0.428s}\frac{0.3036s + 1.2182}{s^2 + 1.6008s + 1.2182} \quad (8)$$

Here, TFLH, and TFRH define the transfer function of Left Side and Right Side, respectively.

Also, it has been observed that there is a delay between the input/output stroke values while obtaining transfer functions. These delays may occur for different reasons originating from hydraulics or electronics. To have a better understanding of this delay, Current/PWM graphs were plotted and the parameters were compared at different joystick values. When the graphs are examined, it can be seen that there is no any delay between PWM and Current. An example measurement is shown in Figure 12.

A certain amount of time is required when hydraulic oil fills or drains from the cylinders. The reason for the delay between input/output is that the response speed of the hydraulic system cannot reach the response speed of the electronics.

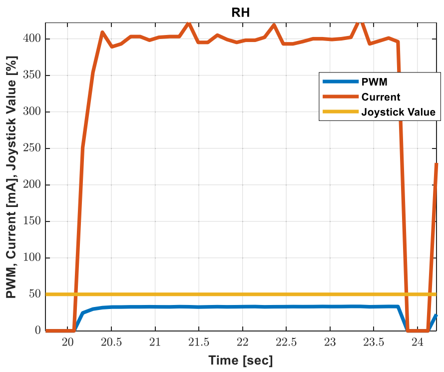

Figure 12. PWM/Current Graph for %50 JV

When the input/output relations in Figure 13 are examined, it is seen that the behavior of the hydraulic system is similar at different JVs. In response to the ‘Desired Stroke’ value given to the system as step input, the system always reacts as an integrator. Depending on the joystick values, the extraction and retraction speeds of the cylinders vary. The higher joystick values are given, the higher the hydraulic oil flowing through the valves, since the current equivalent of the joystick values is converted to PWM and activates the valves (See Figure 13).

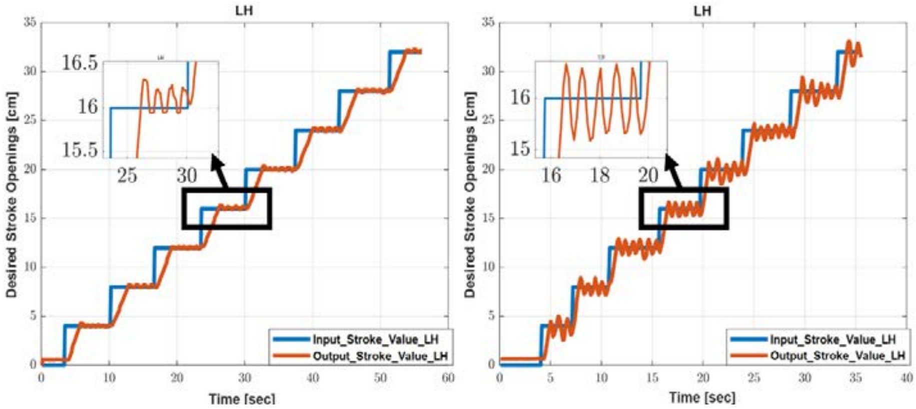

Figure 13. JV Effects with Desired and Actual Stroke Openings in 20% and 80% JVs

The slopes of the graphs give the cylinder velocities in cm/sec. Table 1 represents the cylinder velocities for the test results in Figure 13. The reason for obtaining the values in Table 1 was to see if there was a linear proportionality between the cylinder speeds and joystick values. However, such a relationship could not be seen for these three joystick values. For this reason, cylinder velocities from 10% to 80% of joystick values were calculated. As seen in Figure 14, cylinder speeds from 10% to 30% show linear behavior. This means that in the control algorithm to be created, the hydraulic cylinders can be activated up to a certain level with a constant joystick value of 30%.

Table 1. Calculated Cylinder Speeds

cm/sec	RH	LH
JV20_Down	1.07	1.07
JV20_Up	1.68	1.72
JV50_Down	2.90	3.50
JV50_Up	4.80	3.95
JV80_Down	6.48	6.98
JV80_Up	5.88	6.17

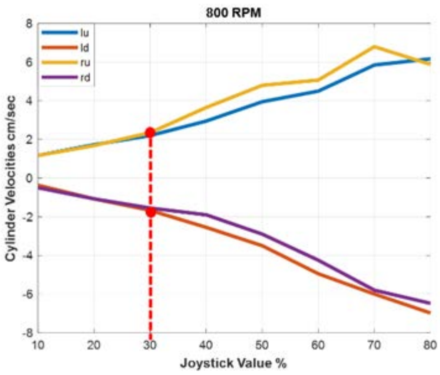

Figure 14. Cylinder Velocities Calculation

Equations (7), (8), (9) ve (10), indicate the relationship of cylinder velocities with joystick values x in % for upward and downward directions.

$$lu = 0.076 \cdot x \tag{7}$$

$$ld = -0.097 \cdot x \tag{8}$$

$$ru = 0.081 \cdot x \tag{9}$$

$$rd = -0.089 \cdot x \tag{10}$$

Here, lu, ld, rd and rd are cylinder velocities in upward and downward directions.

Figure 15 shows the control algorithm flow diagram. According to the figure, the value of 'Desired Height' is entered into the system. Then, the system calculates the 'Desired Stroke' value and compares it with the 'Actual Stroke' value read from the sensor. If the two values are very close to each other (a 5 mm difference was taken in this study), the PI controller is switched on to ensure precise control. Here, the system continuously calculates the joystick value according to the distance to provide precise position control, PWM is produced accordingly and the valves are activated. If the difference between the 'Desired Stroke' and 'Actual Stroke' values is large, a feedforward controller is used. The cylinders start to move with a 30% joystick value until the distance where the PI controller run is reached. The decision of which controller to operate is made in the switch block. The block called plant represents the characteristics of an electro-hydraulic valve (See Figure 16).

To determine the coefficients of the PI controller, the algorithm was first tested on the machine for different KP coefficients. Figure 17 and Figure 18 show the test results with a KP value of 2.5. In the tests taken for both the right and left cylinders, precise cylinder position control up to 3 mm was achieved.

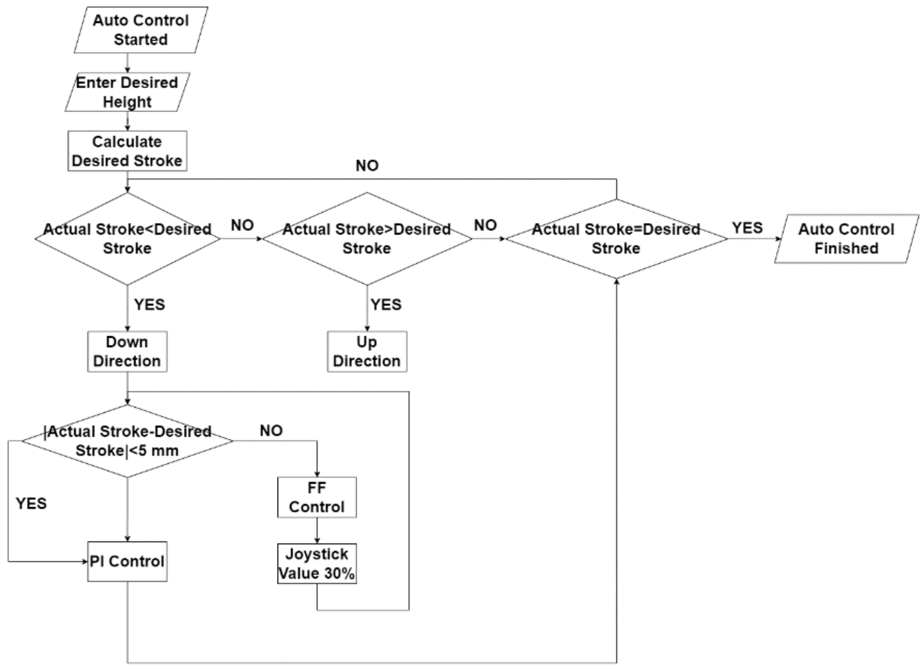

Figure 15. Control Algorithm

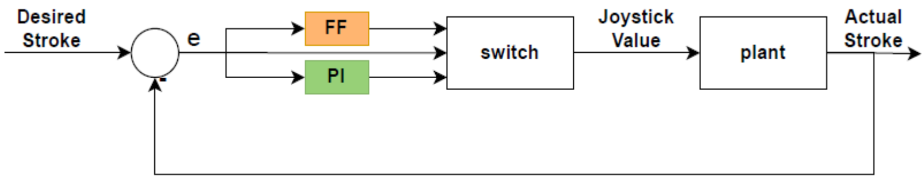

Figure 16. Overall Control Structure

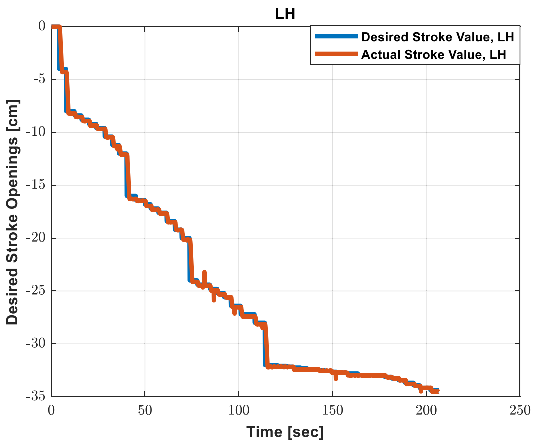

Figure 17. Left Lifting Cylinder, Down Direction, KP Value is 2.5

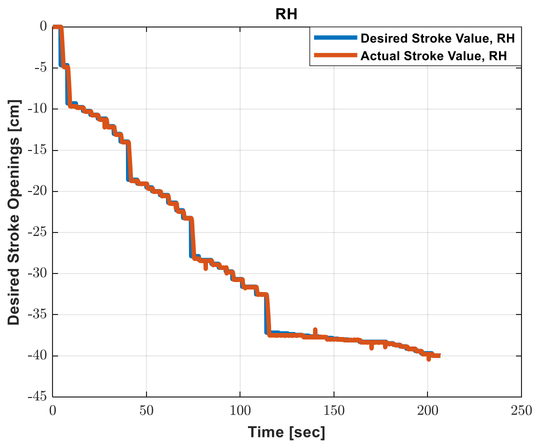

Figure 18. Right Lifting Cylinder, Down Direction, KP Value is 2.5

5 Conclusion and Future Work

This study provides parallel lifting control, which is the first stage of automatic function control for the motor grader blade mechanism. Since the expression of the motor grader blade mechanism using kinematic equations is challenging, the analysis technique used in this study can be applied for similar mechanisms which have 3D CAD data. However, the important point is that the obtained equations should be continuous, that is a single equation should be applicable for many models.

The created control algorithm provides precise stroke control, and the algorithm has been verified by various tests taken on the machine. The control algorithm parameters were obtained using data taken at 800 RPM engine speed but can be used at other RPM values, because the controller was created by considering the distance, not fluid displacement. The external loads on the blade will be a subject of further research.

Certain mechanism constraints were accepted for the analysis. Specifically, this study has aimed at developing an assist system where operators can easily adjust the height of the blade from the terrain. In future studies, improvements can be made by adding sensors to the system for circle rotation, blade tilt angle, and blade slope. In this way, automatic function control will be provided for different terrain conditions by considering both blade and machine positions. In this way, automatic function control will be provided for different terrain conditions by considering both blade and machine positions. Accordingly, the assist system will be extended by improved control algorithms based on the additional sensor measurements.

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