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The system design and evaluation of a microprocessor controlled dispenser using a radar ground-speed sensor

Yu-Charn Chen
University of Northern Iowa

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The system design and evaluation of a microprocessor-controlled dispenser using a radar ground-speed sensor

Chen, Yu-Charn, D.I.T.

University of Northern Iowa, 1988

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Ann Arbor, MI 48106

THE SYSTEM DESIGN AND EVALUATION OF A MICROPROCESSOR CONTROLLED DISPENSER USING A RADAR GROUND-SPEED SENSOR

A Dissertation
submitted
In Partial Fulfillment
of the Requirement for the Degree
Doctor of Industrial Technology

Approved:

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July 10, 1988

Dedicated to

My parents CHARNG-SHOU and YU-MEI

on their sixtieth birthdays

and to

My wife LIH-JIUN and son Clifford

for without their support

and understanding

this study would have been possible.

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THE SYSTEM DESIGN AND EVALUATION OF A MICROPROCESSOR CONTROLLED DISPENSER USING A RADAR GROUND-SPEED SENSOR

An Abstract of a Dissertation
Submitted
In Partial Fulfillment
of the Requirements for the Degree
Doctor of Industrial Technology

Approved:

Rex W Pershing

Dr. Rex W. Pershing, Faculty Advisor

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July 10, 1988

ABSTRACT

This experimental research focused on the design of a new approach to control seeds dispensers and to analyze the performance characteristics of a Doppler radar ground speed sensor for a microprocessor control dispenser. The research focused on comparing the effectiveness of using a radar unit with a fifth-wheel encoder for measuring ground speed when both were connected to a microprocessor controlled seed dispenser.

The system designed for this study consisted of hardware and a computer program in 6502 assembly language. The hardware for this study consisted of a monitor device, microprocessor control unit, stepper motor, fifth-wheel encoder, Doppler radar and the device for the planting of seeds.

The software was designed by the researcher during an internship at Rawson Control Systems Corporation. Laboratory tests and field tests were used in the study to test the Doppler radar and microprocessor control unit. Laboratory tests were conducted to determine the accuracy of the microprocessor based speedometer, seed spacing control and the output waveforms from the Doppler radar and the fifth-wheel encoder under controlled conditions. The laboratory provided an environment for controlling the variables of this research. Field tests were conducted to test the accuracy and variability of the seed spacing control under actual conditions. The resultant data were analyzed using the _t_ test, _F_ test and one-way ANOVA. The most important findings were:

1. There was a significant difference between the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices (calculated by the microcomputer in M. P. H.) when an input signal was varied from 1 Hz to 574 Hz to the control box. The Doppler radar was more sensitive to frequency changes than the fifth-wheel encoder.

2. Under the laboratory tests, without considering the slippage of the wheel, there was no significant difference between using the fifth-wheel encoder and the Doppler radar as sensors in dispensing seed at a uniform spacing.

3. In the field tests, a significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder with regard to dispensed seeds at a uniform spacing, due to possible wheel slippage. The Doppler radar controlled unit dispensed seeds at a more uniform spacing than the fifth-wheel encoder control unit.

4. There was a significant difference between using the Doppler radar sensor and the fifth-wheel encoder with regard to variability of output signals from the sensors. The Doppler radar provided a less variable output signal than the fifth-wheel encoder.

5. During the field test, the researcher observed that one problem of using the Doppler radar unit was the slight vibration of the Doppler radar caused by the engine of the tractor. This caused some erroneous input signals to the microprocessor control unit because the monitor displayed a fractional part of a ground speed (MPH) while the tractor was stationary.

The results obtained from the data analyses show that using the Doppler radar unit as a sensor in the field tests will provide a more uniform spacing control. In general, the Doppler radar controlled unit was considered to be more accurate than the fifth-wheel encoder control unit.

CHAPTER I

Introduction

Traditionally, occupations like farming was not thought of as being highly sophisticated. Today, in truth, as Badrkhan, Daggett and Williams (1985) indicated, "agritechnology in the United States is probably the country's most mechanized profession" (p. 158). Farming is an extremely efficient profession. People who work in farming in the United States make up only 2.2 percent of the population (U. S. Bureau of the Census, 1986, p. 619). Yet, this small group of farmers not only feed more than two hundred million American citizens, but also export food that feeds a large part of the population of the rest of the world.

As the world's population increases, decisions about how to produce as much food as possible are important. Since, only about forty percent of the land in the world can be used for crop production, the objective of agriculture is to produce as efficiently as possible.

Production efficiency is defined by some as ways of reducing the expense of growing crops. A major variable cost in crop production is fertilizer and seeds which, at present, are being spread by mechanical metering devices, which are traditionally driven by carrying and driving wheels. These metering devices are inaccurate and wasteful because of the possibility of wheel slips.

The Nebraska tractor test as shown in the Doane's agriculture report (1986, pp. 341.1-341.6) indicated that the percentages of slip by drivers varied from 10.15% to 15.00% when testing 108 kinds of tractors (see Appendix A). This problem was addressed by this study using a microprocessor-controlled seed dispenser and a Doppler radar ground-speed sensor.

This study had two major phases, the first was to design an interface device for the Doppler radar and microprocessor control unit and develop a software program to instruct the "control unit." The second phase of the study was to compare the results of using the Doppler radar and the fifth-wheel encoder microprocessor control units for accuracy of dispensing seeds.

Significance of the Study

When using agricultural equipment for planting or spraying operations, it is important to apply the exact number of seeds, and/or amount of herbicides, fertilizers, or pesticides required for economic production. A major factor affecting the planting and spraying operations is the ground condition which affects the speed of the equipment. By accurately determining true ground speed, the correct amount of chemicals and seeds can be applied.

Presently, most off-highway and agricultural equipment uses the wheel method to determine the ground speed. The most common practice is to use a magnetic pickup which, when attached to the driving wheels, converts the rotary motion to electrical pulses that are converted to speed on a monitor to be readily viewed by the driver. It is very difficult to measure accurately the true speed of a tractor in the field, since tires slipping through loose soil produce erroneous speedometer readings.

Tsuha, McConnell and Witt (1982) noted the following problems with this technique:

> 1. Rear or driving wheels can slip relative to the ground, therefore producing erroneous ground speed readings.
> 2. When sending ground speed from front wheels, the front wheels may be off the ground at times, hence, not indicating true ground speed.
> 3. Poor accuracy and resolution.
> 4. As a result of steerage, front wheels may not track ground speed because of wheel skidding. (p. 47)

Stuchly, Thansandote, Mladek, and Townsend (1978) stated "the fifth-wheel method, generally used for testing automobiles on test grounds, does not provide satisfactory results in typical agricultural operating conditions because of the slip of drive wheels which occurs at all practical drawbar loads" (p. 24). Grimes and Jones (1974) found that "the output of the mechanical units is proportional to the angular rotation rate of the drive shaft and therefore is subject to errors resulting from tire wear, variations in tire inflation, and wheel slip" (p. 804).

Another important reason to monitor ground speed is to check how much the tractor's wheels are slipping. The amount of slippage is controlled by adding or removing ballast. If a tractor is weighed down so much that its tires bite into the soil without any slip, the extra weight strains the drive train and the increased rolling resistance sends fuel consumption "skyrocketing." On the other hand, with too little ballast, or allowing too much slip, the farmer is using his fuel energy to tear up his tires rather than doing any productive work.

The solution to the problems associated with measuring ground speed for off-highway and agricultural equipment requires a method with greater accuracy than the drive wheels and fifth-wheel method. The method used in this study combined a Doppler radar unit for measuring ground speed and a microprocessor control unit for dispensing seeds.

Statement of the Problem

The study was designed to compare the effectiveness of using a Doppler radar unit with a fifth-wheel unit for measuring ground speed when both were connected to microprocessor-controlled seed dispensers. Specifically, the study focused on the following research questions:

1. Did the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices (calculated by the microcomputer in miles per hour) differ significantly when the input signal was varied from 1 Hertz (Hz) to 574 Hz to the control box?

2. Did the Doppler radar sensor and the fifth-wheel encoder differ significantly in dispensing seeds with a uniform spacing?

3. Did the output signals from the sensors significantly differ in variability for the Doppler radar and the fifth-wheel encoder?

Limitation

Because of the constraint of time and financial resources, the research focused on the design and testing of the ability of the software to control the assembled Doppler radar/microprocessor system. Since this research was for a chosen industry, the researcher used the fifth-wheel encoder and the Doppler radar units supplied by the Rawson Control Systems Incorporated.

Definition of Terms

To eliminate possible confusion, the following definitions of terms are provided to establish a common interpretation.

Agritechnology. A system of technologies that applies the principles of agriculture, mechanics, and computer science (Badrkhan, Daggett, & Williams, 1985, p. 180).

Assembler. The software routines which translate source language programs into a machine-readable language or object code (Queyssac, 1978, p. 111).

Doppler Effect. The apparent change in the frequency or radio wave reaching an observer. The change is due either to motion of the source toward or away from the observer, to motion of the observer, or both (Graf, 1978, p. 210).

Encoder. An electromechanical device that is attached to a shaft to produce a series of pulses to indicate shaft position; when the output is differentiated, the device is an accurate tachometer (Graf, 1978, p. 250).

Phase. In a periodic wave, phase is a fraction of the period of time which has elapsed, measured from some fixed origin (Graf, 1978, p. 522).

Phase Difference. The time in electrical degrees by which one wave leads or lags another (Graf, 1978, p. 523).

Photo-Coupled Isolator (H11L2). An electronic device which has a gallium arsenide, infrared emitting diode optically coupled across an isolating medium to a high speed integrated circuit detector (General Electric Corporation, 1984, p. 274).

Quadrature. The state or condition of two related periodic functions or two related points separated by a quarter of a cycle, or 90 electrical degrees (Graf, 1978, p. 576).

Slip. Slip is travel reduction of the driving surface of the wheel relative to the supporting surface (Hunt, 1986, p. 19).

Spectral Spread. The result of the divergence of the antenna beam (Brookner, 1977, p. 253).

Stability. The ability of a component or device to maintain its nominal operating characteristics after being subjected to changes in temperature, environment, current and time (Graf, 1978, p. 694).

Stepper Motor (or Step Motor). A device used to convert electrical pulses into discrete mechanical rotatory movements (Airpax Corporation, 1982, p. 2).

CHAPTER II

Review of Literature

A computer-assisted literature search was done to identify appropriate literature for review. A professional engineering computer data base, called Compendex (COMP), was identified and subsequently screened through the facility located in the University of Northern Iowa library. COMP provided worldwide bibliographical coverage of technical and engineering-related journal articles, conference proceedings, dissertations and monographs. BRS Information Technologies (1983) indicated "COMP covers worldwide technical literature in civil, environmental, geological, petroleum, mechanical, nuclear, aerospace, computer, electrical, chemical and industrial engineering" (p. 6).

Several reports were found dealing with the design of Doppler radar and microcomputer applications in the last ten years. A review of the literature indicated that research had concerned mainly with meteorological or aeronautical aspects in mathematical or theoretical models.

Few studies were found from the aforementioned search with regard to the use of a Doppler radar in agriculture for dispensing seeds. Because of the paucity of literature on the use of a Doppler radar in this area, the emphasis was shifted to non-radar-microprocessor dispensing techniques.

Review of Related Research

The history of corn dispensers in the United States is quite interesting. Davison (1937) stated the following:

> Up to 1850 corn was grown almost entirely by the use of hand tools, being planted and cultivated with the hand hoe. The next step was a hand planter which combined the functions of opening the soil and depositing the seed in hills . . . In 1839, D. S. Rockwell secured a patent on a corn planter carried on rollers and having shovel furrow openers. Corn was dropped with a reciprocating slide, with cells moving alternately under the seed box and over the seed tube . . . G. W. Brown was responsible for the rotary seed planter and shoe furrow openers . . . The earliest machines simply drilled the corn in rows. Later, a hand dropping machine was introduced permitting the operator to drop hills on lines laid out across the field with a sled marker. (pp. 163-172)

The accurate of dispensing corn kernels has been of interest since the development of early corn planters. In 1912, Sjogren reported that "corn planter tests with accuracy varying from 72.3 percent to 91.3 percent for three-kernel hills with four makes of edge drop planters using graded seed" (p. 46).

In 1946, Morrison developed a corn planter dropping mechanism for ungraded seed. He found that:

> The cumulative dropping system had remained relatively unchanged since its introduction in the 1890's. Only the shape of the seed cells was varied slightly to overcome a tendency for the largest seeds to remain in the hopper while the smallest seeds were planted first. Otherwise, the present dropping mechanism was the same as the one in common use more than 40 years ago. (p. 10)

Grimes and Jones (1974) found that "it was generally difficult to accurately determine speed directly; consequently, a distance measurement was often employed" (p. 812). In their research, errors of less than 4 percent over the speed range of 16-112 km/h and various road surfaces were reported. They suggested that "further improvement was possible by filtering the effects of spectral reflection in the presence of vehicular bounce" (p. 813).

Stuchly et al. (1978) performed an experiment using Doppler modules, MA-86656A (Microwave Associates) and General Electric (GE) 2071 to measure the true ground velocity of a tractor. The ground velocity was also monitored by a fifth-wheel assembly. Measurements of the ground velocity were conducted at different viewing angles and on four different surfaces of the gravel road, asphalt road, grass-covered field and plowed field. During field tests, the signals from the Doppler radar and from the fifth-wheel assembly were simultaneously recorded on a magnetic tape recorder. The signals from both the Doppler radars and the fifth-wheel assembly were then used to determine the ground velocity through mathematical calculations. Findings indicated that:

> The true ground velocity of the tractor could be measured by a Doppler radar on different field surfaces . . . the differences between the velocities measured by both methods were found to be below 0.5 percent for the MA radar and below 2 percent for the GE radar (p. 30). The Doppler velocity meter is particularly suitable for plowed field. (p. 29)

This research demonstrated that the Doppler radar could be used to determine ground velocity. However, they did not apply their Doppler radars and the fifth-wheel encoder to a microprocessor controlled dispenser to control seed spacing, which was the main thrust of this research.

Skotnicki and Stewart (1980) conducted research on an x-band collision avoidance radar for emergency vehicles. They explored one possible implementation of the theoretical design and predicted that "the signal processing capabilities of the microprocessor are barely tapped, and can be expanded at very little cost" (p. 85).

Polise and Moskovitz (1981) studied the architecture of the microprocessor system and reported this at the 1981 Southeast Conference of the Institute of Electrical and Electronics Engineers (IEEE). They presented "an overview of the computer program functional specification and design implementation which would satisfy the Automatic Target Detector (ATD) requirements" (p. 26).

Lumia (1981) investigated a microprocessor-based quality control system. He found that one of the processes in the manufacture of aluminum pressure cookers involved welding a thick plate to the bottom of the pot to help spread the heat as well as to reduce the thermal fatigue of the metal. He developed a microprocessor-based system to test the quality of this weld based on the frequency analysis of sound eminating from the joint when mechanically stimulated. He found that "Acceptable error rates were obtained within the 6-second-processing time limit" (p. 791).

Raghavan and Satyanarayana (1983) indicated that "digital systems were stable and flexible. They were free from drift and interference problems and occupy less space in a microprocessor-based digital controller system" (p. 57).

Robbins and Nnaji (1985) were able to develop techniques for acquiring digital radar rainfall data via commercial grade telephone lines and to demonstrate use of the rainfall data using a commercial microcomputer. The radar sets were operated by the National Weather Service (NWS) but the rainfall data were transmitted over telephone lines by private companies. The microcomputer system developed in their research accessed the digital rainfall data, decoded it and allowed its use in applications other than graphical display. Findings indicated that "radar rainfall data can be effectively collected, processed and applied" (p. 766).

Buckingham (1986) conducted a survey in which he attempted to determine what will be the greatest changes in agricultural machinery in the next 25 years. It was found that "more than a third of the respondents predicted additional development in sensors for crop and soil moisture, and additional monitors for speed and accuracy of equipment operations would be needed" (p. 14). He also projected that "the increasing use of electronics and microprocessor controls for automatic adjustment of planting and harvesting equipment would be the greatest change in the next 25 years" (p. 14).

Adams (1980) stated that "microprocessors were being used in many of the radar's subsystems to simplify control, minimize costs and extend the automatic fault detection and isolation capability of the system" (p. 2). Williams (1980) indicated the following were the most significant current and future applications in the radar's subsystem:

Antenna
- Compute interelement phase shift commands for electronic beamsteering.

Transmitter
- Monitor performance continuously on-line.
- Protect high value components when a fault occurs.
- Notify maintenance personnel of location of component failures.

Synchronizer
- Generate timing sequences for control of radar as a function of mode and waveforms.

Signal Processor
- Track velocity of moving weather clutter to allow cancellation by clutter filter.
- Monitor system noise level.
- Set thresholds to maintain constant false alarm rate.
- Correlate target returns from adjacent beams.
- Provide correlated target reports to system computer.
- Perform time and angle alignment of radar and beacon videos for display.

Radar Set Control
- Provide prompts to operator.
- Perform validity checks on operator-entered commands. (p. 1)

Review of Related Technology

Doppler Radar

The Doppler radar-microprocessor controlled system which was developed for this study was based on the use of equipment known as Doppler radar. Usually it is arranged as shown in Figure 1.

An operating frequency (f_o), 24.125 GHz±40 MHz, is generated in the continuous wave (CW) oscillator. A small portion of this signal is extracted through a direct coupler while the remainder is transmitted to the target. The signal reflection, at shifted frequency (f_s), is returned and picked up by the antenna. This signal is fed into the mixer where f_o and f_s were compared.

Since the signal had to travel to the target and reflected to the transceiver, the distance it would travel is equal to twice the range

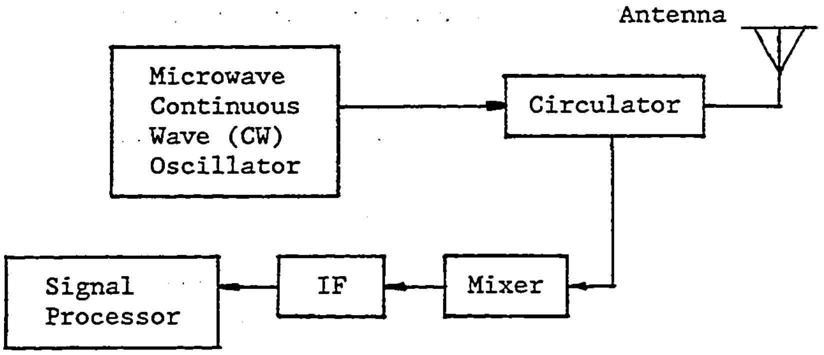


Figure 1. Block diagram of a Doppler radar system. From "Radar/Microprocessor Measurement System for Near-zero Speeds and Vehicle Dynamics" by M. E. Smirlock, 1981, Applications of Electronics to Off-highway Equipment, p. 4. Warrendale, PA: Society of Automotive Engineers.

of the target. The total number of wavelengths corresponds to the time that is required for the signal to travel to the target and be reflected to the radar. This appears as a fixed difference in phase between the transmitted signal and the receiver signal at the mixer of the radar unit when both the radar and the target were stationary.

As relative motion between the ground and the Doppler radar unit takes place, the range and the phase relationship between transmitted and observed signals would continuously change with time. Smirlock (1981) stated "the change of phase that is produced when the target is moving becomes a frequency. This frequency is in effect the Doppler frequency, because velocity is the time rate of change of distance" (p. 4).

If a Doppler radar is mounted on a tractor moving with a velocity V, then the Doppler frequency is given by:

$$f_d = 2V/\lambda * \cos\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (1).$$

Where V is the velocity of the tractor in m/sec

λ is the transmitter wavelength in meters

θ is the antenna viewing angle in degrees, and

f_d is the Doppler frequency in Hz (Brookner, 1977, p. 253).

Differentiating equation (1) yielded

$$df_d = -2V*\sin\theta * d\theta/\lambda$$

or $$f_d = -2V*\sin\theta * \Delta\theta/\lambda$$

Where df_d is the differential change in f_d for a differential change, $d\theta$, in the scatterer squint angle, $\Delta\theta$. f_d is also contributed by the "fluctuation noise."

It was found that the higher the frequency, the stronger the Doppler return signal (Stuchly, Thansandote, Mladek, & Townsend, 1978, p. 24). However, an increase in the operating frequency was associated with an equivalent increase of the spectral spread and did not directly improve the accuracy of measurement. In addition, the price of the Doppler unit increases sharply as the operating frequency increased (Stuchly et al., 1978, p. 25).

Stepper Motor

To operate the control system correctly, a stepper motor was employed in this study. The operation of a stepper motor consisted of discrete motions of uniform magnitude, rather than continuous motion. Kordik (1974) found the following:

> When properly applied and controlled, the output steps are always equal to the number of input pulses. Each pulse advances the rotor shaft and latched it magnetically at the precise point to which it is stepped. (p. A-1)

It was reported that "the no load or constant load accuracy of each step is within ± 6.5%, noncumulative" (Airpax Corporation, 1982, p. 3). Therefore, a 48-step stepper motor would position to within 0.5°, whether the rotatory movement was 7.5°--one step, or 7500°--one thousand steps. The report from Airpax (1982) also pointed out:

> The step error is noncumulative. It averages out to zero within a 4-step sequence which corresponds to 360 electrical degrees . . . Thus, the most accurate movement would be to step in multiples of four since electrical and magnetic inbalances are eliminated. (p. 3)

The control of stepper motors can generally be classified under open-loop and closed-loop control circuits. The simplest operation of a stepper motor is the open-loop control circuit. In the open-loop control circuit, the phase switchings of the stepper motor are controlled by a pulse generator which sends a sequence of pulses to the motor driver circuit. The motor makes one step for each pulse the motor driver receives from the pulse generator. For a pulse-train with uniformly spaced pulses, the repetition rate of the pulses determines the speed of rotation of the motor. Kuo and Yackel (1973) stated that:

> Under the open-loop control, the stepper motor is subject to a sequence of pulses. If the motor remains in synchronism with its input pulses train, the time intervals between the successive pulses determine the speed of the motor . . . In many situations stepper motors are considered more attractive for incremental motor control than D.C or A.C motors, because of the simplicity of the open-loop control which does not require feedback encoders, and the system is always stable. (p. B-3)

The basic elements of an open-loop stepper motor are shown in Figure 2. Notice that there is no feedback routine used.

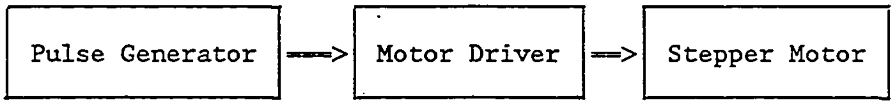


Figure 2. Basic elements of an open-loop stepper motor control system. From "On Current Detection in Variable-Reluctance Step Motor Control Systems and Devices" by B. C. Kuo, 1977, Proceedings Six Annual Symposium Incremental Motor Control Systems and Devices, p. 205.

Various devices such as optical encoders or magnetic Hall effect sensors can be used to close the control loop in order to obtain the maximum torque and acceleration from a given stepper motor. "In a typical closed loop system, a two quadrature track encoder capable of detecting direction could be used to sense that a step had been made before allowing the next pulse to step the motor" (Airpax, 1982, p. 10). The basic elements of the closed-loop control scheme of a stepper motor are shown in Figure 3.

One disadvantage with the closed-loop control system, however, was that the exact speed of the step motor was dependent on the drive voltage, the load, and the lead angle of the pulses that were fed back

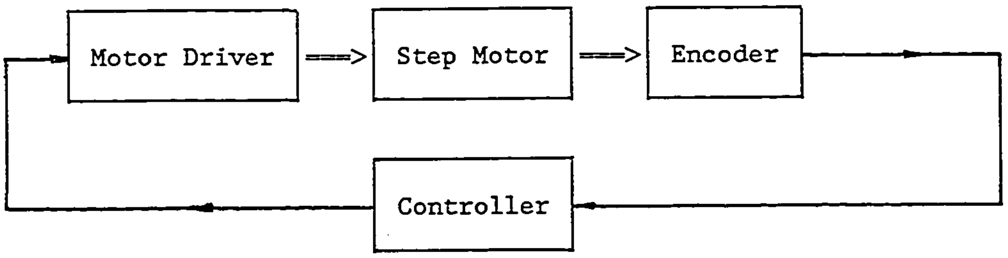


Figure 3. Basic elements of a closed-loop stepper motor control system. From "On Current Detection in Variable-Reluctance Step Motor Control Systems and Devices" by B. C. Kuo, 1977, Proceedings Six Annual Symposium Incremental Motor Control Systems and Devices, p. 205.

from the encoder. This made it more difficult to precisely adjust for the desired motor speed compared to the open-loop case where the speed was determined by the input pulse rate (Kuo & Yackel, 1973, p. B-3).

Also, the closed loop system would be more complicated and expensive than the open loop system. Kuo (1977) noted "In certain applications, the closed-loop control cannot be cost effective when compared with the simple open-loop scheme" (p. 205). Therefore, the open-loop control system would be used in this study.

Encoder

The four basic components of an optical encoder are "the light source, the rotating code disk, the light detector and the signal processing unit" (Kafrissen, 1984, p.125). The light source can be either a Light Emitting Diode (LED) or the incandescent lamp. LEDs can generally withstand mechanical vibrations that lamps cannot, and are better for rugged field application. The light detector (e.g., phototransistor) generates an output when excited by light energy. The rotating code disk is a mechanical device usually made of glass or plastic. The disk has opaque and transparent areas deposited onto it in a concentric pattern, which determines the accuracy and the resolution of the encoder. The signal processing unit detects the signal, generates digital pulses, shapes the output, filters and amplifies for transmission.

Two types of rotary optical encoders are available as "incremental" and "absolute position" encoders. Kafrissen (1984) indicated that:

> Incremental optical encoders generally have two signal outputs that are in quadrature (i.e., 90^{o} phase difference) for position and direction data, plus a marker signal output for initialization. The absolute optical encoder makes absolute position data available in the form of natural binary, gray code, or binary-coded decimal formats. The code is determined by the coding pattern on the disk, while the format in the resolver system is accomplished by the electronics. (p. 127)

As the disk rotates, light pulses converted by the light detector into electric pulses are filtered, shaped and amplified. The signal then can be counted by a counter in a computer. In this study, an incremental optical encoder was used for the purpose of the research.

Summary

The review of literature included a review of related research and a review of related technology. A review of the related research indicated that research has been mainly concerned with meteorological or aeronautical aspects in mathematical or theoretical models. Very few studies were found regarding the design and evaluation of a Doppler radar in agriculture for dispensing seeds, although some unpublished work has been reported by private industry. An overview of agriculture and Doppler radar/microcomputer technology development was provided in order to provide a framework for this research. Related technology, the nature of the Doppler radar, the stepper motor and the fifth-wheel encoder were discussed. These led to the hardware and software designs presented in the next chapter.

CHAPTER III

Methodology

This research was experimental in nature. A new software program was designed and the effectiveness of the performance characteristics of a Doppler radar ground speed sensor for a microprocessor-control dispenser was to be evaluated through laboratory tests and field tests.

System Design

The system designed for this study consisted of hardware and a computer program in 6502 assembly language. The hardware for this study consisted of a monitor, microprocessor control unit, stepper motor, fifth-wheel encoder, Doppler radar and device for the planting of seeds or dispensing of various chemicals used in planting. Some of the hardware was developed and improved upon by Mr. Douglas M. Bruce and by this researcher of the Rawson Control Systems Corporation at Oelwein, Iowa. The software, however, was specifically developed by the researcher and adapted to this microcomputer system.

Doppler Radar

The output frequency (Doppler frequency) of the Doppler radar unit was based on (a) the antenna viewing angle, (b) the velocity of the tractor, and (c) the transmitter wavelength. Since the wavelength of the Doppler radar frequency was a constant, the antenna viewing angle therefore was critical when checking the speed of a tractor or vehicle. A small angle error would cause a greater frequency error.

For example, if the antenna viewing angle changed from 37 degrees to 47 degrees, the Doppler frequency would be changed from 57.4211 Hz to 49.0351 Hz. This change in viewing angle would create a 14.60 percent error (see Appendix B). In this study, the Doppler radar unit selected was made by the TRW Corporation, and was mounted on the tractor at 37 degrees viewing angle using a "Level and Angle Finder" (see Appendix C for specifications of the Doppler radar and the Level and Angle Finder).

Encoder

A photo-electronic type encoder was used in this research and was set up as shown in Appendix D. It consisted of an opaque cylindrical disk on the shaft connected to the fifth-wheel, as illustrated in Figure 4. This disk had 1270 slots (transparent portions) along its periphery. At one side of the disk, there was an infra-red light sensor and a fixed mask with the same number of slots per unit as the disk. At the other side of the disk, and on a line with the infra-red light sensor, was placed an infra-red light source. When the opaque portion of the disk and the mask were between the light source and the light sensor, the sensor would not receive any light and produces no output. However, when the transparent portion of the disk and the mask were between the two (light sensor and light source), the light falling upon the sensor produced an output pulse.

The frequency at which these pulses were produced depended upon the number of slots in the disk and its speed of rotation. Since the number of holes was fixed, the pulse rate thus was a function of the speed of rotation. The pulse rate was be counted by the microprocessor used in this study.

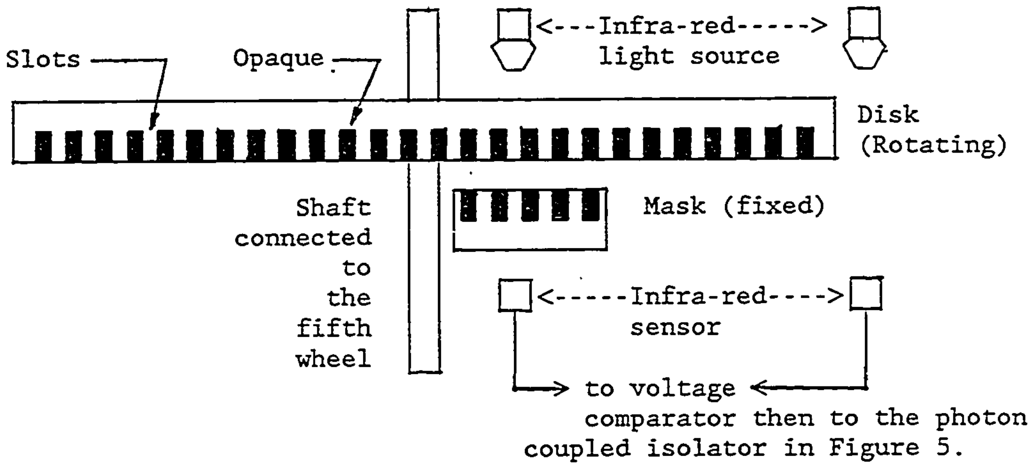


Figure 4. The diagram of the fifth-wheel encoder disk.

Microprocessor Based Control Box

Due to an unacceptable level of accuarcy in the microprocessor based control box, it was necessary to develop a new program that used the Doppler radar signal to determine ground speed and control the seed dispensing. The new program was stored in the EPROM chip in the control box. The function block diagram of the control box is illustrated in Figure 5.

The following paragraph describes the operation principle of the block diagram in Figure 5. As relative motion between the ground and the Doppler radar unit on the tractor took place, the Doppler radar

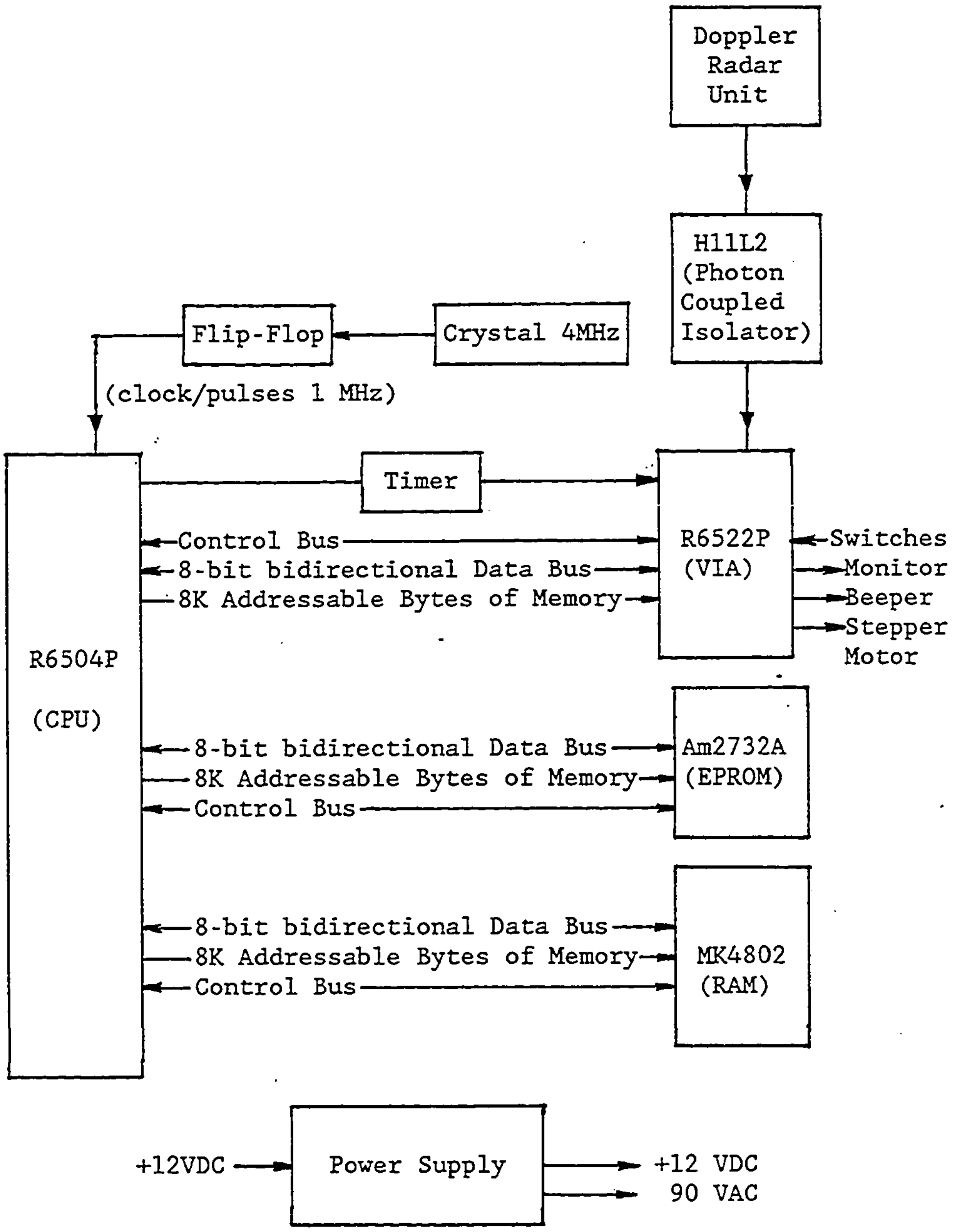


Figure 5. A block diagram of the microprocessor and Doppler radar control system.

unit converted this motion to a Doppler frequency, which was transformed into digital pulses. These digital pulses were transmitted to the microprocessor control unit (R6504P) through a photo-coupled isolator (H11L2) and a Versatile Interface Adapter (VIA) (R6522) (as indicated in Figure 5). The VIA contained a Schmitt Trigger for noise immunity and pulse sharpening. Also, the VIA was used to interface other external devices to the microprocessor.

The Central Processing Unit (CPU) responded to inputs and produced outputs as determined by the sequence of instructions which were stored in an Erasable Programmable Read Only Memory (EPROM) (Am2732A). New and variable information was stored in Random Access Memory (RAM) (MK4802). The CPU used RAM to store information used in the decision making process. The crystal used in the control box generates a series of 4 MHz clock pulses. The pulses are sent to a flip-flop circuit in order to improve the waveform quality and to reduce the output frequency from 4 MHz to 1 MHz, as required by the central processor unit.

Software Design

All functions of the microprocessor control unit required the use of the computer program. The program had several functions including system control, performance monitoring and advancing the counters. The computer program for this study was developed by the researcher at the Rawson Control Systems Corporation during an internship.

In order to down-load the program into an EPROM chip, the "ORCA/M 6502 Assembler for the Apple II Computer (version 3.5)" was used to convert the source program into object program ("B" type file). A EPROM programmer and a "Super Serial Card" were then used to program the EPROM chip (see Appendix E). The software could only be tested with the control box (microcomputer) since this was a special design for this specific control box. It took more than one and a half years to complete the software design and laboratory tests.

System Control

The computer program was a sequence of instructions that order the CPU to control the operations of all the equipment. All information received through the input device, which included the Doppler radar and switches was processed by the computer and then forwarded to the designated equipment such as the monitor, beeper and stepper motor (as indicated in Appendix F). Information handling by the computer was on a "first in first out" (FIFO) base, which contained all interface states and timing outputs. The computer program allowed the operator to control the following variables: number of rows, row width, seeds per acre (population), number of seeds per five revolutions of the stepper motor, manual speed and test distance.

Performance Monitoring

The computer program provided continuous information regarding the performance of the control unit with respect to speed, distance, area, and population messages which were necessary to control the planting or fertilizing processes. The messages were updated every half second.

Principle of Operation

The computer program counted the number of input signal pulses from the Doppler radar before the stepper motor was advanced by one step. Each time a pulse was received from the Doppler radar, a counter was incremented, and then compared to the number calculated by the computer program. When the two values were equal, the stepper motor was advanced by one step, and the counter was cleared. The procedure was then repeated. Figure 6 shows the principle of this operation.

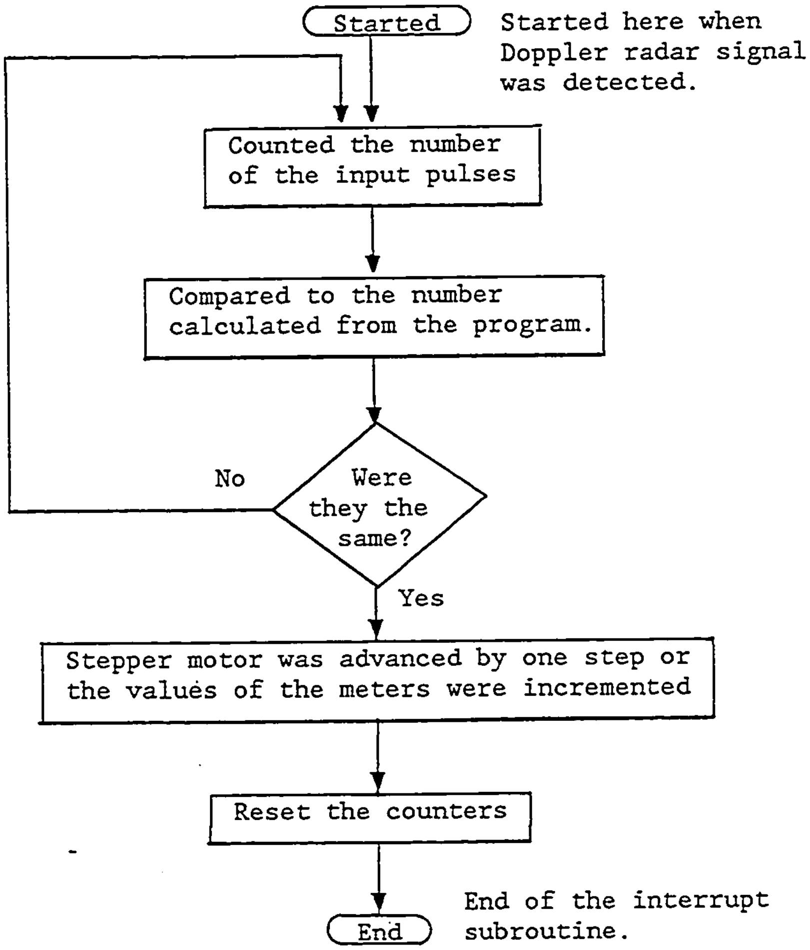


Figure 6. The first algorithm of the software function design.

Notice that the software was written based on using the Doppler radar at 37 degree viewing angle, therefore the Doppler frequency f_d would be:

$$f_d = 2 * 0.44704 * \cos 37 /0.0124352$$
$$= 57.421194 \text{ (Hz)}$$

Research Procedures

There were two kinds of tests in the study--laboratory tests and field tests. The laboratory tests were conducted to determine the accuracy of the microprocessor-based speedometer, seed spacing control and the output waveforms from the Doppler radar and the fifth-wheel encoder under controlled conditions. The laboratory at Rawson Control Systems Corporation provided an environment for controlling the variables of this research. Field tests were conducted to test the accuracy and variability of the seed spacing control under actual conditions. Mr. Allen L. Lorenc, President of Rawson Control Systems Corporation, gave the researcher permission to field-test the hardware and software in his field located in Fairfax, Iowa. The equipment used in this study is listed in Appendix C.

Laboratory Test Procedure

In the laboratory test, the following procedural steps were performed for testing both the Doppler radar unit and the fifth-wheel encoder.

1. The computer program was loaded into the microprocessor control unit.

2. An audio generator was connected to the input port of the R6522P Versatile Interface Adapter (VIA) (as indicated in Figure 5). The purpose of using the audio generator was to produce a variable input frequency simulating the fifth-wheel encoder and the Doppler radar frequency.

3. A digital frequency counter was used to monitor the input frequency.

4. A reed switch pulse-generator was attached to the stepper motor that would sent a signal to a counter for recording the revolutions.

5. The revolutions of the stepper motor were displayed on the digital counter.

6. By varying the audio generator, different frequencies were sent to the microcomputer. The speed of the stepper motor was controlled by the computer according to the program stored in the EPROM (as shown in Figures 7 and 8). The speed from the control box and the number of counts from the digital revolution counter was recorded for later analyses.

The Criteria of the Tests

Once the row width and seeds per acre were chosen, the seed spacing was calculated as follows: In this example, the number of seeds per acre was 25,000 and the row width was 36 inches. Given 1 acre = 43,560 ft^2 = 6,272,640 in^2.

$$\text{Seed spacing} = \frac{\text{Distance}}{\text{Seed}} = \frac{6{,}272{,}640\ (in^2)}{36\ (in) \times 25{,}000\ (seed)} = 6.9696\ (in)$$

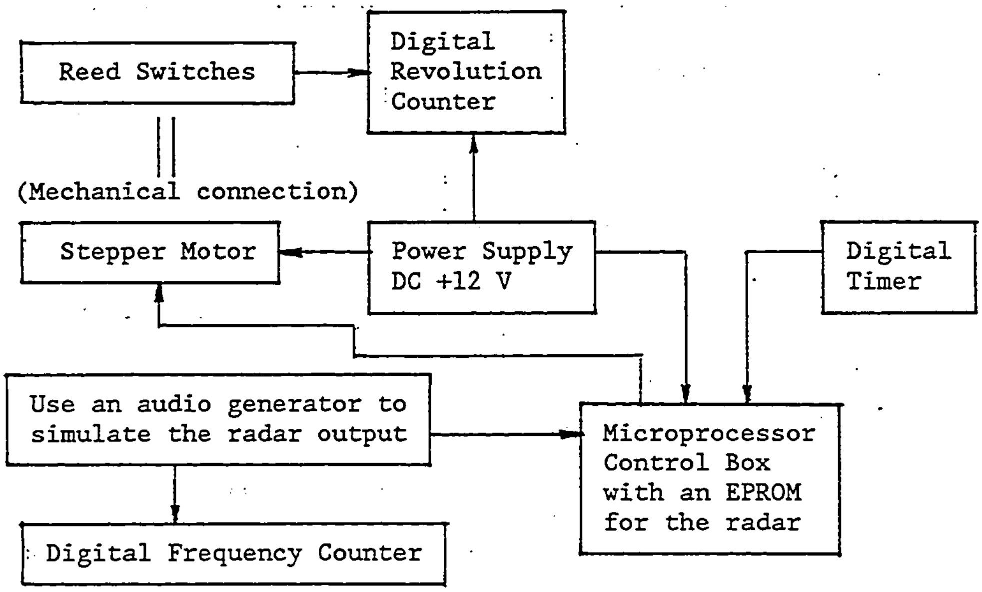


Figure 7. Equipment model for data acquisition using the Doppler radar in a laboratory test (speed vs. frequencies).

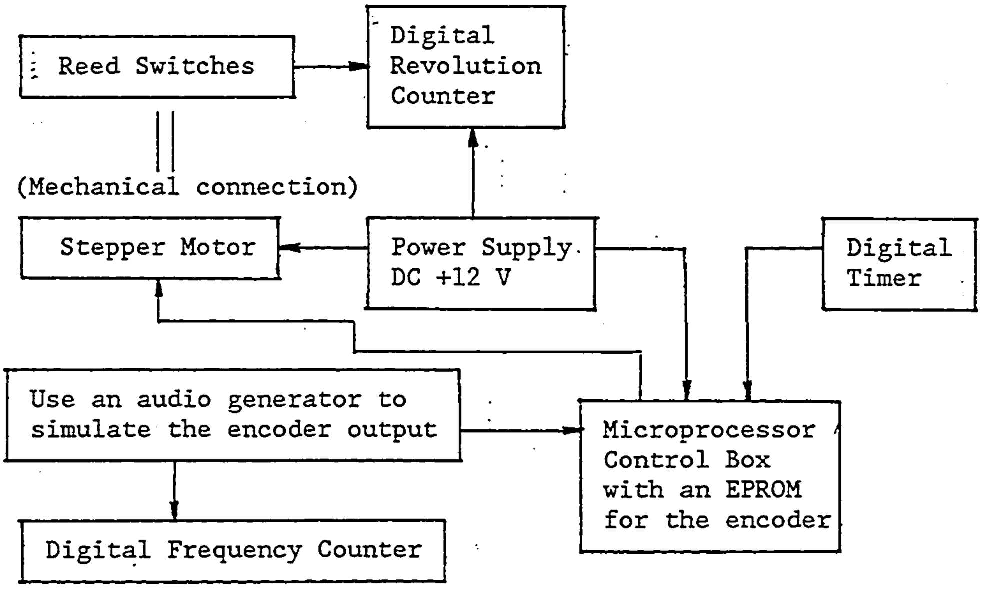


Figure 8. Equipment model for data acquisition using the encoder in a laboratory test (speed vs. frequencies).

Test of the Spacing of Seeds from the Laboratory Test

Laboratory tests were conducted before the field tests. Since the spacing was calculated from the ratio of distance/seed, 6.9696 inches as shown above, the seeds spread and the distance traveled were simulated as follows.

The number of seeds spread. From the digital revolution counter, the number of revolutions per minute of the stepper motor was obtained (8 counts was equal to 1 revolution). According to the design of the seed disc used in this study, one revolution of the seed disc would spread 6 seeds. Therefore, the number of seeds spread was 6 times as many as the number of revolutions of the stepper motor, or 0.75 times as many as the number of counts read directly from the counter.

The distance. The distance (feet) that the tractor traveled in one minute was obtained from the calibrated odometer on the microprocessor control box. In this test, the distance was 88 feet.

The variability of output signals of the fifth-wheel encoder and the Doppler radar unit were measured with an oscilloscope and a digital frequency counter as shown in Figures 9 and 10. The digital frequency counter reported this output frequency from the Doppler radar and the fifth-wheel encoder separately every second. The researcher recorded the frequency 30 times. An oscilloscope was used to observe the output waveform from both the Doppler radar and the encoder units. A clear, sharp and still square waveform meant that the output was stable. Since the fluorescent lamp was operated by a 60 Hz AC power source, a 120 Hz waveform would show on the oscilloscope and the digital frequency counter would detect a 120 Hz signal.

The AC shaded-pole motor was used to drive the fifth-wheel encoder. If a constant output was found from the oscilloscope and the frequency counter, the output of fifth-wheel encoder was stable. Due to the nature of the differences between the configurations of the Doppler radar and the fifth-wheel encoder, it was anticipated that the output frequencies would appear on different measurement scales.

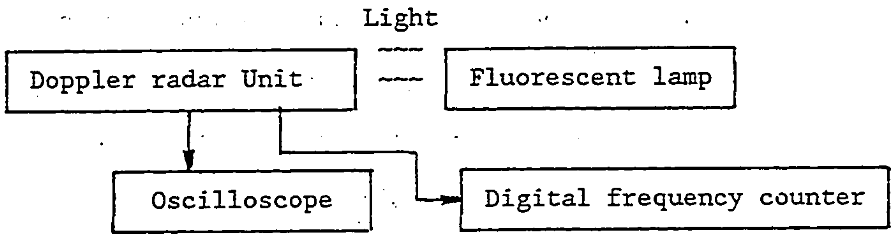


Figure 9. Doppler radar output waveform test.

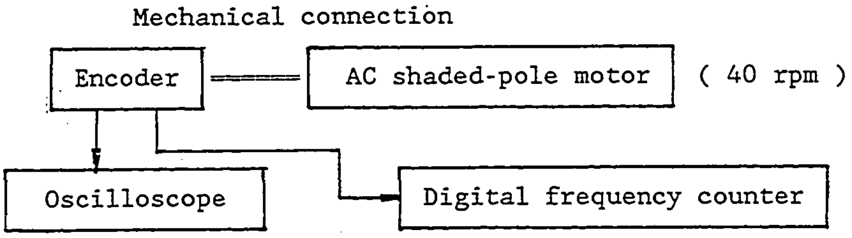


Figure 10. Fifth-Wheel encoder output waveform test.

Field Test Procedure

Field tests were conducted to test the control systems under actual conditions. In the field test, an experimental system was developed to test the accuracy and variability of the fifth-wheel encoder and the Doppler radar microprocessor control units, as shown in the Appendix G.

Normally, corn and soybeans were planted in different row width with different population (seeds per acre). The Pioneer Corp Notes (Pioneer Hi-Bred International, 1985-1986) provided a planting guide, showing that row width varied from 7 to 40 inches and population varied from 16,000 to 32,000 seeds per acre (p. 4).

In this study, the row width chosen was 36 inches and the population chosen was 25,000 seeds per acre. Two hundred seed spacings were measured and recorded. A Buffalo Plateless planter (4 rows) was used to spread the seeds in the field at Fairfax, Iowa; however, tractor engine difficulty prevented accurate measurement of seed spacings in the outlying parameters. Therefore, the researcher measured only the spacing between the center 200 seeds with a tape measure. The measurements were obtained for both the fifth wheel encoder (as indicated in Appendix D) and the Doppler radar control units. The 2nd test was conducted two weeks later. Since the seeds per acre were 25,000 and the row width was 36 inches, the spacing should be about 7 inches (6.9696 inches) as previously calculated.

Data Collection

Speed (MPH) and the number of revolutions of the stepper motor were collected from laboratory tests to answer the research questions in Chapter I. A prototype unit was then constructed to simulate the operation of the Doppler radar microprocessor-control unit (see Figures 7 and 8) to answer research question 1. By varying the audio generator output from 1 to 574 Hz, frequency vs. speed tables and curves (from the speedometer on the microprocessor based control box) were found for both the Doppler radar and the fifth-wheel encoder units (see Appendix H for data collection design).

To answer the research question 2, the following data (#Counts, Seeds, Distance, Spacing and Error%) were obtained from laboratory test (see Appendix H for data collection design). In this study, Row Width was 36 inches and Seeds per Acre was 25,000. Appendix H shows the data (Spacings) which were gathered from the field test.

Output frequencies from the Doppler radar and the fifth-wheel encoder were to be obtained from the laboratory test for research question 3. The output waveform from the oscilloscope is also included in Chapter IV.

Data Analyses

The objective of the analyses was to determine whether a significant difference existed between the using of the fifth-wheel encoder and the Doppler radar unit as a sensor to the microcomputer-control box. A package of statistical programs for the Apple II microcomputer (by Steinmetz, Romano, & Patterson, 1982) was used to analyze the data. Lotus 1-2-3 (Lotus Development Corporation, 1983) and MATC-CAD (Milwaukee Area Technical College Computer-Aided Drafting, 1985) programs were used for graphical representations. To answer research question 1, the t test was used to test the significance of the difference between two means of the matched samples.

One-Way analysis of variance (ANOVA) was used to decide whether the variance between means was greater than that expected from random sampling fluctuation. "With two groups only, the significance of the differences between means may be tested using either a "t test" or the analysis of variance." Ferguson (1981) said, "These procedures lead to the same result (p. 244). Therefore, one-way ANOVA was selected.

To answer research question 2, a one-way ANOVA was used to analyze the data obtained for the laboratory and field tests of seed spacing. The F test was used to compare the variances of the seed spacing from field tests for the Doppler radar and the fifth-wheel encoder. The F test was also used to compare the variances of the Doppler radar and the fifth-wheel encoder frequencies to answer research question 3.

CHAPTER IV

Data Analyses

The results of the data collected in this study, the statistical tests used for analyses and the results of the analyses are presented in this chapter. A probability of .05 was selected as the criterion for determining the significance of the findings.

Input Signal vs. Speed Display

Laboratory tests were conducted to investigate the relationship between the input signal frequency and the display of the speedometers to answer research question 1: Did the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices (calculated by the microcomputer in miles per hour) differ significantly when the input signal was varied from 1 Hertz (Hz) to 574 Hz to the control box?

The 574 pairs of speeds of the dispensing vehicle using the Doppler radar and the fifth-wheel encoder when input frequencies were varied from 1 Hz to 574 Hz are displayed in Appendix I. Notice that speeds increased from 0.0 M. P. H. to 10.0 M. P. H. for the Doppler radar and from 0.0 M. P. H. to 1.3 M. P. H. for the fifth-wheel encoder. The mean speed using the Doppler radar unit was 5.01 MPH and the standard deviation of the speeds was 2.89, while the mean speed using the fifth-wheel encoder unit was 0.67 MPH and the standard deviation of the speeds was 0.39 (see Table 1). Note that the speedometer was designed to show the speed up to one digit after the decimal point, therefore, the results were not continuous since the microcomputer would "round" the results of calculations before they were displayed on the speedometer on the control box (as indicated in Figures 7 and 8).

A two-tail *t*-test was employed to test the significance of the difference between two means of the matched samples. A significant difference was found between the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices when an input signal was varied from 1 Hz to 574 Hz to the control box, $t = 41.52$, $p < .001$.

Table 1

Means and Standard Deviations of Speeds

	Speed (M. P. H.)	
	Radar	Encoder
M	5.01	0.67
n	574	574
SD	2.89	0.39

*** $p < .001$ $t = 41.52$ ***

A computer graphic representation of the input signals vs. the Doppler radar and the fifth-wheel encoder speed displays is shown in Figure 11. One notes that the Doppler radar speed display was more sensitive to the input frequencies than the fifth-wheel encoder was, since the Doppler radar speedometer changed the speed display every 5 or 6 Hz while the fifth-wheel encoder changed the speed display every 43 Hz.

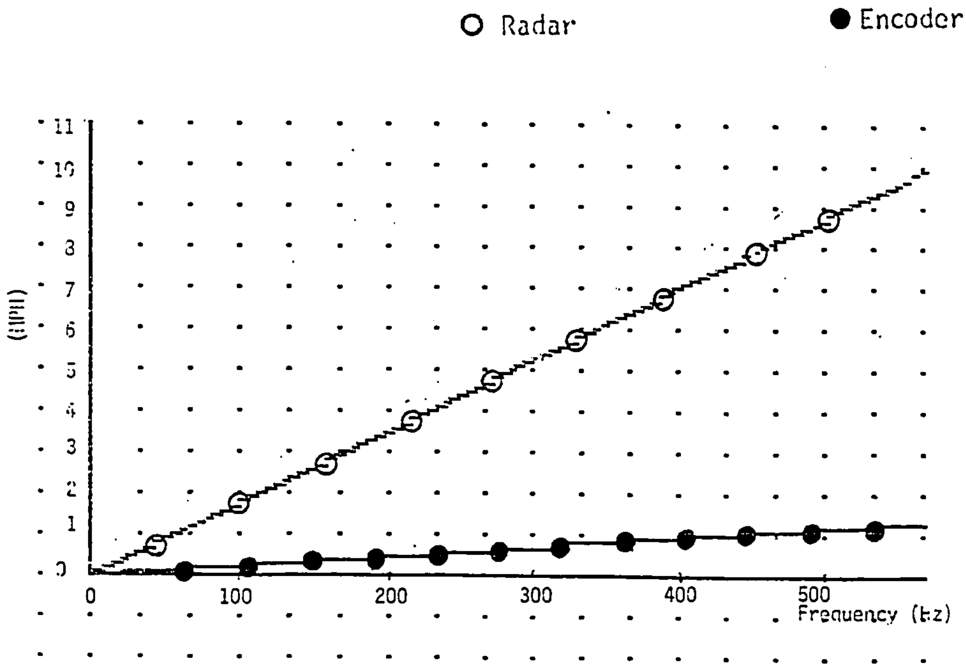


Figure 11. Graphic representation of the input signals vs. speed displays from the Doppler radar and the fifth-wheel encoder control boxes.

A Comparison of Spacing Control

Laboratory tests and field tests were conducted to answer the research question 2: Did the Doppler radar sensor and the fifth-wheel encoder differ significantly in dispensing seed with a uniform spacing? A second (2nd) test was conducted to determine the reliability of the laboratory tests.

Laboratory Test

The data collected from this laboratory test for research question 2 are presented in Appendix J. A graphic representation of the results from this laboratory test for research question 2 is presented in Figure 12.

In Appendix J, the number of counts was 203 which was multiplied by 0.75 to obtain the seeds value of 152.25. The distance of 1056 inches was divided by 152.25 to obtain the spacing of 6.94 inches. A similar procedure was followed to obtain the other forty nine spacing values. The error in percentage was obtained by dividing the difference between actual spacing with the 6.97 inches (standard spacing) by 6.97 inches (standard spacing). For the laboratory test on the Doppler radar, the error was 0.03/6.97 or 0.43%. An increase of the resolution of the reed switches counter (8 counts per revolution) might increase the "#Counts" and therefore decreased the error in percentage (Error%).

Notice that: (1) "#Counts" is the number shown on the digital revolution counter, 1 revolution is equal to 8 counts; (2) "Seeds" is the number of seeds calculated by: "Seeds" = "Counts" * 0.75;

(3) "Distance" is the distance that the tractor traveled in one minute at one mile per hour, or 1056 inches; (4) "Spacing" is calculated from dividing "Distance" by "Seeds"; (5) Error% = [(Spacing - SSP)/SSP] x 100%; the standard spacing SSP = 6272640/(Row Width x Seeds per Acre) = 6.97 inches.

Figure 12 shows a graphic representation of Appendix J. Notice that 6.97 inches was the correct value and only ± 0.03 inches in error was found in this figure.

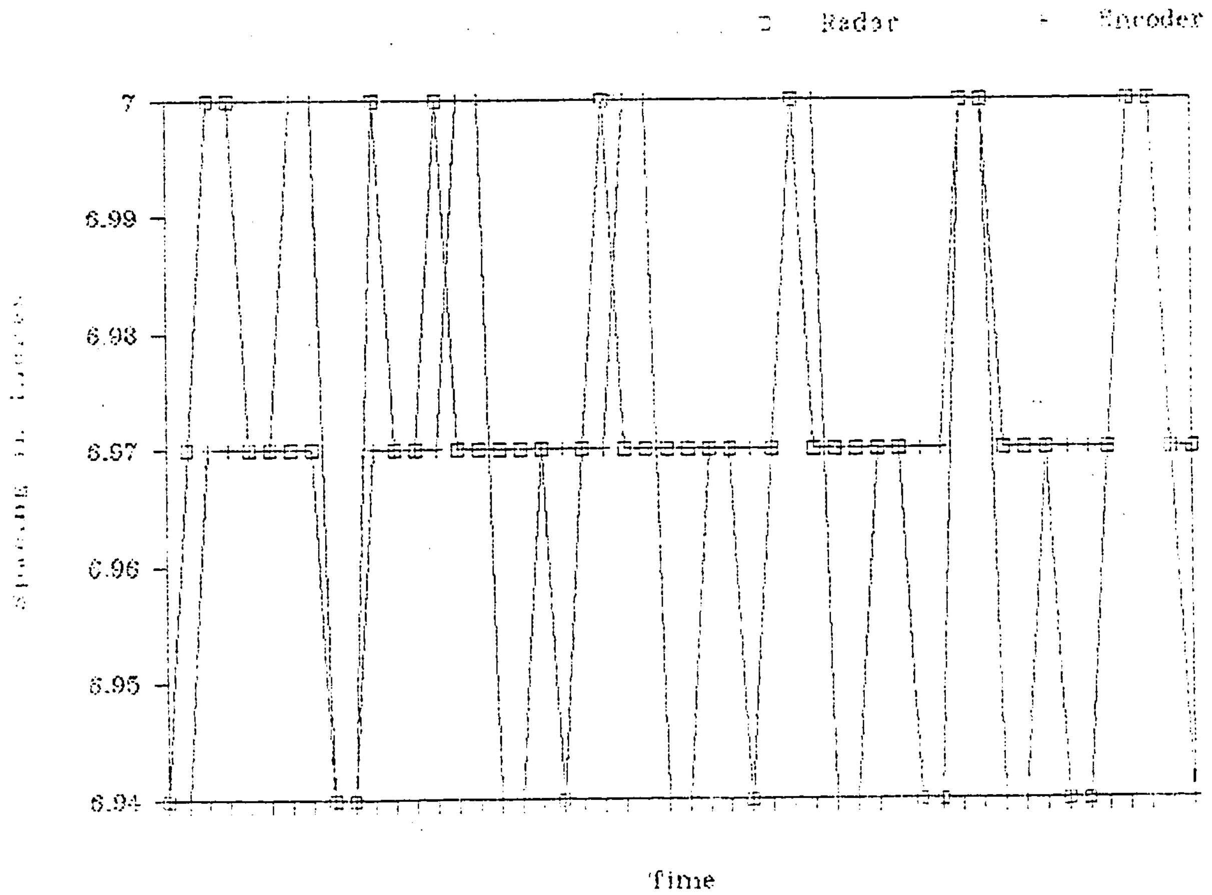


Figure 12. Graphic representation of results from laboratory test for research question 2.

The data are presented in summary form in Table 2. There are two groups (Doppler radar and fifth-wheel encoder). The number of degrees of freedom associated with the between-groups sum of squares is 1. The number of degrees of freedom associated with the within-groups sum of squares is 98. The number of degrees of freedom associated with the total is 99. The mean spacing using the Doppler radar and the fifth-wheel encoder are 6.9694 and 6.9706 inches, respectively.

Table 2

Analysis of Variance of Data for Appendix J

Source of variation	Sum of squares	Degrees of freedom	Variance estimate	
Between	0.000038	1	0.000038	
Within	0.039553	98	0.000404	
Total	0.039591	99	F = 0.094517	n.s.

No significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder in dispensing seed at a uniform spacing ($F = 0.094517$, $p > .05$).

Field Test

The raw data were reported in Appendix K. Two hundred pairs of spacings were measured with a tape measure (see "Field Test Procedure" in Chapter III for detail). The high/low value of seed spacing for the Doppler radar control unit was 12/3.5 inches in the 1st test and 13/3 inches in the 2nd test, however, the high/low value of seed spacing for the fifth-wheel encoder control unit was 13.5/1.5 inches in the 1st test and 17.25/1.5 inches in the 2nd test. In the 1st test, the mean spacing using the Doppler radar unit was 7.11 inches and the standard deviation was 1.86 inches while those using the fifth-wheel encoder were 7.61 inches (mean) and 2.69 inches (standard deviation), respectively (see Table 3). Notice that the accurate spacing should be 6.97 inches.

In the 2nd test, the mean spacing using the Doppler radar unit was 7.16 inches and the standard deviation was 2.00 inches while those using the fifth-wheel encoder were 7.66 inches (mean) and 3.01 inches (standard deviation), respectively (see Table 3).

In the 1st test, the variance ratio was known as an F ratio: that was, $F = (2.69)^2/(1.86)^2 = 2.09$. A value of 1.44 was required for significance at the 5 percent level. Since $F = 2.09 > 1.44$, thus, the difference between the variances for the Doppler radar and the fifth-wheel encoder could be considered statistically significant.

In the 2nd test, the variance ratio F was equal to $(3.01)^2/(2.00)^2$ or 2.28. A value of 1.44 was required for significance at the 5 percent level. Therefore, the difference between the variances for the Doppler radar and the fifth-wheel encoder could be considered statistically significant.

Data in Table 4 indicate that a significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder with regard to dispensing seed at a uniform spacing ($F = 4.64$, $p < .05$). Data in Table 5 show the analysis of variance for the data from the 2nd field test. Based on this test, a significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder in dispensing seed at a uniform spacing ($p < .05$).

Table 3

Summary of Data Collected in the Field Tests

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
	1st Test	2nd Test	1st Test	2nd test
M	7.11	7.16	7.61	7.66
n	200	200	200	200
SD	1.86	2.00	2.69	3.01

Table 4

Analysis of Variance for Data Collected in the Field Tests: 1st test

Source of variation	Sum of squares	Degrees of freedom	Variance estimate
Between	24.85	1	24.85
Within	2129.42	398	5.35
Total	2154.27	399	$F = 4.64$ *

* $p < .05$

Table 5

Analysis of Variance for Data Collected in the Field Tests: 2nd test

Source of variation	Sum of squares	Degrees of freedom	Variance estimate
Between	25.78	1	25.78
Within	2594.90	398	6.52
Total	2620.68	399	$F = 3.95$ *

* $p < .05$

Computer graphic representations were presented in Figures 13 and 14 to compare the results from the first (1st) test and the second (2nd) test field tests for research question 2. Based on these two figures, it appears that the fifth-wheel encoder control unit spread the seeds in a wider range than did the Doppler radar control unit.

Variability of Output Signals

The 1st and the 2nd tests of the variability of output signals were conducted in the electronics laboratory at the Rawson Control Systems Corporation in Oelwein, Iowa, to answer research question 3: Did the output signals from the sensors significantly differ in variability for the Doppler radar and the fifth-wheel encoder?

Table 6 shows the data collected from the laboratory tests (as indicated in the Laboratory Procedure in Chapter III). Both the 1st and 2nd tests on the Doppler radar and the fifth-wheel encoder control unit were repeated 30 times. Note that 29 of the 30 Doppler radar output frequencies on the 1st and the 2nd tests were 120 Hz while the Doppler radar output frequencies varied from 815 to 819 Hz, with one exception of 850 Hz. The 850 Hz could be an error signal produced by the signal processing unit due to mechanical problems and was omitted for the calculation of statistical values.

The mean frequency of the output signals using the Doppler radar unit was 120.03 Hz and the standard deviation was 0.18 Hz, while those using the fifth-wheel encoder were 817.41 Hz (mean) and 1.18 Hz (standard deviation), respectively (see Table 7). The variance ratio

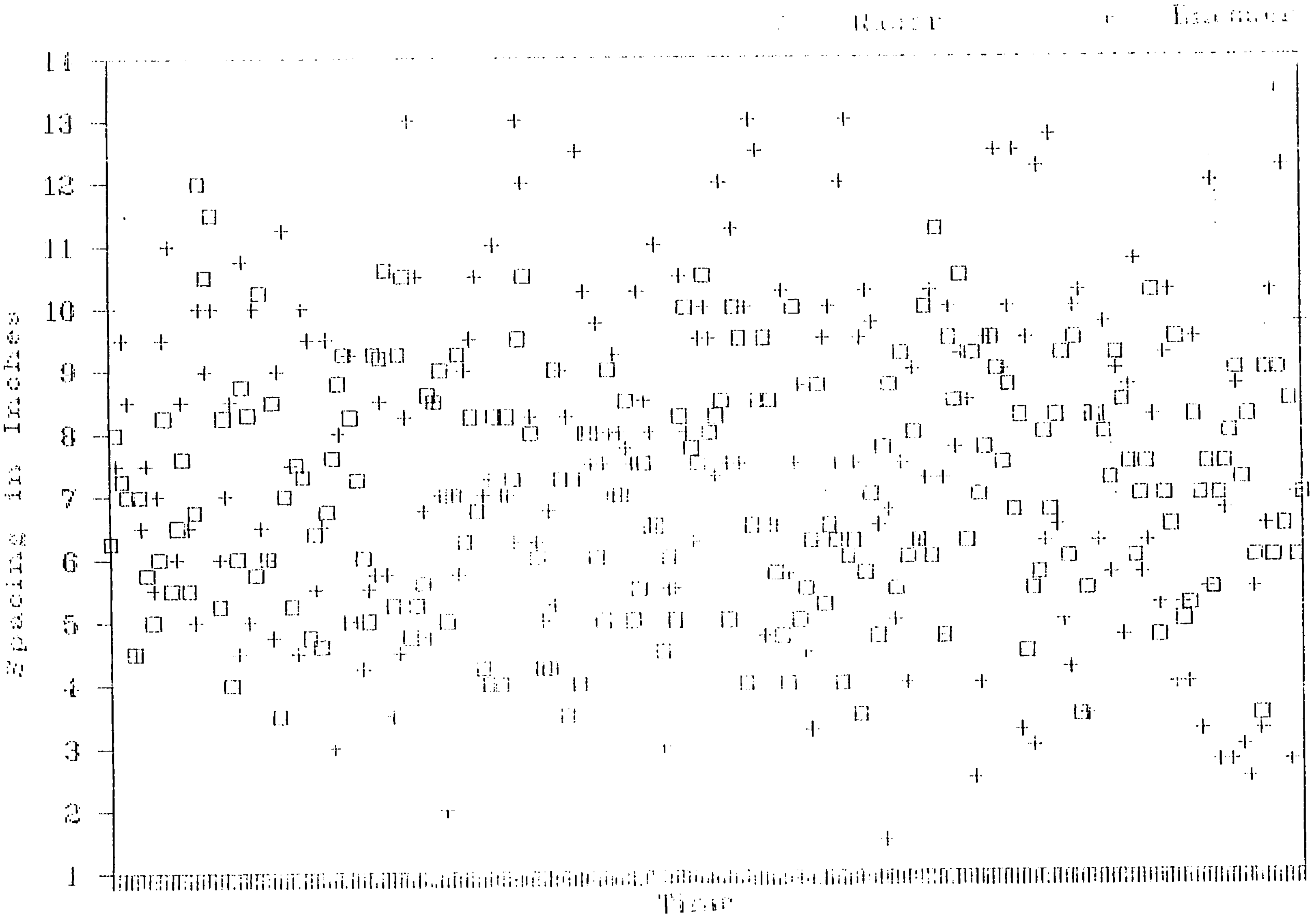


Figure 13. Graphic representation of results from the 1st field test for research question 2.

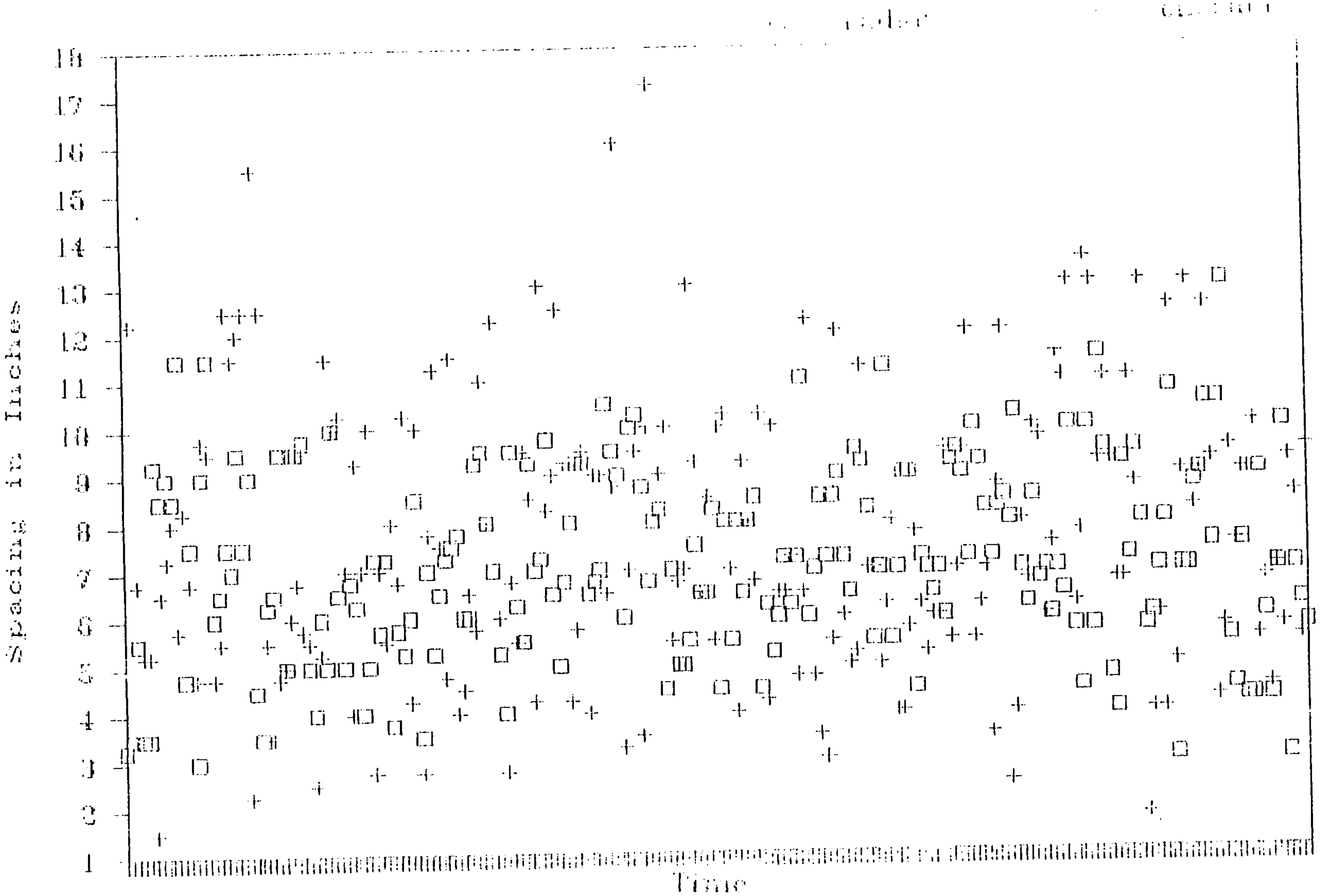


Figure 14. Graphic representation of results from the 2nd field test for research question 2.

F is equal to $(1.18)^2/(0.18)^2$ or 42.97 and a value of 2.13 was required for significance at the 5 percent level. In other words, the difference between the variances for the Doppler radar and the fifth-wheel encoder was considered statistically significant.

A 2nd test was executed to verify the reliability of this test. The mean frequency of the output signals using the Doppler radar unit was 120.03 Hz and the standard deviation was 0.18 Hz while those using the encoder were 816.90 Hz (mean) and 0.96 Hz (standard deviation) respectively. The variance ratio F is equal to $(0.96)^2/(0.18)^2$ or 28.44 and a value of 2.10 was required for significance at the 5 percent level. Based on this 2nd test, a significant difference was found between using the Doppler radar sensor and the fifth-wheel encoder with regard to variability of output signals from the sensors ($p < .05$).

Based on the 1st and the 2nd tests, a significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder with regard to variability of output signals from the sensors ($p < .05$).

A camera with a "+3" close-up lens was used to take pictures of an oscilloscope screen to show the output waveforms from the Doppler radar and the fifth-wheel encoder. The camera was fixed on a tripod and the timer on the camera was used to avoid any possible vibrations. The same exposure times were chosen for both pictures.

To get a clear display from the oscilloscope screen, the oscilloscope was adjusted to display a range of one to two cycles of the output signals from the Doppler radar and the fifth-wheel encoder.

Table 6

Output Frequencies from the Doppler Radar and the Fifth-Wheel Encoder

	Output frequencies (Hz)			
	Radar		Encoder	
No.	1st Test	2nd Test	1st Test	2nd test
1	120	120	816	817
2	120	120	819	816
3	120	120	819	817
4	120	120	850	817
5	120	120	819	818
6	120	120	817	817
7	120	120	816	816
8	120	120	816	816
9	120	120	819	816
10	120	120	819	818
11	120	120	816	818
12	120	120	816	817
13	120	120	817	817
14	120	120	818	816
15	120	120	818	817
16	120	120	819	816
17	120	120	817	817
18	120	120	816	819
19	120	120	816	818
20	120	120	816	816
21	120	120	817	816
22	120	121	818	816
23	120	120	818	817
24	120	120	817	818
25	120	120	816	819
26	121	120	817	817
27	120	120	818	817
28	120	120	819	815
29	120	120	818	816
30	120	120	818	817

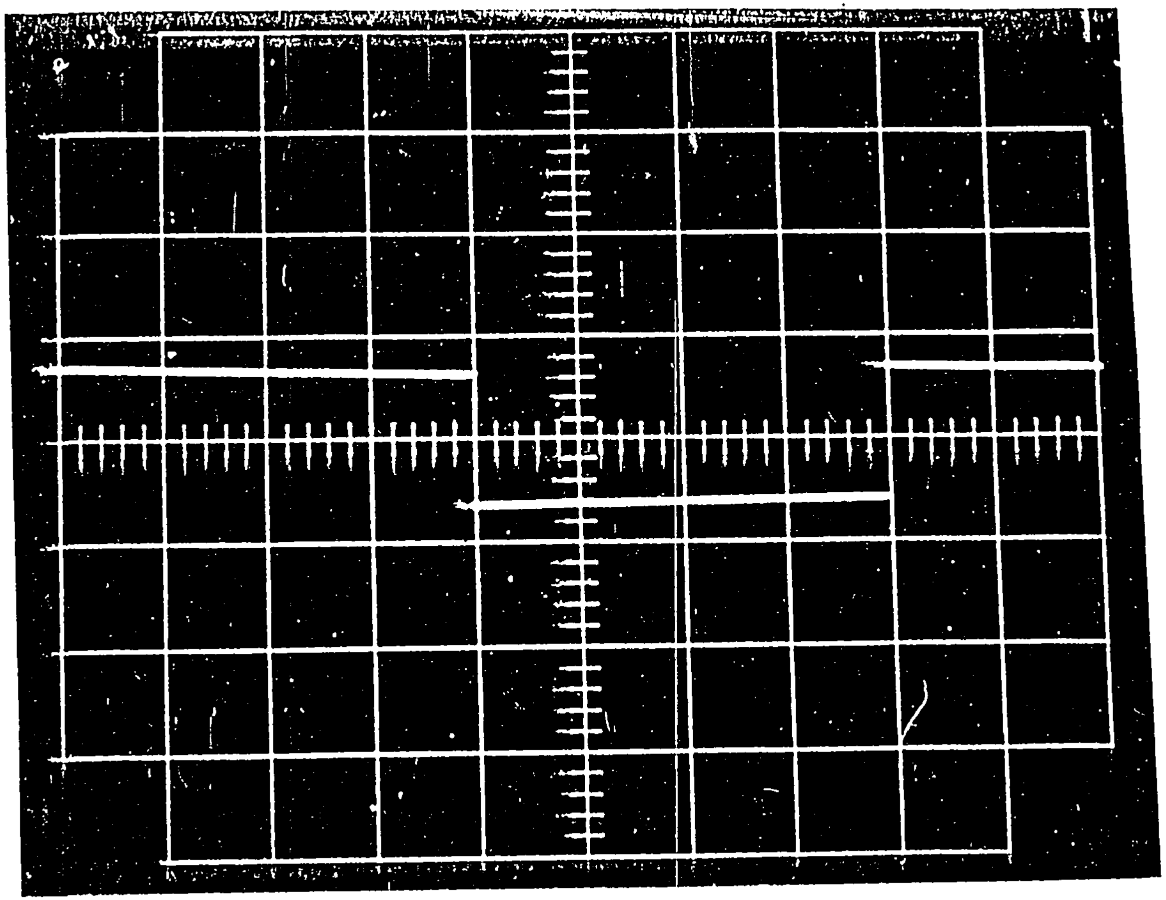
Table 7

Summary of Data for Table 6

	Output frequencies (Hz)			
	Radar		Encoder	
	1st Test	2nd Test	1st Test*	2nd Test
M	120.03	120.03	817.41	816.90
n	30	30	29	30
SD	0.18	0.18	1.18	0.96

* Excluding the value of 850.

Figures 15 and 16 show the output waveforms from the Doppler radar and the fifth-wheel encoder. It appears that the output waveform from the Doppler radar was sharp, while the output waveform from the fifth-wheel encoder was fuzzy.



Volt/cm = 0.5 volt.

Sweep time/cm = 1 millisecond

Figure 15. The output waveform from the Doppler radar.

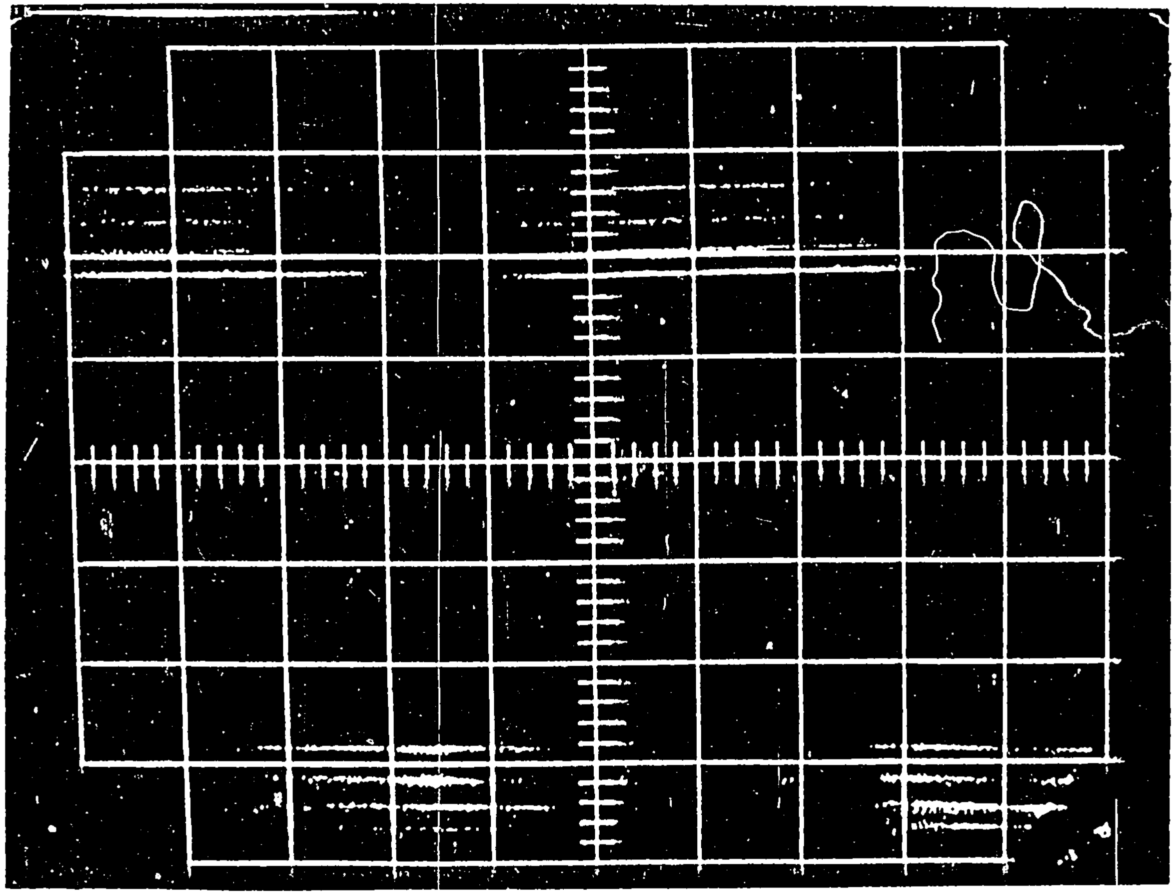


Figure 16. The output waveform from the fifth-wheel encoder.

CHAPTER V

Summary, Findings, Conclusions and Recommendations

This chapter includes a summary of the study, conclusions drawn from the data analyses and recommendations for future study. Because the forty-five page computer program was proprietary information, it was not included in the dissertation.

Summary

This experimental research focused on the design of a new approach to control seed dispensers and to analyze the performance characteristics of a Doppler radar ground speed sensor for microprocessor controlled dispensers. The specific objective was to compare the effectiveness of using a Doppler radar unit with a fifth-wheel unit for measuring ground speed when both were connected to a microprocessor-controlled seed dispenser.

The research questions were: 1. Did the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices (calculated by the microcomputer in miles per hour) differ significantly when the input signal was varied from 1 Hertz (Hz) to 574 Hz to the control box? 2. Did the Doppler radar sensor and the fifth-wheel encoder differ significantly in dispensing seed with a uniform spacing? 3. Did the output signals from the sensors significantly differ in variability for the Doppler radar and the fifth-wheel encoder?

The system designed for this study consisted of hardware and computer software. The hardware for this study consisted of a monitor device, microprocessor control unit, stepper motor, fifth-wheel encoder, Doppler radar and device for the planting of seeds. The software was designed by the researcher.

Laboratory tests and field tests were used in the study to test this new Doppler radar and microprocessor-control unit. Laboratory tests were conducted to determine the accuracy of the microprocessor-based speedometer, seed spacing control and the output waveforms from the Doppler radar and the fifth-wheel encoder under controlled conditions. The laboratory test provided an environment for controlling the variables of this research. Field tests were conducted to test the accuracy and variability of the seed spacing control under actual conditions. The resultant data were analyzed using the t test, F test and one-way ANOVA. All tests of significance were evaluated at the .05 level.

The results obtained from the data analyses showed that using the Doppler radar unit as a sensor in the field tests should provide a more uniform spacing control. In general, the effectiveness of using a Doppler radar controlled unit was considered to be more accurate in dispensing seeds than the fifth-wheel encoder control unit.

Findings

The findings in this research were encouraging and they showed that the Doppler radar controlled unit can be a very attractive alternative to the more complicated fifth-wheel encoder controlled system. Based on the data analyses presented and discussed earlier in Chapter IV, the most important findings were:

1. There was a significant difference between the mean indicated ground speeds of the Doppler radar and the fifth-wheel encoder controlled dispensing devices (calculated by the microcomputer in M. P. H.) when an input signal was varied from 1 Hz to 574 Hz to the control box. The Doppler radar was more sensitive to frequency changes than the fifth-wheel encoder.

2. Under the laboratory tests, without considering the slippage of the wheel, there was no significant difference between using the fifth-wheel encoder and the Doppler radar as sensors in dispensing seed at a uniform spacing.

3. In the field tests, a significant difference was found between using the Doppler radar sensor and a fifth-wheel encoder with regard to dispensed seeds at a uniform spacing, due to possible wheel slippage. The Doppler radar controlled unit dispensing seed at a more uniform spacing than the fifth-wheel encoder control unit.

4. There was a significant difference between using the Doppler radar sensor and the fifth-wheel encoder with regard to variability of output signals from the sensors. The Doppler radar provided a less variable output signal than the fifth-wheel encoder.

5. During the field test, the researcher observed that one problem of using the Doppler radar unit was the slight vibration of the Doppler radar caused by the engine of the tractor. This caused some erroneous input signals to the microprocessor control unit

because the monitor displayed a fractional part of a ground speed (MPH) while the tractor was stationary.

Conclusions

Based on the results of statistical analyses and the findings, one may conclude that:

1. Because the software program designed for the Doppler radar must be different from that of the fifth-wheel encoder (different speed displays), the EPROM used in the fifth-wheel encoder controlled system should not be used directly in the Doppler radar control system. Since the speedometer on the control box would report incorrect messages and therefore, the stepper motor would run at erroneous speeds.

2. Using the Doppler radar unit as a sensor will provide a more uniform control of spacing of seeds than the fifth-wheel encoder ($p. < .05$), subsequently, it will increase production efficiency since the number of seeds required can be pre-determined.

3. Using the Doppler radar as a sensor will provide more stable and uniform output signals than the fifth-wheel encoder ($p. < .05$).

Recommendations

The technology and the economics of microprocessors, as well as Doppler radar, have opened a new horizon to agricultural equipment controls. Topics for further research might include:

1. A real-time microprocessor controlled system using a digitized soil map to selectively distribute fertilizer by soil types.

2. The design and evaluation of a sonar sensed microprocessor controlled agricultural dispenser.

3. A comparison between using a Doppler radar sensor and a sonar sensor with regard to dispensing seed uniformly.

4. A cost-benefit analysis of using a fifth-wheel encoder, a Doppler radar, and a sonar sensor with a microprocessor controlled system for agricultural equipment.

5. New ways of minimizing the vibration of the tractor using a Doppler radar ground-speed sensor for a microprocessor controlled dispenser.

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Appendix A

Percentage Slip of Tractor Drivers

Tractor Model	% slip of drivers	Tractor Model	% slip of drivers
ALLIS-CHALMERS		ALLIS-CHALMERS	
175 Gas	14.71	7030 Dsl	14.97
7040 Dsl	14.09	7050 Dsl	10.53
7060 Dsl	14.86	7080 Dsl	13.97
7000 Dsl	14.98	7040 Dsl	12.63
7060 Dsl	14.59	7580 Dsl	14.93
5040 Dsl	14.73	5050 Dsl	14.74
CASE			
2470 Dsl	14.84	---	---
DAVID BROWN			
1212 Dsl	13.11	995 Dsl	14.81
DEUTZ			
D 68 06 Dsl	14.53	---	---
FORD			
2600 Dsl	14.59	3600 Gas	14.96
3600 Dsl	13.46	4100 Dsl	14.40
5600 Dsl	14.35	6600 Dsl	13.49
8600 Dsl	14.52	9600 Dsl	12.35
3600 Gas	14.96	3600 Dsl	14.99
4600 Dsl	14.80	5600 Dsl	14.85
6600 Dsl	11.76	7600 Dsl	14.83
6700 Dsl	14.94	7700 Dsl	14.83
8700 Dsl	14.92	9700 Dsl	14.58
INTERNATIONAL			
Hydro 70 Gas	14.90	Hydro 70 Dsl	14.71
Hydro 100 Dsl	14.72	666 Gas	14.89
666 Dsl	15.00	674 Gas	14.94
674 Dsl	14.72	766 Dsl	14.63
1468 Dsl	10.15	1566 Dsl	14.31
4166 Dsl	14.79	4366 Dsl	14.88
1566 Dsl	14.31	1568 Dsl	14.81
4568 Dsl	14.82	1586 Dsl	14.97
1086 Dsl	14.10		
J. I. CASE			
1570 Dsl	11.17	2870 Dsl	14.81
1410 M Dsl	14.99	1410 P. S. Dsl	14.98
2670 Dsl	14.81		

(Continued)

Tractor Model	% slip of drivers	Tractor Model	% slip of drivers
JOHN DEERE			
830 Dsl	14.94	1530 Dsl	14.87
2630 Dsl	14.66	4840 Dsl	14.82
2040 Dsl	14.81	2240 Dsl	14.96
8430 Dsl	14.86	8630 Dsl	14.87
2840 Dsl	14.98	4040 Dsl	14.88
4240 Dsl	14.81	4440 Dsl	14.78
4640 Dsl	14.81		
LEYLAND			
255 Dsl	14.99	2100 Dsl	14.86
MASSEY-FERGUSON			
MF 1085 Dsl	14.90	MF 1105 Dsl	14.89
MF 1135 Dsl	14.99	MF 1155 Dsl	14.72
MF 265 Dsl	14.98	MF 1505 Dsl	14.74
MF 1805 Dsl	14.66	MF 235 Dsl	14.88
MF 255 Gas	14.85	MF 255 Dsl	14.95
MF 275 Dsl	12.79	MF 285 Dsl	13.74
MF 230 Gas	12.37	MF 230 Dsl	13.77
MF 2805 Dsl	14.89		
S. A. M. E.			
Panter Dsl	14.73	Buffalo	14.72
STEIGER			
Wildcat III	14.91	Bearcat III	14.74
CougarIII ST250	14.64	CougarIII ST251	14.64
CougarIII PT270	14.98	PantherIIIST310	14.33
PantherIIIST325	14.76	Tiger II Dsl	14.76
Bearcat II Dsl	14.95	Cougar II Dsl	15.00
WHITE			
F.B. 2-50 Dsl	14.85	F.B. 2-60 Dsl	12.94
G1355 Dsl	14.94	F. B. 4-150Dsl	14.52
G955 Dsl	14.76	4-180 Dsl	14.51
2-70 Dsl	14.92	2-85 Dsl	14.99
2-105 Dsl	14.94	2-150 Dsl	14.81

(Doane's Agricultural Service, 1986, pp. 341.1-341.6).

Appendix B

Radar Angles and Doppler Frequencies

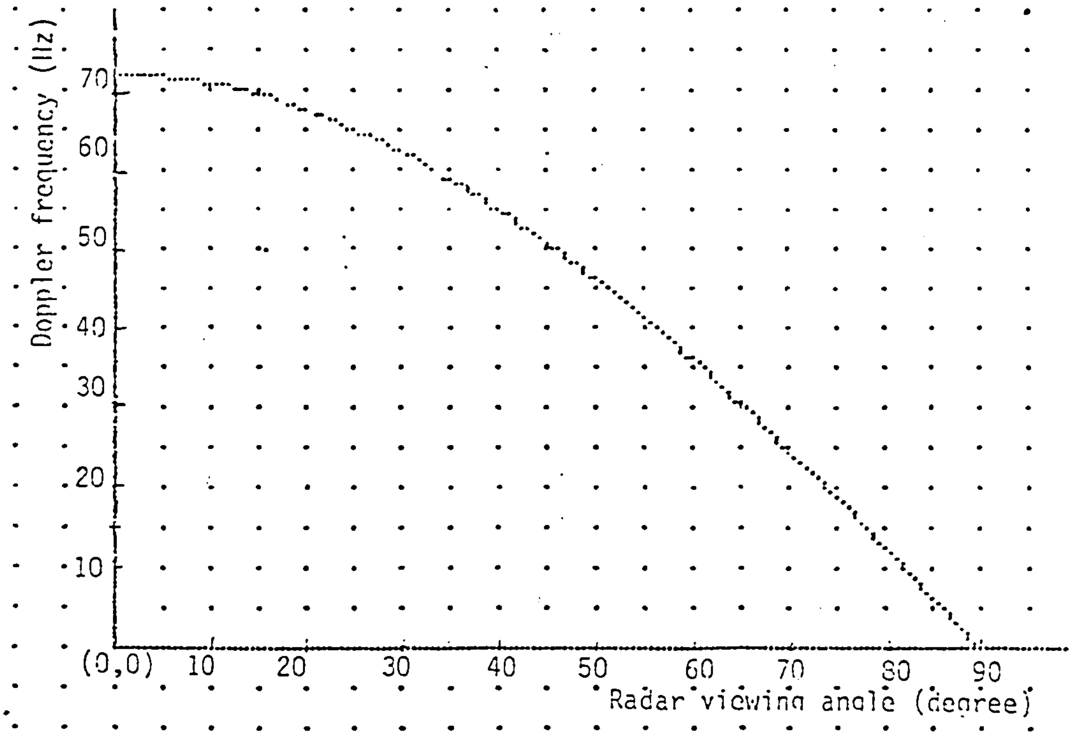
Degree	Doppler frequency	Error(%)
0	71.8991251	25.2135658
1	71.8881744	25.1944951
2	71.8553261	25.1372891
3	71.8005898	25.0419649
4	71.7239824	24.9085518
5	71.6255272	24.7370903
6	71.5052541	24.5276327
7	71.3631999	24.2802429
8	71.1994077	23.9949959
9	71.0139275	23.6719790
10	70.8068158	23.3112903
11	70.5781356	22.9130399
12	70.3279567	22.4773489
13	70.0563551	22.0043502
14	69.7634138	21.4941877
15	69.4492218	20.9470170
16	69.1138749	20.3630046
17	68.7574753	19.7423285
18	68.3801314	19.0851777
19	67.9819583	18.3917524
20	67.5630773	17.6622638
21	67.1236158	16.8969342
22	66.6637079	16.0959966
23	66.1834936	15.2596951
24	65.6831191	14.3882843
25	65.1627369	13.4820297
26	64.6225055	12.5412074
27	64.0625895	11.5661040
28	63.4831594	10.5570165
29	62.8843917	9.5142522
30	62.2664688	8.4381288
31	61.6295789	7.3289741
32	60.9739161	6.1871260
33	60.2996800	5.0129323
34	59.6070761	3.8067506
35	58.8963153	2.5689483
36	58.1676140	1.2999026
37	57.4211944	- 6.9849193 x10^{-8}
38	56.6572837	- 1.3303637
39	55.8761146	- 2.6907831
40	55.0779252	- 4.0808438
41	54.2629585	- 5.5001224
42	53.4314627	- 6.9481866
43	52.5836912	- 8.4245953
44	51.7199022	- 9.9288987
45	50.8403588	-11.4606387

46	49.9453290	-13.0193485
47	49.0350853	-14.6045537
48	48.1099050	-16.2157710
49	47.1700701	-17.8525098
50	46.2158667	-19.5142715
51	45.2475854	-21.2005501
52	44.2655213	-22.9108316
53	43.2699735	-24.6445952
54	42.2612452	-26.4013129
55	41.2396438	-28.1804494
56	40.2054803	-29.9814629
57	39.1590699	-31.8038047
58	38.1007313	-33.6469196
59	37.0307868	-35.5102464
60	35.9495624	-37.3932173
61	34.8573874	-39.2952590
62	33.7545945	-41.2157918
63	32.6415196	-43.1542309
64	31.5185018	-45.1099858
65	30.3858832	-47.0824606
66	29.2440087	-49.0710548
67	28.0932262	-51.0751623
68	26.9338862	-53.0941728
69	25.7663420	-55.1274713
70	24.5909490	-57.1744384
71	23.4080654	-59.2344506
72	22.2180515	-61.3068803
73	21.0212698	-63.3910963
74	19.8180847	-65.4864639
75	18.6088629	-67.5923445
76	17.3939726	-69.7080969
77	16.1737840	-71.8330764
78	14.9486687	-73.9666358
79	13.7189998	-76.1081253
80	12.4851521	-78.2568924
81	11.2475012	-80.4122828
82	10.0064242	-82.5736397
83	8.7622992	-84.7403049
84	7.5155051	-86.9116183
85	6.2664218	-89.0869185
86	5.0154295	-91.2655431
87	3.7629096	-93.4468282
88	2.5092434	-95.6301094
89	1.2548129	-97.8147217
90	1.5777380x10^{-7}	-99.9999997

Where Degree is the antenna viewing angle

Error% = (Cos(d1)/Cos(d2)-1)x100% and d2 = 37

The Doppler radar viewing angle and Doppler frequency curve at the tractor speed of one mile per hour.



For calculation of Doppler frequencies and errors, see the computer program that follows.

```
1  REM  ************************

2  REM  This program is designed
4  REM  to calculate the Doppler
5  REM  frequency and ERROR%.
6  REM  ERROR% is defined as
8  REM  ((Cos(d1)/Cos(d2)-1)*100%

10  REM  ************************

11 PI = 3.141592654
12 I = 0
13  REM
14  REM
15  REM  Print label
16  REM
20  PRINT "DEGREE                Fd
                     ERROR (%)"
21  PRINT : PRINT
24 DO = PI / 180
25 D1 = 0
26 D2 = PI / 2
27  REM
28  REM  DO is angle increment
29  REM  D1 is starting angle
30  FOR R = D1 TO D2 STEP DO
31 FD = 2 * .44704 *  COS (R) / .
      0124352
32 S = 37 * PI / 180
33 E = (( COS (R) /  COS (S)) - 1
      ) * 100
40  PRINT I,FD,"          "E
45 I = I + 1
50  NEXT R
```

Appendix C

Equipment Specifications

The following equipment was used in designing and testing of the microprocessor based radar ground speed sensor:

A. Hardware:

I. Radar Sensor Specification:

Product of TRW Inc. Farmington Hill, MI. USA.

Operation Voltage: +10.0 VDC to +16.0 VDC.

Power Consumption: Less than 8 watts at 16 volts.

Operating Temperature: $-40^{\circ}C$ to $+85^{\circ}C$.

Output Signal: Square Wave at a rate of 57.5 Hz per mile per hour (at 37 viewing angle).

Output Driver: Open collector transistor capable of sinking up to 10 milliamperes.

Output Voltage Level: Less than 0.4 volts DC at 10 milliamperes.

Operating Frequency: 24,125 MHz±40MHz over temperature.

Power Output: Less than 0.3 mW/cm at the lens.

2. Digital Frequency Counter:

Product of SOAR Corporation, Japan.

Model: SOAR FC-845.

Input: 9 VDC SUM-3 X 6 or AC Adapter.

Output: 1.3 W.

3. Oscilloscope:

Product of Dynascan Corporation, Japan.

Model: BR Precision 1474 -- 30 MHz.

Input: 100 VAC (90 ~ 110V).

117 VAC (108 ~ 132V).

220 VAC (198 ~ 242V).

240 VAC (216 ~ 264V).

50 ~ 60 Hz.

Output: 25 W.

4. EPROM Programmer:

Product of B&C Microsystems, 6322 Mojave Dr. San Jose, CA 95120.

Mode: Version 4.0, February 1985.

Input: 110 VAC.

5. EPROM Eraser:

Product of Argo, Made in Hong Kong.

Model: LA6T.

Input: 110 VAC, 60 Hz 15 VA.

Output: 2540 Å wavelength.

Erasure Time: 15 ~ 40 minutes.

6. Apple IIe Microcomputer:

Product of Apple Computer, Cupertino, CA 95014.

Model: 606-5001.

Input: 120 VAC, 60 Hz, 1 Amp.

7. Diskette Drives:

Product of Apple Computer, Cupertino, CA 95014.

Made in Japan.

Model: Duodisk A9M0108.

8. Monitor:

Product of Apple Computer, Cupertino, CA 95014.

FCC ID: BCG7Y6 Monitor II, Made in Korea.

Model: A2M2010, Green Phosophor.

Input: 120 VAC, 60 Hz, 0.3 A.

9. Power Supply:

Product of Dynascan Corporation, Japan.

Model: BK Precision 1640 Mobil.

Input: 110 VAC

Output: 15 VDC (max.), 3 Amp. (max.)

10. Power Supply:

Product of World Wide, USA.

Model: "Midland 18-114."

Input: 110 VAC.

Output: 20VDC (max), 200 mA (max).

11. Stepper Motor:

Product of The Pittman Corporation, Harleysville, PA. 19438.

Model: GM9413D666.

Ratio: 1419:1. Steps per revolution: 48 steps.

Input: 12 VDC.

12. DC Power Supply:

Product of Dynascan, Inc., Taiwan, The Republic of China.

Model: 1040.

Input: 117 VAC, 60 Hz.

Output: 12 VDC, 4 Amp.

13. EE/EPROM Programmer:

Product of Logical Devices, Inc. USA.

Model: Shooter, Rev. 1.0 (1985).

Series: PROMPRO.

Input: 115 VAC, 50-60 Hz.

14. Sine-Square Audio Generator.

    Product of Zenith Corporation, Made in Taiwan.

    Model: IG-5218.

    Input: 120/240 VAC, 50/60 Hz.

    Output: 6W.

15. Level and Angle Finder.

    Product of PRO Products Co. Rockford, Illinois.

    Mode: Magnetic Based.

B. Software:

Westerfield, M. (1983). ORCA/M--6502 Macro Assembler for the Apple II Computer (Version 3.5). Lowell MA: Hayden Book.

Appendix D

The Encoder

MODEL 711 [illegible]

Provides a high amplitude output signal, requires only a single polarity power supply and has high resolution

ELECTRICAL SPECIFICATIONS

INPUT

Voltage	5 V. DC or 15 V. DC. *Specify choice* (other voltages are optional)
Current	80 milliamperes
Ripple	2%
Regulation	±5%

OUTPUT

Amplitude	0 to 4 volts. (With 5 V. DC input) 0 to 12 volts. (With 15 V. DC input)
Current	Sink up to 20 milliamperes.
Polarity	Positive.
Wave Shape	Square wave, 50% "on" and 50% "off".
Pulse Rate	0 to 20,000 pulses per second.
Rise Time	Less than 1 microsecond.
Pulses per Revolution	1 to 1270. *Specify choice.*
Accuracy	Within ±0.1° from one pulse to any other pulse.

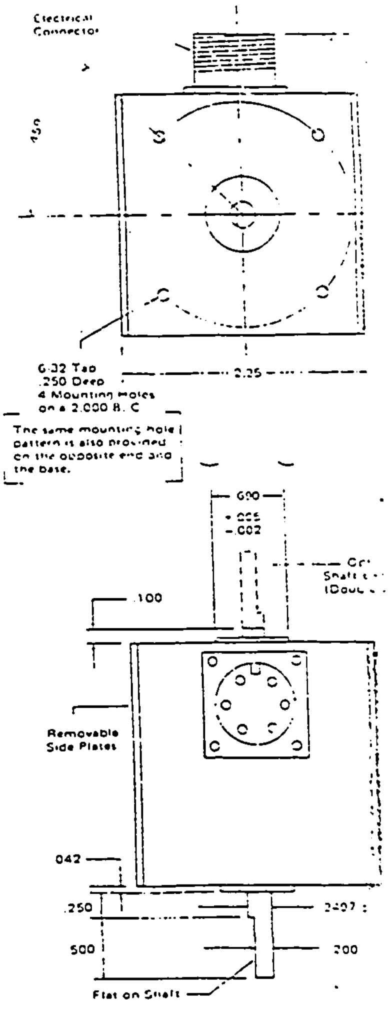
ENVIRONMENTAL SPECIFICATIONS

Temperature	-25°C to +75°C
Vibration	3 g's at 5 to 1000 CPS.
Shock	20 g's, 10 milliseconds.

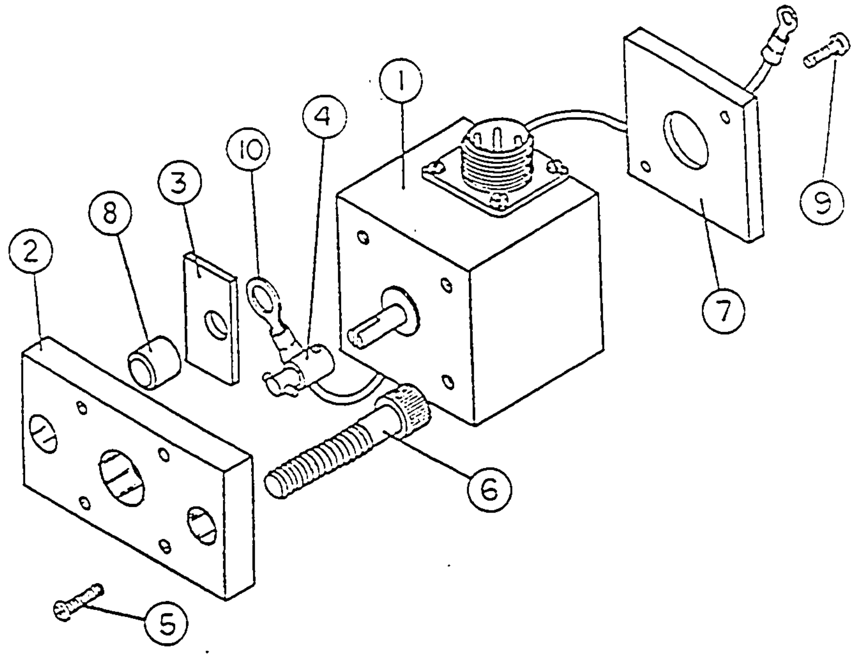
MECHANICAL SPECIFICATIONS

Shaft Speed	6,000 RPM maximum.
Shaft Rotation	Either direction.
Bearings	Sealed ball bearings.
Starting Torque	0.10 ounce-inches.
Moment of Inertia	0.0025 ounce-inches seconds squared.
Radial Loading	15 pounds operating.
Axial Loading	7 pounds operating
Shaft	Single or double ended. *Specify choice.*
Operating Life	100,000 hours average.
Housing	Aluminum with black anodized finish. Sealed against dust, oil vapor and moisture.
Mounting	Provisions for either base or face mounting.
Weight	10 ounces.
Connector	MS-3102E-14S-6P

DIMENSION



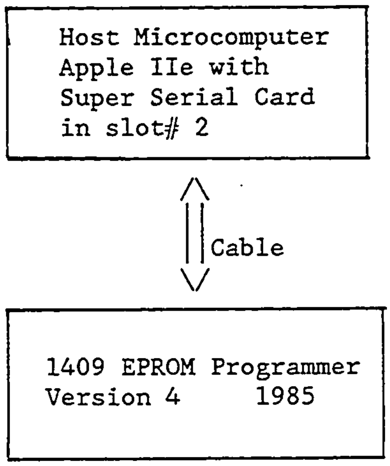
All dimensions are in inches with a tolerance of ±.005 unless otherwise specified



ITEM	DESCRIPTION
1	Assembly - Encoder
2	Adapter - Rubber, Encoder Mtg.
3	Washer - Rect.
4	Assembly - Coupler, Encoder
5	Screw - Machine #6-32 - 5/8
6	Capscrew - Socket HD 3/8-16 x 2
7	Cover - Encoder
8	Bushing - Mtg.
9	Screw - Machine #6-32 x 1/2
10	Assembly - Ground Wire

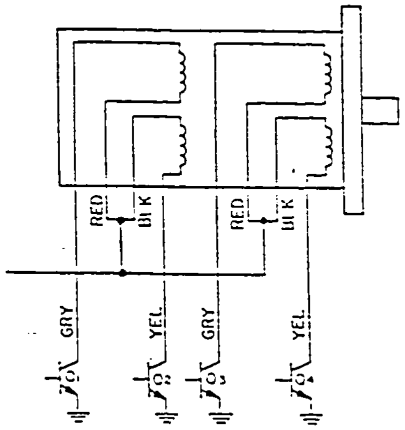
Appendix E

EPROM Programmer and Apple IIe



Appendix F

The Stepper Motor



UNIPOLAR

Normal
4 Step Sequence

CW ROTATION

CCW ROTATION

Step	Q1	Q2	Q3	Q4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

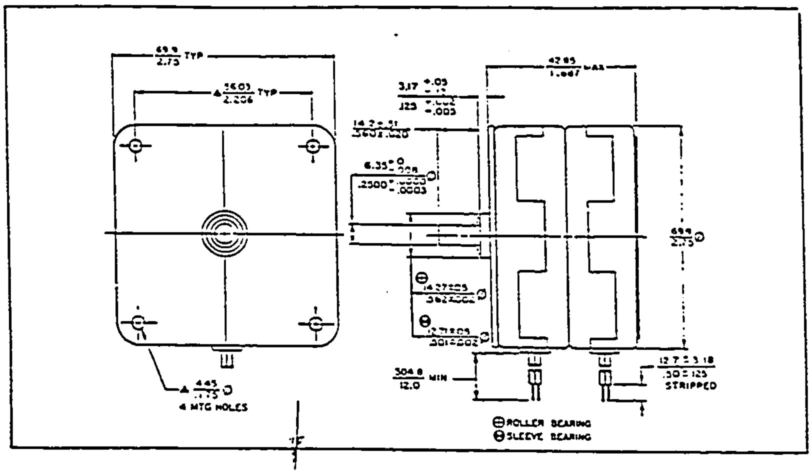
½ Step
8 Step Sequence

CW ROTATION

CCW ROTATION

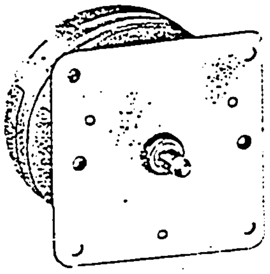
Step	Q1	Q2	Q3	Q4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

Schematic unipolar switching sequence. (Direction of rotation viewed from shaft end). From "Stepper Motor Handbook" by Airpax Corporation, A Northern American Philips Company Cheshire Division, 1982, p. 7.

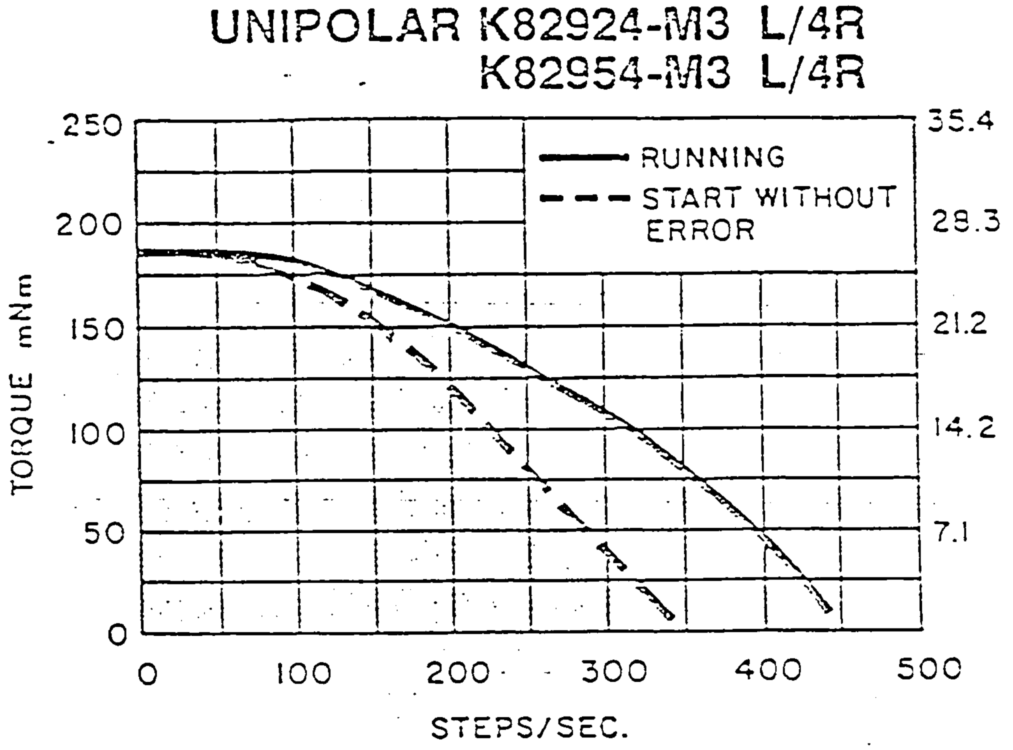


SPECIFICATIONS	BIPOLAR	UNIPOLAR	BIPOLAR	UNIPOLAR	BIPOLAR	UNIPOLAR	BIPOLAR	UNIPOLAR
ORDERING PART NO.	K82912-M3	K82924-M3	K82912-M4	K82924-M4	K82942-M3	K82954-M3	K82942-M4	K82954-M4
DC Operating Voltage	3.7	5	3.7	5	10	14	10	14
Res. per Winding Ω	1.8	3.6	1.8	3.6	13	27	13	27
Ind. per Winding mH	5	5	5.4	5	45	47	45	47
Holding Torque mNm/oz-in	325/46	254/36	254/36	184/26	325/46	254/36	254/36	184/26
Step Angle	7.5°		15°		7.5°		15°	
Step Angle Tolerance	±0.5°		±1°		±0.5°		±1°	
Steps per Rev.	48		24		48		24	
Rotor Moment of Inertia g.m²	1.5x10^{-2}							
Max. Operating Temp.	100°C							
Ambient Temp. Range Operating Storage	 —20°C to 70°C —40°C to 85°C							
Insulation Res. @ 500Vdc	100 mΩ							
*Bearings	Bronze Sleeve							
Weight	740g/26oz							
Lead Wires	No. 24 AWG							

*Also available with roller bearing use Suffix M1 7.5°/M2 15°



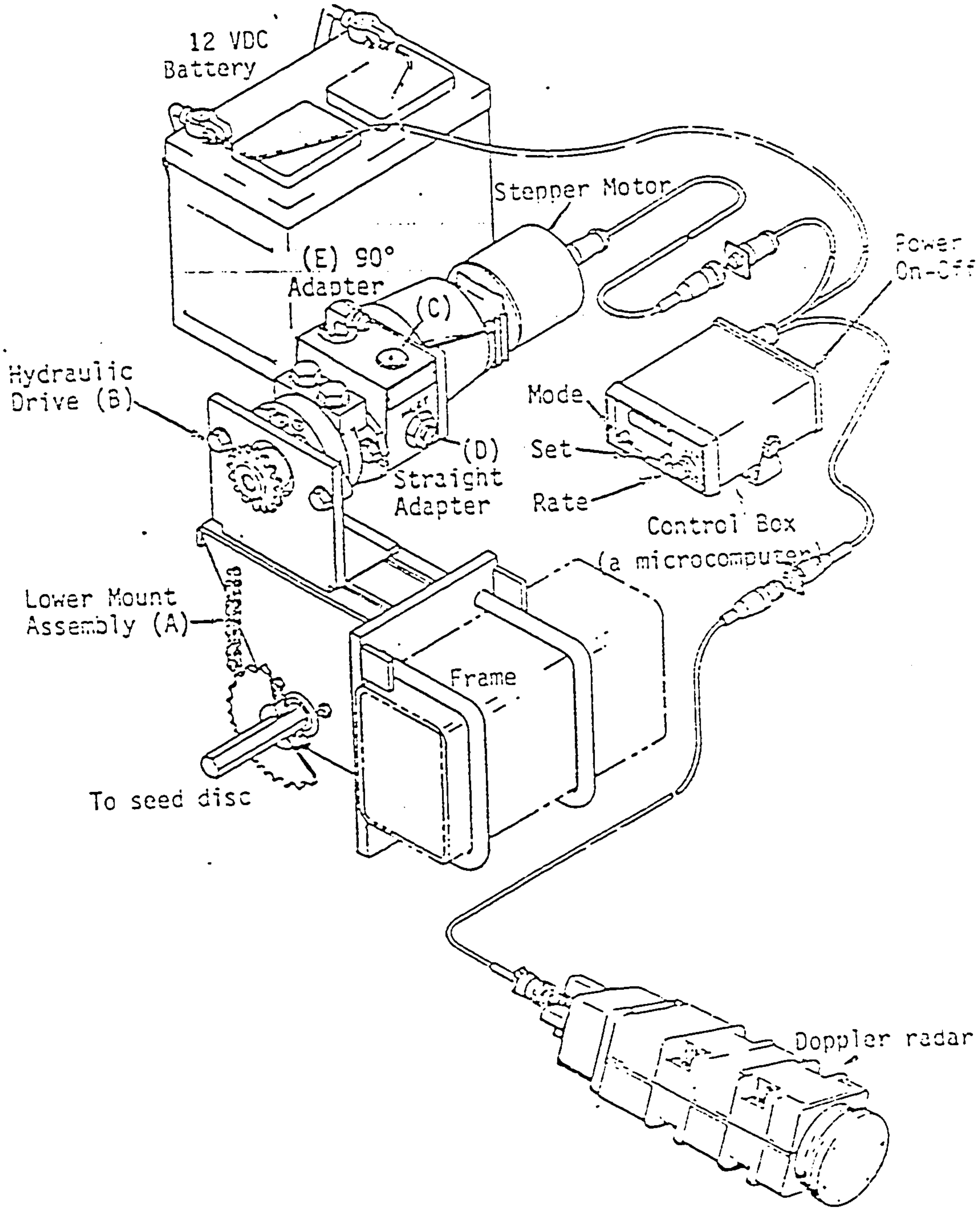
Specifications of the stepper motor. From "Stepper Motor Handbook" by Airpax Corporation, A Northern American Philips Company Cheshire Division, 1982, p. 26.



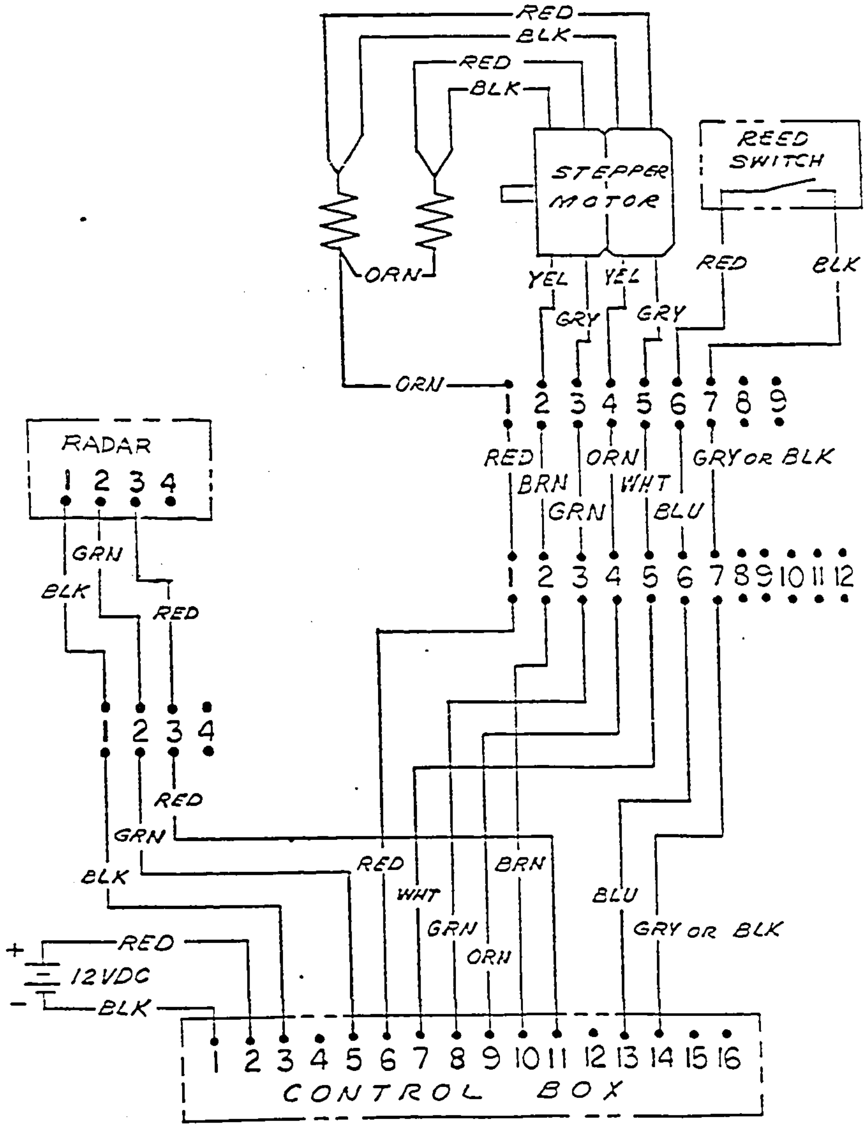
The torque and steps/second curve of the stepper motor used in this research. From "Stepper Motor Handbook" by Airpax Corporation, A Northern American Philips Company Cheshire Division, 1982, p. 27.

Appendix G

Doppler Radar, Microprocessor control box and Hydraulic System



Electric Wiring of Doppler Radar, Microprocessor Control Box, Reed Switch and Stepper Motor.



Appendix H

Data Collection Design

A. Data collection design for research question 1.

Input frequency(Hz) (Pulses per second)	Speed (MPH)	
	Radar	Encoder
1		
2		
3		
(to)		
574		

(Lab test)

B. Data collection design for research question 2 (Lab. test).

EPROM Type	(1) #Counts	(2) Seeds	(3) Distance (inch)	(4) Spacing (inch)	(5) Error%
Radar					
Encoder					

** (1) "#Counts" was the number shown on the digital revolution counter, 1 revolution was equal to 8 counts.

(2) "Seeds" was the number of seeds.

(3) "Distance" was the distance that the tractor travels in one minute at one mile per hour, or 88 feet.

(4) "Spacing" could be calculated by dividing Seeds into Distance.

(5) $$\text{Error\%} = \frac{(\text{Spacing} - \text{SSP})}{\text{SSP}} \times 100\%$$

SSP was the true spacing which could be obtained by: SSP = 6272640/(Row Width x Seeds per Acre)

** One acre is equal to 6,272,640 square inches.

C. Data Collection Design for Research Question 2 (Field test)

Spacing Type	1 to 200 times
Radar	
Encoder	

D. Data collection design for research question 3

No.	Output frequencies (Hz)	
	Radar	Encoder
1 to 30		

Appendix I

Raw Data of Input Signals vs. Speed Displays

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
1	0.0	0.0	36	0.6	0.1
2	0.0	0.0	37	0.6	0.1
3	0.1	0.0	38	0.7	0.1
4	0.1	0.0	39	0.7	0.1
5	0.1	0.0	40	0.7	0.1
6	0.1	0.0	41	0.7	0.1
7	0.1	0.0	42	0.7	0.1
8	0.1	0.0	43	0.7	0.1
9	0.2	0.0	44	0.8	0.1
10	0.2	0.0	45	0.8	0.1
11	0.2	0.0	46	0.8	0.1
12	0.2	0.0	47	0.8	0.1
13	0.2	0.0	48	0.8	0.1
14	0.2	0.0	49	0.9	0.1
15	0.3	0.0	50	0.9	0.1
16	0.3	0.0	51	0.9	0.1
17	0.3	0.0	52	0.9	0.1
18	0.3	0.0	53	0.9	0.1
19	0.3	0.0	54	0.9	0.1
20	0.3	0.0	55	1.0	0.1
21	0.4	0.0	56	1.0	0.1
22	0.4	0.1	57	1.0	0.1
23	0.4	0.1	58	1.0	0.1
24	0.4	0.1	59	1.0	0.1
25	0.4	0.1	60	1.0	0.1
26	0.5	0.1	61	1.1	0.1
27	0.5	0.1	62	1.1	0.1
28	0.5	0.1	63	1.1	0.1
29	0.5	0.1	64	1.1	0.1
30	0.5	0.1	65	1.1	0.2
31	0.5	0.1	66	1.1	0.2
32	0.6	0.1	67	1.2	0.2
33	0.6	0.1	68	1.2	0.2
34	0.6	0.1	69	1.2	0.2
35	0.6	0.1	70	1.2	0.2

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
71	1.2	0.2	106	1.8	0.2
72	1.3	0.2	107	1.9	0.2
73	1.3	0.2	108	1.9	0.3
74	1.3	0.2	109	1.9	0.3
75	1.3	0.2	110	1.9	0.3
76	1.3	0.2	111	1.9	0.3
77	1.3	0.2	112	2.0	0.3
78	1.4	0.2	113	2.0	0.3
79	1.4	0.2	114	2.0	0.3
80	1.4	0.2	115	2.0	0.3
81	1.4	0.2	116	2.0	0.3
82	1.4	0.2	117	2.0	0.3
83	1.4	0.2	118	2.1	0.3
84	1.5	0.2	119	2.1	0.3
85	1.5	0.2	120	2.1	0.3
86	1.5	0.2	121	2.1	0.3
87	1.5	0.2	122	2.1	0.3
88	1.5	0.2	123	2.1	0.3
89	1.6	0.2	124	2.2	0.3
90	1.6	0.2	125	2.2	0.3
91	1.6	0.2	126	2.2	0.3
92	1.6	0.2	127	2.2	0.3
93	1.6	0.2	128	2.2	0.3
94	1.6	0.2	129	2.2	0.3
95	1.7	0.2	130	2.3	0.3
96	1.7	0.2	131	2.3	0.3
97	1.7	0.2	132	2.3	0.3
98	1.7	0.2	133	2.3	0.3
99	1.7	0.2	134	2.3	0.3
100	1.7	0.2	135	2.4	0.3
101	1.8	0.2	136	2.4	0.3
102	1.8	0.2	137	2.4	0.3
103	1.8	0.2	138	2.4	0.3
104	1.8	0.2	139	2.4	0.3
105	1.8	0.2	140	2.4	0.3

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
141	2.5	0.3	176	3.1	0.4
142	2.5	0.3	177	3.1	0.4
143	2.5	0.3	178	3.1	0.4
144	2.5	0.3	179	3.1	0.4
145	2.5	0.3	180	3.1	0.4
146	2.5	0.3	181	3.2	0.4
147	2.6	0.3	182	3.2	0.4
148	2.6	0.3	183	3.2	0.4
149	2.6	0.3	184	3.2	0.4
150	2.6	0.3	185	3.2	0.4
151	2.6	0.4	186	3.2	0.4
152	2.6	0.4	187	3.3	0.4
153	2.7	0.4	188	3.3	0.4
154	2.7	0.4	189	3.3	0.4
155	2.7	0.4	190	3.3	0.4
156	2.7	0.4	191	3.3	0.4
157	2.7	0.4	192	3.3	0.4
158	2.8	0.4	193	3.4	0.4
159	2.8	0.4	194	3.4	0.5
160	2.8	0.4	195	3.4	0.5
161	2.8	0.4	196	3.4	0.5
162	2.8	0.4	197	3.4	0.5
163	2.8	0.4	198	3.4	0.5
164	2.9	0.4	199	3.5	0.5
165	2.9	0.4	200	3.5	0.5
166	2.9	0.4	201	3.5	0.5
167	2.9	0.4	202	3.5	0.5
168	2.9	0.4	203	3.5	0.5
169	2.9	0.4	204	3.6	0.5
170	3.0	0.4	205	3.6	0.5
171	3.0	0.4	206	3.6	0.5
172	3.0	0.4	207	3.6	0.5
173	3.0	0.4	208	3.6	0.5
174	3.0	0.4	209	3.6	0.5
175	3.0	0.4	210	3.7	0.5

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
211	3.7	0.5	246	4.3	0.6
212	3.7	0.5	247	4.3	0.6
213	3.7	0.5	248	4.3	0.6
214	3.7	0.5	249	4.3	0.6
215	3.7	0.5	250	4.4	0.6
216	3.8	0.5	251	4.4	0.6
217	3.8	0.5	252	4.4	0.6
218	3.8	0.5	253	4.4	0.6
219	3.8	0.5	254	4.4	0.6
220	3.8	0.5	255	4.4	0.6
221	3.9	0.5	256	4.5	0.6
222	3.9	0.5	257	4.5	0.6
223	3.9	0.5	258	4.5	0.6
224	3.9	0.5	259	4.5	0.6
225	3.9	0.5	260	4.5	0.6
226	3.9	0.5	261	4.5	0.6
227	4.0	0.5	262	4.6	0.6
228	4.0	0.5	263	4.6	0.6
229	4.0	0.5	264	4.6	0.6
230	4.0	0.5	265	4.6	0.6
231	4.0	0.5	266	4.6	0.6
232	4.0	0.5	267	4.7	0.6
233	4.1	0.5	268	4.7	0.6
234	4.1	0.5	269	4.7	0.6
235	4.1	0.5	270	4.7	0.6
236	4.1	0.5	271	4.7	0.6
237	4.1	0.6	272	4.7	0.6
238	4.1	0.6	273	4.8	0.6
239	4.2	0.6	274	4.8	0.6
240	4.2	0.6	275	4.8	0.6
241	4.2	0.6	276	4.8	0.6
242	4.2	0.6	277	4.8	0.6
243	4.2	0.6	278	4.8	0.6
244	4.3	0.6	279	4.9	0.6
245	4.3	0.6	280	4.9	0.7

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
281	4.9	0.7	316	5.5	0.7
282	4.9	0.7	317	5.5	0.7
283	4.9	0.7	318	5.5	0.7
284	4.9	0.7	319	5.6	0.7
285	5.0	0.7	320	5.6	0.7
286	5.0	0.7	321	5.6	0.7
287	5.0	0.7	322	5.6	0.7
288	5.0	0.7	323	5.6	0.8
289	5.0	0.7	324	5.6	0.8
290	5.1	0.7	325	5.7	0.8
291	5.1	0.7	326	5.7	0.8
292	5.1	0.7	327	5.7	0.8
293	5.1	0.7	328	5.7	0.8
294	5.1	0.7	329	5.7	0.8
295	5.1	0.7	330	5.7	0.8
296	5.2	0.7	331	5.8	0.8
297	5.2	0.7	332	5.8	0.8
298	5.2	0.7	333	5.8	0.8
299	5.2	0.7	334	5.8	0.8
300	5.2	0.7	335	5.8	0.8
301	5.2	0.7	336	5.9	0.8
302	5.3	0.7	337	5.9	0.8
303	5.3	0.7	338	5.9	0.8
304	5.3	0.7	339	5.9	0.8
305	5.3	0.7	340	5.9	0.8
306	5.3	0.7	341	5.9	0.8
307	5.3	0.7	342	6.0	0.8
308	5.4	0.7	343	6.0	0.8
309	5.4	0.7	344	6.0	0.8
310	5.4	0.7	345	6.0	0.8
311	5.4	0.7	346	6.0	0.8
312	5.4	0.7	347	6.0	0.8
313	5.5	0.7	348	6.1	0.8
314	5.5	0.7	349	6.1	0.8
315	5.5	0.7	350	6.1	0.8

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
351	6.1	0.8	386	6.7	0.9
352	6.1	0.8	387	6.7	0.9
353	6.1	0.8	388	6.8	0.9
354	6.2	0.8	389	6.8	0.9
355	6.2	0.8	390	6.8	0.9
356	6.2	0.8	391	6.8	0.9
357	6.2	0.8	392	6.8	0.9
358	6.2	0.8	393	6.8	0.9
359	6.3	0.8	394	6.9	0.9
360	6.3	0.8	395	6.9	0.9
361	6.3	0.8	396	6.9	0.9
362	6.3	0.8	397	6.9	0.9
363	6.3	0.8	398	6.9	0.9
364	6.3	0.8	399	7.0	0.9
365	6.4	0.8	400	7.0	0.9
366	6.4	0.9	401	7.0	0.9
367	6.4	0.9	402	7.0	0.9
368	6.4	0.9	403	7.0	0.9
369	6.4	0.9	404	7.0	0.9
370	6.4	0.9	405	7.1	0.9
371	6.5	0.9	406	7.1	0.9
372	6.5	0.9	407	7.1	0.9
373	6.5	0.9	408	7.1	0.9
374	6.5	0.9	409	7.1	1.0
375	6.5	0.9	410	7.1	1.0
376	6.6	0.9	411	7.2	1.0
377	6.6	0.9	412	7.2	1.0
378	6.6	0.9	413	7.2	1.0
379	6.6	0.9	414	7.2	1.0
380	6.6	0.9	415	7.2	1.0
381	6.6	0.9	416	7.2	1.0
382	6.7	0.9	417	7.3	1.0
383	6.7	0.9	418	7.3	1.0
384	6.7	0.9	419	7.3	1.0
385	6.7	0.9	420	7.3	1.0

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
421	7.3	1.0	456	7.9	1.1
422	7.4	1.0	457	8.0	1.1
423	7.4	1.0	458	8.0	1.1
424	7.4	1.0	459	8.0	1.1
425	7.4	1.0	460	8.0	1.1
426	7.4	1.0	461	8.0	1.1
427	7.4	1.0	462	8.0	1.1
428	7.5	1.0	463	8.1	1.1
429	7.5	1.0	464	8.1	1.1
430	7.5	1.0	465	8.1	1.1
431	7.5	1.0	466	8.1	1.1
432	7.5	1.0	467	8.1	1.1
433	7.5	1.0	468	8.2	1.1
434	7.6	1.0	469	8.2	1.1
435	7.6	1.0	470	8.2	1.1
436	7.6	1.0	471	8.2	1.1
437	7.6	1.0	472	8.2	1.1
438	7.6	1.0	473	8.2	1.1
439	7.6	1.0	474	8.3	1.1
440	7.7	1.0	475	8.3	1.1
441	7.7	1.0	476	8.3	1.1
442	7.7	1.0	477	8.3	1.1
443	7.7	1.0	478	8.3	1.1
444	7.7	1.0	479	8.3	1.1
445	7.8	1.0	480	8.4	1.1
446	7.8	1.0	481	8.4	1.1
447	7.8	1.0	482	8.4	1.1
448	7.8	1.0	483	8.4	1.1
449	7.8	1.0	484	8.4	1.1
450	7.8	1.0	485	8.4	1.1
451	7.9	1.0	486	8.5	1.1
452	7.9	1.1	487	8.5	1.1
453	7.9	1.1	488	8.5	1.1
454	7.9	1.1	489	8.5	1.1
455	7.9	1.1	490	8.5	1.1

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
491	8.6	1.1	526	9.2	1.2
492	8.6	1.1	527	9.2	1.2
493	8.6	1.1	528	9.2	1.2
494	8.6	1.1	529	9.2	1.2
495	8.6	1.2	530	9.2	1.2
496	8.6	1.2	531	9.3	1.2
497	8.7	1.2	532	9.3	1.2
498	8.7	1.2	533	9.3	1.2
499	8.7	1.2	534	9.3	1.2
500	8.7	1.2	535	9.3	1.2
501	8.7	1.2	536	9.3	1.2
502	8.7	1.2	537	9.4	1.2
503	8.8	1.2	538	9.4	1.3
504	8.8	1.2	539	9.4	1.3
505	8.8	1.2	540	9.4	1.3
506	8.8	1.2	541	9.4	1.3
507	8.8	1.2	542	9.4	1.3
508	8.9	1.2	543	9.5	1.3
509	8.9	1.2	544	9.5	1.3
510	8.9	1.2	545	9.5	1.3
511	8.9	1.2	546	9.5	1.3
512	8.9	1.2	547	9.5	1.3
513	8.9	1.2	548	9.5	1.3
514	9.0	1.2	549	9.6	1.3
515	9.0	1.2	550	9.6	1.3
516	9.0	1.2	551	9.6	1.3
517	9.0	1.2	552	9.6	1.3
518	9.0	1.2	553	9.6	1.3
519	9.0	1.2	554	9.7	1.3
520	9.1	1.2	555	9.7	1.3
521	9.1	1.2	556	9.7	1.3
522	9.1	1.2	557	9.7	1.3
523	9.1	1.2	558	9.7	1.3
524	9.1	1.2	559	9.7	1.3
525	9.1	1.2	560	9.8	1.3

(Continued)

Input signal (Hz)	Speed (MPH)		Input signal (Hz)	Speed (MPH)	
	Radar	Encoder		Radar	Encoder
561	9.8	1.3	568	9.9	1.3
562	9.8	1.3	569	9.9	1.3
563	9.8	1.3	570	9.9	1.3
564	9.8	1.3	571	9.9	1.3
565	9.8	1.3	572	10.0	1.3
566	9.9	1.3	573	10.0	1.3
567	9.9	1.3	574	10.0	1.3

Appendix J

Raw Data from Laboratory Tests for Spacing Control

A. Tests of the Radar Unit

EPROM Type: Radar	(1) #Counts	(2) Seeds	(3) Spacing (inch)	(5) Error (%)
1	203	152.25	6.94	0.43
2	202	151.50	6.97	0.00
3	201	150.75	7.00	0.86
4	201	150.75	7.00	0.86
5	202	151.50	6.97	0.00
6	202	151.50	6.97	0.00
7	202	151.50	6.97	0.00
8	202	151.50	6.97	0.00
9	203	152.25	6.94	0.43
10	203	152.25	6.94	0.43
11	201	150.75	7.00	0.86
12	202	151.50	6.97	0.00
13	202	151.50	6.97	0.00
14	201	150.75	7.00	0.86
15	202	151.50	6.97	0.00
16	202	151.50	6.97	0.00
17	202	151.50	6.97	0.00
18	202	151.50	6.97	0.00
19	202	151.50	6.97	0.00
20	203	152.25	6.94	0.43
21	202	151.50	6.97	0.00
22	201	150.75	7.00	0.86
23	202	151.50	6.97	0.00
24	202	151.50	6.97	0.00
25	202	151.50	6.97	0.00
26	202	151.50	6.97	0.00
27	202	151.50	6.97	0.00
28	202	151.50	6.97	0.00
29	203	152.25	6.94	0.43
30	202	151.50	6.97	0.00

(Continued)

EPROM Type: Radar	(1) #Counts	(2) Seeds	(3) Spacing (inch)	(5) Error (%)
31	201	150.75	7.00	0.86
32	202	151.50	6.97	0.00
33	202	151.50	6.97	0.00
34	202	151.50	6.97	0.00
35	202	151.50	6.97	0.00
36	202	151.50	6.97	0.00
37	203	152.25	6.94	0.43
38	203	152.25	6.94	0.43
39	201	150.75	7.00	0.86
40	201	150.75	7.00	0.86
41	202	151.50	6.97	0.00
42	202	151.50	6.97	0.00
43	202	151.50	6.97	0.00
44	203	152.25	6.94	0.43
45	203	152.25	6.94	0.43
46	202	151.50	6.97	0.00
47	201	150.75	7.00	0.86
48	201	150.75	7.00	0.86
49	202	151.50	6.97	0.00
50	202	151.50	6.97	0.00

B. Tests of the fifth-Wheel Encoder Unit

EPROM Type: Encoder	(1) #Counts	(2) Seeds	(3) Spacing (inch)	(5) Error (%)
1	203	152.25	6.94	0.43
2	203	152.25	6.94	0.43
3	202	151.50	6.97	0.00
4	202	151.50	6.97	0.00
5	202	151.50	6.97	0.00
6	202	151.50	6.97	0.00
7	201	150.75	7.00	0.86
8	201	150.75	7.00	0.86
9	203	152.25	6.94	0.43
10	203	152.25	6.94	0.43
11	202	151.50	6.97	0.00
12	202	151.50	6.97	0.00
13	202	151.50	6.97	0.00
14	202	151.50	6.97	0.00
15	201	150.75	7.00	0.86
16	201	150.75	7.00	0.86
17	203	152.25	6.94	0.43
18	203	152.25	6.94	0.43
19	202	151.50	6.97	0.00
20	202	151.50	6.97	0.00
21	202	151.50	6.97	0.00
22	202	151.50	6.97	0.00
23	201	150.75	7.00	0.86
24	201	150.75	7.00	0.86
25	203	152.25	6.94	0.43
26	203	152.25	6.94	0.43
27	202	151.50	6.97	0.00
28	202	151.50	6.97	0.00
29	202	151.50	6.97	0.00
30	202	151.50	6.97	0.00

(Continued)

Tests of the Fifth-Wheel Encoder Unit

EPROM Type: Encoder	(1) #Counts	(2) Seeds	(3) Spacing (inch)	(5) Error (%)
31	201	150.75	7.00	0.86
32	201	150.75	7.00	0.86
33	203	152.25	6.94	0.43
34	203	152.25	6.94	0.43
35	202	151.50	6.97	0.00
36	202	151.50	6.97	0.00
37	202	151.50	6.97	0.00
38	202	151.50	6.97	0.00
39	201	150.75	7.00	0.86
40	201	150.75	7.00	0.86
41	203	152.25	6.94	0.43
42	203	152.25	6.94	0.43
43	202	151.50	6.97	0.00
44	202	151.50	6.97	0.00
45	202	151.50	6.97	0.00
46	202	151.50	6.97	0.00
47	201	150.75	7.00	0.86
48	201	150.75	7.00	0.86
49	202	151.50	6.97	0.00
50	203	152.25	6.94	0.43

Appendix K

Raw Data from the Field Tests for Spacing Control

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
1	6.25	3.25	10.00	10.00
2	8.00	3.50	7.50	12.25
3	7.25	5.50	9.50	6.75
4	7.00	3.50	8.50	5.25
5	4.50	3.50	4.50	5.25
6	7.00	9.25	6.50	1.50
7	5.75	8.50	7.50	6.50
8	5.00	9.00	5.50	7.25
9	6.00	8.50	7.00	8.00
10	8.25	11.50	9.50	5.75
11	5.50	4.75	11.00	8.25
12	6.50	7.50	6.00	6.75
13	7.60	3.00	8.50	4.75
14	5.50	9.00	6.50	9.75
15	6.75	11.50	5.00	9.50
16	12.00	6.00	10.00	4.75
17	10.50	6.50	9.00	5.50
18	11.50	7.50	10.00	12.50
19	5.25	7.00	6.00	11.50
20	8.25	9.50	7.00	12.00
21	4.00	7.50	8.50	12.50
22	6.00	9.00	4.50	2.25
23	8.75	4.50	10.75	15.50
24	8.30	3.50	5.00	12.50
25	5.75	6.25	10.00	5.50
26	10.25	6.50	6.50	3.50
27	6.00	9.50	6.00	4.75
28	8.50	5.00	4.75	5.00
29	3.50	9.50	9.00	6.00
30	7.00	9.50	11.25	6.75

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
31	5.25	9.75	7.50	5.75
32	7.50	5.00	4.50	5.50
33	7.30	4.00	10.00	2.50
34	4.75	6.00	9.50	5.25
35	6.40	5.00	5.50	11.50
36	4.60	10.00	6.50	10.00
37	6.75	6.50	9.50	10.25
38	7.60	5.00	3.00	7.00
39	8.80	6.75	8.00	4.00
40	9.25	6.25	5.00	9.25
41	8.25	4.00	9.25	7.00
42	7.25	5.00	5.00	10.00
43	6.00	7.25	4.25	2.75
44	5.00	5.70	5.50	7.00
45	9.25	7.25	5.75	5.50
46	9.20	3.75	8.50	8.00
47	10.60	5.75	5.75	6.75
48	5.25	5.25	3.50	10.25
49	9.25	6.00	4.50	4.25
50	10.50	8.50	8.25	10.00
51	4.75	3.50	13.00	2.75
52	5.25	7.00	10.50	7.75
53	5.60	5.25	6.75	11.25
54	8.60	6.50	4.75	7.50
55	8.50	7.25	8.50	4.75
56	9.00	7.50	7.00	11.50
57	5.00	7.75	2.00	4.00
58	7.00	6.00	7.00	4.50
59	9.25	6.00	5.75	6.50
60	6.25	9.25	9.00	5.75

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
61	8.25	9.50	9.50	11.00
62	6.75	8.00	10.50	8.00
63	4.25	7.00	7.00	12.25
64	4.00	5.25	7.25	6.00
65	8.25	4.00	11.00	2.75
66	4.00	9.50	7.00	6.75
67	8.25	6.25	7.00	5.50
68	7.25	5.50	6.25	9.50
69	9.50	9.25	13.00	8.50
70	10.50	7.00	12.00	4.25
71	8.00	7.25	8.25	13.00
72	6.00	9.75	6.25	8.25
73	4.25	6.50	5.00	9.00
74	4.25	5.00	6.75	12.50
75	9.00	6.75	5.25	9.25
76	7.25	8.00	9.00	4.25
77	3.50	9.25	8.25	5.75
78	7.25	9.25	4.00	9.50
79	4.00	6.50	12.50	4.00
80	8.00	6.75	10.25	9.00
81	8.00	7.00	7.50	9.00
82	6.00	10.50	9.75	6.50
83	5.00	9.50	7.50	8.75
84	9.00	9.00	8.00	16.00
85	7.00	6.00	9.25	3.25
86	7.00	10.00	8.00	7.00
87	8.50	10.25	7.75	9.50
88	5.00	8.75	7.50	3.50
89	5.50	6.75	10.25	10.00
90	7.50	8.00	8.50	17.25

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
91	6.50	8.25	8.00	9.00
92	6.50	4.50	11.00	10.00
93	4.50	7.00	3.00	5.50
94	6.00	5.00	5.50	6.75
95	5.00	5.00	5.50	7.00
96	8.25	5.50	10.50	13.00
97	10.00	7.50	8.00	9.25
98	7.75	6.50	6.25	6.50
99	7.50	6.50	9.50	8.50
100	10.50	8.25	10.00	5.50
101	8.00	4.50	9.50	10.00
102	8.25	8.00	7.30	10.25
103	8.50	5.50	12.00	7.00
104	5.00	8.00	7.50	4.00
105	10.00	6.50	11.25	9.25
106	9.50	8.00	7.50	8.00
107	4.00	8.50	10.00	6.75
108	6.50	4.50	13.00	10.25
109	8.50	6.25	12.50	4.25
110	9.50	5.25	4.75	10.00
111	8.50	6.00	6.50	6.50
112	5.75	7.25	6.50	6.50
113	4.75	6.25	10.25	7.25
114	4.00	7.25	5.75	4.75
115	10.00	11.00	7.50	6.50
116	5.00	6.00	8.75	12.25
117	5.50	7.00	4.50	4.75
118	6.25	8.50	3.25	3.50
119	8.75	7.25	6.25	3.00
120	5.25	8.50	9.50	5.50

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
121	6.50	9.00	10.00	12.00
122	6.25	7.25	7.50	6.00
123	4.00	6.50	12.00	5.00
124	6.00	9.50	13.00	5.25
125	6.25	9.25	7.50	11.25
126	3.50	8.25	9.50	7.00
127	5.75	5.50	10.25	7.00
128	7.00	7.00	9.75	5.00
129	4.75	11.25	6.50	6.25
130	7.75	5.50	1.50	8.00
131	8.75	7.00	6.75	4.00
132	5.50	9.00	5.00	4.00
133	9.25	9.00	7.50	5.75
134	6.00	4.50	4.00	7.75
135	8.00	7.25	9.00	6.25
136	6.25	7.00	6.25	5.25
137	10.00	6.50	7.25	6.00
138	6.00	7.00	10.25	6.00
139	11.25	6.00	4.75	9.50
140	4.75	9.25	7.25	5.50
141	9.50	9.50	10.00	7.00
142	8.50	9.00	7.75	9.50
143	10.50	7.25	9.25	12.00
144	6.25	10.00	8.50	5.50
145	9.25	9.25	2.50	6.25
146	7.00	8.25	4.00	7.00
147	7.75	7.25	9.50	3.50
148	9.50	8.25	9.50	8.75
149	9.00	8.50	12.50	12.00
150	7.50	8.00	9.00	2.50

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
151	8.75	10.25	10.00	4.00
152	6.75	7.00	12.50	8.00
153	8.25	6.25	3.25	6.75
154	4.50	8.50	9.50	10.00
155	5.50	6.75	3.00	9.75
156	5.75	7.00	12.25	6.00
157	8.00	6.00	6.25	7.50
158	6.75	7.00	12.75	11.50
159	8.25	6.50	6.50	11.00
160	9.25	10.00	5.00	13.00
161	6.00	5.75	4.25	6.25
162	9.50	4.50	10.00	7.75
163	3.50	10.00	10.25	13.50
164	5.50	5.75	3.50	13.00
165	8.25	11.50	8.25	9.25
166	8.25	9.50	6.25	11.00
167	8.00	4.75	9.75	9.25
168	7.25	4.00	5.75	6.75
169	9.25	9.25	9.00	6.75
170	8.50	7.25	4.75	11.00
171	7.50	9.50	8.75	8.75
172	6.00	8.00	10.75	13.00
173	7.00	5.75	5.75	1.75
174	7.50	6.00	6.25	4.00
175	10.25	7.00	8.25	6.00
176	4.75	8.00	5.25	4.00
177	7.00	10.75	9.25	12.50
178	6.50	3.00	10.25	5.00
179	9.50	7.00	4.00	9.00
180	5.00	7.00	5.25	13.00

(Continued)

	Radar		Encoder	
	Spacing (inch)		Spacing (inch)	
No.	1st Test	2nd Test	1st Test	2nd Test
181	5.25	8.75	4.00	8.25
182	8.25	9.00	9.50	9.00
183	7.00	10.50	3.25	12.50
184	7.50	7.50	5.50	9.25
185	5.50	10.50	12.00	4.25
186	7.00	13.00	2.75	5.75
187	7.50	5.50	6.75	9.50
188	8.00	4.50	2.75	7.50
189	9.00	7.50	8.75	9.00
190	7.25	4.25	3.00	9.00
191	8.25	4.25	2.50	10.00
192	6.00	9.00	5.50	5.50
193	3.50	6.00	3.25	6.75
194	9.00	4.25	6.50	4.50
195	6.00	7.00	10.25	7.00
196	9.00	10.00	13.50	5.75
197	6.50	3.00	12.25	9.25
198	8.50	7.00	2.75	8.50
199	6.00	6.25	7.00	5.50
200	7.00	5.75	9.75	9.50