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PID control for sprayer sections under laboratory conditions

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Abstract. The objective of this study was to develop and test a PID controller to adjust the height of bum sections of sprayer booms. This study was conducted under laboratory conditions using an experimental frame representing the boom sections of the sprayer. The boom section was operated using an electro-hydraulic system driven by a hydraulic power pack. Ultrasonic distance sensors were used to adjust the height of the boom tips based on the set height values. During the on-off control, the sudden openings of the hydraulic valve conduits caused oscillations, resulting in unstable operation. In the PID control, increased gain up to 100% resulted in unstable operations and resembled the response of on-off control. With the use of low gain values, oil flow delivered to the hydraulic actuator was adjusted accurately using the proportional valves and smoother boom section motion was possible. The effects of different disturbances on the system dynamic responses were presented graphically using PID control.

Key words: field sprayer, active boom equalization, electro-hydraulic control, PID control.

INTRODUCTION

In modern field sprayers, boom sections are controlled for levelling using two different types of systems: passive and active balancing systems. In passive balancing system, the boom sections become parallel to the ground plane by themselves. For this purpose, passive balancing systems with different designs are used. In the active control system, the boom sections are forced to maintain their horizontal balance using sensors (Çilingir & Dursun, 2009).

Jamming in the cylinders which ensure the vertical parallelism of the boom sections causes increased vibrations in section tips. The most important factors related to jamming are the type of flow rate valves in use and the electronic system controlling the valves. For an electronic control system to perform successfully, the electro-hydraulic system needs to be compatible. It is more appropriate to use a hydraulic system designed for proportional valves or servo valves for precise speed and pressure control (Anthonis et al., 2000; Kartal, 2007).

If the valve controlling a cylinder is turned on and off abruptly while the cylinder operates, the cylinder and the load on it vibrate. This vibration often leads to high levels of noise and impact, resulting from hydro-mechanical resonance. These vibrations can be prevented using servo valves or proportional valves.

Today, there are spraying machines with an working width up to 50 meters and more in different countries. However, increasing working width created the problem of balancing the vibrations at operation. The spraying machines which operate at a high width are equipped with sensors and other relevant equipment to prevent the vibrations from adversely affecting the quality of pest control (Güler et al., 2010).

Deprez et al. (2003) developed a mathematical model which can follow the inclination of the field so that the field sprayers will not be adversely affected by effect of slopes on the ground. The structure of the model was examined in trials on four different suspension systems. Analytically developed models were verified by the same researchers. For a slow and active suspension, a control mechanism was developed to filter out the ground plane ripples. A good performance was achieved despite the use of a low-power accelerator.

O'Sullivan (1988) reported the results of experiments carried out to verify the accuracy of mathematical models used for active and passive versions of a pendulum boom sections and concluded that the mathematical models could be used to design pendulum suspensions.

Koç & Keskin (2011) developed a system for developing and modelling a mechanism to ensure parallelism to the ground plane in oscillating agricultural machines. For the trials of the system developed, a prototype machine equipped with a boom with 5 m sections were embedded in an articulated way.

Pontelli & Mucheroni (2012) equipped each boom section with three position sensors 4, 8 and 12 meters away from the centre of the boom to apply PID and fuzzy logic control. As a control strategy, coefficients associated with the distance from the centre of the boom to the sensors and the weighted average of the information obtained from the sensors was used. A control equation was developed to maintain the height of the boom 50 cm above the ground plane. Tahmesebi et al. (2012) used PID simulations to control spray booms using intelligent active force control. PID control is utilized not only for section control in spray booms but also in tank level and mixture control in agricultural sprayers (Kushwaha & Giri, 2013) since the output can be generated in a short time with minimal overshoot and small error (Bartelt, 2001).

The aim of this study was to use PID as a control method on a sprayer section to reduce the instabilities that were experienced in on-off control method in the laboratory setting.

MATERIALS AND METHODS

The control system used in this study consists of a controller, electro-hydraulic system, and distance sensors. Prototype boom sections were made in the laboratory with short (1.5 m long) boom sections attached to the both sides of the representative sprayer frame. Ultrasonic distance sensors were fixed at both ends of the section tips where each boom section is controlled using a hydraulic cylinder (Fig 1).

Closed-loop block diagram to control the hydraulic cylinder is given in Fig. 2. Depending on the distance information collected from the sensors, the amount of fluid passing through the proportional valve was controlled by the PID and the cylinder speed was adjusted by the proportional valve. The control system consisted of a technological

CPU, a proportional valve for each cylinder, an ultrasonic sensor for height/distance measurements, and the hydraulic power pack.

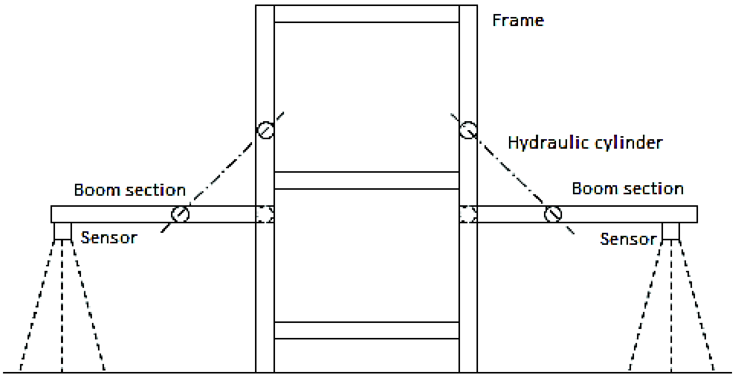

Figure 1. Schematic of the boom sections used in the study (Karadöl & Arslan, 2014).

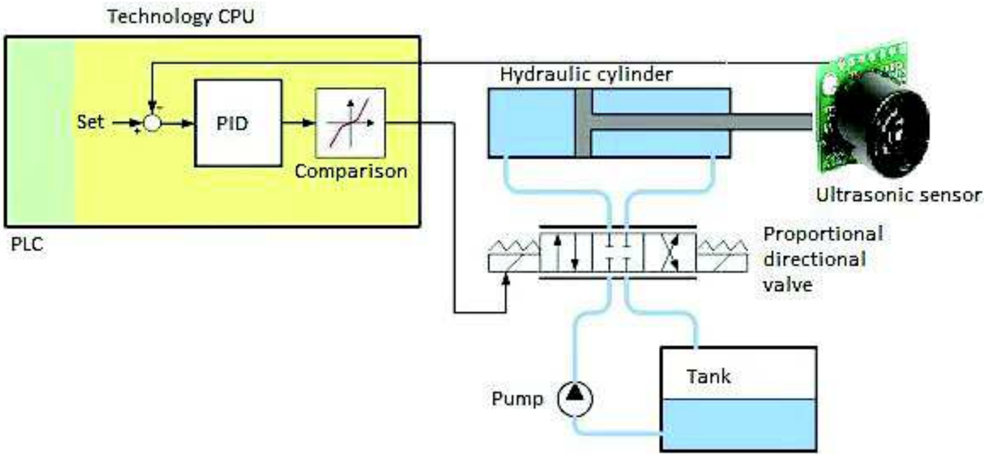

Figure 2. Cylinder control with a PID controller (Siemens, 2015).

The feedback signals that the sensors produced, depending on the distance to the ground plane, were applied to the PLC (Programmable Logic Controller) analogue input channels. Depending on the error signal, the analogue signal in the 0–10 V range produced from each PID analogue output was processed and the cylinders were controlled using the proportional direction control valve. PID controller generates an output based on the error signal and the error signal is sent the proportional valve card to control the hydraulic cylinder.

PID control was done using the signal output of the distance sensors for feedback, which was explained by Eq. 1.

$$c(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

where c (t) is control signal, e (t) is error signal, Kp is proportional gain, K_i is integral time constant, and T_d is derivative time constant. The block diagram of the commonly used closed-loop PID controller system is shown in Fig. 3 (Kaçar et al., 2013).

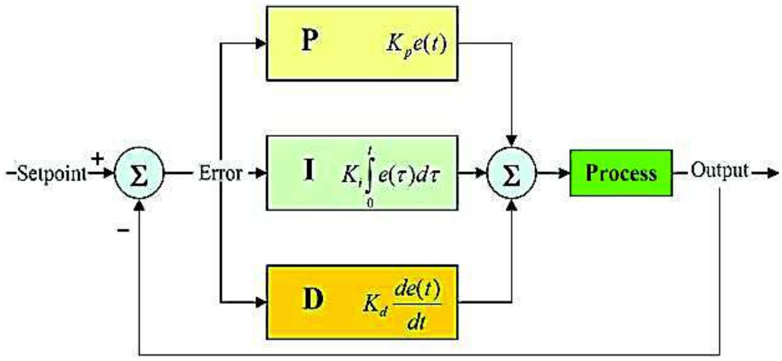

Figure 3. PID controlled closed-loop system.

Proportional valves were controlled by special electronic cards generating PWM (Pulse-Width Modulation) outputs with a variety of duty cycles. PWM pulse width was determined by applying an analogue input within the range of 0–10 V to the control card and the fluid path was opened proportionally to the analogue signal fed in the control card. Theoretically, 0 V input meant that the fluid path was completely sealed whereas 10 V input meant that the fluid path was completely open.

The distance sensor was able to determine the objects from 15 to 646 cm distance and could produce 9.766 mV output signal for each 2.54 cm difference in distance starting from 15 cm. In this study, ultrasonic distance sensors (LV Maxsonar EZ1) were used. The stable operating voltage and the frequency of the sensor were 5 V and 42 kHz, respectively.

Eq. 2 was used to measure the distance between the sensor and the ground.

$$V_i = (V_{cc}/512) \quad (2)$$

where V_{cc} is the supply voltage whereas V_i is the voltage value produced by the sensor.

For the supply voltage value of 5 V, the analogue voltage value produced by the sensor within 80 cm distance was calculated as follows.

For 2.5 cm; $V_i = 5.0$ V/512 = 9.766 mV

For 80 cm; $V_i = 9.766 \cdot 80/2.54 = 307.6$ mV

The distance from the sensor and the ground was varied by 10–20 cm with the introduction of disturbances and the system's response was observed under different operating conditions.

RESULTS AND DISCUSSION

The distance sensors were attached to the tips of boom sections and were able to produce outputs with 2.54 cm precision. It was estimated that it could operate with 3% error margin for a height setting of 80 cm in field conditions. The measured voltage values were correlated with boom height with $R^2 = 0.99$ and the sensor output signal could be measured up distances much greater than the boom heights in real applications.

When the analogue signal from a sensor was applied to the analogue input of PID controller (Input_PER), the controller generated a signal from the output channel (Output_PER) within the 0–10 V range in accordance with the error value (Fig. 4). The analogue signal produced by using the amount of error change in the output of the PID block is applied to the control card of the proportional valve. Based on the signal applied to the control card input, a PWM signal is produced in the card output. By adjusting the duty cycle of the PWM signal in response to the 0–10 V value, the oil flow rate passing through the proportional valve was adjusted precisely. The oil flow rate delivered to the cylinders increases as the system drifts away from the set value (as the error value increases) and decreases in the opposite scenario, thus enabling to reach the set value smoothly. The openness rate of the PID controller's output channel was tracked online and by switching this value to the manual mode the output rate was brought to the desired level (Fig. 5).

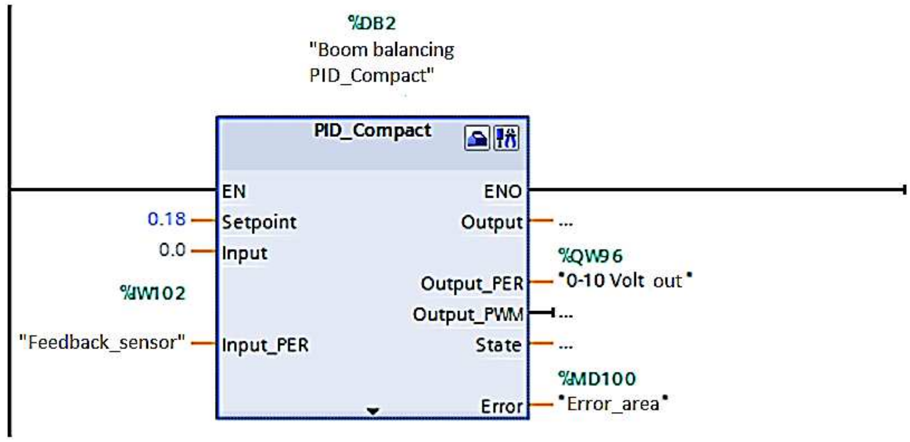

Figure 4. The structure of the PLC-PID block.

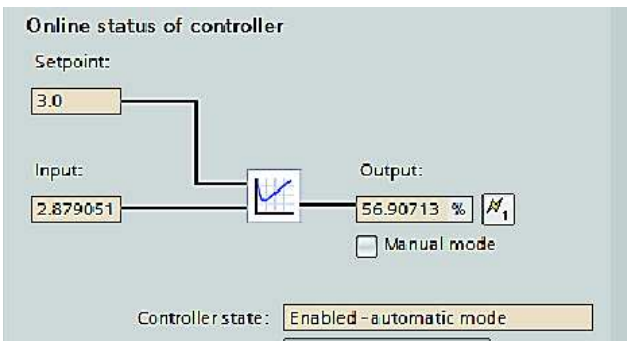

Figure 5. PLC-PID controller input and output statues – values on the chart were amplified using an op-amp in this trial.

During control operation, the input, output, and set values were tracked graphically online, shown by the red, green, and blue lines in Fig. 6, respectively. In this figure, the disturbance generated a voltage value greater than the set point because the distance between the boom section and the ground was increased.

Figure 6. Tracking the set point, input, and output signals in an ongoing process.

In an ongoing operation with no disturbances, all three lines were at the set value (0.180 V corresponding to about 47 cm) with zero feedback as seen in the leftmost part of Fig. 7. When a disturbance was introduced between the sensor and the ground, the magnitude of the measured signal voltage reduced proportionally to the distance between the sensor and the disturbance. Output voltage signal was increased based on the feedback signal, allowing the proportional valve to open to compensate for the input so that the boom section height could be maintained at the initial height setting (Figs 7–8). The system quickly responded to short (1 s) and long (10 s) disturbance signals and brought the boom section to balance. It was demonstrated that the control system was able to return to the set point as a response to continual disturbances by generating an immediate output signal based on a disturbance signal (Fig. 8). However, the response should be improved when the disturbance is introduced successively between the ground and the sensor (Fig. 7). Although the output signal could be generated in response to disturbance signal, the set point could be reached with an error from 2.5 to 5 cm until the next disturbance was introduced. However, the system behaviour was better when mixed disturbances were used at lower and higher locations from the set point (Fig. 8). Successive disturbances were off set successfully by the control system both at a constant height and varying heights, corresponding to varying levels of disturbance signals. The system optimizes its dynamic response to the disturbances through the automatic tuning function that is used for obtaining the best gain value during operation. More tests under laboratory and field conditions can help improving the system response.

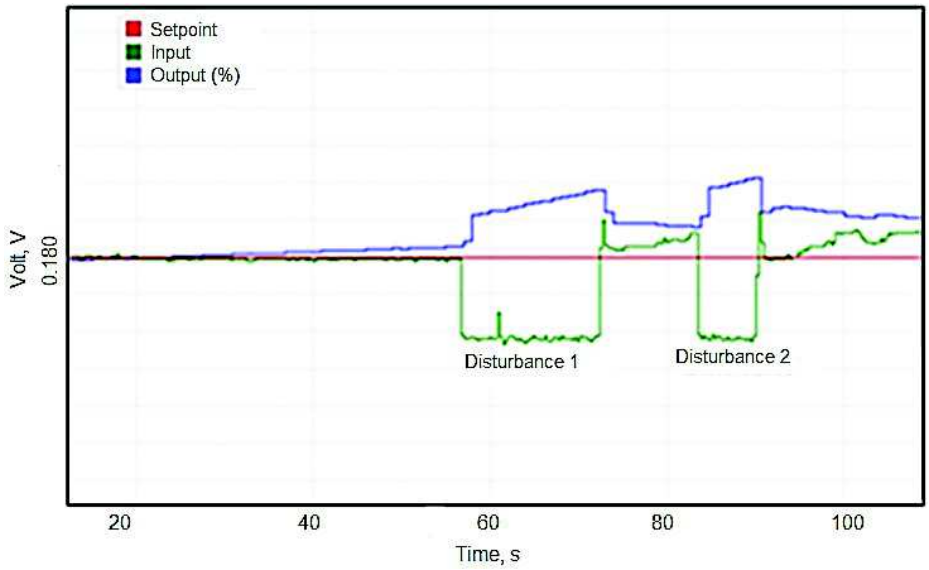

Figure 7. The status chart of the ongoing system at set values against disruptive factors.

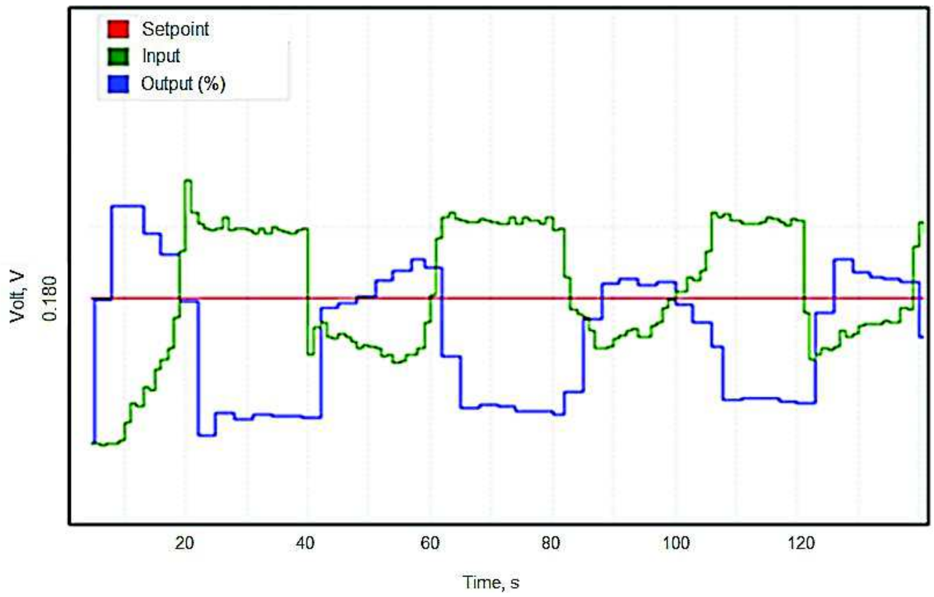

Figure 8. The status chart of the system against continual disturbances.

To draw a comparison between PID and the on-off control, the PID gain (K) value was set very high and the operation of the system was simulated as an on-off controller. In this case, the proportional valve was fully open and lead to occasional oscillations in the system by giving 100 percent output on all error values (Fig. 9). This behaviour was similar to the dynamic behaviour observed in on-off control experiments where the signal fluctuated before reaching the set point (Karadöl & Arslan, 2014). In this case, the control system tries to bring the boom section to the set value, but surpasses it, changes direction and draws closer to the set value or reaches it. Due to this operation model, the set values cannot be reached smoothly but may be possible through several back and forth movements. Subsequently, an oscillating control was achieved.

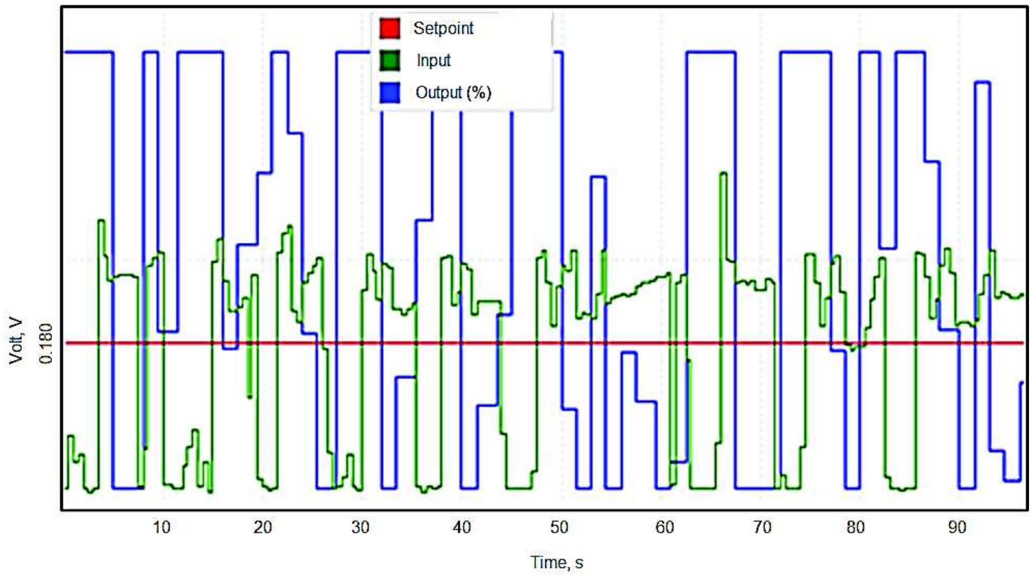

Figure 9. The status chart similar to on-off control due to a very high proportional gain value.

Consequently, the experimental findings showed that when the on-off control was used to balance the boom section, the balance point was reached through a series of intermittent movements. In the case of PID control, a proportional controller was used and the section balance disrupted by the disturbance was restored to the set value with a smooth transition. As the gain was increased by the PID, the system behaviour was similar to that of the on-off system. In order to adapt these findings obtained in laboratory conditions to the boom levers of an actual spraying machine, a few small adaptations may be needed in the controller that was developed.

CONCLUSIONS

PID controller with a technological CPUenabled smooth boom section movements when disturbances were introduced up to 20 second durations. The gain can be optimized by executing the software program developed under various operating conditions. Increased gain resulted in an operation similar to on-off control, which is not favourable. More appropriate gain values should be determined using the results from both laboratory and field tests. In on-off control to adjust the boom section heights, the solenoid valves fully open the conduits resulting in unwanted oscillations in the system and results in an intermittent control process.

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