Monitoring the response times to variable-rate herbicide application in a direct-injection sprayer

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Abstract

An intelligent direct-injection implement for variable-rate herbicide application was designed and constructed under the RHEA project: Robot Fleets for Highly Effective Agriculture and Forestry Management. This system provides precise herbicide application rates based on weed infestation maps, resulting in minimal operator exposure to chemicals. The use of weed infestation maps is becoming more widespread with the development of remote (satellite, aerial imagery, and small aerial unmanned vehicle) and proximal (soil, weed, and crop parameter) sensors. However, it is crucial to determine the limitations of the hydraulic system of the herbicide application device in use. The primary issue with injection sprayers is that there is a continuous transport lag in the system. The transport lag is the time required for the mixed solution to flow from the injection point to the spray nozzles. When herbicides are applied based on a weed map, it is crucial to anticipate the lag time between the changes in the herbicide concentration and the arrival of this new solution at the sprayer nozzle. Disregarding the transport lag will result in important discrepancies between the desired and the actual application rates as the new concentration travels from the point of injection to the nozzles. This study was designed to monitor the response times to measure the performance of the injection metering system. In addition, we used this method in experimental investigations to assess the response time of the proposed direct-injection system. The average ingredient lag time for the injection variable rate technology was based on the flow rate of the carrier liquid and ranged from 30 to 80 s. This transport lag time varied for each nozzle of the direct-injection implement for variable-rate herbicide application.

Keywords: site-specific weed control, direct-injection system, sprayer, automation

1 Introduction

The rising input prices in Europe and EUR 8 billion annual spending on agrochemicals in 2010 (ECPA, 2011) are increasing the pressure on pesticide and fertilizer operators to reduce the application rate, which has motivated manufacturers to develop spray equipment with greater application accuracy. In particular, at two international workshops, stakeholders highlighted the importance of sensors, decision support systems, and site-specific variable-rate applicators in future crop operations. Agricultural systems require safe, effective and efficient weed control operations to ensure the success of crop production. Unfortunately, pesticide and nutrient applications are required for efficient and economic agricultural and forest crop production (e.g., annual crop, forestry, orchards, etc.). In addition, the overall uni-
form broadcast application technique, which is commonly employed in crop production, is appropriate and efficient when the weed distribution in a large field area is uniform in species composition. This type of application has become sub-optimal now that remote sensing (satellite and aerial imagery) and proximal sensing (soil, weed, and crop parameter) data can be collected and georeferenced (Bareth & Doluschitz, 2010) and because weeds are typically unequally distributed over a field (Marshall, 1988; Gerhards & Oebel, 2006).

In recent years, manufacturers and pioneering farmers have been building and retrofitting spray machines to incorporate Automatic Section Control (ASC) technology, which is an input-saving technology available for many agricultural applications. The ASC system is able to close boom sections or nozzle solenoid valves (Off-On) whenever the sprayer covers a zone that has already been sprayed or senses a no-spray area within a crop field. With such a system, Troesch et al. (2010) reduced the over-application of pesticides and fertilizers by 1-12% per pass across a field and improved the environmental protection by not applying agricultural chemicals in non-target areas. The application of ASC technology in Alabama (USA) has resulted in 15.2-17.5% savings in sprayed zones by efficiently managing the boom sections (Luck et al., 2010).

The elimination or reduction of the active ingredients of herbicide application in weed-free areas within a field and increasing the amount of fertilizer in low-productivity sites is known as variable-rate application (VRA). Both the ASC and VRT require many different instruments and sensors to obtain the necessary data from the soil, crops, weeds, and other variables, but these data can be aggregated in maps (called "prescription maps") using global positioning coordinates from a Global Navigation Satellite System (GNSS) receiver.

Considerable research has been performed on the use of a central direct-injection pesticide system (CDIS), and this technology achieves VRT by spraying the carrier at a predetermined constant flow rate while varying the concentration of the active ingredient as needed (Walker & Bansal, 1999; Goudy et al., 2001; Vondricka & Schulze, 2009). A key challenge with the injection system is the total time elapsed from the moment the order is given to the controller or computer until the appropriate flow leaves the nozzle. This effect is called the "transport lag" and can be compensated for by changing the desired application rate far enough in advance in the controller or computer so that the change in concentration at the nozzle occurs by the time the sprayer arrives at the desired field location. The transport lag is correlated with the distance lag in moving systems such as a field sprayer. This distance is the length that the sprayer travels before the concentration change reaches the nozzles (Rockwell & Ayers, 1996).

As reported by Christensen et al. (2009), autonomous or robotic applications of herbicides require a high-precision sprayer, which is a direct-injection sprayer than can apply at different rates, e.g., using prescription weed maps to control a set of nozzles, a boom section or the whole boom. In field robotic systems, high-level motion planning is required to accomplish tasks autonomously, meaning that the implement attached to such a vehicle must be a very precise sprayer. Therefore, it is critical to study and control factors such as the controller interval time, system pressure, ground speed, controller error tolerance, sensitivity of the flow-regulating valve, and sensitivity of the injection pump motor. The injection pump has a motor speed sensor that is time dependent, which is considered a dynamic characteristic. This characteristic is a disadvantage of the direct-injection system due to the dynamic characteristics of the sprayer being affected by the time required for the agrochemical to travel from the controller pulse to the nozzles. Such delays result in substantial misapplications in the target area. For example, a sprayer that is equipped with an injection system with a response time of 30 s and a standard forward speed of 8 km h⁻¹ will travel approximately 66 m before the desired concentration of solution in the nozzles is reached (BBA, 2005).

The maximum potential of precision agriculture technologies can only be achieved when the accuracy and efficiency of conventional farming tasks are increased with the use of a large amount of data and multiple sensors (Mowitz, 2003; Rovira-Más et al., 2010). The objective
of the present study was to investigate the performance of an automated sprayer prototype to be eventually integrated into an autonomous system for the site-specific management of weed control using sensors and instrumentation that allow for a CDIS and VRT. The specific objectives were i) to develop an automated sprayer that is suitable for RTK-DGPS control based on a weed map and ii) to develop a theoretical method for measuring the performance of the injection metering system and to use this method to assess the dynamic response characteristics of the proposed system in experimental investigations.

2 Materials and methods

Twelve high-speed solenoid valves (Model VC01, NTech Industries, Inc., CA, USA) were mounted on a stainless steel sprayer boom with an equidistant spacing of 0.5 m. These solenoid valves consist of a ¼" hose barb brass inlet for the incoming liquid, a spray nozzle, a nozzle cap, an LED indicator, a 3-pin electrical connector (signal, negative and positive), and two captive screws. The boom sprayer was divided into twelve sections, each containing one solenoid valve. Each of these valves was energized by a 12 V source that allowed the spray from each section to be controlled independently. The LED indicator was on when the solenoid was open.

A commercial central direct-injection system (Model Sidekick Pro, Raven Industries Inc., Sioux Falls, SD, USA) was equipped with a water tank (200 L) and a separate container for the herbicide (15 L) injection according to the prescription information from the High Level Decision-Making System (HLDMS). The controller (SCS-sidekick) unit was controlled by the HLDMS and signal inputs from various sensors. The HLDMS program, written in LabVIEW, uses the RTK-GPS position and the application rate map to determine the desired application rate. A PCB interface between the sprayer and HLDMS was created and installed to accommodate the signal sensors and to host the injection system controller and the automation (PLC) device. The injection system controller supplied a variable voltage to the gear motor to power the injector pump. This voltage caused the injector pump to turn at the appropriate speed to generate the desired flow rate of the active ingredient. An encoder integrated into the system measured the flow rate of the active ingredient based on the injector pump speed. The controller used the active ingredient flow rate from the pump speed to determine whether a change in the active ingredient flow rate was needed.

The mixing chamber of the injection system ensures that the flow of the agrochemical that is incorporated into the stream of water will be evenly distributed throughout the resulting volume.

The experimental values obtained during the test using a sensor of concentration located on the nozzle demonstrate that a time lag exists between the time that the order is given to start the injection and the time that the first demonstration nozzle increases the concentration. This response time is due to the trajectory that the liquid must travel through the pipes from the injection point to the nozzle and therefore depends on the length to be traveled and the section of pipeline. The response time consists of the time delay of the injection pump, transport and mixing time, and concentration increase time. The concentration increase time is the time from the first response of the injection pump until reaching the demanded concentration flow.

In the nozzle shows that the sensor reading rises gradually, eventually plateauing at a constant value. This behavior of the reading time sensor may be due to the transitional period during which the entire volume of the liquid in the mixer changes from the initial concentration $c_0$ to the final concentration $c_f$, whose value depends on the concentration of the liquid injected, $c_i$, and the relationship $\rho$ between the carrier flow and the injected flow.

To test this hypothesis, a numerical model was developed to follow the concentration with time considering the operating parameters of the injection pump. Then, the readings that were taken by the sensor during the trial were compared. This model begins with a water
carrier flow \( Q_w \) that circulates the liquid into the injection system and causes the injection of injected flow \( Q_{ch} \) such that

\[
\frac{Q_{ch}}{Q_w} = p
\]  

(1)

The differential equation below describes the evolution of the concentration \( c \) as a function of time \( t \) when a carrier flow \( Q_w \) of zero concentration is supplied simultaneously with a injected flow \( Q_{ch} \) of concentration \( c_s \), this equation assumes an enclosure (the mixer chamber in our case) of volume \( V \), which receives the total flow equal to the sum of \( Q_w \) and \( Q_{ch} \), considering the relationship \( p \) between \( Q_{ch} \) and \( Q_w \) described in equation 1:

\[
dc = \frac{Q_w}{V} \left( p \cdot c_s - (1 + p) \cdot c \right) dt
\]  

(2)

Integrating Equation 2 for the overall case, \( t=0 \) can exist at an initial concentration of \( c_0 \), giving the following expression:

\[
c = c_s \cdot \frac{p}{1+p} - \left( c_s \cdot \frac{p}{1+p} - c_0 \right) \cdot e^{-\frac{Q_w}{V} \cdot (1+p) \cdot t}
\]  

(3)

When the start of an initial concentration is null, this equation is reduced to

\[
c = c_s \cdot \frac{p}{1+p} \cdot \left( 1 - e^{-\frac{Q_w}{V} \cdot (1+p) \cdot t} \right)
\]  

(4)

Experimental measurements were compared to the above equation and corresponded to the tests conducted using three replicates at the sensor placed in a nozzle (N12) only when it was operating. These measurements were previously corrected reading zero (offset); thus, for comparison to the measurements obtained from the theoretical model, the unit of measurement is expressed as g/L.

The values of the different parameters for the conditions under which the test was conducted were \( c_s = 3 \) g/L; \( p = 0.1 \); \( Q_w = 0.01217 \) L/s; and \( V = 0.274 \) L.

### 3 Results and Discussions

An automatic sprayer that controlled the HLDS through a GNSS prescription map to determine its geospatial position and to control the spray valves in the field was successfully developed. With all of the components assembled on the implement, the sprayer was tested in the workshop by simulating situations that would occur under field conditions. This system included mechanical (stability of the boom, hose length, etc.) and electrical (cables, voltage levels, power, communication equipment, etc.) subsystems. The reduction of the DIS response time and the increase in the uniform processing requires knowledge of the system’s functional parameters.

Figure 1 illustrates the comparison of the experimental measurements and those estimated as a function of time (Equation 4). A good fit was observed between these measurements beginning 25 s from the start of the increased concentration.
Figure 1: Evolution over time of the concentration level at the nozzle. Experimental values and values estimated by the model obtained from Equation 3 are shown.

During this initial period, the experimental concentration did not follow the theoretical model but then gradually approached the experimental values until they matched. This phenomenon can be explained by the behavior of the injection pump due to the time required to stabilize the injection rate to the required value assuming a null injection flow.

This alteration causes the value of $p$ to not start from $t=0$ to its nominal value of 0.1 L/L but, rather, to start from scratch and increase following the transient function $p=f(t)$, thereby amending the expected theoretical results until it reaches its final value.

To account for this additional transition in the general model, the value of $p$ increases linearly from $t=0$ to $t=25$ s, representing a growth rate of 0.04 L/L per second.

A comparison of the fit of the experimental values with the resulting final model was performed by calculating the estimated values at discrete time intervals of 1 s, considering that the value of the concentration in the second $i$ will behave as follows:

$$c_i = c_s \cdot p \cdot \frac{Q_w}{V} + c_{i-1} \cdot \left(1 - \frac{Q_w}{V} \cdot (p + 1)\right)$$

where $c_{i-1}$ is the value of the concentration in the second prior of calculation, starting from an initial value $c_0$ equal to zero, allowing for the use of a different value of $p$ for each discrete value of time in the initial 25 s.

Figure 2 shows the time evolution of the resulting model estimates with experimental values, showing, in this case, a good fit for the entire tested range.

Figure 3 represents the estimated versus the experimental trend line and a coefficient $r^2=0.9995$ for a relationship between these values of 1.
Figure 2: Evolution over time of the concentration level nozzle. Experimental values and values estimated according to Model (1), which was obtained from the differential equation, and Model (2) at discrete intervals are shown.

Figure 3: Estimated values according to Model (2) of discrete intervals versus values from experimental data.

4 Conclusions

An automatic sprayer, which utilizes a GNSS-based prescription weed map to determine its geospatial position and control the spray valves in the field, was successfully developed and tested under laboratory conditions. The following conclusions were drawn based upon the results of this research:
- The developed model is able to predict discrete hydraulic profiles by applying the control volume element method, aiding in the design of an optimal boom for a direct-injection sprayer.

- This study has been focused in the most difficult response time of a direct-injection system on one nozzle. Has been shown very satisfactory fit of the proposed theoretical model.

- To reduce the concentration increase time, the injection process should be optimized to reach the desired chemical concentration as fast as possible. This study shows that 25 s are required to stabilize the injection rate to the required value assuming a null injection flow. Proportional-integral-derivative controller (PID controller) adjustment may reduce this time.

- Knowing the transport lag time allows to anticipate it between the changes in the herbicide concentration and the arrival of this new solution at the sprayer nozzle.

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6 References


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