Development and testing of application systems for precision variable rate fertilization

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Introduction:

Precision or "site-specific" management of ag production requires application of fertilizer, pesticides, water and other inputs on spatial scales much smaller than previously used. The concept is simple; by using accurate navigation and positioning to guide collection, sensors for crop yield, soil properties and other conditions can be used to develop maps or databases of crop response and geographic variation. From the collected information and an understanding of crop development, the inputs supplied to the crop and the management practices used can be refined on small areas. The overall economic return can be increased while environmental effects can be reduced. Significant research is underway to determine how to adapt this tool to California agriculture.

This project is working on one essential machine component for precision farming, namely, a fast system for varying the application rate of liquid and gaseous fertilizer. This is complicated by the real-world problems of fast ground speeds, a wide range of rate control, and the ever-present demands of simplicity and high reliability during busy seasons. When a fertilizer applicator is traveling at 8 mph, 3 feet are covered in approximately 0.25 seconds. If fertilizer rate changes are desired in, for example, a 6-foot distance, the application system must respond in 0.5 seconds. Most application equipment, even that with electronic rate control, cannot respond quickly enough. Even when it is fast, a typical rate controller has a limited range and resolution.

A unique spray control system has been developed and patented at UC-Davis that can control pesticide application rates over an 8:1 range and respond within 0.3 seconds and often within 0.1 second. The system uses electronically-controlled valves at each spray nozzle to meter the desired flowrate, without disrupting the spray droplet size or spray pattern. Performance and durability of the system has been proven by commercial use. The report describes investigations of the control technique for application of liquid fertilizers and anhydrous ammonia. Accuracy of the system approach and suitability for GPS- or manually-directed variable rate application was established.

Objectives:

The goal was to determine if desired rate changes could actually be achieved with existing application equipment and improved metering systems. Another goal was to address the question, “Can uniformity and accuracy of fertilizer application rates be improved with the pulsing valve flow rate control approach?” The specific objectives were:

1. Determine if the control valves are suitable for use with typical fertilizer liquids at typical application flow rates and supply pressures.

2. Install the control system on a liquid fertilizer applicator and document accuracy and uniformity in application rate and speed of response to changes in application rates in a field setting.

3. Determine if the control system can be modified for use with anhydrous ammonia in order to improve uniformity of application, reduce vapor formation in supply lines and allow a wide range of rate control.

Project Techniques:

Objective 1

The work on Objective 1 consisted of a factorial experiment. Two common liquid fertilizers (UN 20 and UN 32) were tested with three common nozzles (8008, 11015 and TF-10) and liquid supply pressures of 10-30 psi. In this factorial design experiment, the following objectives were addressed:

a) To confirm that the flow rate of liquid through the PWM (pulse width modulation) solenoid valve and nozzle are proportional to the product of duty cycle of the valve and the square root of the pressure at the inlet of the valve.
b) To determine parameter values of a simple mathematical model of flow rate versus the controllable pressure and duty cycle.
c) To determine if actuation frequency, in the rate of 5 to 15 Hz, has a significant effect on the model estimate

The layout of the equipment setup for the experiment is shown in Figure 1. A test chamber with centrifugal pump was constructed for recirculating the test liquids. Pressure and flow rate were measured by an electronic pressure transducer and turbine flow meter, respectively. The pressure transducer and flow meter were commercial units (TeeJet) used for typical agricultural spray rate controllers. Additionally, the flow rate was measured manually with a calibrated cylinder and a stop watch in order to verify the flow meter data. Four nozzles and solenoid

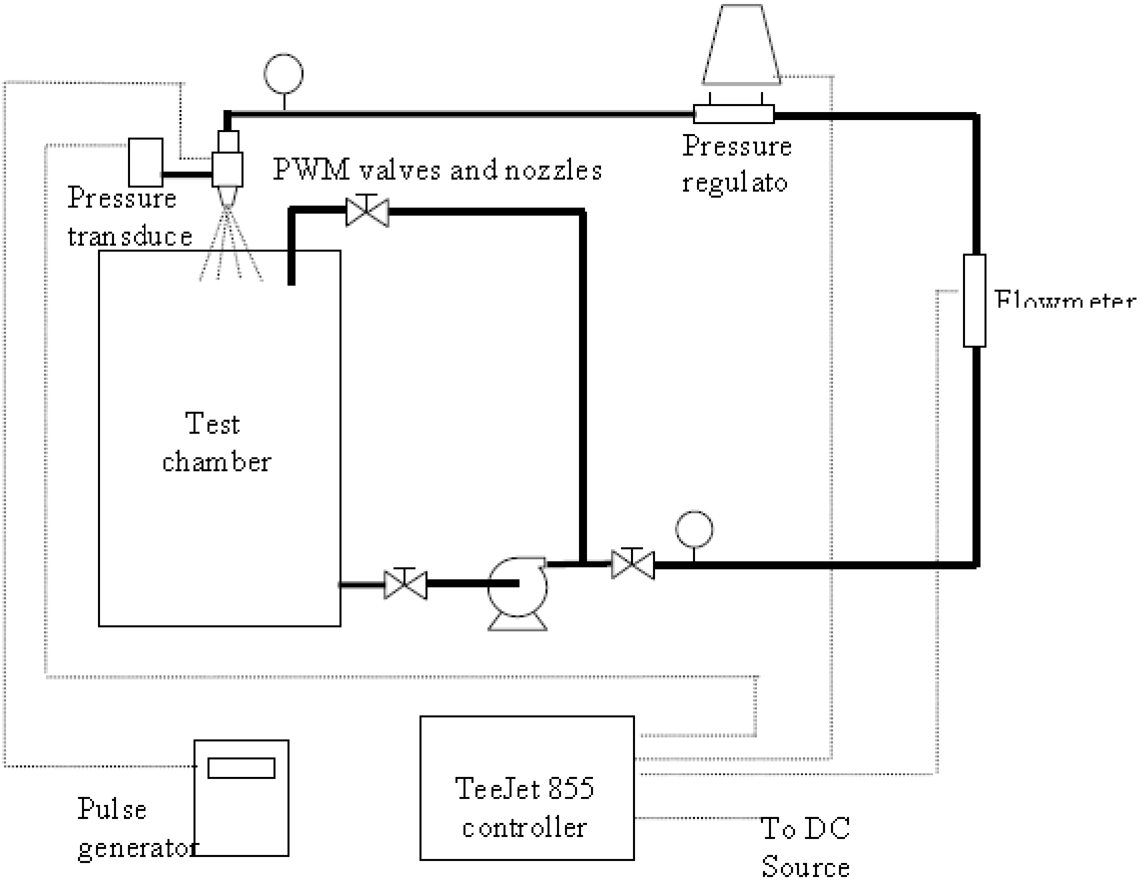


Figure 1. Experimental setup for flow control testing.

valves were installed on the boom section. Boom pressure was controlled with a pressure regulating valve (ball valve). A pulse width modulation valve controller was used to adjust the operating duty cycle and frequency of the solenoid valve. A commercial rate controller (TeeJet 855) displayed the pressure and flow rate values.

In the experiment, three pressures, three frequencies and five duty cycles were tested. Therefore, the total number of treatments was 3*3*5 = 45. For each treatment, the experiment was repeated three times. The nozzles were selected to cover a range of orifice designs and flow rates typical in fertilizer application. Nozzles were an 80° flat fan nozzle (in English units: 0.8 gpm water @ 40 psi), a 110° flat fan nozzle (in English units: 1.5 gpm water @ 40 psi) and a deflector plate nozzle (in English units: 2.0 gpm water @ 40 psi). All nozzles were TeeJet® brand, manufactured by Spraying Systems, Inc. The system was pre-tested using water. Table 1 summarizes the factorial experiment design.

Table 1. Factorial experiment design.

Nozzle type	Fertilizer	Pressure	Frequency	Duty cycle
8008 11015 TF-10	UN-20 UN-32	75 kPa 150 kPa 225 kPa	5 Hz 10 Hz 15Hz	100% 90% 50% 10% 5 %

Test result data are shown in Tables 2 and 3. Figures 2 – 4 show graphic results for the solutions UN-20 and UN-32 on 8008 nozzles, 11015 nozzles, and TF-10 nozzles, respectively. Linear regression analyses, best subsets regression and stepwise regression were done on the test result data to find the most suitable predictor variables from the pool of duty cycle, frequency, square root of pressure, and product of duty cycle and square root of pressure. Both methods chose product of duty cycle and square root of pressure as best predictor variable and rejected frequency.

The plots of flow rate versus product of duty cycle and square root of pressure clearly show linear relationships. An hypothesis (t) test indicated that the intercepts of these straight lines are equal to zero. The slopes of these straight lines give a model parameter (1/ß). The calculated ß values are shown in Table 4.

Table 4. Calculation results of ß values.

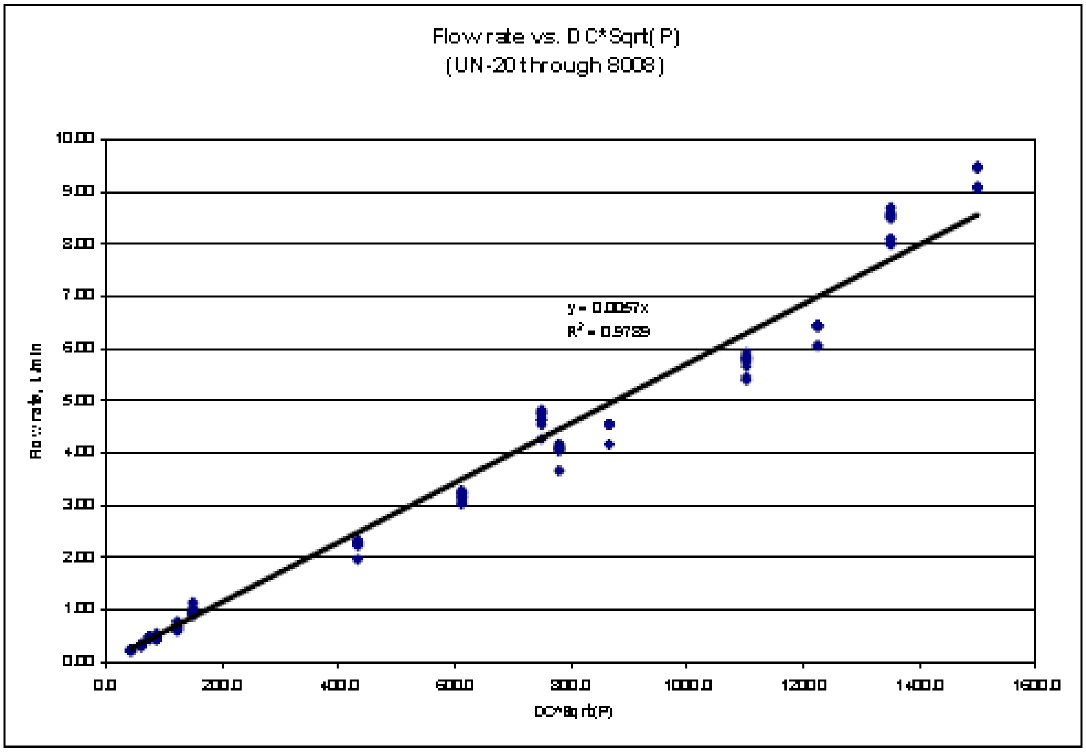
Nozzle	Liquid	Slope	Beta value
8008	UN-20	0.1426	7.013
	UN-32	0.1262	7.924
11015	UN-20	0.2394	4.177
	UN-32	0.2137	4.679
TF-10	UN-20	0.2200	4.545
	UN-32	0.1797	5.565

Nozzle	P (kPa)	DC (%)	5 Hz			10Hz			15Hz		
8008	75	100	4.54	4.54	4.16	4.54	4.54	4.54	4.54	4.54	4.54
		90	4.13	4.04	3.66	4.18	4.07	4.09	4.11	4.05	4.10
		50	2.23	2.32	1.96	2.32	2.23	2.28	2.28	2.27	2.29
		10	0.55	0.44	0.42	0.45	0.50	0.45	0.45	0.45	0.45
		5	0.23	0.22	0.20	0.23	0.22	0.23	0.23	0.23	0.22
	150	100	6.43	6.06	6.43	6.43	6.43	6.06	6.43	6.43	6.43
		90	5.86	5.39	5.66	5.92	5.77	5.45	5.82	5.74	5.81
		50	3.15	3.09	3.02	3.28	3.15	3.05	3.22	3.21	3.25
		10	0.77	0.59	0.64	0.64	0.71	0.59	0.64	0.64	0.64
		5	0.33	0.30	0.30	0.33	0.32	0.31	0.32	0.32	0.32
	225	100	9.46	9.08	9.08	9.46	9.46	9.46	9.46	9.08	9.46
		90	8.61	8.08	7.99	8.71	8.49	8.52	8.55	8.10	8.54
		50	4.64	4.63	4.27	4.83	4.64	4.76	4.74	4.53	4.78
		10	1.14	0.88	0.91	0.95	1.04	0.93	0.94	0.91	0.94
		5	0.48	0.45	0.43	0.48	0.46	0.48	0.48	0.45	0.46
11015	75	100	8.33	7.95	8.33	8.33	7.95	7.95	7.95	7.95	7.95
		90	7.58	7.07	7.33	7.66	7.13	7.15	7.19	7.09	7.18
		50	4.08	4.05	3.91	4.25	3.89	4.00	3.98	3.97	4.01
		10	1.00	0.77	0.83	0.83	0.87	0.78	0.79	0.79	0.79
		5	0.42	0.39	0.39	0.42	0.39	0.40	0.40	0.40	0.39
	150	100	11.73	12.11	12.11	11.73	12.11	12.11	12.11	12.11	11.73
		90	10.68	10.78	10.66	10.79	10.86	10.90	10.95	10.80	10.60
		50	5.75	6.18	5.69	5.98	5.93	6.09	6.07	6.04	5.93
		10	1.41	1.17	1.21	1.17	1.33	1.19	1.20	1.21	1.16
		5	0.60	0.59	0.57	0.60	0.59	0.61	0.61	0.61	0.57
	225	100	14.38	14.00	14.38	14.38	14.38	14.00	14.38	14.38	14.38
		90	13.09	12.46	12.66	13.23	12.90	12.60	13.00	12.83	12.99
		50	7.05	7.14	6.76	7.34	7.05	7.04	7.21	7.18	7.26
		10	1.73	1.36	1.44	1.44	1.58	1.37	1.42	1.44	1.42
		5	0.73	0.69	0.68	0.73	0.70	0.71	0.73	0.72	0.70
TF-10	75	100	7.57	7.19	7.95	7.57	7.57	7.57	7.57	7.57	7.19
		90	6.89	6.40	6.99	6.96	6.79	6.81	6.84	6.75	6.49
		50	3.71	3.67	3.74	3.86	3.71	3.81	3.79	3.78	3.63
		10	0.91	0.70	0.79	0.76	0.83	0.74	0.75	0.76	0.71
		5	0.39	0.35	0.37	0.39	0.37	0.38	0.38	0.38	0.35
	150	100	11.36	10.98	10.60	10.98	10.98	11.36	10.98	10.98	10.98
		90	10.33	9.77	9.33	10.10	9.85	10.22	9.92	9.79	9.91
		50	5.56	5.60	4.98	5.60	5.38	5.71	5.50	5.48	5.54
		10	1.36	1.06	1.06	1.10	1.21	1.11	1.09	1.10	1.09
		5	0.58	0.54	0.50	0.56	0.54	0.57	0.55	0.55	0.54
	225	100	13.25	12.87	12.87	12.87	13.25	13.25	12.87	13.25	13.25
		90	12.06	11.45	11.32	11.84	11.88	11.92	11.63	11.82	11.96
		50	6.49	6.56	6.05	6.56	6.49	6.66	6.45	6.61	6.69
		10	1.59	1.25	1.29	1.29	1.46	1.30	1.27	1.32	1.31
		5	0.68	0.63	0.60	0.66	0.65	0.67	0.65	0.66	0.65

Table 2. Flowrate measurements for 20% fertilizer solution Unit: L/min for a 4 valve / nozzle set

Nozzle	P (kPa)	DC (%)	5 Hz			10Hz			15Hz		
8008	75	100	4.49	4.49	4.19	4.18	4.49	4.20	3.90	4.49	4.48
		90	3.57	3.80	3.49	3.60	3.52	3.71	3.74	3.80	3.53
		50	2.06	1.83	2.14	1.83	2.06	1.81	1.80	2.09	1.81
		10	0.43	0.41	0.39	0.39	0.39	0.38	0.39	0.43	0.41
		5	0.21	0.21	0.21	0.22	0.20	0.21	0.22	0.21	0.21
	150	100	6.26	5.89	6.25	6.25	6.26	5.90	6.27	6.26	6.24
		90	5.69	5.24	5.50	5.75	5.61	5.31	5.67	5.59	5.64
		50	3.07	3.01	2.94	3.19	3.07	2.97	3.14	3.12	3.15
		10	0.75	0.57	0.63	0.62	0.69	0.58	0.62	0.63	0.62
		5	0.32	0.29	0.29	0.32	0.31	0.30	0.32	0.31	0.31
	225	100	7.85	7.55	7.53	7.84	7.85	7.87	7.87	7.55	7.84
		90	7.15	6.72	6.63	7.21	7.05	7.08	7.12	6.73	7.08
		50	3.67	3.67	3.37	3.81	3.67	3.77	3.76	3.59	3.77
		10	0.90	0.70	0.72	0.75	0.82	0.73	0.74	0.72	0.74
		5	0.38	0.35	0.34	0.38	0.37	0.38	0.38	0.36	0.37
11015	75	100	7.90	7.55	7.89	7.89	7.54	7.55	7.56	7.55	7.52
		90	7.19	6.72	6.95	7.26	6.76	6.80	6.83	6.73	6.79
		50	3.87	3.85	3.71	4.02	3.69	3.80	3.79	3.77	3.80
		10	0.88	0.68	0.74	0.74	0.77	0.69	0.70	0.70	0.70
		5	0.38	0.35	0.35	0.38	0.34	0.36	0.36	0.35	0.34
	150	100	10.57	10.92	10.91	10.56	10.92	10.93	10.94	10.92	10.55
		90	9.62	9.72	9.60	9.71	9.79	9.84	9.89	9.74	9.53
		50	5.18	5.57	5.13	5.38	5.35	5.50	5.48	5.45	5.33
		10	1.16	0.97	0.99	0.96	1.10	0.98	0.99	1.00	0.95
		5	0.49	0.49	0.47	0.49	0.49	0.50	0.50	0.50	0.47
	225	100	12.51	12.19	12.50	12.49	12.51	12.20	12.54	12.52	12.48
		90	11.38	10.85	11.00	11.49	11.22	10.98	11.33	11.17	11.27
		50	6.13	6.22	5.87	6.37	6.13	6.14	6.28	6.25	6.30
		10	1.41	1.11	1.17	1.17	1.29	1.12	1.16	1.17	1.16
		5	0.60	0.56	0.55	0.60	0.57	0.58	0.59	0.59	0.57
TF-10	75	100	7.18	6.83	7.53	7.17	7.18	7.19	7.20	7.19	6.81
		90	6.53	6.08	6.63	6.60	6.44	6.47	6.51	6.41	6.15
		50	3.52	3.48	3.54	3.66	3.52	3.62	3.61	3.59	3.44
		10	0.86	0.66	0.75	0.72	0.79	0.70	0.71	0.72	0.67
		5	0.37	0.33	0.35	0.37	0.35	0.36	0.36	0.36	0.33
	150	100	8.98	8.68	8.37	8.66	8.68	8.99	8.70	8.68	8.66
		90	8.17	7.73	7.37	7.97	7.78	8.09	7.86	7.75	7.82
		50	4.40	4.43	3.93	4.42	4.25	4.52	4.36	4.33	4.37
		10	1.08	0.84	0.84	0.87	0.95	0.88	0.86	0.87	0.86
		5	0.46	0.43	0.39	0.44	0.43	0.45	0.44	0.43	0.42
	225	100	10.47	10.18	10.17	10.16	10.47	10.49	10.20	10.48	10.45
		90	9.53	9.06	8.95	9.34	9.39	9.44	9.22	9.35	9.43
		50	5.13	5.19	4.78	5.18	5.13	5.28	5.11	5.23	5.28
		10	1.26	0.99	1.02	1.02	1.15	1.03	1.01	1.05	1.03
		5	0.53	0.50	0.48	0.52	0.51	0.53	0.51	0.52	0.51

Table 3. Flowrate measurements for 32% fertilizer solution Unit: L/min for a 4 nozzle / valve



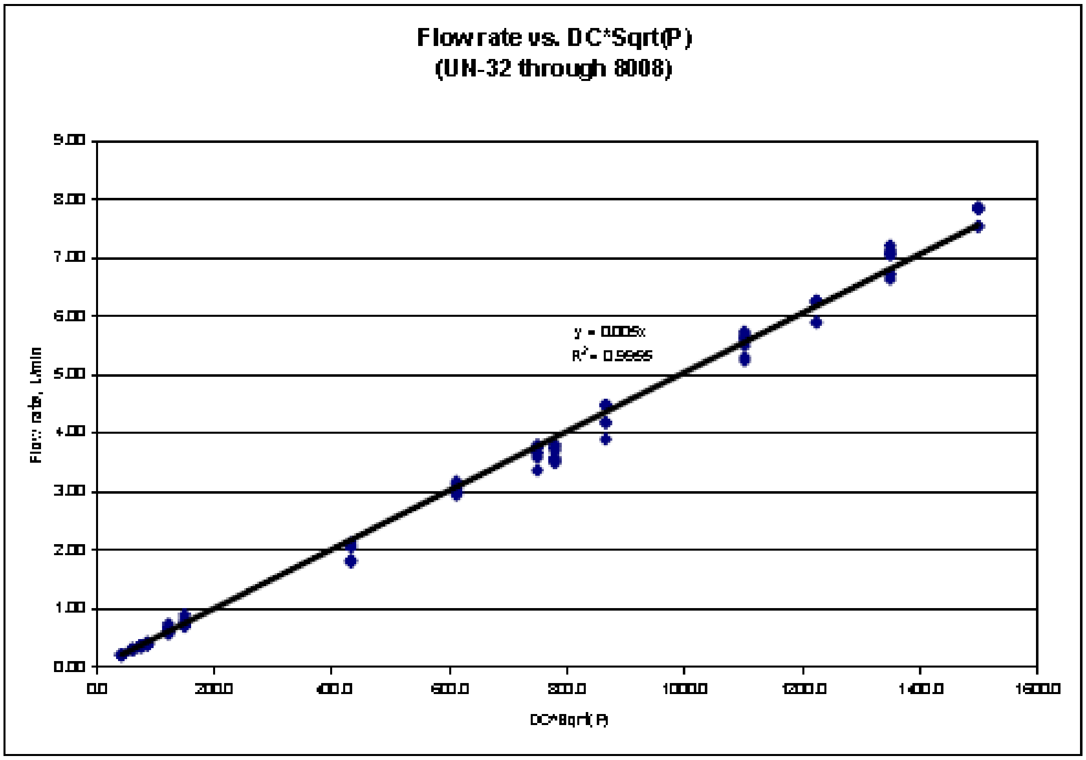


Figure 2. Flow characteristic curves for 8008 nozzles.

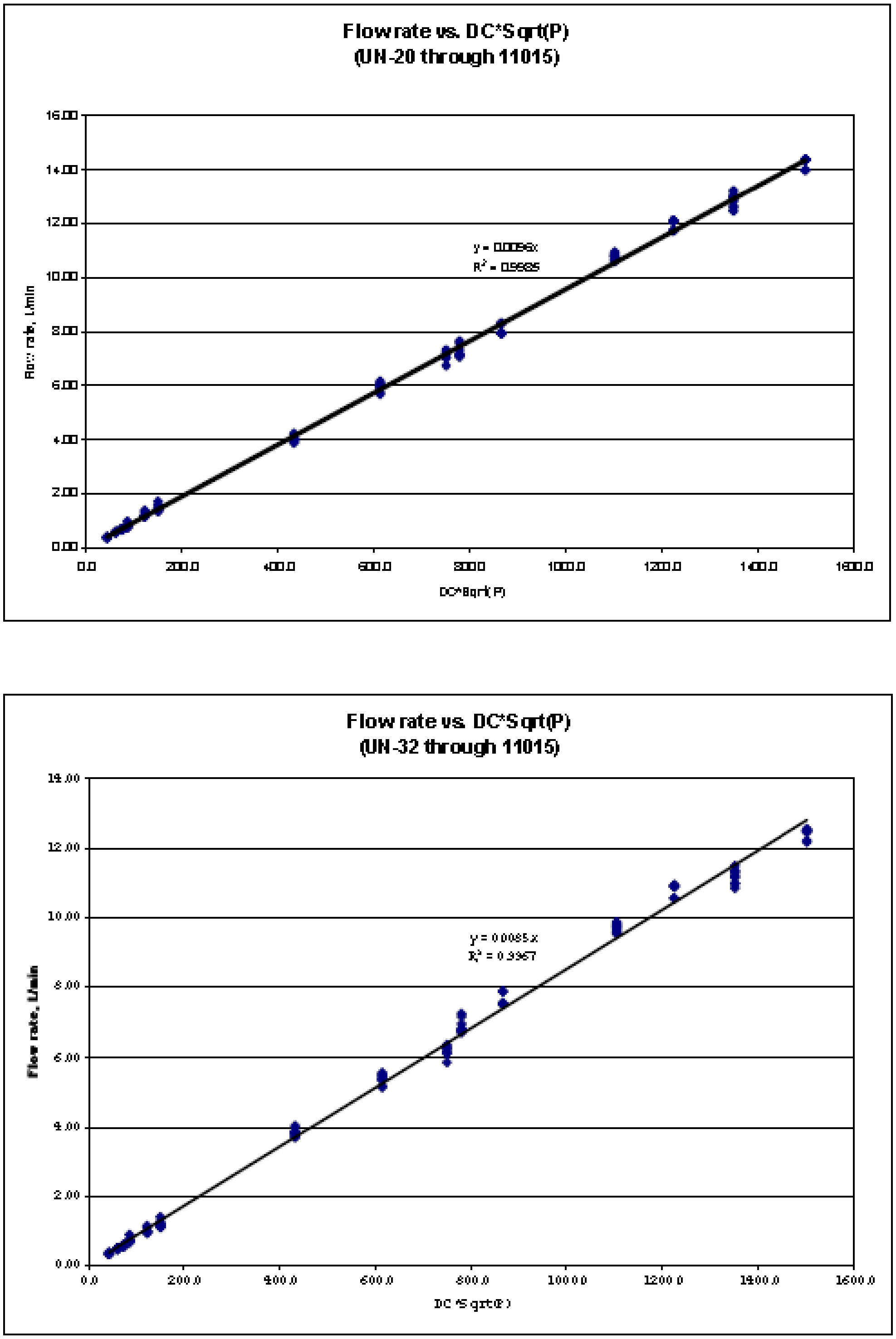


Figure 3. Flow characteristic curves for 11015 nozzles.

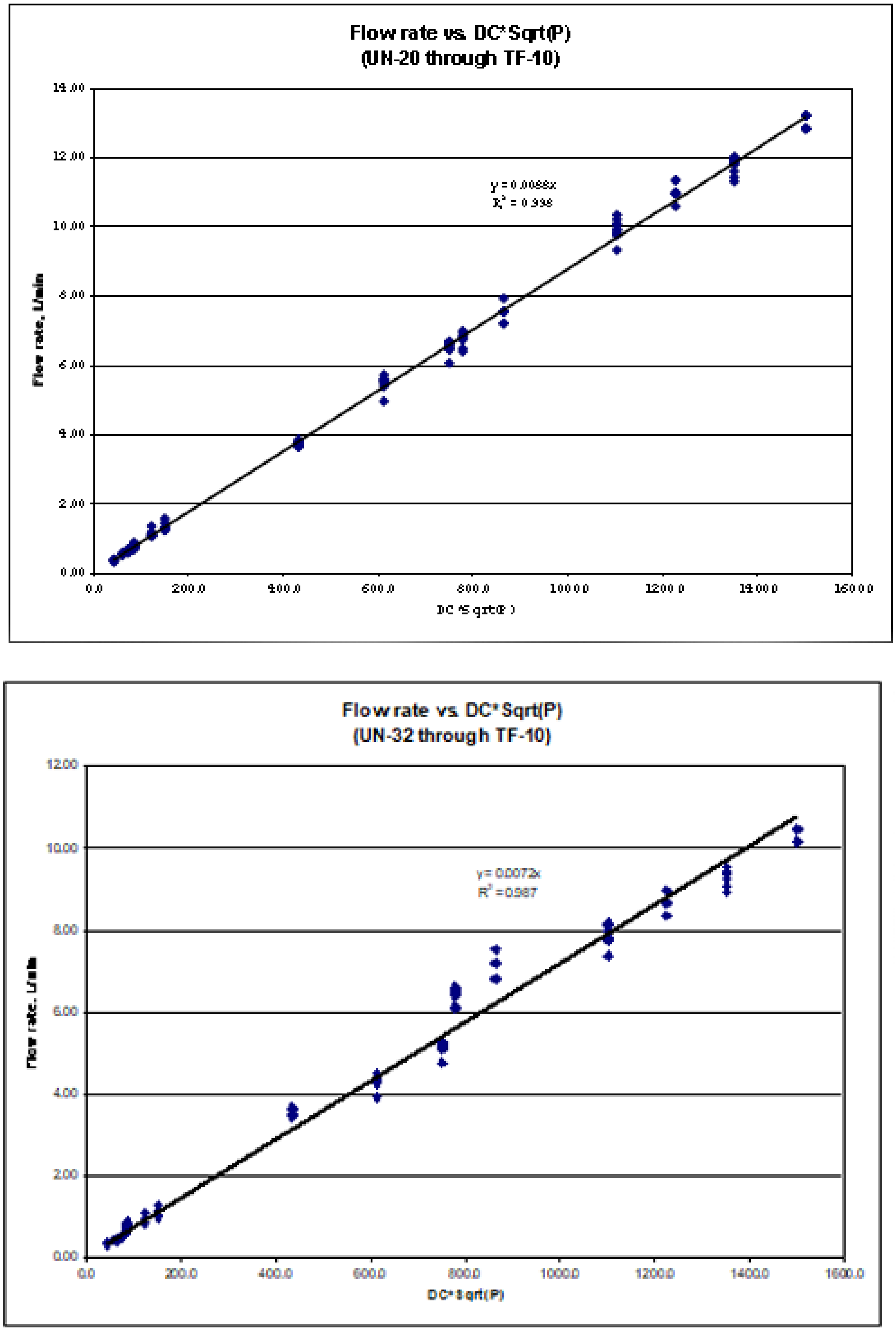


Figure 4. Flow characteristic curves for TF-10 nozzles.

These results established that the pulse flow control technique could be readily used with fertilizer application. No excessive wear was found on the valves and the relationship between flow and valve operation was linear and predictable. This established that the technique could provide useful flow control for constant and variable rate applications without the need for complex electronic components such as flow meters. However, the experiments and experience also found that there was no inherent problem with using flow meters.

Objective 2

Work on Objective 2 used a commercial-type application system rather than a lab stand. Quantitative work used a 500 gal spray trailer with 30 ft boom. This work established that the system could provide a wide range of application rate control while maintaining consistent nozzle pressure for good pattern and droplet control. Later, work expanded to a self-propelled 700 gallon, 75 ft boom Case vehicle. The vehicle was installed with a Case Tyler Ag Navigator• GPS system, Mid-tech TASC• rate controller and the AIM Command• commercial version of the UC-Davis rate flow control system. The Case vehicle was used to demonstrate using the pulsed valves with an actual GPS-directed application map in a test field.

On the trailer applicator, the pulsing actuation required for the control technique was straightforward and physically required only the installation of 12 Vdc, 6 W electrical solenoid valves machined to mate directly with commercial agricultural spray nozzle fittings. Similarly, the control of liquid pressure was provided by an in-line, continuously-adjustable ball valve actuated by a 12 Vdc gearmotor.

The flow control loop received a desired fertilizer application rate and adjusted the pulse signal to the valves while receiving flow feedback from an in-line turbine, digital flow meter. Since objective 1 of this project had established that pulsing control allowed feedforward, or predictive control, (since the relationship between flow rate and duty cycle was linear) initial changes in duty cycle were based on the flow setpoint change and the feedback was a corrective term implemented as a conventional PI (proportional-integral) control strategy

Pressure control was achieved by adjustment of a throttling valve in the liquid supply line. An analog 1-5 Vdc solid-state pressure transducer provided feedback. Control was implemented as a typical PID (proportional-integral-derivative) loop with variable speed motor actuation using a PWM signal.

Since spatial resolution of any variable rate application is critical to accomplishing precision chemical application, two important constraints must be met. First, the system must respond quickly since spray vehicle travel speeds may exceed 7 m/s. Secondly, individual boom sections must be independently controlled since boom lengths may exceed 25 m. Speed of flow rate changes was increased by using feed-forward control of the PWM actuation. Individual boom sections were controlled by having a distinct and independent control system for each section.

Each boom section was controlled by an independent module that contained communication electronics, flow rate and pressure sensors, a pressure control valve and PWM driving electronics. A Boom Control Module is shown in Figure 5. A CAN (controller area network) bus and network configuration was chosen to allow the BCM's to be integrated into any future vehicle and fertilizer control system that would be based on standard protocols. The message set was developed to allow standard CAN software tools to be used for testing and diagnosis.

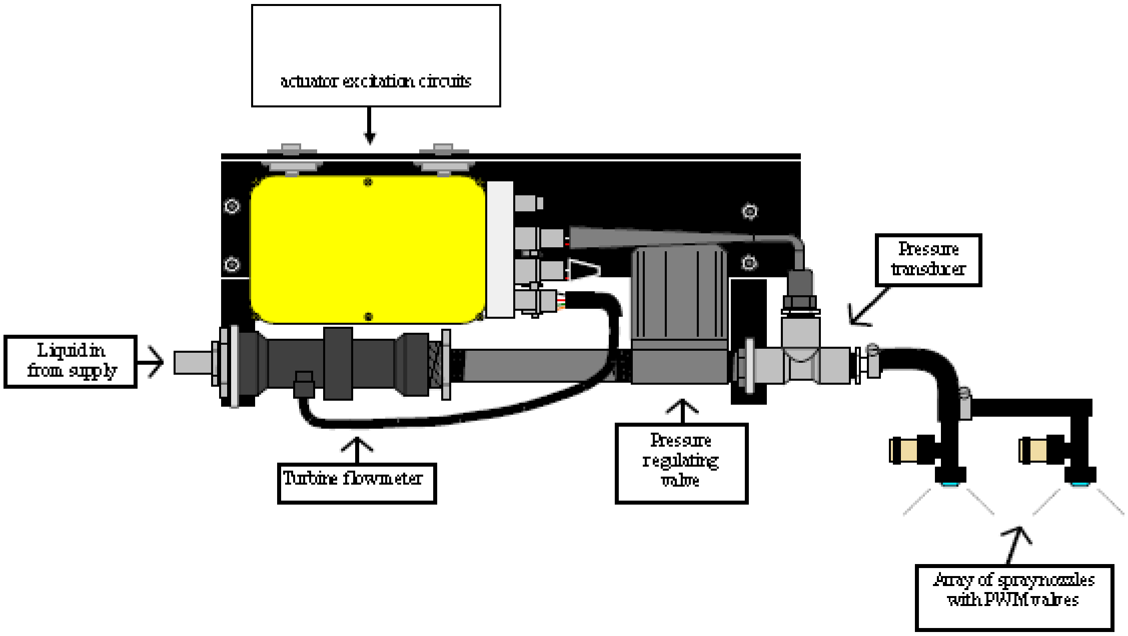


Figure 5. The Boom Control Module (BCM) which contained the flow rate and pressure control loops and associated sensors, actuators and communication electronics.

The BCM's were installed on a typical commercial trailer-mounted sprayer. The spray boom was partitioned into three sections. Each section was controlled by a distinct BCM. The complete system layout is shown in Figure 6.

Performance of the system was investigated by sending a sequence of varying rate and pressure setpoint messages to individual BCM's and receiving the BCM messages which contained the actual system rate and pressure status. The setpoint sequences, or command files, were created to mimic typical field conditions where the GPS/GIS system would be adjusting the application rate and spray droplet size setpoints as the vehicle traveled through the field. This allowed data collection from a stationary vehicle and removed any confounding effect from GPS system performance.

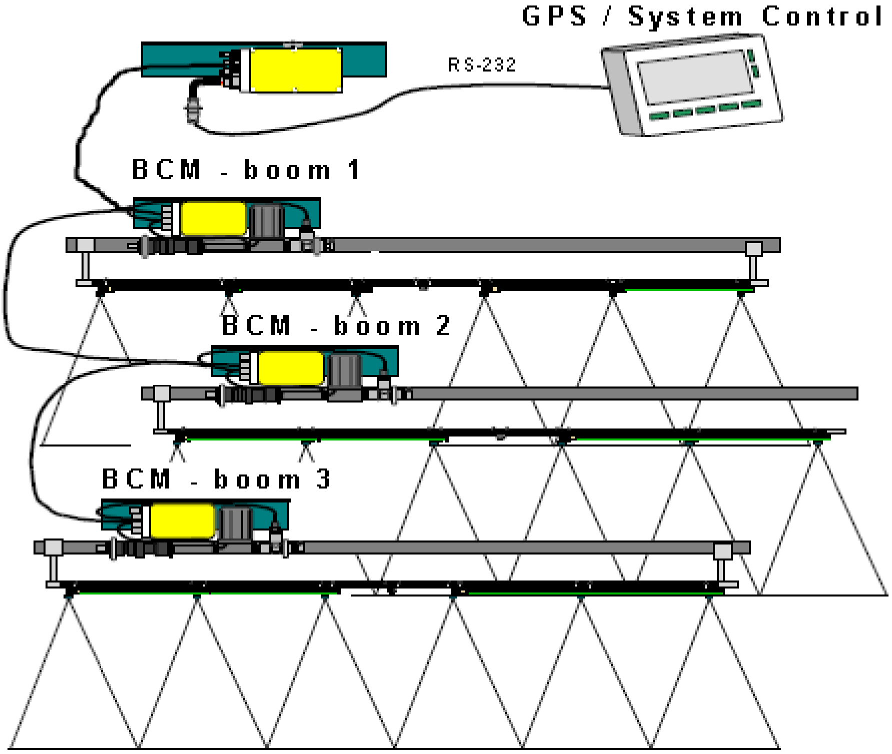


Figure 6. The implemented spray control system showing individual boom sections with the corresponding Boom Control Modules, the supervisory Interface Unit and the GPS controller.

Since the system was tested on a stationary vehicle, a simulated ground speed of 2.5 m/s was provided from a function generator. Each boom section was tested individually and performed very similarly; only data from a single BCM will be shown in this report. The spray boom consisted of 8 TeeJet 11005 nozzles (110° angle, 1.6 l/min @ 275 kPa – 0.5 gal/min @ 40 psi).

The commercial GPS system updated setpoints at 1 Hz; this speed is typical for most commercial equipment. While the CAN bus was capable of much higher data rates, the testing retained the 1 Hz rate of setpoint and actual state recording. While the PWM flow actuation technique allowed significantly faster changes in application rate, the closed loop flow performance was limited by the digital flow meter that required integration times of 0.5 to 1 s to provide accurate data. Additionally, the pressure control loop used an electric motor for actuating the pressure control valve; full open to close time was on the order of 3 s. Allowing for the 1 Hz communication rate, the integration time for the digital flow meter and the speed of the electric motor, the temporal resolution of control and recorded data was likely no greater than 2 s, approximately an order of magnitude slower than the PWM flow control actuator. However, if a full commercial system made full use of the results from Objective 1, then the linear relationship between duty cycle, square root of pressure and flow rate could be used to avoid all these time delays.

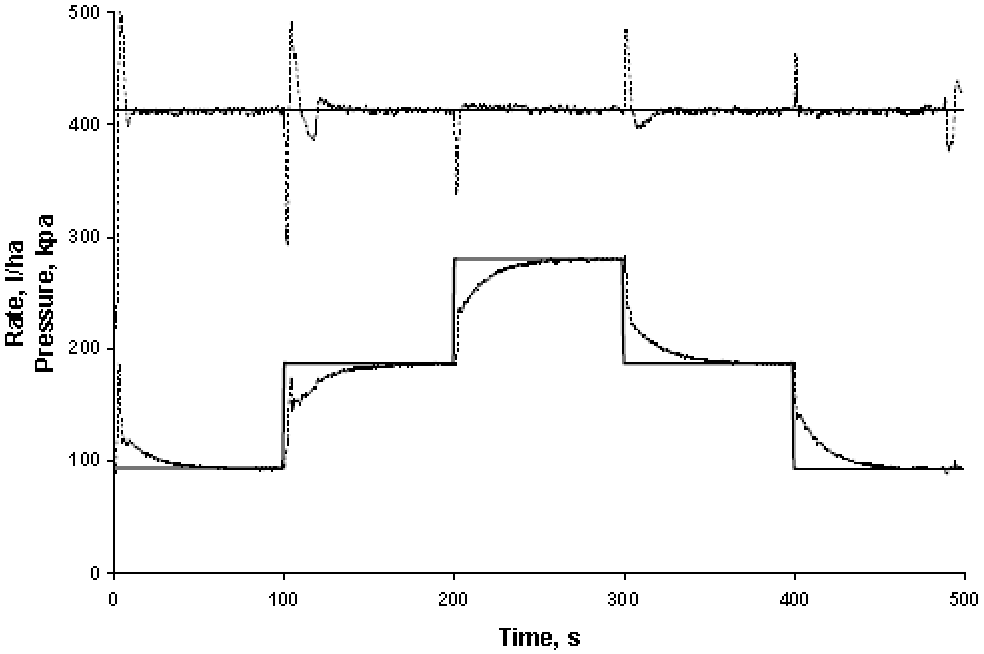
Additionally, the pressure control loop was a complete PID (proportional-integral-derivative) controller and the flow loop was a PI with feedforward controller. Therefore each loop required tuning to optimize the response for acceptable stability and speed. A complete report on system tuning is being developed; the results of most interest and use are reported here. For each loop, effects of gain and integral times were investigated; for the flow loop, feedforward scalars were also adjusted; for the pressure loop, derivative time was also adjusted.

Since variable rate application, by definition, requires changes in the application rate, a command file was created with increased application rate over steps from 94 to 188 to 282 l/ha and back downward while maintaining a spray pressure of 414 kPa. (In English units, this corresponds to 10 to 20 to 30 gal/acre at 60 psi. These values were chosen to provide a maximum pressure and reasonable application rates, based on total land area, not banded or partial applications.)

Example response for the flow loop configured as PI only and the PI pressure loop is shown in Figure 7. The results clearly reveal the mechanical coupling between the boom flow and liquid pressure. When the flow rate is increased, the pressure drop across the in-line pressure regulating valve increases and the boom nozzle supply decreases. However the pressure disturbances are quickly corrected by the pressure control system.

The improvement in flow control response from the addition of the feed forward component in the loop is shown in Figure 8. All control parameters were identical to the test shown in Figure 7 except the feed forward term was activated. The linear relationship between flow rate and duty cycle enables a simple feed forward capability. Since the current flow rate and duty cycle are known in the controller, when a new setpoint is received, an estimated duty cycle is calculated by scaling the system current state. The estimated duty cycle is then implemented immediately as an output, afterwards the PI feedback loop provides subsequent correction to flow rate. Addition of the feed forward term reduced the time required for the application rate to reach the setpoint after a step change. As expected, the faster change in flow rate resulted in a greater magnitude of pressure disturbance.

While the individual control loops were relatively straightforward to implement, the mechanical coupling between the two was apparent during transient periods. The PWM controlled valves are capable of producing significant changes (10:1) in flow rate over relatively short periods (< 1 s). Such capability can lead to severe disturbances to the pressure control system. The actuator for pressure control is an electrically-driven throttling valve placed in-line between the liquid pump and the spray boom. When stable at a fixed flow rate and pressure, the valve position creates the necessary pressure drop between the pump supply and the spray boom. When the flow rate changes suddenly, such as in the near instantaneous 3:1 change, the pressure drop is significantly altered and the pressure system initiates a response, often resulting in an overshoot of the setpoint. The significant change in pressure in turn created a secondary disturbance to the flow system although the disturbance was relatively minor due to the non-linear (square-root) relationship between pressure and flow rate.



To allow the pressure on individual booms to be controlled, the pressure regulating valves had to be positioned in-line between the pump and each boom section. If individual boom control of pressure was not necessary, then pressure supply for the entire sprayer could be controlled with a pressure regulating valve to control by-pass flow from the pump. Such a configuration, when combined with a properly sized spray pump, would be inherently more stable and less sensitive to changes in liquid flow rate through an individual boom section. Alternatively, the pressure could be controlled by modulating the pump rotational speed, as is done on some.commercial systems.

Figure 7. Application rate setpoint (lower solid line) and actual (dotted line) shown with pressure setpoint (upper solid line) and actual (dotted line) for PI rate and pressure control test.

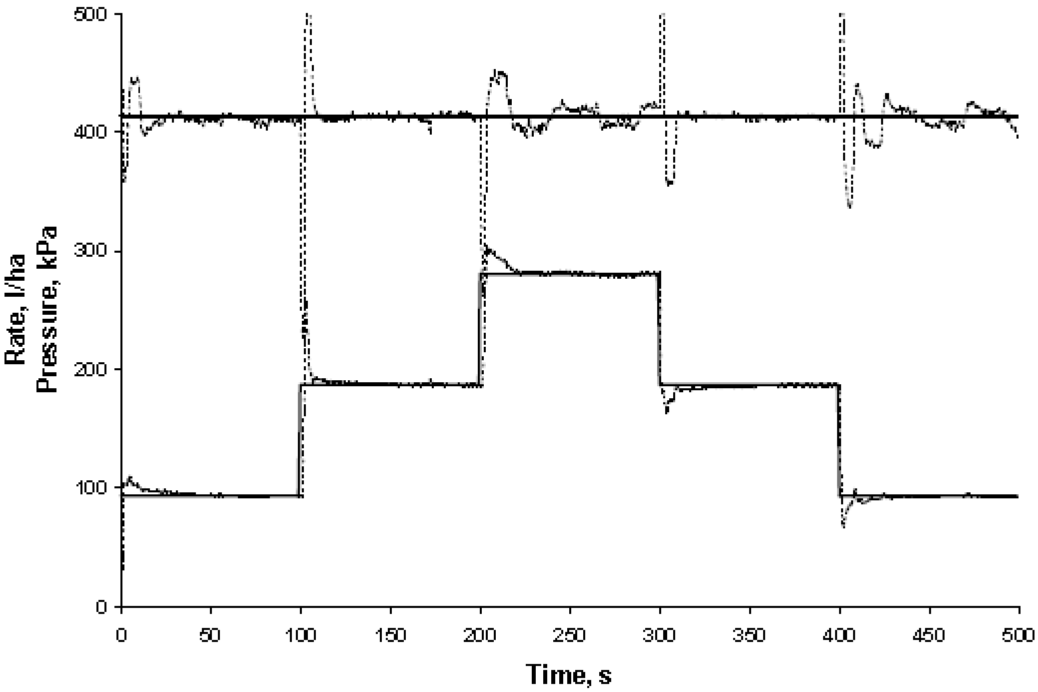


Figure 8. Application rate setpoint (lower solid line) and actual (dotted line) shown with pressure setpoint (upper solid line) and actual (dotted line) for PI + feedforward rate control and PI pressure control test with constant pressure and varying rate.

Objective 3

The third objective was investigated with Capstan Ag Systems, Inc., an equipment manufacturer based in California and Kansas; Prof. Mark Schrock at the Dept. of Agricultural Engineering at Kansas State University; Lee Hazeltine of Precision Applicators in Winters, CA. and Tony Turkovich of Button and Turkovich in Winters, CA. Preliminary static testing of the pulsed control for anhydrous ammonia was done at Kansas State University where an ammonia handling and recovery system was available and work was ongoing with multi- and single-port injection systems for ammonia. Field implementation of the ammonia system was done in Winters, CA during spring planting in 2000.

The static test system was designed and operated by Prof. Mark Schrock and consisted of an ammonia supply system and 10 commercial knives. Each knife discharged ammonia into a bucket of water suspended from a load cell. By electronically measuring and recording the weight of the bucket over the duration of a test, the flow rate from each knife could be determined.

Four systems for metering and distributing the NH_3 were tested. The first consisted of the standard NH_3 regulator, combined with a simple cast-iron manifold. This established a performance baseline for the most common system in use today. The cast manifold used in this study was a Continental 01-07 having 18 outlets. This manifold was tested with both an irregular spacing (10 of 18 outlets used) and a regular spacing (9 of 18 outlets used). Standard hose barbs were installed around the periphery of the manifold, and unused outlets were closed with pipe plugs. Standard reinforced NH_3 hose was used to connect the manifold barbs to the steel discharge tubes. Equal length hoses were used.

The second system substituted a Continental “Vertical Dam” manifold for the simple cast unit. The Vertical Dam manifold (VDM) is a more complex manifold that separates most of the vapor from the liquid NH_3 and meters the two phases through separate orifices. The VDM recombines the liquid and vapor prior to delivery into the individual outlet hoses. The VDM is intended to reduce the lateral (shank-to-shank) variation in ammonia flow. The metering ring used in the VDM was a model Continental 16037-10.

The third system was the “single-point” pulse-width-modulation (SP-PWM) system. The basic cast manifold was modified by placing a PWM valve directly at its inlet. This concept does not use the regulator that was required for the first two systems. Instead, the NH_3 was supplied to the liquid PWM valve at essentially tank pressure, and the flow rate was controlled by the duty cycle (the % open time) of the valve.

The fourth system was a “multi-point” pulse-width-modulation (MP-PWM) system using the UC-Davis valving approach and hardware. This system used seven individual small liquid PWM valves, installed on a standard Continental cast manifold. No NH_3 regulator was used. The choice to reduce the outlets to seven was based on hardware and time constraints. Each of the seven small liquid PWM valves fed a single discharge tube, and all other ports on the manifold were blocked. This system used the same standpipe of the third (SP-PWM) system. However, the multi-point PWM system fed liquid NH_3 to seven small PWM valves, so vaporization took place after the flow was divided. In contrast, the single-point PWM system fed liquid NH_3 through a single large PWM valve and divided the liquid into individual hose tubes after metering and vaporization. All seven valves of the MP-PWM were actuated in phase, and were driven by a single function generator.

Similar to the liquid testing of objective 1 in this project, the flow response of the multi-port pulse system was evaluated by changing the duty cycle of the valves during the test. Test duty cycle began at 50%, then was turned down to 13% after about 120 seconds, then increased to 90% after about 240 seconds. The absorption weight slope of each of the three test segments was determined by regression, yielding the flow for each outlet at the three duty cycles. At a constant pressure, flow is expected to be linearly proportional to duty cycle, achieving roughly a 7:1 turndown ratio for the applied duty cycles of 13 to 90%. The results found that flow dropped below the regression line at high duty cycles. The MP-PWM achieved approximately 5.5:1 turndown instead of the expected 7:1.

The reason for the reduced turndown is that that a substantial reduction in manifold pressure was occurring at high flows. Because orifice flow is proportional to the square root of pressure, correcting observed data for manifold pressure drop essentially restored the linear relationship. A carefully designed production system would exhibit a linear flow versus duty cycle relationship.

The distribution tests showed clear differences in the various systems, and are summarized in Table 4.

Table 4: Summary of ammonia distribution tests

System	No. Tests	No. Outlets	Flow/ Outlet (lb/hr)	Average Lateral COV	Lateral Max/ Min	Effect Tilt 15^o	Effect 2X Hose
Cast	10	10	45-120	16.07%	1.70	-	-
Cast	6	9	58-135	19.18%	1.91	~15%	~13%
VDM	12	10	45-126	10.49%	1.41	~6%	~3%
SP-PWM1	7	10	30-37	20.9%	2.01	-	-
SP-PWM2	3	10	33-39	10.6%	1.41	-	-
SP-PWM3	3	10	26-33	9.08%	1.35	-	-
MP-PWM	6	7	59-66	3.79%	1.12	-	~0

The standard manifold was tested under conditions considered to be “worst case,” in that the manifold pressure was very low. Most of the NH_3 pressure drop occurred at the regulator and a relatively large amount of NH_3 vaporized before reaching the manifold. The large amount of vapor, plus the relatively small amount of pressure available at the manifold, caused gravity (tilt) and other minor irregularities to degrade the performance of the standard manifold. It is likely that these problems could have been reduced by installing orifices in the individual manifold outlets to maintain back-pressure on the NH_3 and improve its quality at the manifold, where flow is divided into the individual hoses.

The test results indicated relatively poor distribution from the standard manifold. Furthermore, uniformity was affected by both the flow rate and inlet conditions of the manifold. These factors would make it impossible to obtain consistent, uniform distribution in a variable-rate system. Manifold tilt and hose length had substantial influence on uniformity, but outlet spacing did not affect uniformity in our tests.

In general, the vertical dam manifold produced about half as much variation in flow as the cast manifold. Lateral COV values for the vertical dam manifold ranged from 8.7 to 12.5% and the average Max/Min ratios ranged from 1.28 to 1.51. The vertical dam manifold was about half as sensitive to tilt as the standard cast manifold. Sensitivity to outlet hose length was only about one-fourth as high as the cast manifold. The reduced effects of hose length and tilt are believed to be due to the fact that the VDM meters vapor and liquid separately, and maintained higher manifold pressure than the cast manifold. The higher manifold pressure of the VDM reduces the effects of tilt and hose pressure drop.

The performance of a simple single-port pulsing design SP-PWM1 was slightly poorer than the standard cast manifold. The term “single-port” means that a large valve was used to pulse the flow into the manifold instead of individual “multi-port” valves after the manifold. However, an alternative single-port design, SP-PWM3, produced distribution was equal to or slightly better than the VDM. The SP-PWM3 was not tested for sensitivity to hose length or tilt, but the low manifold pressures would imply that it would be more sensitive than the VDM. Like the cast manifold, orifices could be added at the individual outlets to elevate manifold pressure and reduce that sensitivity.

Valve size may be a limiting factor for the single-point concept. The valves used on the single point PWM systems were the largest available as standard production, but they were marginal in flow capacity. Total valve flow at 50% duty cycle was in the range of 250-350 lbs/hour, implying a capacity of approximately 600 lbs/hour at maximum duty cycle. For comparison, a typical 20-shank, 16” spacing applicator, applying 200 lbs N/acre at 6 mph would require a total flow of 4730 lbs of NH_3 per hour. If the 20 shanks are fed by two SP-PWM units, each unit would have to flow nearly 2400 lbs of NH_3 per hour, roughly four times the capacity of the valves used on this project.

At 50% duty cycle, the MP-PWM design produced by far the most uniform distribution, averaging less than half the COV of the nearest competitor (the SP- PWM3). Uniformity decreased at high and low duty cycles, but was always competitive with the VDM. The MP-PWM meters and divides the total NH_3 flow while the NH_3 is in the high-pressure liquid state.

pressure liquid state. The fact that pressure drop across the individual PWM valves is very high essentially eliminates any influence of unequal hose lengths on uniformity. Although not tested for sensitivity to tilt, the MP-PWM concept is expected to be virtually unaffected by that factor, as well.

Results from the Kansas testing of a static system were encouraging enough to lead to a field implementation of the multi-port ammonia application using pulsed valves and a commercial rate controller. While no detailed quantitative data were recorded from the field, the system allowed faster vehicle speeds and more uniform application to the obtained. The hardware and components used are shown in Figures 9-11.

Figure 9. System for precision application of anhydrous ammonia. Electronic rate controller installed in tractor, pulsing valves installed on radial manifold with individual tubes to each knife.

Figure 10. Anhydrous cooling tower and electronic module for controlling pulsed emissions.

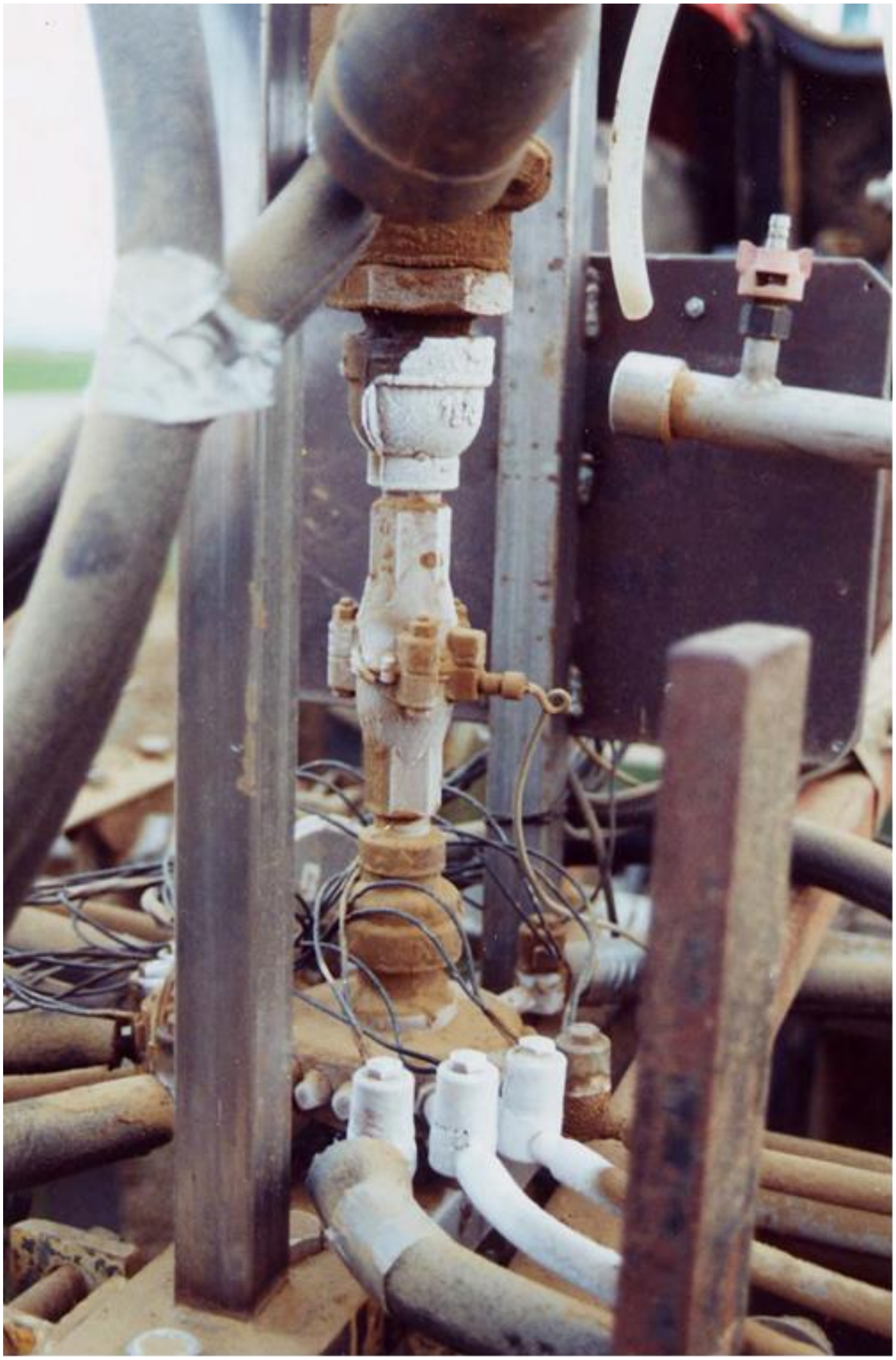


Figure 11. System flowmeter, radial manifold and individual pulse metering valves for each knife.