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Development of a specialty crop harvesting system

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Development of a specialty crop harvesting system

by

Brian Joseph McEvoy

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in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Industrial and Agricultural Technology

Program of Study Committee:
Stuart Birrell, Major Professor
Brian Steward
Steven Hoff

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ABSTRACT

With the field of agriculture constantly growing and evolving, new crops are constantly being developed in order to meet world consumer demands. As technology progresses, more and more specialty crops are being grown not only for food, but also for other properties such as chemical extracts for use in many applications. Because of the rising cost of labor, many people involved in the specialty crop industry are turning to mechanization in order to reduce their production costs. A problem with mechanization is that there is a lack of harvesting technology for every specialty crop. This technology needs to be developed, and a crucial part of this development is the hydraulic and electrical system that is used to reliably control the actions of any specialty crop harvesting system.

A self-propelled crop harvesting system was developed to mechanically harvest a desired flower from a plant, separate the flower from foreign material, and store approximately 1,200 pounds of product onboard while leaving the plant intact for future harvests. The machine developed utilizes a four row head with a set of rotating picking fingers that harvest the desired mature flowers from the plant.

Structural, hydraulic, electrical, and control systems were included in development and fabrication of a working prototype harvesting system. An initial prototype was developed to determine the harvesting efficiency of the mechanical harvester in comparison to hand harvesting. The initial prototype was found to harvest 45% of the desired mature flower crop. This outcome led to the development of a full scale prototype harvesting system.

CHAPTER 1: INTRODUCTION

Many unique crops, besides our typical grains, are produced because they are needed for everyday use. Some of these distinctive crops have unique and highly desired properties such as oil and chemical extracts. It is often more economical for companies to grow the crops for their extracts than it is to synthesize the chemical in a laboratory setting. Various specialty crops demand mechanization due to the demand for the crop, and the economics involved with its production. A good example of specialty crops that already utilize mechanization can be seen in the fruit and nut industries. However, there are still large quantities of specialty crops that require significant manual labor to plant, maintain, harvest, collect, and process the product. This makes the crops very expensive to the end consumer. The goal of this project is to design and build a prototype self-propelled harvester that will allow for commercial harvesting of a specific breed of flowers.

1.1 Overview of Crop Characteristics

The plant's height can range from 18-40 inches. This is dependent the maturity of the plant as well as any plant stressors such as drought, insects, or disease. It is an annual plant, which needs replanted each spring. The plant also grows like a shrub with a central stem connected to a root system. Off this central stem shoots branches with leaves and flowers. Flowers from this plant begin as small-unopened buds. They then pass through a juvenile stage followed by an immature stage before reaching its mature (fully opened) stage. The flowers in the mature stage are desired for harvest. However, if other development stages of flowers are harvested, the future yield of the crop is reduced. If too much time passes between the harvesting of the mature flowers, they will began to go to seed and the plant grows around the over mature flower making it inaccessible to a mechanical harvester.

Many challenges are associated with this type of project. The primary concern is causing minimal damage to the plants during the harvesting application. Since this is a multiple pass harvesting process, it is better to leave some crop behind and to increase the frequency of the harvests. Special attention was given to the selection of the power unit. The power unit is selected for its physical capacity, tire spacing, and ground clearance. Proper tire spacing and ground clearance allows the machine to track in-between the rows with relative ease leaving the plants intact. Leading edges and sharp corners on the harvester are reduced, or rounded, to prevent the crop from catching on the machine causing plant damage. The harvesting mechanism also has to be designed to leave the plant intact after the mature flower is harvested. Focus is shifted to existing specialty crop harvesting systems and technologies to see if they can be adapted for this particular crop.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Specialty Crop Harvesting Systems and Methods

The specialty crop production industry remains to be one of the few agricultural industries in which the harvesting processes remains un-mechanized. Most fruit grown to be sold as fresh produce is manually harvested by hand in order to prevent damage to the fruit. However, many different techniques and methods are utilized to harvest fruit mechanically when it is feasible. Mechanical shakers have been used in many fruit crops with huge success. This differentiation between hand harvesting and mechanical harvesting within a single crop can be seen in great depth within the coffee industry.

2.1.1 Vibration and Shaker Harvesting

The harvesting of coffee is usually completed by hand picking, similar to current flower harvesting. Hand harvesting allows for precise selectivity during the harvesting process. Only ripe coffee berries can be harvested, leaving the unripen berries on the coffee tree to mature and be harvested later on. This creates a premium product that is highly desired and financially rewarded within the coffee industry. Other methods that have been employed to aid hand harvesting include; waiting for the berries to mature and fall to the ground and then gathering them, striking the coffee berries off branches with long poles, or stripping berries together with leaves and winnowing later (Wrigley, 1988). Many of these methods are rarely used because of their destructive nature. This reduces coffee production and reduces the final quality of the product. This holds true for flower crops as well.

A majority of mechanical coffee harvesters use variations of related vibration technology used by the fruit and nut growing industry. Coffee harvesters are usually designed to straddle a single row of trees. The fruit is then the removed from the tree as the machine progresses down the row. As the tree enters the harvester, it is met by two vertical shaker columns with radially protruding plastic fingers (Figure 2.1). The plastic fingers impact the trees, causing an excitation force to detach the desired mature coffee fruit. This harvesting method is similar to most vibration harvesting techniques utilized throughout the fruit and nut industries. The basic principle is to accelerate each fruit so the inertia force developed is greater than the bonding force (stems) between the fruit/nut and tree (Kepner et al, 1987). The excitation force is typically derived from the cyclic oscillation of either a crank slider or two opposite rotating eccentric masses connected to the tree to be harvested (Thomson, 1988). As fruits are detached from the plant they drop vertically through the plant onto catching units near ground level.

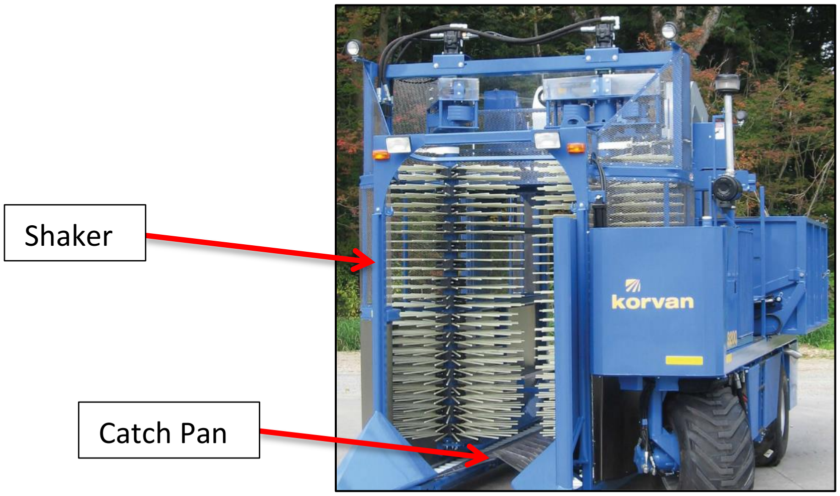


Figure 2.1: Coffee Bean Harvester

The catching units used in shaker harvesting are collection surfaces located below the shaker that extend under the tree, covering the drop area of the fruits (Cargill, 1999). Coffee harvesters, for instance, have complicated plastic panels that individually rotate around a pivot point allowing the trunk of each tree to pass through the machine (Figure 1). These serve as catching panels for the collected product. A conveyor system continuously transfers the harvested fruits to a collection wagon towed between the adjacent rows of trees.

There are limits to this type of mechanical harvesting. Normally, vibratory harvesting systems perform well in crops that have low fruit detachment forces, low crop densities, and require minimal vibration to detach the desired crop. Excessive vibration increases the probability of causing damage to the plant/tree reducing future production and quality. In order to reduce the vibration requirements, it is common practice to apply the power source to shake trees on an individual basis (Den Hartog, 1958). Mechanical vibratory systems also demand that crops are grown in uniform rows for several reasons. Primarily, machinery must be able to move throughout the crop efficiently. In addition, catch units must be placed under each plant/tree being harvested in order to collect detached crop, and the vibration columns or clamps must have sufficient access to the crop. These requirements limit the amount of diverse crops that can be effectively harvested using vibratory techniques.

Mechanical harvesters utilizing shaker or vibratory technology has been used to harvest a variety of other crops besides coffee including; apples, peaches, pears, plums, prunes, apricots, grapes, lemons, grapefruit, olives, and many others. However, due to the indiscriminate nature of vibratory harvesting, all of the available fruit (ripe and unripe) is usually harvested during the initial pass through the crop. This reduces quality and consequently decreases the market price received for the product. This is a challenge for many producers and attempts have been made to reduce the amount of unripen fruit harvested. In many crops, ripe fruits are easier to detach than unripen fruits. Therefore, in developing principles for a mechanical shaker, it is necessary to determine the optional mechanical parameters.

2.1.2 Robotic Harvesting

Another harvesting method involves the use of robotic systems to harvest the desired produce. The use of robotics in agriculture has been growing steadily as technology improves. Many harvesting systems have been developed to utilize robotics and computer vision systems. While this type of harvesting system offers a solution to many of the issues of mechanical harvesting, there are restrictions on the type of crop that can be harvested. This type of bulk harvesting requires (in addition to the canopy-like growth habit) uniform fruit ripeness at harvest, firm and tough fruit, high resistance to damage, and short/stiff limbs (Peterson, 2005). Flowers pose another challenge, due to the fact that they retain a strong attachment bond while growing on flexible stems instead of trees or bushes. This arrangement makes detachment of the flower difficult without harming the main plant stem.

Crop density also affects the efficiency of robotic harvesting system. Robotic harvesting works well in low-density crops where a finite quantity or large fruits are available. High density crops raise two main concerns; as the number of required operations increases, the computing power demanded is increased in order to retain field capacity. In addition, higher crop densities cause the number of harvesting cycles per second required to maintain acceptable harvesting rate to increase. While robotic and computer vision technology offer solutions for many of the problems associated with mechanical harvesting, several challenges remain. According to Sarig (1993), the major problems with robotic picking that must be solved include recognizing and locating the fruit, and detaching it according to specific criteria without damaging the fruit or the tree. Non-uniform crops present another challenge. In non-uniform crops, fruits are distributed throughout the canopy in randomly, making it impossible to clearly model (Plebe and Grasso, 2001). In addition to these challenges, the robotic system needs to be economically sound to warrant its use as an alternative method to hand picking. These limitations coupled with the characteristics of the flower plants reduce the possibility of developing a successful robotic harvesting system capable of achieving desired field capacity and efficiency.

2.1.3 Stripping Header Systems

Another approach that has been widely researched and implemented is stripping fruit or grain from the plant stem. Stripping is a very old harvesting concept that continues to challenge designers through the centuries (Tado et al, 1998). Stripping harvesters have mainly been designed for the small grains and cereal crops. These crops are easily stripped because of their single, vertical stems, and uniform grain.

One of the most influential developments in stripping technology is the Silsoe Stripper. Initial investigations of this design began at Silsoe Research Institute in the UK in 1984 (Tado et al, 1988). The Silsoe design utilizes a rotor that is placed transversely to the direction of the harvester travel (Figure 2.2). Flexible arrowhead stripping elements are mounted on the rotor and in essence comb through the cop, stripping the grain from the plant stem. The arrowhead stripping elements consist of a molded thermoplastic material forming a “V” shape with circular recess at the base (Tado et al, 1998). These are usually referred to as keyhole stripping teeth (Figure 2.3). The sizes of the circular recess are directly related to the size of the crop being harvested. This dimension can be varied to fit the specific crop being harvested.

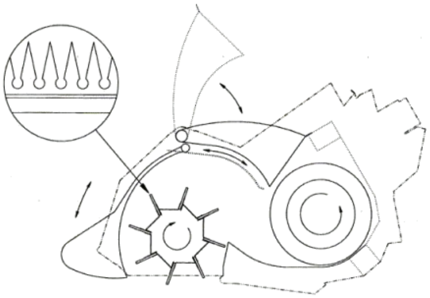


Figure 2.2: Silsoe Header Concept

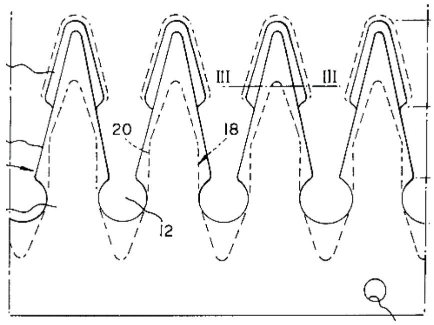


Figure 2.3: Keyhole Stripping Teeth

The efficiency of the operation is directly related on the ability of the stripping elements to collect only the desired grain leaving behind all other material (trash). Damage that can occur to the plant during stripping can cause large amounts of unwanted material to be collected with the grain. For this reason, it has been common to make the comb plates of a thermoplastic material, which causes minor, if any damage to the crop stems (Shelbourne, 2001).

The most popular current production machine using this stripping technology is the Shelbourne-Reynolds stripper header. This header is currently being used to harvest wheat, and other small grain crops. Shelbourne-Reynolds stripper headers are attached to production combines, and they are operated in a similar fashion to regular cutter-bar headers. This technology has shown to be very productive and efficient in a variety of conditions. In Germany, research at Halle showed that combine capacity would be improved by 70-90% with the stripper header (Papesch *et al*, 1995). This is mainly due to the reduced amount of material other than grain (MOG) entering the threshing system of the combine. Reducing MOG allows for increased cleaning efficiency of the grain than when harvesting with conventional cutter-bar headers. However, performance of the stripper has a higher sensitivity to machine settings as well as crop and weather conditions (Tado et al, 1998).

There are many settings to be explored when adapting stripping technology for other crops. Extensive work has shown that the application of rotary stripping systems can be extended to include the harvesting of other crops (Klinner *et al*, 1987). Data needs to be collected from the desired crop to be harvested in order to design the correct stripping elements. The rotational speed of the transversely mounted rotor will need to be adjusted for different conditions existing within the crop to be harvested. Further research and development is needed in order to properly utilize and optimize this technology for various specialty crops.

While many stripping systems have been developed for self-propelled, large-scale harvesters, others have focused on creating an aid to increase the efficiency of hand-harvesting labor. Merritt (1995) developed a hand held unit with powered oscillating rake member that is designed to aid in the harvest of olives and comparable fruit. This tool also has extending tines to strip fruit from branches. Similar devices have been developed such as the portable stem vibrator (PSV) for use in small fruit and berry harvesting. This class of devices aid in the manual harvesting process, and dramatically increases harvesting efficiencies. A small internal combustion engine is used to create hydraulic pressure; this is utilized to oscillate an end-effector. Many types of end-effectors are utilized including c-clamps that attach to branches.

Another type of end-effector includes rake fingers that strip through the branches while oscillating. Oliveros and Eugenio (2005) has shown that the use of PSV devices to harvest coffee can increase harvest efficiencies by up to 458.3% when compared to traditional hand harvesting methods. It was also shown that 80% reduction in labor requirements can also be achieved by utilizing PSV's. However, although PSV devices have shown to be advantageous during the detachment phase of harvest, the collection phase remains manual and labor intensive.

CHAPTER 3: OBJECTIVES

The goal of this research was to design and implement a control system for a prototype specialty crop harvesting system. The eventual outcome of this project is to serve as a foundation for the development of a control system on a production machine. In order to accomplish this goal, two main objectives were defined as follows:

- Objective #1: Analyze the characteristics of the crops to determine a harvest schedule.
  - Perform hand harvest tests to establish a baseline for comparison.
    - Determine the total amount of available flower mass.
    - Determine the total amount of over mature flower mass.
  - Perform mechanically harvest tests to test the harvesting mechanism concept.
    - Determine the total amount of available flower mass harvested.
- Objective #2: Develop a Hydraulic and Control System to Reliably Control the Harvesting System.
  - Develop a system, which uses a closed circuit pump to drive the harvesting mechanism.
    - Implement a closed loop control system to maintain the desired reel speed.
    - Implement a reel index control for the harvesting head.
  - Develop a system that utilizes an open circuit load sense pump and closed center valves to control auxiliary harvesting functions.

CHAPTER 4: METHODS AND MATERIALS

Since harvesting properties of the crop were relatively unknown, tests were needed to determine yield characteristics of the crop and which harvest intervals were needed to maximize the amount of desired material harvested. To determine the actual yield of the crop, and the efficiency of the harvesting mechanism design, field tests were conducted in order to determine this information. In addition to the crop yield and mechanical harvesting efficiency, physical characteristics of the crop had to be quantified as well. Field-testing took place at the Kemin SCI Research Farm located near Kelly, Iowa.

4.1 Testing Materials and Equipment

Basic materials were required in order to carry out these tests successfully. To set up the experiment several items were needed. First, a plot map was needed to be developed in order to plan out the hand harvested and mechanically harvested plots. These plots had to be designed to fit the available space in the research field. A tape measure was used to accurately measure plot lengths to ensure that the plot markers were spaced at the 17.5 feet intervals.

For collecting the individual flower attribute data points, a small 1000 gram scale was used to determine the overall weight of the flower. A tape measure was used to determine the flower diameter in inches to the nearest 1/8 of an inch. A digital caliper was used to measure the base of the flower in inches. These results were entered into JMP Pro 10 statistical software to determine any correlations and distributions.

For the mechanical testing, a small-scale prototype harvesting system was used to harvest the crops. The harvested material was then collected from each plot and weighed on a scale with a 100 kilogram limit. These weighs were recorded in Microsoft Excel and were compared to their respective hand harvested weights to determine the harvesting efficiency.

4.2 Testing Procedure

Two tests were utilized in the testing of the prototype harvesting system. The first test was a set of hand harvested plots. These plots were harvested on different harvest schedules. This was used to establish any infield yield losses that occurred naturally, total available yield, which harvest schedule is optimum, and distributions for various flower attributes. The second test was a set of mechanically harvested plots. These plots were used to evaluate the performance of the mechanical harvesting system, and to help determine a harvest schedule that would result in the highest total yield harvested.

4.2.1 Hand Harvesting

The hand harvesting experiment was used to determine naturally occurring field losses, total yield, and to quantify physical flower attributes. This experiment utilized three plots spaced at equal distance from each other. These plots were four rows wide and were 1/1000th of an acre in length (17.5 feet). Two rows from each plot were harvested on a weekly basis, while the other two rows were harvested on a biweekly basis. Each plot contained the same four rows, and utilized the west two rows for the weekly harvest. The spacing of the plots through various parts of the field accounts for the variability within the field itself. At each pre-defined harvest date for weekly and biweekly harvests, all mature and over-mature flowers were harvested by hand. These flowers were then transported back to the lab, and they had their physical attributes logged. Attributes that were logged included weight in grams, base diameter in inches, flower diameter in inches, and state (mature or over mature). The data from this test was then compiled and analyzed after the harvest season.

4.2.2 Mechanical Harvesting

To determine the harvesting efficiency of the prototype harvesting system, a mechanical harvest experiment was needed. The goal of this experiment was to determine an actual yield of mature flowers harvested. This experiment consisted of nine plots divided into three groups. Group one was initially harvested on week one, group two was initially harvested on week two, and week three was initially harvested on week three. The initial week one harvest occurred when the plants had a full flush of flowers that justified taking the harvesting system through the field. Plots one, four, and seven were harvested on a weekly basis, and plots two, five, and eight were harvested on a biweekly interval. In addition, plots three, six, and nine were harvested in a triweekly harvest interval. Each plot consisted of three sampling areas spaced evenly across the field. These areas were three rows wide and 17.5 feet (1/1000th of an acre) in length. Harvested material was deposited on the ground in between each row by the harvesting system. The mature flowers that were harvested in the sample area were gathered and weighed to determine the weight of the harvested mass for the sample area. This data was then analyzed at the end of the harvest season to determine the yield of the mechanically harvested material.

CHAPTER 5: RESULTS AND DISCUSSION

By conducting the hand harvest and initial mechanical harvest tests, the physical attributes for the crops were able to be quantified. These tests were also able to determine total yield of the crop in addition to the natural occurring infield losses. The best harvest interval for the crop was also able to be determined based on the collected data from the hand harvested plots. From the mechanical testing plots, the yield behavior on different harvest intervals was able to be determined as well as the effect of delaying the initial harvest on the harvest yield. Results from these two tests can be utilized in future deigns of the harvesting system, and they can be used in the logistics planning of the farming operation that harvests this crop.

5.1 Hand Harvest Test Results

As was previously stated in the testing procedure, both over mature flowers and mature flowers were collected at the specified harvest intervals from each plot. The over mature flowers can be defined as a naturally occurring in-field loss. This is because these flowers can't be processed for their desired properties because of the severe degradation in the quality of the material. Thus, it was important do determine not only the total yield and physical properties of the crop, but to determine which harvest interval yielded the lowest in field loss.

5.1.1 Hand Harvest Yield Results

Although some potential yield data was known from green house trials, this data was not representative of the behavior of the cops in the field throughout the season. Therefore, it was necessary to run a series of tests that would help determine the total available yield mass of the crop throughout the season. In addition to this, naturally occurring in-field yield losses could also be determined. Another goal of this study, was to determine whether a weekly or biweekly harvest schedule would result in the highest total obtainable yield with the lowest in-field yield loss. This yield data was then used to determine the necessary capacities required of the material conveyance system of the harvester.

From Figure 5.1, it can be seen that the weekly and biweekly harvests yielded approximately the same total mass of 4000 pounds/acre. However, the biweekly harvest had a larger over mature flower mass of 1105 pounds/acre. This reduced the mature flower mass of the biweekly harvest plots to 2906 pounds/acre. In contrast, the weekly harvest over mature flower mass of 770 pounds/acre, and a mature flower mass of 3348 pound/acre. It can be stated that weekly and biweekly harvests can achieve similar total mass results. However, the biweekly harvest had an infield loss 442 pounds/acre more than the weekly harvest reducing the actual harvestable yield. This is caused by the delay in the harvest of the flower, causing the flower to die off and become overgrown by the rest of the plant. From these yield results, it can be concluded that it is advantageous to harvest this crop on a weekly basis than a biweekly basis.

To determine if the results from the hand-harvest yield tests are statistically different, an ANOVA table was used to compare the cumulative total mass, mature flower mass, and over-mature flower mass yields of the weekly and biweekly harvest plots. According to the ANOVA table in Figure 5.2, there is no statistical difference between the weekly and biweekly harvests.

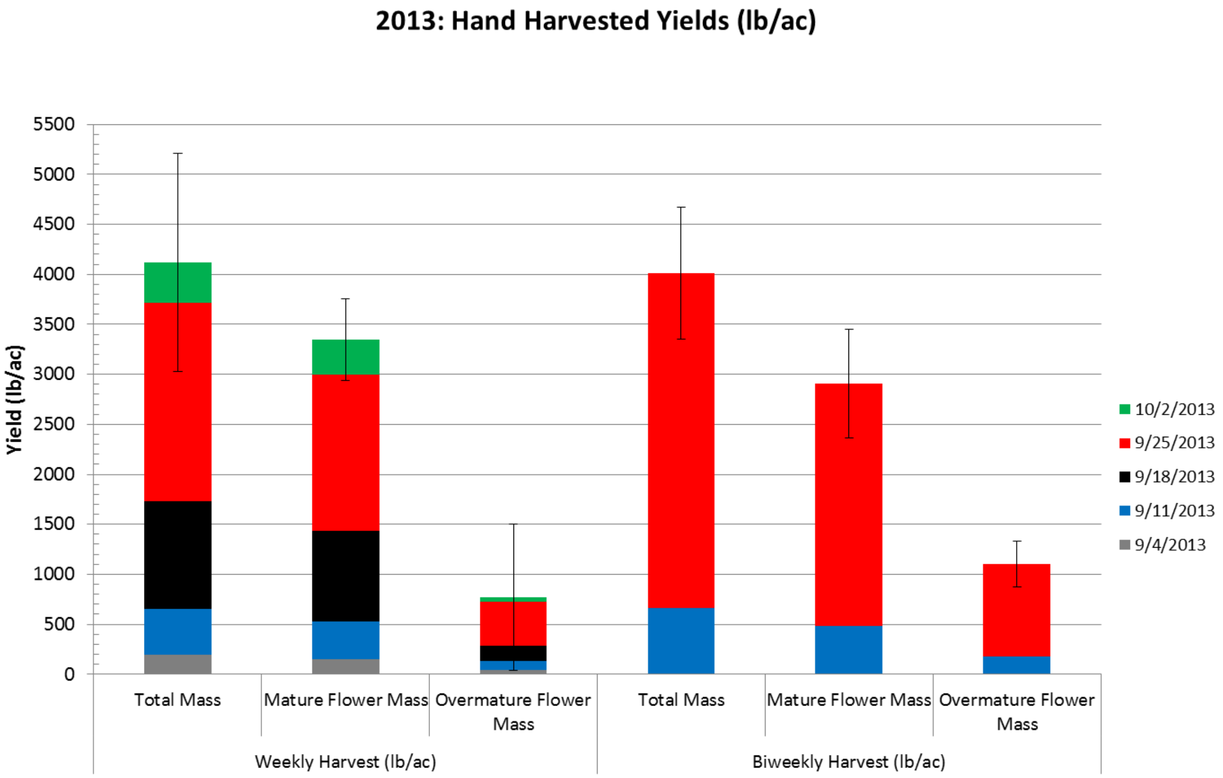
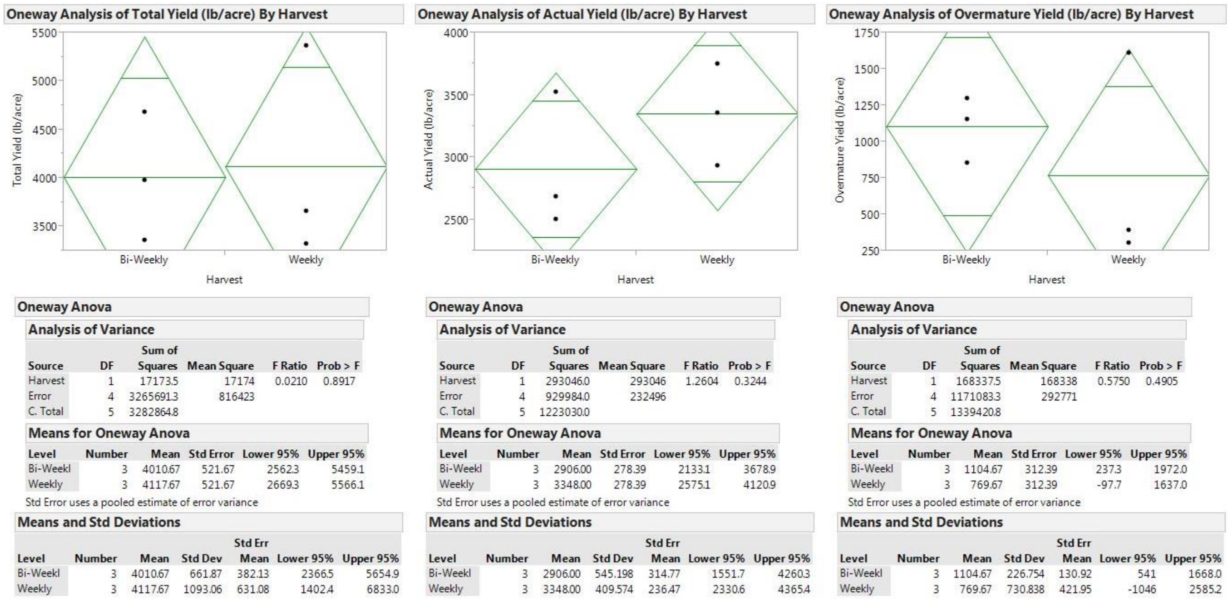


Figure 5.1: Hand Harvested Plot Yields



Oneway Analysis of Total Yield (lb/acre) By Harvest

Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Harvest	1	17173.5	17174	0.0210	0.8917
Error	4	3265691.3	816423		
C. Total	5	3282864.8			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Bi-Weekl	3	4010.67	521.67	2562.3	5459.1
Weekly	3	4117.67	521.67	2669.3	5566.1

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Bi-Weekl	3	4010.67	661.87	382.13	2366.5	5654.9
Weekly	3	4117.67	1093.06	631.08	1402.4	6833.0

Oneway Analysis of Actual Yield (lb/acre) By Harvest

Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Harvest	1	293046.0	293046	1.2604	0.3244
Error	4	929984.0	232496		
C. Total	5	1223030.0			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Bi-Weekl	3	2906.00	278.39	2133.1	3678.9
Weekly	3	3348.00	278.39	2575.1	4120.9

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Bi-Weekl	3	2906.00	545.198	314.77	1551.7	4260.3
Weekly	3	3348.00	409.574	236.47	2330.6	4365.4

Oneway Analysis of Overmature Yield (lb/acre) By Harvest

Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Harvest	1	168337.5	168338	0.5750	0.4905
Error	4	1171083.3	292771		
C. Total	5	1339420.8			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Bi-Weekl	3	1104.67	312.39	237.3	1972.0
Weekly	3	769.67	312.39	-97.7	1637.0

Std Error uses a pooled estimate of error variance

Means and Std Deviations

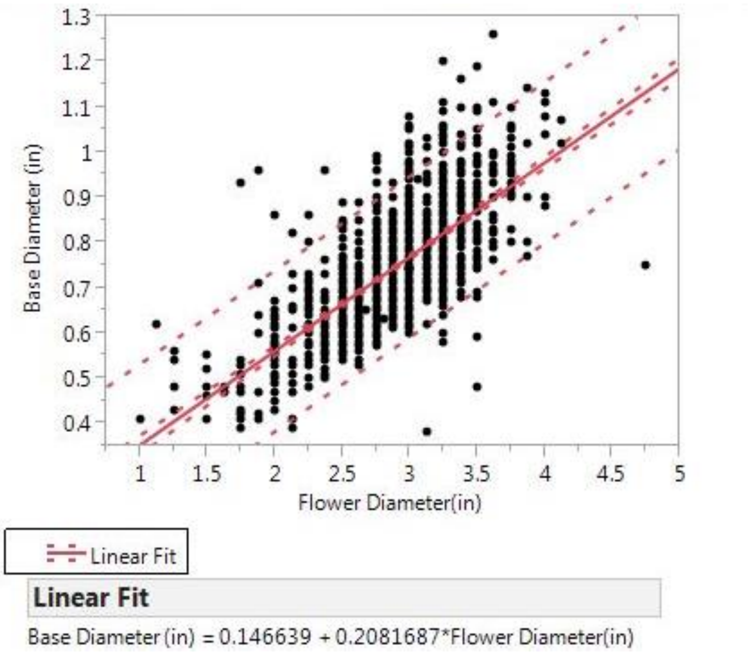
Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Bi-Weekl	3	1104.67	226.754	130.92	541	1668.0
Weekly	3	769.67	730.838	421.95	-1046	2585.2

Figure 5.2: Hand Harvested Plot Yield ANOVA Results

5.1.2 Hand Harvest Flower Attribute Results

Previously, no data has been collected regarding the physical attributes of the harvested material. Because of this, there was no information readily available to adequately design a harvesting mechanism to harvest the desired crop material. Also, the variability of the harvested material throughout the season was unknown. From the collected data, regression models were able to be generated that would aid in the design the harvesting mechanism. In addition, the data allows for samples of the harvested material to be collected at various points throughout the season that would allow the correctly sized harvesting mechanism to be installed on the harvesting system

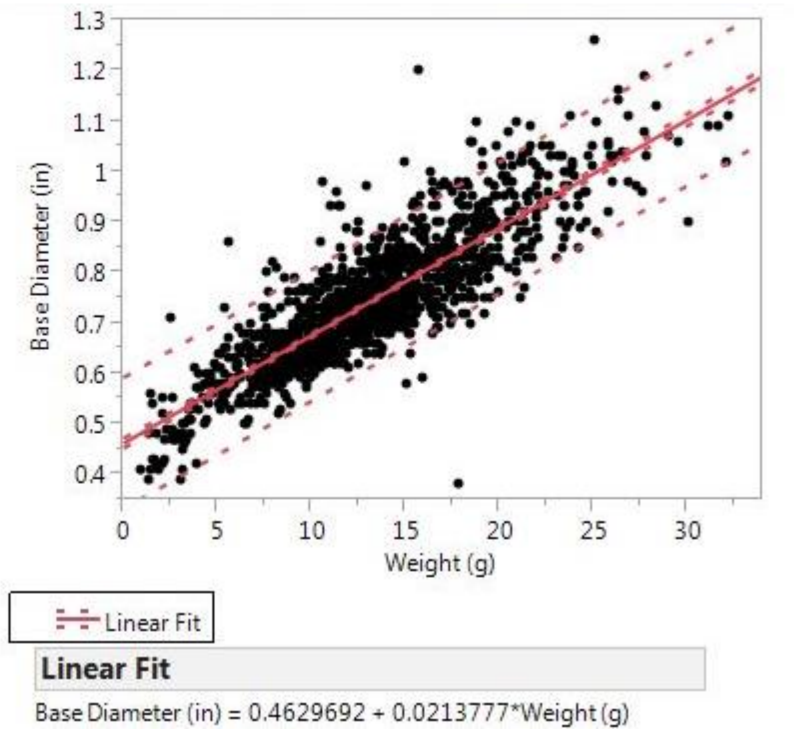
As was previously stated in the procedure for the hand harvested testing, the physical attributes of each flower collected was quantified and logged. The goal of this experiment was to try to find a possible correlation between the flower diameter, base diameter, and flower weight. The flower diameter can be defined as the average diameter of the opened flower pedals by measuring from pedal to pedal intersecting the center axis of the flower with the tape measure. The base diameter of the flower can be defined as the diameter of the flower calyx, or base of the flower from which the flower pedals grow and develop from. A total of 1362 observations were made for each attribute. Each attribute observation was measured and then recorded by hand from each hand-harvested flower. Possible correlations that were tried was flower weight and flower diameter, flower weight and base diameter, and flower diameter and base diameter. The correlation of base diameter and flower diameter, with a linear regression yielded an R-Squared value of 0.51 (Figure 5.3). This suggests that there is a weak relationship between these two attributes. It is not recommended to use the flower diameter property to determine the base diameter. However, when the flower weight was compared to the base diameter with a liner regression, an R-Squared value of 0.74 was achieved in Figure 5.4.



Linear Fit

Base Diameter (in) = 0.146639 + 0.2081687*Flower Diameter(in)

Figure 5.3: Regression of Flower Diameter and Bud Diameter



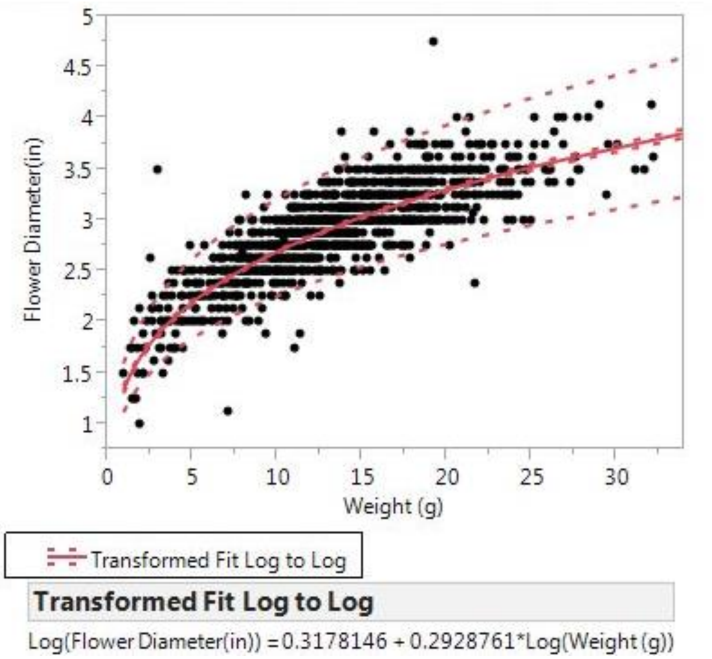
Linear Fit

Base Diameter (in) = 0.4629692 + 0.0213777*Weight (g)

Figure 5.4: Regression of Flower Weight and Bud Diameter

This value suggests that there is the potential for a strong relationship between these two properties. It also suggests that a new experiment designed to measure this relationship can be performed to determine if there is a stronger relationship between the two properties. This regression model can be used for in field estimations of the base diameter of the flower by measuring the flower weight.

The last correlation that was tried, was the correlation of the flower weight with respect to the flower diameter. Initially, a linear model was tried and resulted in a poor correlation with an R-Squared value of less than 0.5. However, there appeared to be a pattern in the data points in the regression model that the linear fit was not the appropriate choice of representation. Polynomial and exponential function lines of fit were also tried, and they resulted in similar R-Squared values. These outcomes suggested using the log function to transform the axis's because no line of fit could be applied to achieve a strong R-Squared value. The logarithmic transformation function available in JMP Pro10 was used to transform the line of fit to match the pattern of the data points. Transforming the line of fit resulted in a line that matched the pattern of the data points resulting in an R-Squared value of 0.71 (Figure 5.5).



Transformed Fit Log to Log

Log(Flower Diameter(in)) = 0.3178146 + 0.2928761*Log(Weight (g))

Figure 5.5: Regression of Flower Weight and Flower Diameter

From this regression model, it can be stated that there is a potential strong relationship between these two properties. This model is can also be used for infield estimations of the flower diameter by measuring the flower weight. An experiment designed to measure this relationship may be needed in order to establish a stronger correlation between these flower properties.

5.2 Mechanical Harvest Test Results

In order to develop a harvesting mechanism for this crop, a prototype concept head had to be developed and tested. This head was tested to determine the feasibility of harvesting the desired crop material without affecting the crop in a negative manner. The mechanical harvesting test results were used to determine the harvest schedule for a mechanical harvesting system and the impact of the initial harvest date on harvest yields. In addition, this test provided information regarding the total yield harvested material, which was compared to the total available yield of the crop, obtained from the hand harvest test results. This was used to determine the harvesting efficiency of the mechanically harvesting system.

The mechanically harvested tests were not completed because the crops were killed off due to frost. In addition, plots one, two, and three suffered significant wind damage causing the crops to lodge. When this crop becomes lodged, it experiences a significant reduction in harvestable yield. This occurred prior to the initial harvest.

Initial findings show that when the mechanically harvested results are compared with the hand harvested results approximately 45 percent of the available mature flowers were harvested. The initial results also support that there is little difference in initial harvest yield when the initial harvest is either delayed two or three weeks. However, the data does support delaying initial harvest to week two. This initial harvest yield increase is caused by the plants becoming more mature, and producing a larger flush of flowers. When comparing plots one and two, the data supports a biweekly harvest over a weekly harvest because the total yields for each plot are similar. This is contradictory to the results from the hand harvested plot results. The data from the mechanical testing can be seen in Figure 5.5.

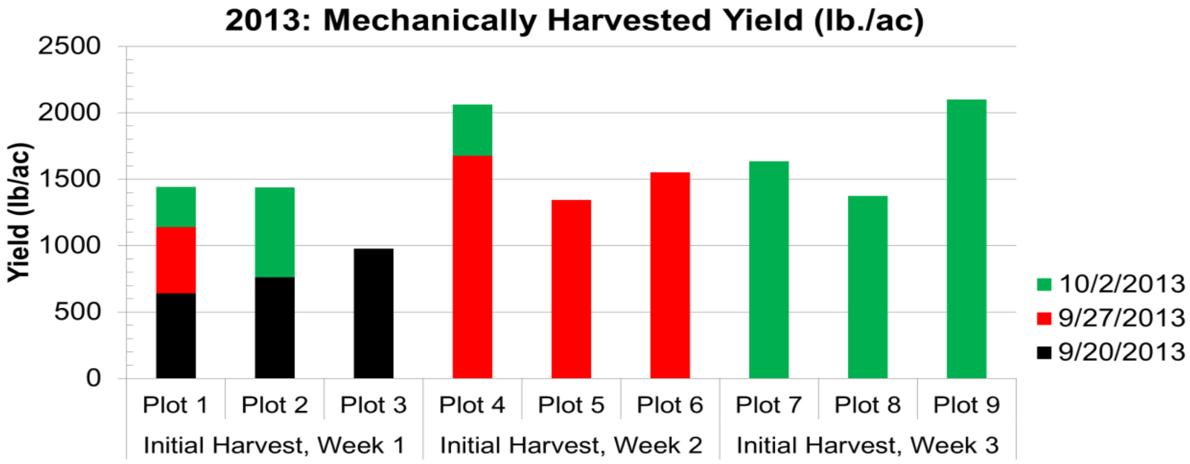


Figure 5.6: Mechanically Harvested Plot Yields. Note: Plots 1, 2, & 3 Received Significant Wind Damage.

CHAPTER 6: HARVESTING SYSTEM DEVELOPMENT

Several constraints were initially placed on the harvesting system before the design even began. Primarily, the harvesting system had to be a row crop system that tracked easily between the rows of standing crop without causing damage to the crop. In addition, the harvesting head's minimum width could not be narrower than the platform selection, and its maximum width could not exceed 17.5 feet. The harvester's overall height had to remain under 16 feet. This allowed the machine to be driven with the head attached on secondary roads from location to location. The system also had to be able to harvest lodged material, and to guide lodged material into the harvesting reel mechanism. This was accomplished with a set of snouts whose height could be hydraulically controlled by the machine operator.

These snouts also have free-floating tips that allows the snouts to float along the ground and under any lodged crop material (similar to a corn head snout). After the material was guided into the harvesting mechanism, the harvested material (including the MOG) was conveyed through a conveyance system to a cleaning system. A two stage cleaning system was developed to remove light foreign material such as leaves, and heavy foreign material such as stems. MOG collected by the cleaning system was ejected over the side of the machine through a chute in the wheel-track. This was to ensure that the trash would land under the crop canopy, and not on top of it causing potential future harvest difficulties. The clean product was then collected into an onboard storage hopper. After the hopper became full, it was unloaded into a collection vessel that took the crop to a processing area.

6.1 Platform Selection

Before any designs could be considered, a platform on which to construct the new harvesting system had to be selected. This platform needed to have ample ground clearance, a front mount lifting mechanism to attach the harvesting head, and adequate engine power for additional hydraulic pumps. The frame of this machine had to possess enough strength to handle the additional weight of an attached harvesting head, and the weight of a fully loaded hopper. After the addition of the complete harvesting system, the platform had to remain easily maneuverable and able to reach desired field speeds without any issues.

Platform constraints and expectations limited the selectable platforms down to three options: Oxbo 2475 green bean harvesters, Miller Nitro 5000 Series Sprayers, or Hagie Manufacturing STS Series sprayers. The Oxbo 2475 was given great consideration because of its manufactured role as a specialty crop harvester. This machine already has a material conveyance system designed and integrated to remove material from the harvesting head, and into a 530ft^3 hopper. This harvester also has a dual stage fan cleaning system incorporated into the system for MOG removal. This platform also has integrated control system that utilizes components similar to the developing design of the harvesting system, allowing for an easier integration of the system. A major concern for this machine was having enough ground clearance to avoid crop damage. In conjunction to this concern, was the concern that the machine’s wheel track could not be configured for row crops. Other concerns about this platform was how to integrate a stem removal system, and how to attach the harvesting head. Finally, in addition to the large cost support from the manufacturer would also be needed.

A lower cost solution that may be economically feasible for this project was to go with a Hagie Manufacturing or Miller sprayer platform. Both of these platforms can be purchased second hand at a lower cost with the lifting arms, and without the spraying system (booms, lines, solutions tanks, and pumps). Each machine fulfils the primary constraints by having sufficient ground clearance as well as being a row crop machine with adjustable tread widths with a front mount lift. This provides a “blank slate” for the design of the new specialty crop harvesting system. Both machines have ample frame space and strength for an onboard storage unit and cleaning system. However, additional hydraulic and electrical systems would need to be added to both machines in order to run and control the harvesting system.

A used Hagie Manufacturing STS10 Sprayer platform was chosen on which to construct the new harvesting system. This platform was chosen because of cost, and because it could be purchased as a “blank slate” enabling a system to be designed from the ground up to meet the harvesting demands of the crop. An additional reason that this was chosen, was because of the location of the manufacturer. Hagie Manufacturing is located relatively close to Iowa State University, allowing for effective product support and design insights to be conveyed to the Iowa State University design team.

6.2 Material Conveyance

After the material was harvested, it had to be transported from the head to the onboard storage vessel and pass through a cleaning system. A pneumatic transportation system was initially considered to transport the material. However, complications arose when SolidWorks flow analysis revealed that the volume and velocity of air needed to capture the harvested material was not a feasible design concept. Since pneumatic transportation was eliminated from the design considerations, a conveyor system was chosen to implement into the harvesting system design.

In order to accomplish this, a system of conveyors were designed to collect the harvested material from the harvesting mechanism and transport efficiently into the on board storage hopper. The flow chart in Figure 6.1 was used to develop the basic layout of the material flow for the harvesting system. The harvested product was collected onto two cross conveyors. These cross conveyors then moved the material to the center of the head onto a central gathering conveyor. This conveyor also collected harvested product from the harvesting mechanism. From the gathering conveyor, material flowed onto a feeder-house conveyor, and then into a bucket elevator. The gathering conveyor was needed in order to increase the ground clearance of the harvesting head. By adding this additional conveyor, the pivot point of the feeder house was translated horizontally towards the rear of the machine, and vertically in a positive direction until the tangent of the feeder house conveyor pulley was located one inch below the surface of the gathering conveyor. This was needed to increase the ground clearance of the conveyor system. By not increasing ground clearance to the necessary distance, severe and irreversible damage can be caused to the crop. Either this damage would kill the crop resulting in total yield loss, or it would cause a significant loss in yield. Total yield loss and a decrease in yield are not desirable outcomes in any crop production.

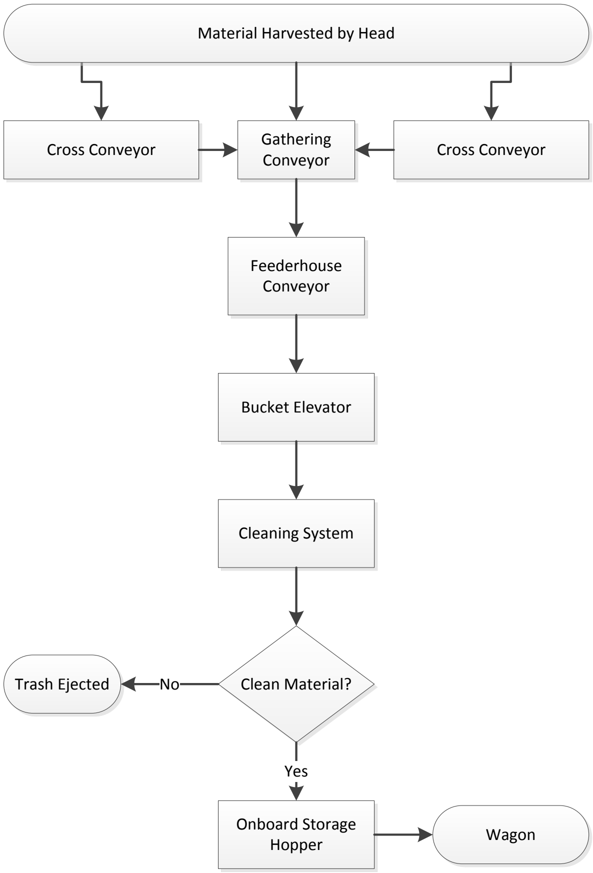


Figure 6.1: Flowchart Used to Develop the Harvester Material Handling System

The theoretical capacities of the conveyors were calculated by using Equation 6.1. The feeder-house conveyor, gathering conveyor, and cross conveyor needed to operate at a linear speed equivalent to if not greater than the maximum harvesting forward speed of five miles per hour of the harvester.

$$Q = \frac{\pi * d * N * D * W}{1728} \qquad \textbf{Equation 6.1}$$

Where:

Q = Theoretical Conveyor Capacity, ft^3/min

d = Pulley Diameter of the Conveyor, Inches

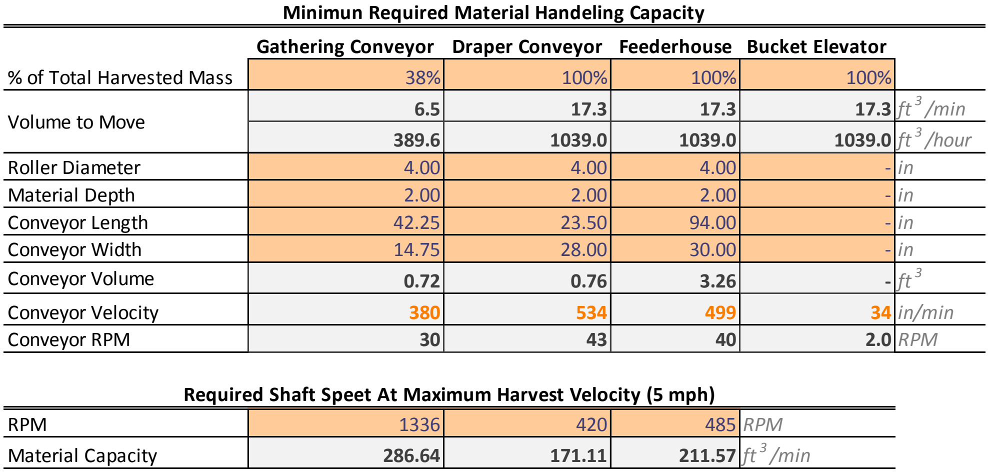
N = Drive Shaft Speed, Revolutions/Minute

D = Material Depth, Inches

W = Conveyor Width, Inches

From this, the minimum shaft speeds for each conveyor could be determined for the maximum harvest velocity of five miles/hour. From Table 6.1, it can be seen that these values greatly exceed the minimum required shaft speeds for the given material flow rate. By calculating the conveyor speed based off ground speed, the risk of over feeding the conveyor was greatly reduced. By comparing this value to the minimum required shaft, it can be determined if the conveyor is adequately sized to handle the volume of the harvested material at the highest forward harvest velocity.

Table 6.1: Conveyor Material Handling Capacities



Minimun Required Material Handeling Capacity

	Gathering Conveyor	Draper Conveyor	Feederhouse	Bucket Elevator	
% of Total Harvested Mass	38%	100%	100%	100%	
Volume to Move	**6.5**	**17.3**	**17.3**	**17.3**	*ft^3/min*
	389.6	**1039.0**	**1039.0**	**1039.0**	*ft^3/hour*
Roller Diameter	4.00	4.00	4.00	-	*in*
Material Depth	2.00	2.00	2.00	-	*in*
Conveyor Length	42.25	23.50	94.00	-	*in*
Conveyor Width	14.75	28.00	30.00	-	*in*
Conveyor Volume	**0.72**	**0.76**	**3.26**	**-**	*ft^3*
Conveyor Velocity	**380**	**534**	**499**	**34**	*in/min*
Conveyor RPM	**30**	**43**	**40**	**2.0**	*RPM*

Required Shaft Speet At Maximum Harvest Velocity (5 mph)

RPM	1336	420	485	*RPM*
Material Capacity	**286.64**	**171.11**	**211.57**	*ft^3/min*

Several methods were considered in order to move the material from the feeder-house conveyor into the hopper system: pneumatic system, screw conveyors, or a bucket elevator. The pneumatic system was not a feasible method to transport the crop from the feeder-house conveyor into the hopper. Because there was not sufficient hydraulic power available to move the necessary amount of air required. In addition to this, the reliability of the system could not be guaranteed because of the potential for plugging. A vertical screw conveyor system was also considered to move the crops vertically into the hopper. Although the theoretical capacity of the system could keep up with the volume of material entering the harvesting system, the harvested material would have become compacted. The compacted material would be unable to go through the necessary material cleaning system. Because of this drawback, the screw conveyor concept was rejected for the harvester design. A bucket elevator was chosen to move the crop vertically into the storage system. The bucket elevator would not cause compaction of the harvested material, and would be a more reliable system when compared to the other systems. The minimum velocity of the elevator in feet/minute that was required to successfully eject the material from the elevator buckets was calculated using Equation 6.2. The speed required of the hydraulic motor was calculated by taking the linear velocity of the elevator divided by the number of inches per revolution. To determine if the elevator had sufficient capacity at the required speed, Equation 6.3 was utilized to calculate the capacity in ft^3/min. This value was compared to the actual volume of material flow entering the bucket elevator system.

$$V = 60 * \sqrt{g * r} \qquad \textbf{Equation 6.2}$$

Where:

V = Linear Velocity of the Elevator, Feet/Min

g = Gravitational Constant 32.2 ft/s^2

r = Radius of Mass About the Axis of Rotation, Feet

$$Q = \frac{Qb * \mathrm{N} * V}{1728} * \frac{12}{D} * E \qquad \textbf{Equation 6.3}$$

Where:

Q = Capacity, ft^3/min

Qb= Capacity of each Bucket, $in^3/Bucket$

V = Velocity, ft/min

N = Buckets per Row

D = Distance Between Buckets, Inches

E = Elevator efficiency (75%)

6.3 Theoretical Harvesting Capacities

The proposed harvesting system was to utilize a four row crop head for 30-inch rows. The harvesting system would operate between one and five miles per hour with an unloading time from zero to 10 minutes. To model the harvester characteristics, velocities between 0.5 mph and 5.0 mph were chosen at 0.5 mph increments. Field capacity and field efficiencies (Equation 6.4 & 6.5) were modeled at several unloading intervals: zero, two, five, and ten minutes based off a weekly harvest interval. The unloading interval is the time it takes the harvester to unload the crop in addition to the total travel time to and from the unloading site. A pass is defined as a single harvest pass on a unique set of rows across the field, and a turning time is defined as the amount of time it takes the harvester to turn around at the end of the field from one harvest pass to another. An unloading interval of zero minutes represents that the harvester is unloading on the go and is not slowing down or stopping to unload its cargo. This is similar to what grain combines do. For the theoretical field capacities, a hopper volume of 99 ft^3, a material density of 14 lb/ft^3, and a turning time of 30 seconds were assumed. The theoretical field capacity is the equivalent of the harvester harvesting at a consistent speed nonstop without turning around. Since the harvester needs to turn on the end, the theoretical field capacity can never be achieved.

$$TFC = \frac{V*5280*RS*N*FE}{12*43560}$$ **Equation 6.4**

Where:

TFC = Theoretical Field Capacity, Acres/Hour

V = Velocity, Miles/Hour

RS = Row Spacing, Inches

N = Number of Rows Harvested

FE = Field Efficiency (See Equation 6.5)

$$FE = \frac{HT}{HT+P*TT+UT}$$ **Equation 6.5**

Where:

FE = Field Efficiency as a Percentage Actual Harvest Time

P = Number of Passes/Load

HT = Time to Harvest a Single Pass, Minutes (See Equation 6.6)

TT = Time to Turn on the Field End, Minutes

UT = Time to Unload the Harvester, Minutes

$$HT = \frac{FL*60*P}{V}$$ **Equation 6.6**

Where:

HT = Harvest Time, Minutes

FL = Field Length, Miles

P = Number of Passes/Load

V = Velocity, Miles/Hour

From Figure 6.2 it can be stated that as the harvesting system moves at higher velocities through the fields the field capacity of the machine increases as well. However, at increased speeds and unloading times, this rate of increased capacity begins to decay exponentially. The cause of this result can be explained by observing the field efficiencies Figure 6.3.

As the harvester increases its forward velocity, the same volume of material is being harvested at a higher rate resulting in the harvester to unload on a more frequent basis decreasing its field efficiency. Two solutions could be implemented to reduce the drop in field efficiencies in future designs. First, would be to develop a hopper system proportional to its header size that allows the harvester to stop on a less frequent basis at higher harvesting speeds. Second, develop an unload system proportional to the hopper size that has an unload time that approaches zero minutes.

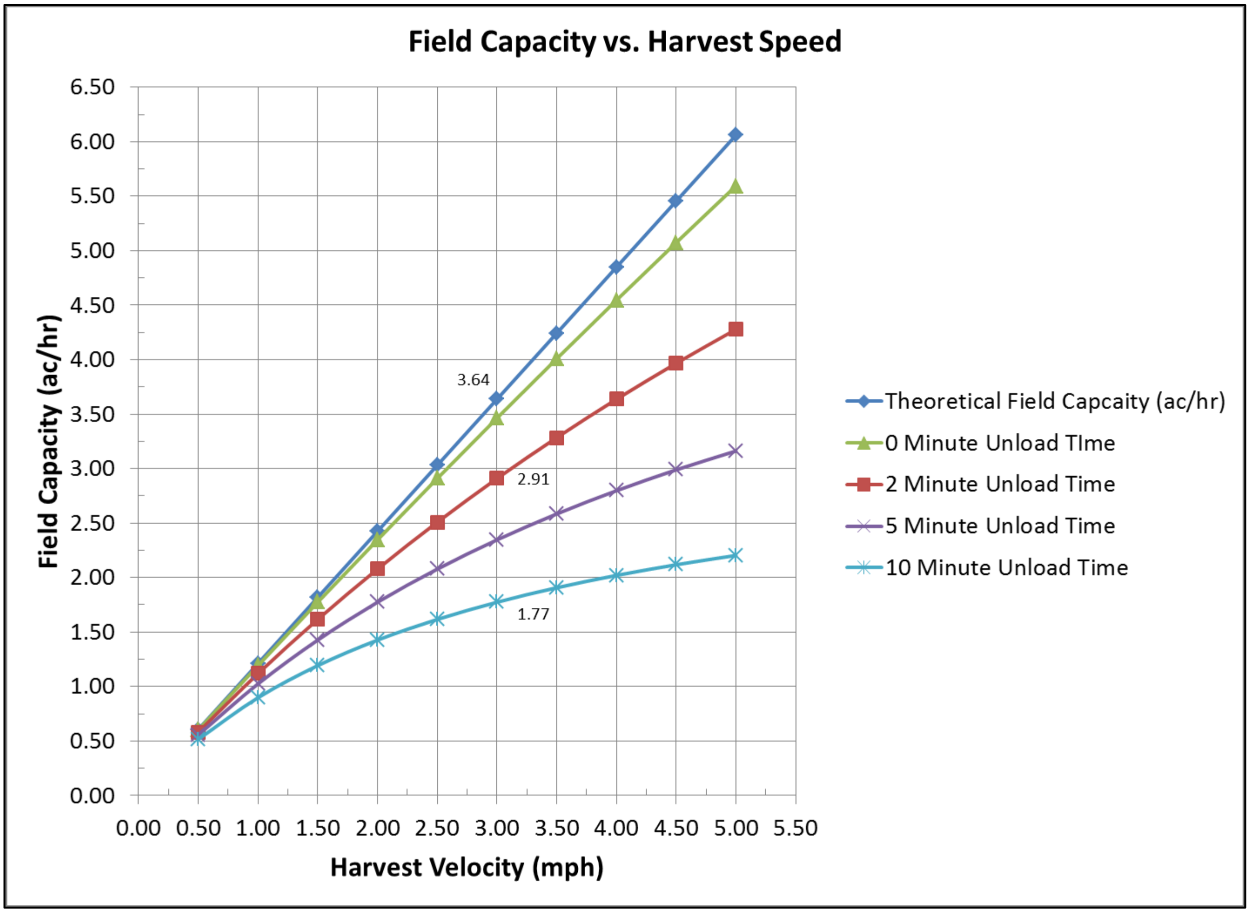


Figure 6.2: Harvester Field Capacity Compared to Harvest Velocity

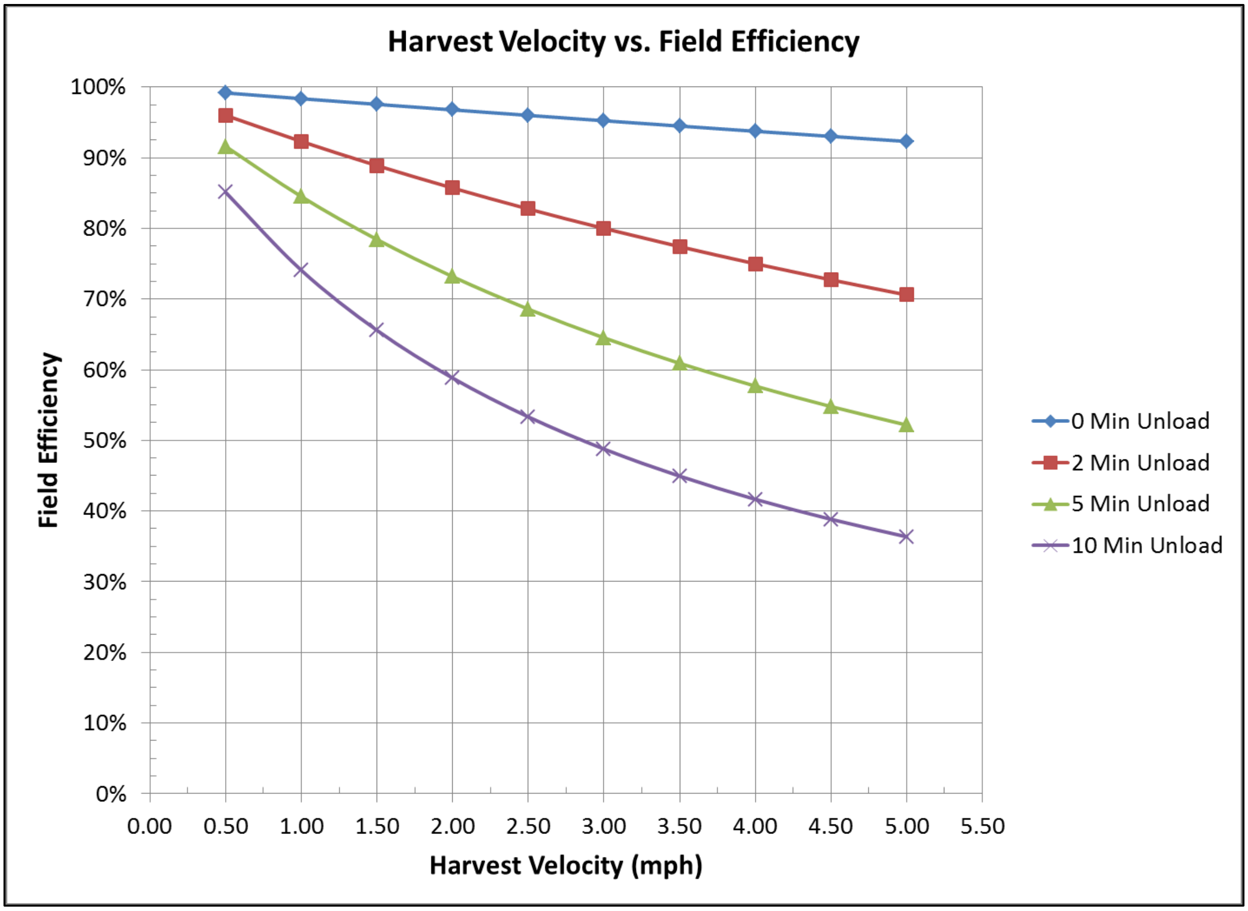


Figure 6.3: Harvest Velocity Compared to Field Efficiency

Since the actual field capacity was able to be modeled successfully, the harvest model was expanded to determine the total number of acres a harvesting system could harvest in a season (See Equation 6.7) at different harvesting velocities and unloading rates by calculating the total number of machine operation hours from Equation 6.8. Parameters from Table 6.2 were used in the calculation of the machine hours. The season length was based off prior knowledge of the crop, and the hours worked per day and days worked per week were based off prior knowledge of a typical workweek for fall corn harvest.

Table 6.2: Machine Hour Calculation Parameters

Work Week

Season Length	8	*Weeks*
Work Week	6	*Days*
Work Day	12	*Hours*
Machine Uptime	70%	
Hours/Season	**576**	*Hours/Season*
Harvest Hours/Season	**403**	*Hours*

$$QC = MH * TFC$$ **Equation 6.7**

Where:

QC = Seasonal Capacity per Harvester, Acres/Year

MH = Machine Operating Hours/Season (See Equation 6.8)

TFC = Theoretical Field Capacity, Acres/Hour (See Equation 6.4)

$$MH = SL * WW * WD * 0.7$$ **Equation 6.8**

Where:

MH = Machine Operating Hours per Season

SL = Season Length, Weeks

WW = Work Week Length, Days

WD = Work Day Length, Hours

0.7 = Probability of a Fit Harvest Day Due to Weather (Iowa State University Ag Extension)

By developing a model for a machine's field capacity, annual machine capacity, and field efficiency, potential problem areas could be identified. Some potential problem areas of this harvesting system include available onboard storage volume and hopper unloading times. The model also helps determine how many acres of crop the machine can physical handle in a season (See Figure 6.4) allowing the farm manager to determine the number of harvesters needed based of the acres planted. In addition to this, the model estimates the number of hours that the machine will be harvesting by estimating the amount of machine downtime due to unfit harvesting conditions, machine repairs and maintenance, and other unforeseen reasons. This will aid in the development of future machines and will also aid in the management of daily farming operations.

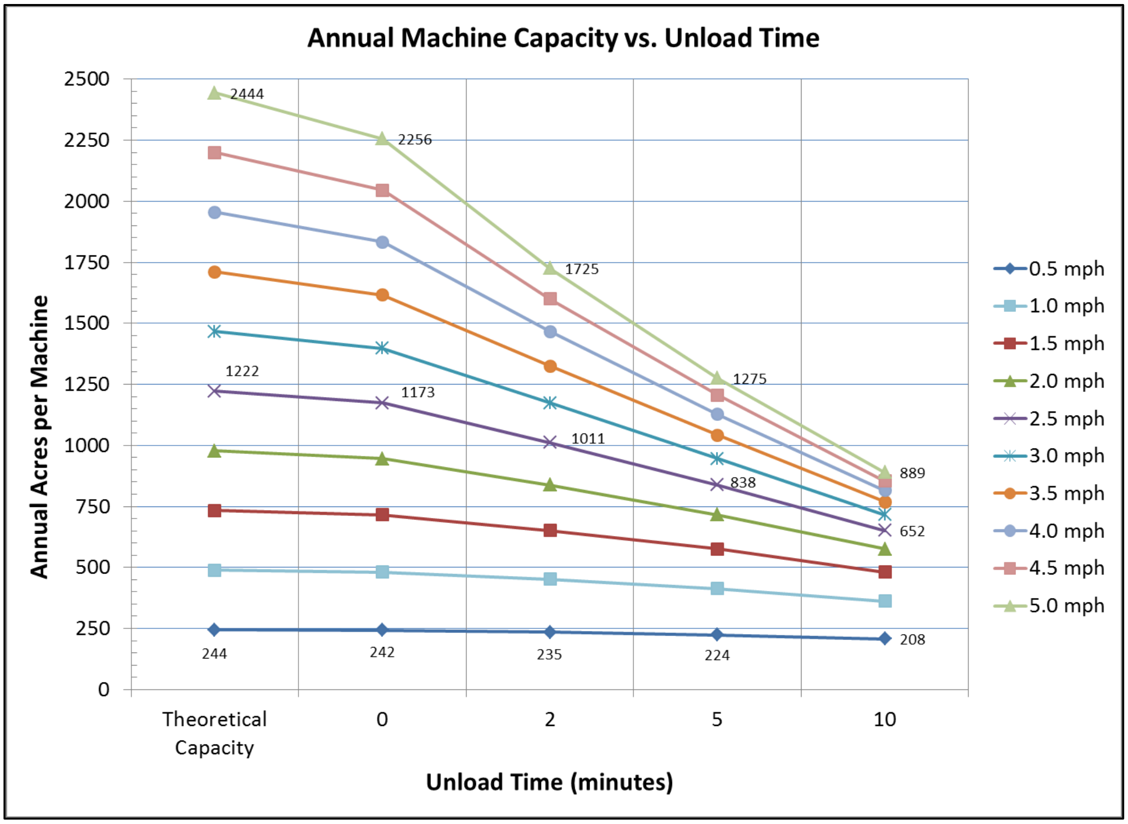


Figure 6.4: Annual Machine Capacity Compared to Various Unload Times

CHAPTER 7: HYDRAULIC SYSTEM DEVELOPMENT

With the development and functionality of the harvesting system designed, focus turned to driving the system. Hydraulic power was the main driving force used to power harvesting head, material conveyance, cleaning, and hopper unloading systems. Hydraulic motors turned the picking mechanism for the head as well as the material conveyance and cleaning systems. Hydraulic cylinders are used to actuate a set of snouts on the head, hopper door latches, and the hopper door. Rotary flow divider valves and sequence valves were also used in order to run multiple functions off the same valve section reducing the volume of hydraulic flow and PVG-32 valve sections needed for the harvesting system. The full system schematic can be found in Figure 7.1. Figure 7.2 is the sub-system schematic for the hopper system. A bill of materials for the hydraulic system schematics can be found in the appendix.

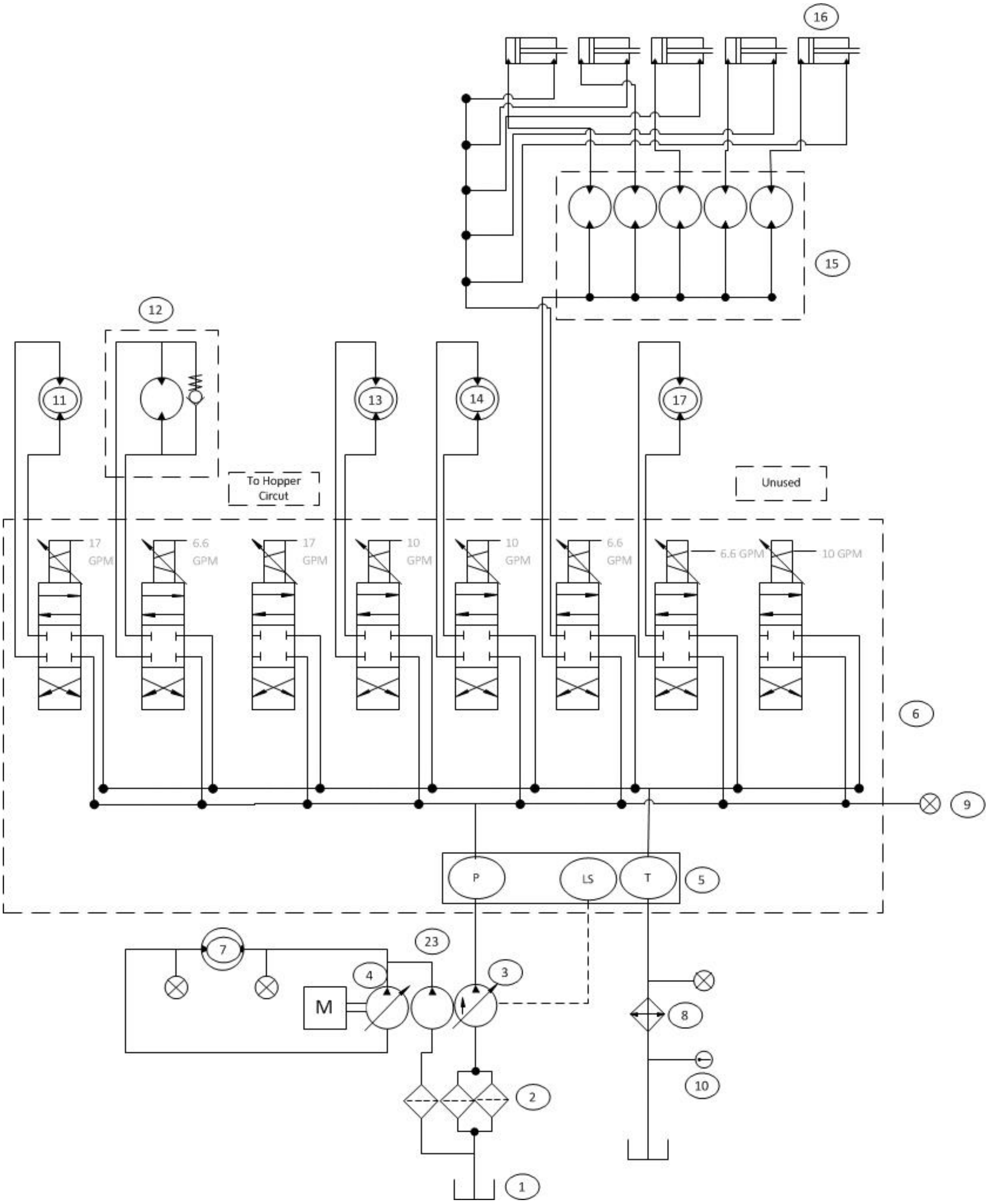


Figure 7.1: Harvester Hydraulic System Schematic (See APPENDIX: HARVESTING SYSTEM MISCELLANEOUS INFORMATION for Bill of Materials).

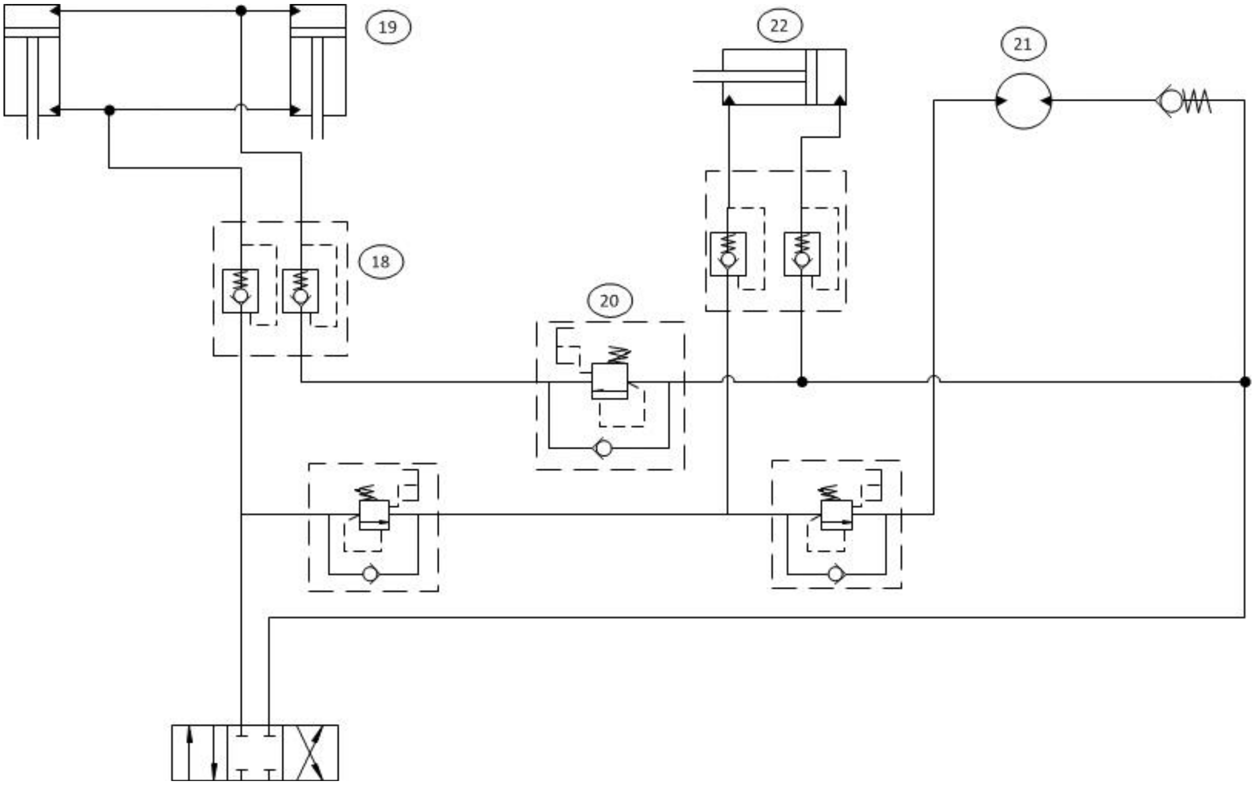


Figure 7.2: Harvester Hopper Hydraulic Circuit (See APPENDIX: HARVESTING SYSTEM MISCELLANEOUS INFORMATION for Bill of Materials).

7.1 Machine Adaptations

In order to adapt the Hagie STS10 sprayer platform into a harvesting system platform, several changes were implemented to the platform's hydraulic system. These changes were necessary in order to add the pumps and valves that were necessary to power the harvesting system. The platform had several gear pumps that were used to provide power to several sprayer functions. These were be removed because all of the sprayer components have been previously removed. The hydraulic tank on this platform was of sufficient capacity; however, its original location did not allow for a simple and efficient way of storing and unloading the crop. The tank was repositioned behind the left-rear tire, and was attached to the frame with a fabricated mounting bracket. Additional fittings and filters were added to the tank to all for the addition of a Danfoss Series 45 open circuit axial piston pump, and a Danfoss H1053 closed circuit axial piston pump (Danfoss Power Solutions: Ames, IA). Shut off valves were added to the suction filters and tank return line that allowed the oil supply to be shut off in order to service the hydraulic filters, and other system components.

Although the spraying platform has an oil cooler already installed, it is inadequate for the additional flow provided by the Series 45 pump (Danfoss Power Solutions: Ames, IA). A Thermal Transfer Products MFR-30 mobile oil cooler (Thermal Transfer Products: Racine, WI) was chosen to install in order to cool the return oil from the Danfoss Series 45 pump (Danfoss Power Solutions: Ames, IA). This cooler was sized to handle 30 gallons per minute of flow, and it can handle an additional 5 gallons per minute of flow allowing an additional pump to be added if necessary. The new system also has a 12-volt DC fan that is controlled by a Danfoss controller with a thermostat allowing the oil to remain in the desired operating temperature without continuous running of the fan. The new oil cooler also is has an internal relief that bypasses the cooler directly to the tank in case there is too much flow going through it. The original stock Hagie oil cooler, was adequately sized to handle the remaining pump and motor case drains in addition to the case drains from the newly added pumps and head motor.

7.2 Hydraulic Pump Components

In order to provide the necessary flow to the harvesting system, the head drive motor needed its own dedicated pump because of its 20 gallons per minute potential flow demand. Running the head drive motor off the PVG-32 valves was not feasible because the valve block was not rated for the total flow demanded by auxiliary harvesting functions in addition to the head motor. A Danfoss H1053 axial piston closed circuit pump (Danfoss Power Solutions: Ames, IA) with electronic displacement control was chosen for this application. The pump has a displacement of 3.28in^3/rev. At high engine idle (2500 rpm) and 100% actuation, the pump provides approximately 30 gallons per minute of flow assuming 85% efficiency of the hydraulic system.

A load sensing system was used for the auxiliary harvesting functions. The PVG-32 valve block is a load-sense valve block with internally ported load sense lines. These lines lead to an external port on the valve block where it was connected to the load-sense line of the Series 45 pump. A Danfoss open circuit Series 45 J Frame axial piston pump (Danfoss Power Solutions: Ames, IA) was chosen to provide the necessary flow to the PVG-32 valve block (Danfoss Power Solutions: Ames, IA). The pump has a displacement of 3.11in^3/rev and provides 29 gallons per minute of flow at high engine idle assuming 85% efficiency.

7.3 Hydraulic Valve Components

Valves were selected to control the hydraulic cylinder and motor components of the harvesting system. A Danfoss PVG-32 valve stack with eight valve sections (Danfoss Power Solutions: Ames, IA) was selected for this project. Each valve section was a three position, closed center four-way valve. Flow rates for the valve sections were determined by calculating the required flow for the assigned work function. Valve sections were then assigned the appropriate spool sizes that allowed the valves to achieve the desired flow rates. These flow rates were based on the size of the hydraulic motors and the desired operating speeds of each function. The valve sections were actuated electrically by using PVEA control modules. PVEA modules utilize a zero to 12 volt signal in order to actuate the valve. A signal of zero volts actuates the valve in the reverse direction. A 12-volt signal operates the valve in the positive direction, and six-volt signal leaves the valve in the neutral position. Internal load sense ports for each valve were used to report the highest pressure provided by the work functions to the load sense line. This line was then connected to the Danfoss Series 45 axial piston open circuit pump (Danfoss Power Solutions: Ames, IA). A bleed valve for the load sense line was not needed since the pump internally bled the line through its case drain.

Seven of the PVG-32 valve sections were assigned into two functionality groups; five valves for harvesting operations and two valves for unloading operations. The function groups did not operate at the same time ensuring there was adequate flow available for all functions. During the harvesting operation the valve stack operates the cross conveyors, feeder-house conveyor, bucket elevator, cleaning fan, and stem remover. During the unloading operations, one valve operates the hopper door latches, hopper door, and the unload conveyor system. The unloading system also has a spare valve in case any additional functions are required for unloading the crop. The remaining valve actuates the five snouts located on the head. These five snouts utilize a Delta Power HPR-23 five-section rotary flow divider valve (Delta Power: Rockford, IL) to extend the cylinders lowering the snouts (Figure 7.1).

Figure 7.3: Delta Power Rotary Flow Divider Valve Block for Snout Control

The rotary flow divider valve was needed because of the limited number of PVG-32 valve sections. There was also a need to adjust the snouts' positions, and to keep them synchronized relative to each other. These rotary flow divider valves utilize an internal relief valve that allows fluid to bypass the internal gear motor once the first cylinder reaches its full stroke. A detailed schematic for a single section of the flow divider valve can be seen in Figure 7.2. The benefit to this system is the simplicity of resynchronizing the snouts. The machine operator simply needs to extend the snout cylinders until all snout cylinders become fully extended. A drawback to this system is that over time the snout cylinders need to be resynced. This usually occurs after periods of not operating the harvesting system.

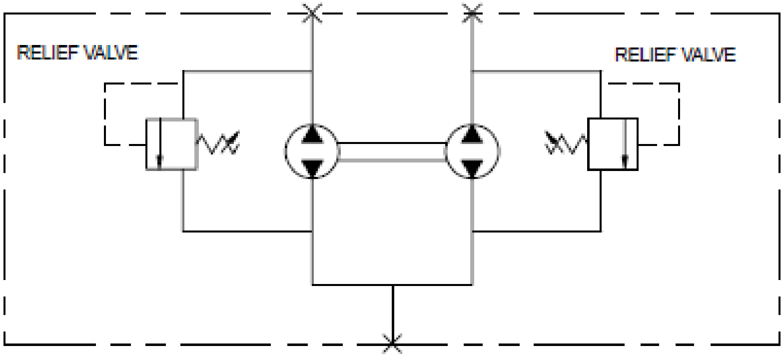


Figure 7.4: Detailed Hydraulic Schematic of a Section of the Rotary Flow Divider Valve Block

Because of the limited number of PVG-32 valve sections and controller outputs, a different approach was needed in order to successfully design and implement the hydraulic system for the unloading system. Two PVG-32 valve sections were selected for this; one for primary functions and one to serve as a spare. In order to unload the harvester a sequence of events had to happen in order; first the door had to unlatch, next the door had to open, and finally the conveyor had to engage. The process was then reversed to close the hopper door and latch it, except the conveyor's motor did not need to turn (See Figure 7.2).

Three Prince Manufacturing RD1075SM sequence valves, two Prince Manufacturing RD1400 locking valves (Prince Manufacturing: North Sioux City, SD), and a check valve were needed to run the complete sequence for the unloading system's operations. The locking valves were a safety feature that helped ensure that the door latch cylinders and door cylinder needed to see a pressure from the PVG-32 valve in order to actuate, preventing an accidental door opening. When the unloading system was activated, the door latches opened first. Once the latches were fully opened, they triggered the sequence valve for the door cylinder, and then the door began to open. After the door opened completely, the final sequence valve was activated, and it allowed the conveyor motor to begin unloading the hopper. The check valve was placed on the motor to keep it from turning in the reverse direction when the hopper door was closed and latched. When the system was reversed, the door closed first and the motor didn't move because of the check valve. After the door was fully closed, it activated a sequence valve that actuated the door latch cylinders latching the door. After this last sequence is completed, the harvester is now ready to resume to harvesting operations.

CHAPTER 8: ELECTRICAL AND CONTROL DEVELOPMENT

Several sensors were used to provide feedback and to control the functions of the specialty crop harvesting system. These sensors were interfaced with to a Danfoss PLUS+1 MC88015B microcontroller and a Danfoss PLUS+1 DP 600 display (Danfoss Power Solutions: Ames, IA). The controller is programmed to supply output signals to the valves. The display served as a user interface that allowed the user to change certain parameters on the go. It also is used to display valve and pump output values as well as values from various sensors. Both devices were programmed using the PLUS+1 language. A simplified system electrical schematic can be seen in Figure 8.1.

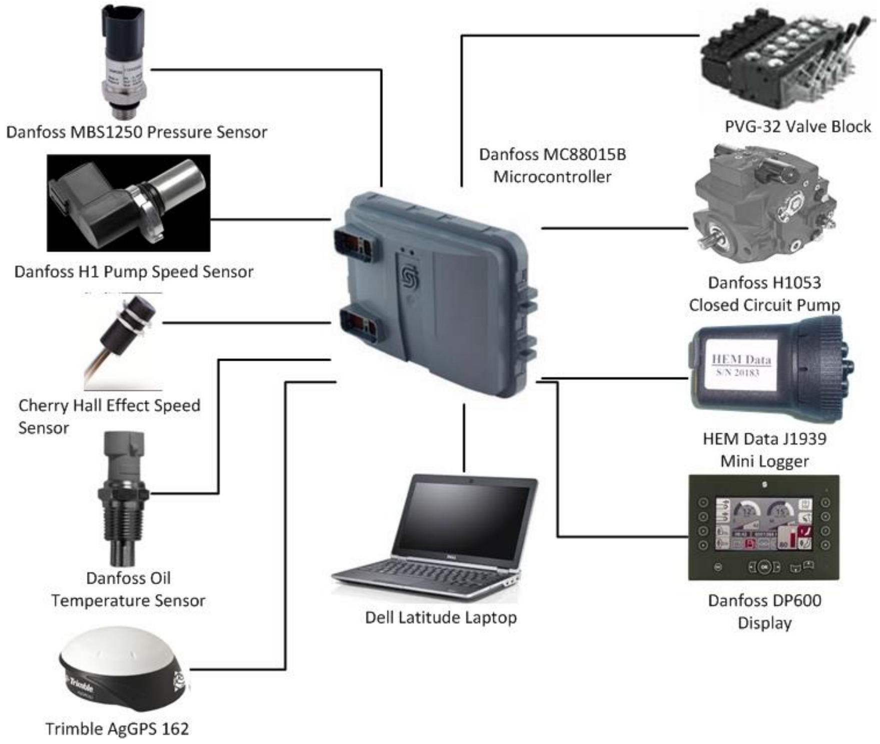


Figure 8.1: Simplified Harvester Electrical Schematic

The power used to supply the system came from the Hagie STS10 12 volt batteries. A battery disconnect was placed in between the new electrical system and the supply batteries. This prevented the additional electrical system from draining power from the supply batteries when the system was not in use. Next, the electrical system was protected by appropriate fuses. From here, the PLUS+1 microcontroller, display, and sensors received their power. The microcontroller read and interpreted the reading from the raw sensor readings, and the relevant H1053 pump and PVG-32 valve control decisions were then made. The microcontroller sent out an electrical signal of varying current to the forward or reverse pump control spool depending on the required flow from the hydraulic motor.

The PLUS+1 Service tool program (Danfoss Power Solutions: Ames, IA) provided diagnostic capabilities for the machine control. In order for the microcontroller to communicate with the display, service tool, and Trimble AgGPS 162, a CAN bus system was used. In addition to this, a HEM Data J1939 Mini Logger was also connected to the CAN network. This allows for the any data transmitted on the CAN bus to be logged and analyzed afterward to determine the performance of the harvesting system. Figure 8.2 shows an overview of the CAN bus.

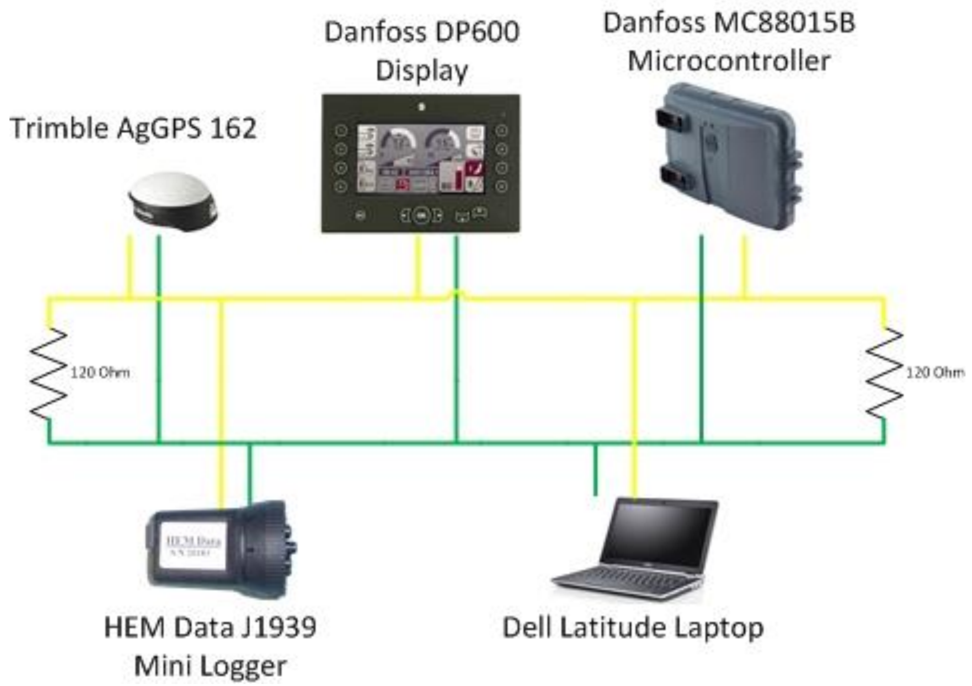


Figure 8.2: Basic Overview of the Harvester CAN Bus Network

The microcontroller, display, and fuse panel were all mounted inside of the platform cab. The microcontroller was mounted directly behind the seat, and the display was mounted on the corner post of the cab that was easily visible and accessible to the machine operator. A short harness ran to a junction area to the right of the operator. In this area, connections from the valves, pump, and sensors were stored. This allowed for components to be easily disconnected and isolated if necessary. A series of switches (See Figure 8.3) activated the various components of the harvesting system. This switch bank was mounted so the operator had easy access and control of the harvesting system components.

Figure 8.3: Harvester Enabling Switch Bank and ISO BUS Diagnostic Port

8.1 Sensor Selection and Implementation

Various sensors were needed on the harvesting system in order to fully comprehend how the system was performing during normal operation and on how to actuate the work functions. Two categories of sensors were implemented on the harvesting system. Cherry GS100502 hall-effect sensors (Cherry Corporation: Pleasant Prairie, WI) were utilized to sense shaft speeds on the cross conveyors, elevator, stem remover, unload conveyor, and the main head drive shaft. These sensors could measure frequencies of up to 15,000 hertz. All components, with the exception of the head drive shaft, used 50 chain 16 tooth sprockets as a frequency source for the Hall-Effect sensor resulting in the maximum frequency being transmitted at approximately 7,200 hertz. The main drive shaft used a 26 tooth 60 chain sprocket resulting in a transmitted frequency of approximately 5,200 hertz. The addition of Hall-Effect sensors to the harvesting system allowed for the system operator to evaluate and diagnose system components.

Danfoss MBS1250 5800psi pressure transmitters (Danfoss Power Solutions: Ames, IA) were also used in the development of the harvesting system. These sensors were installed at critical high and low pressure locations on the hydraulic system: the main head hydraulic motor, fan control valve, and unload conveyor valve. In addition to this, a sensor was also installed on the PVG-32 pump supply port. These sensors allow the operator do evaluate and diagnose the performance of these critical systems.

Even though an additional oil cooler had been installed to handle the additional flow form the Danfoss Series 45 pump (Danfoss Power Solutions: Ames, IA), it was still necessary to monitor the temperature of the return oil supply. This is so that in cooler temperatures the oil can remain within its normal operating temperature range, and in warmer temperatures it does not exceed its operating range. This was accomplished by using a Danfoss liquid temperature sensor (Danfoss Power Solutions: Ames, IA) to monitor the return oil supply temperature. This is a thermistor type sensor, which varies its resistance in relationship to temperature. This value was read by the microcontroller, which controlled the relay that powered the oil cooler fan; cycling it on and off in order to maintain the proper oil temperature.

8.2 Head Control Development

One of the most critical factors in a harvesting operation is the relationship of reel speed of the harvesting mechanism to ground speed. Since reel speed is critical to the harvesting the desired crop material in the most efficient and effective manner possible, it was necessary to control the main drive motor in such a way that the reel speed would be consistent. This speed could either be a constant speed determined from a setting by the machine operator, or it could controlled automatically by use of a reel index that utilizes the speed signal from a Timble AgGPS 162 GPS receiver (Trimble Navigation: Sunnyvale, CA) and a scaling factor entered into the display by the machine operator. By developing an automatic reel index and using closed loop speed control for the head, reliable reel speeds could be easily obtained.

8.2.1 Reel Index

Like most traditional harvesting systems, it was necessary to vary the reel speed proportionally to the vehicle's ground speed in order to harvest the crop in the most efficient manner similar to that of a grain harvester platform head. To determine the reel speed in revolutions/ minute, the peripheral speed of the reel in miles per hour is multiplied by the reel index (Equation 8.1). This increases or decreases the peripheral speed of the reel proportionally to the ground speed of the vehicle. The flexibility allowed by the reel index, allows for the operator of the harvesting system to maintain a consistent ground speed, and to adjust the reel speed with a push of a button from the in cab operating display.

$$RS = \frac{V*RI*5280*12}{60} * \frac{1}{RC} \qquad \textbf{Equation 8.1}$$

Where:

RS = Reel Speed, Revolutions/Minute

V = Velocity, Miles/Hour

RI = Reel Index, Ratio of Reel Speed to Ground Speed

RC = Reel Circumference, Inches

8.2.2 Head Pump Control

Since the head motor requires very little pressure, the motor speed was difficult to maintain. Because of this, a closed loop PID control was implemented in order to help in reducing the steady state error of the motor speed. This closed loop control uses the feedback speed provided by the main motor hall-effect sensor, and scales this value to percent of pump output (0-10000). This scale value is then compared to the user input value or the automatic value based off the chosen user setting in the Danfoss PID function block which uses Equation 8.2.

$$\text{Output}=\frac{P*E}{1000}+\frac{I*T*\sum E}{1000}+\frac{E*\frac{D}{T}}{1000} \qquad \textbf{Equation 8.2}$$

Where:

Output = Current Control Signal
P = Proportional Gain
I = Integral Gain
D = Derivative Gain
E = Error (Set Point – Feed Back)
∑E = Accumulated Error
T = Sampling Time or Control Loop Time

This control needed to have a quick response time with minimal overshoot. From here, the function block used sample time, P-gain, I-gain, and D-gain parameter values to determine the new pump signal necessary to maintain the desired reel motor RPM. Figure 8.4 shows performance of the PID control, and the impact on different engine speeds on the pump signal and feedback signal. Also in Figure 8.4, a delay in response can be seen. Since rise time was not an issue and steady state error was, the focus of setting the system was to minimize the steady state error without causing excessive overshoot. The current PID control parameter settings, produced a steady state error with an error range from -10.53% to 8.53%, and an average steady state error of -0.06%. The steady state error can be seen in Figure 8.4. This is the lowest error that can be obtained with the current feedback sensor. A lower steady state error may be produced by use of a higher quality shaft speed sensor configuration such as a shaft encoder.

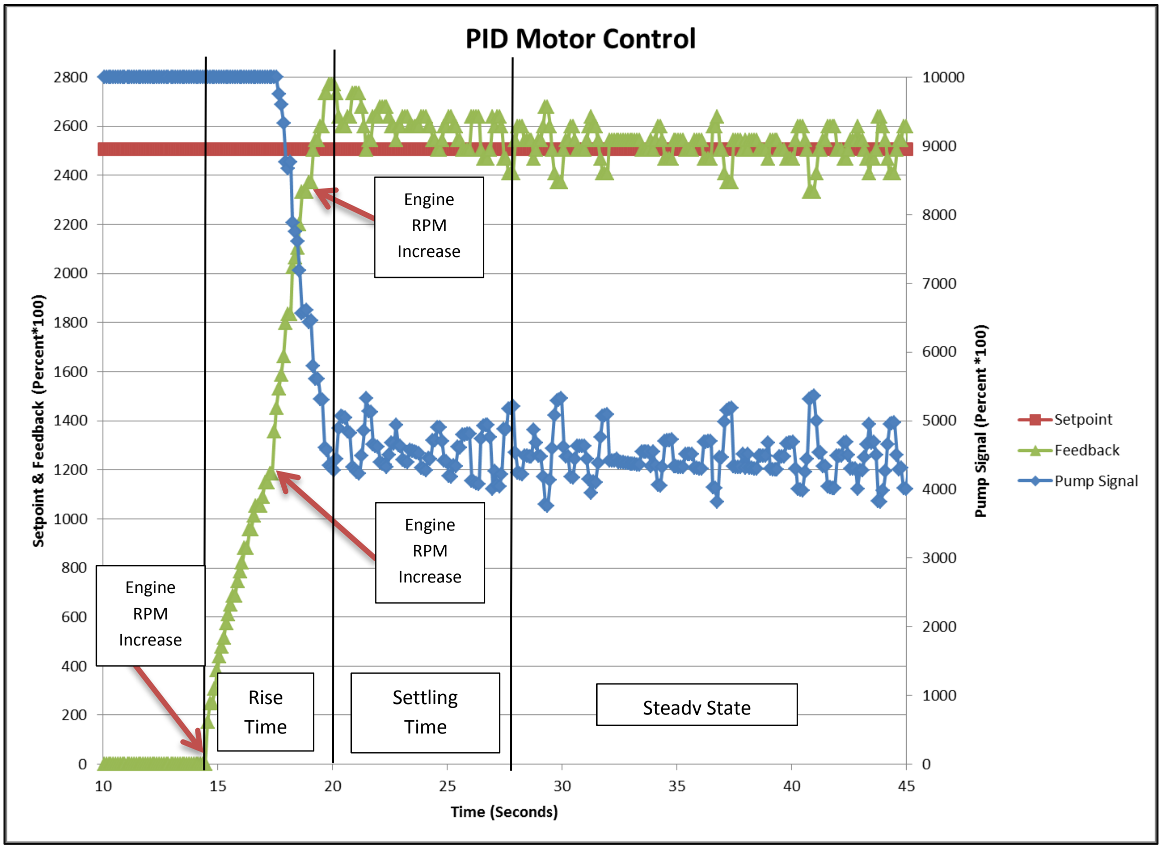


Figure 8.4: Chart of Head Speed Set Point, Head Speed Feedback, and Pump Signal

8.3 User Interface

The harvesting system needed to be user friendly. In order to be user friendly, much focus was put on the design of the user interface. It was a determined that the harvesting system needed to utilize the DP600 Danfoss display to show input values from various sensors and the gps receiver. The output values for the PVG-32 valves and H1053 pump were also displayed on the DP600 in real time. This display also had to allow the user to change certain valve and pump parameters on the go to adjust to varying harvesting conditions. The flowchart in Figure 8.5 was used in the planning the development of the display program.

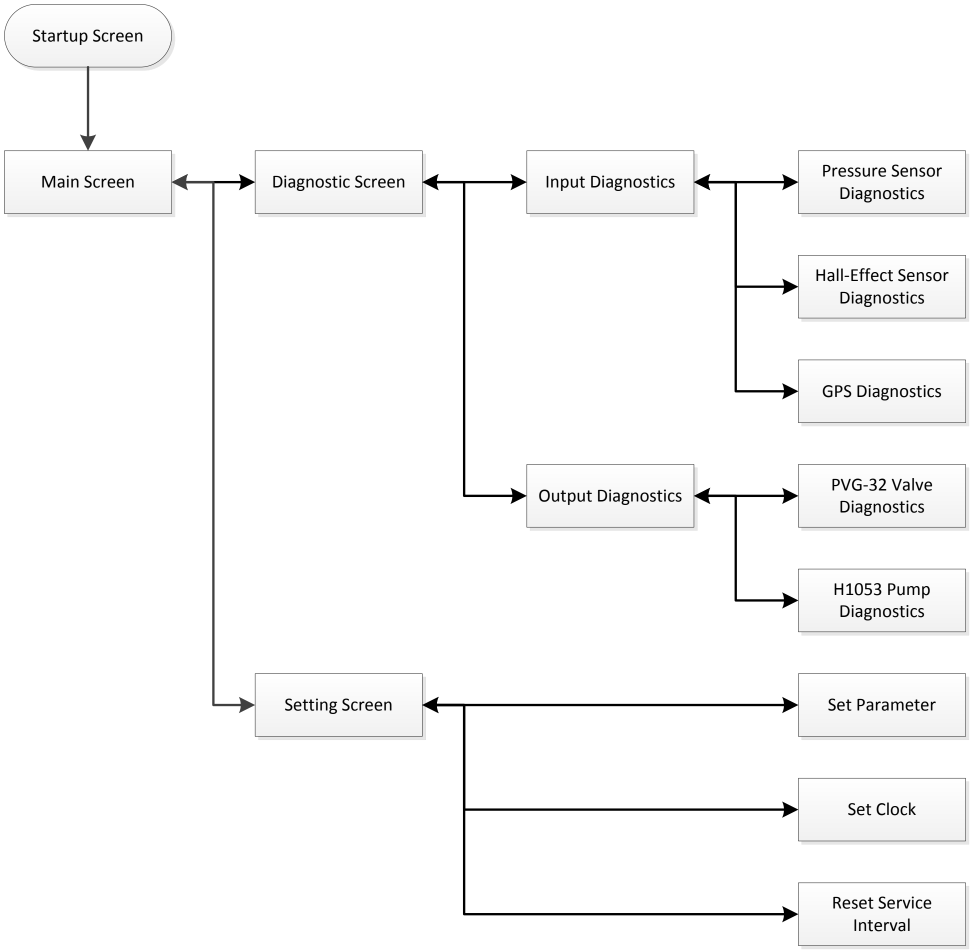
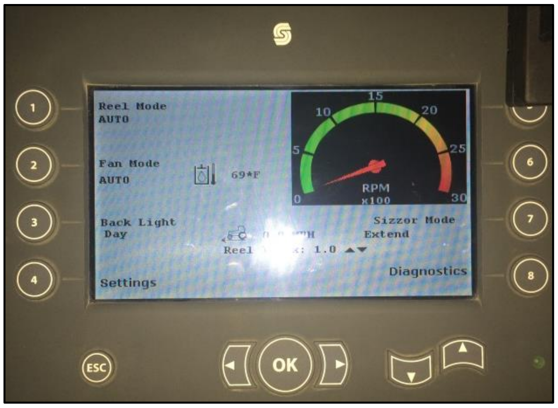


Figure 8.5: Flowchart Used to Develop the Display Program Structure

The main screen of the display program (Figure 8.6) acts as a gateway to navigate to other screen menus and provides little information to the operator. This screen only displays critical information that needs constant monitoring: engine speed, ground speed, and return oil temperature. This screen also allows the operator to change critical setting on the go: reel index, reel mode, fan mode, and backlight mode.



Reel Mode
AUTO

Fan Mode
AUTO

69*F

Back Light
Day

Sizzor Mode
Extend

Reel [illegible]: 1.0

Settings

Diagnostics

Figure 8.6: Main Screen User Interface of the DP600 Display

To adapt to changing harvesting conditions, machine parameters need to have the ability to be easily changed on the go by the machine operator. A main concern with the design of the user interface display was which parameters could the operator change that would not negatively affect the performance of the harvesting system (See Figure 8.7). If the elevator and feeder-house settings were changed, harvested material may not be transported away from the head quick enough, or material may not be ejected from the elevator buckets properly causing a reduction in overall material capacity. The stem remover needs to run at speeds fast enough to ensure that the stems are removed so the clean harvested material can pass through and into the storage hopper. Flow for the unloading system had to remain in a critical area. If the hydraulic flow was too large, the door would slam potentially causing damage to its hinge. If the flow was too small, the conveyor would have troubles functioning properly and unloading the material in a timely manner. From this analysis, it can be concluded that the only parameters that could be changed by the user is the fan speed, cross conveyor, and reel speed settings.

Similar to other harvesting systems, real time diagnostics of the harvesting system is necessary for validating the performance of various machine components, and troubleshooting any system issues that may arise from the operation of the harvester. The diagnostics screen of the display allows the machine operator to view the signals sent to the PVG-32 valve block and the H1053 pump. This diagnostic screen also allows the operator to view the system and sensor supply voltages, various conveyor speeds, fan pressure, head drive motor pressure, PVG-32 supply pressure, hydraulic oil temperatures, and information transmitted by the Trimble AgGPS 162 gps receiver. These diagnostic values allow the operator to view output signals in conjunction with any combination of input signals to aid in diagnosing and evaluating machine performance (See Figure 8.8).

Fan Speed: 10000
Cross Conveyor: 3100
Reel Speed: 2100
Range: (0 - 10000)

Figure 8.7: Parameter Control Screen

Inputs 1/7
Outputs 1/3
ECU 2
Power Supply
C1P02: 12.331 V
PVG Valves 1/2:
Valve 1: 0
Valve 2: 0
Valve 3: 0
Valve 4: 0
Sensor Supply
C1P08: 4.990

Figure 8.8: Diagnostic Application Screen

8.4 Data Logging

The final portion of the control and electrical system involved data logging. In order to understand the detail of the machine performance, data was initially logged through the Danfoss PLUS+1 Service tool. This provided useful information when evaluating and troubleshooting initial machine performance. The values logged with the service tool can be easily configured to log multiple values, or a select few for troubleshooting. However, this is not a feasible data logging method for evaluating overall machine performance. To evaluate the overall machine performance, the CAN bus messages, the display, and the microcontroller were used to communicate with were converted to the J1939 message format. This allowed for the use of a HEM Data J1939 Mini Logger (Figure 8.9).

Figure 8.9: HEM Data J1939 Mini Logger for Logging CAN Messages via the ISO Bus Port

The data logger uses the J1939 database to log any signals that are transmitted on the CAN bus. J1939 is a SAE standard used by industry that governs the content and format of CAN bus messages. This allows all processed sensor input signals, microcontroller output signals, and gps signals to be logged at a one-second interval when the machine is in operation allowing for an accurate performance evaluation of the harvesting system post season. Data collected on the data logger can be processed to determine the correct harvest settings for different stages of crop development, time spent unloading the crop, and overall machine down time for a harvest season. This data can be utilized in the development of a production machine by improving the design of the harvesting system in order to maximize the harvesting efficiency by minimizing the machine down time.

CHAPTER 9: CONCLUSIONS AND DISCUSSION

Although the prototype harvesting system has yielded promising initial results, mechanical testing yielded several issues that were then corrected. A specially designed platform based on the Hagie STS10 sprayer platform is recommended for a production machine. This platform would allow for the harvesting system components to be assembled onto the platform in an efficient manner. These recommendations would also allow a harvesting system to be designed that would be adequately sized for the scope of the farming operation. This would reduce the total number of machines that would be needed reducing the cost to the consumer.

9.1: Initial Machine Recommendations

Initial machine recommendations for the specialty crop harvesting system primarily involve modifications to the existing machine. The elevator system has a uniform surge in speeds that is caused by the buckets turning the corner. In addition to this, an additional cause of the surge in elevator speeds is the use of a chain for attachment points for the elevator buckets. Initially, the chain was chosen to allow for flexibility for attaching the buckets. Now that the behavior of the system is known, the chain and sprockets should be replaced with v-guide pulleys, and have the buckets mounted directly to the conveyor belt just like in a grain elevator application. By reducing this speed surge with the new system, it will allow for smoother operation of the elevator allowing for higher operating speeds increasing the capacity of the system.

9.2 Future Work Recommendations

Future work for this project involves several tests to measure the performance of the harvesting system. The first test would utilize the HEM Data J1939 Mini Logger to help in determining the actual field efficiency of the harvesting system. This can be used measure the time spent unloading and the travel time of the harvester. The second test that needs to be run is a repeat of the previous mechanical harvest test. This will determine what harvest schedule is optimum for a mechanical harvesting system. The same machine parameters will need to be used for each trial. The final test that needs to be run, is a test that determines the optimum travel velocity and reel speeds that are necessary to efficiently harvest the crop. This test will need to utilize a consistent harvest schedule to obtain reliable results.

The final future recommendation is that a specially designed platform is needed for this specialty crop harvesting system. The current platform served the prototype system well, however the stock platform does have its limitations. First, onboard storage capacity had to be sacrificed in order to fit the system in the available space between the engine and the cab. Second, massive modifications had to be made to the platform to allow it to be used in this harvesting system. A new platform would need to utilized a split drive system for the hydraulic pumps. In addition, this platform would already have the hydraulic pumps, hydraulic valve block, air tank, hydraulic tank, oil cooler, and hydraulic filters already integrated into the system. The frame of this system should be designed in such a way that necessary hopper capacity can be obtained without exceeding the width of the machine and a height of 16 feet. Also, the lifting arms need be mounted to the frame in a way that was similar to the prototype harvesting system.

Instead of a PVG-32 Danfoss valve block, which is very costly and large in size, a custom Hydraforce valve block should to utilized instead. These blocks are a fraction of the cost of the PVG-32, and contain properly sized valves for each function. Locking valves and sequencing valves can also be integrated into this valve block to eliminate the external Prince locking and sequencing valves simplifying the hydraulic system. This was not implemented initially because of the unknown demands and functions that would need to be supported by the valve block. This valve block would also allow for the valves for the harvesting system and the valves needed for the platform operation to be combined into one unit, in addition to any pressure sensors that are needed. Doing this also would consolidate hydraulic pumps. This valve block should pre mounted on the machine so the hydraulic hook-ups are easily accessible to attach the hydraulic components of the harvesting system. Any plumbing that could be accomplished before the addition of the harvesting components should be completed.

From an electrical standpoint, the control system and electrical system should also be integrated with the existing harvesting system. Bulkhead electrical connections should preinstalled that will allow for addition of any Hall-Effect sensors. Since this the harvest is conducted while the crop is still standing, a NORAC height control system should be used to automatically adjust and maintain the height of the harvesting head with respect to the crop. This would increase the harvesting efficiency of the harvesting system by reducing the adjustment error caused by the operator. In addition, a control system should be integrated that also control the pitch of the shouts on the harvesting head. This would allow for the snouts to remain in constant contact with the crop, and prevent them from plowing into the ground.

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APPENDIX: HARVESTING SYSTEM MISCELLANEOUS INFORMATION

Table A-1: CAN Message Database used for the HEM J1939 Data Logger

Signal Name	PGN		Byte Start	Byte Stop	Bit Start	Bit Stop	Factor	Offset	Min	Max	Units
Altitude	65256	FEE8	7	8	0	7	0.125	-2500	-2500	5531.875	m
Aux Valve 1 Port Flow Command	65073	FE31	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 1 State Command	65073	FE31	3	3	0	3	1	0	0	15	bit
Aux Valve 2 Extend Port Pressure	65058	FE22	3	4	0	7	1	0	0	5800	psi
Aux Valve 2 Port Flow Command	65074	FE32	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 2 Retract Port Pressure	65058	FE22	5	6	0	7	1	0	0	5800	psi
Aux Valve 2 State Command	65074	FE32	3	3	0	3	1	0	0	15	bit
Aux Valve 3 Extend Port Pressure	65059	FE23	3	4	0	7	1	0	0	5800	psi
Aux Valve 3 Port Flow Command	65075	FE33	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 3 Retract Port Pressure	65059	FE23	5	6	0	7	5	0	0	5800	psi
Aux Valve 3 State Command	65075	FE33	3	3	0	3	1	0	0	15	bit
Aux Valve 4 Port Flow Command	65076	FE34	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 4 State Command	65076	FE34	3	3	0	3	1	0	0	15	bit
Aux Valve 5 Port Flow Command	65077	FE35	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 5 State Command	65077	FE35	3	3	0	3	1	0	0	15	bit
Aux Valve 6 Port Flow Command	65078	FE36	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 6 State Command	65078	FE36	3	3	0	3	1	0	0	15	bit
Aux Valve 7 Port Flow Command	65079	FE37	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 7 State command	65079	FE37	3	3	0	3	1	0	0	15	bit
Aux Valve 8 Port Flow Command	65080	FE38	1	2	0	7	1	0	-10000	10000	%*100
Aux Valve 8 State Command	65080	FE38	3	3	0	3	1	0	0	15	bit
Battery 2 Potential (Voltage)	65165	FE8D	1	2	0	7	1	0	0	14000	mv
Compass Bearing	65256	FEE8	1	2	0	7	0.0078125	0	0	501.99	deg
Cross Conveyor Speed	65283	FF03	1	2	0	7	1	0	0	1500	rpm
Day	65254	FEE6	5	5	0	7	0.25	0	0	62.5	Days
Desticker Speed	65283	FF03	5	6	0	7	1	0	0	1500	rpm
Edit Position	65284	FF04	8	8	0	7	1	0	0	5	int
Enable Parameter	65284	FF04	7	7	1	1	1	0	0	1	bit
Engine Speed	61444	F004	4	5	0	7	1	0	0	2500	rpm
Fan Mode	65284	FF04	7	7	3	3	1	0	0	1	bit
H1 Case Temperature	65282	FF02	5	6	0	7	1	0	-50	225	*F
Head Forward Command	65281	FF01	7	7	0	0	1	0	0	1	bit
Head Forward Parameter	65284	FF04	5	6	0	7	1	0	0	10000	%*100
Head Forward Signal	65281	FF01	1	2	0	7	1	0	0	10000	%*100
Head Pressure High	65282	FF02	3	4	0	7	1	0	0	5800	Psi
Head Pressure Low	65282	FF02	1	2	0	7	1	0	0	5800	Psi
Head Reverse Command	65281	FF01	7	7	1	1	1	0	0	1	bit
Head Reverse Signal	65281	FF01	3	4	0	7	1	0	0	10000	%*100
Hours	65254	FEE6	3	3	0	7	1	0	0	250	Hours
Hydraulic Pressure	61448	F008	1	2	0	7	1	0	0	5800	psi
Hydraulic Temperature	65128	FE68	1	1	0	7	1	0	-50	225	*F
Latitude	65267	FEF3	1	4	0	7	1.00E-07	-210	-210	211.100812	deg
Loading Elevator Speed	65283	FF03	3	4	0	7	1	0	0	1500	rpm
Local hour offset	65254	FEE6	8	8	0	7	1	-450000	-125	125	Hours
Local minute offset	65254	FEE6	7	7	0	7	1	-7500	-125	125	Mins
Longitude	65267	FEF3	5	8	0	7	1.00E-07	-210	-210	211.100812	deg
Minutes	65254	FEE6	2	2	0	7	1	0	0	250	Mins
Month	65254	FEE6	4	4	0	7	1	0	0	250	Months
Navigation-Based Vehicle Speed	65256	FEE8	3	4	0	7	0.0039063	0	0	250.996	kph
Pitch	65256	FEE8	5	6	0	7	0.0078125	-200	-200	301.99	deg
Plunger Mode	65284	FF04	7	7	0	0	1	0	0	1	bit
Reel Index	65281	FF01	8	8	0	7	1	0	0	5	int
Reel Mode	65281	FF01	7	7	2	2	1	0	0	1	bit
Reel Speed	65281	FF01	5	6	0	7	1	0	0	1500	rpm
Save	65284	FF04	7	7	1	2	2	0	0	1	bit
Seconds	65254	FEE6	1	1	0	7	0.25	0	0	62.5	Seconds
Serial Number	65259	FEEB	6	6	0	0	1	0	0	255	ASCII
Total Vehicle Hours	65255	FEE7	1	4	0	7	0.05	0	0	210554061	Hours
Unload Conveyor Speed	65283	FF03	7	8	0	7	1	0	0	1500	rpm
Valve 2 Parameter	65284	FF04	1	2	0	7	1	0	0	10000	%*100
Valve 4 Parameter	65284	FF04	3	4	0	7	1	0	0	10000	%*100

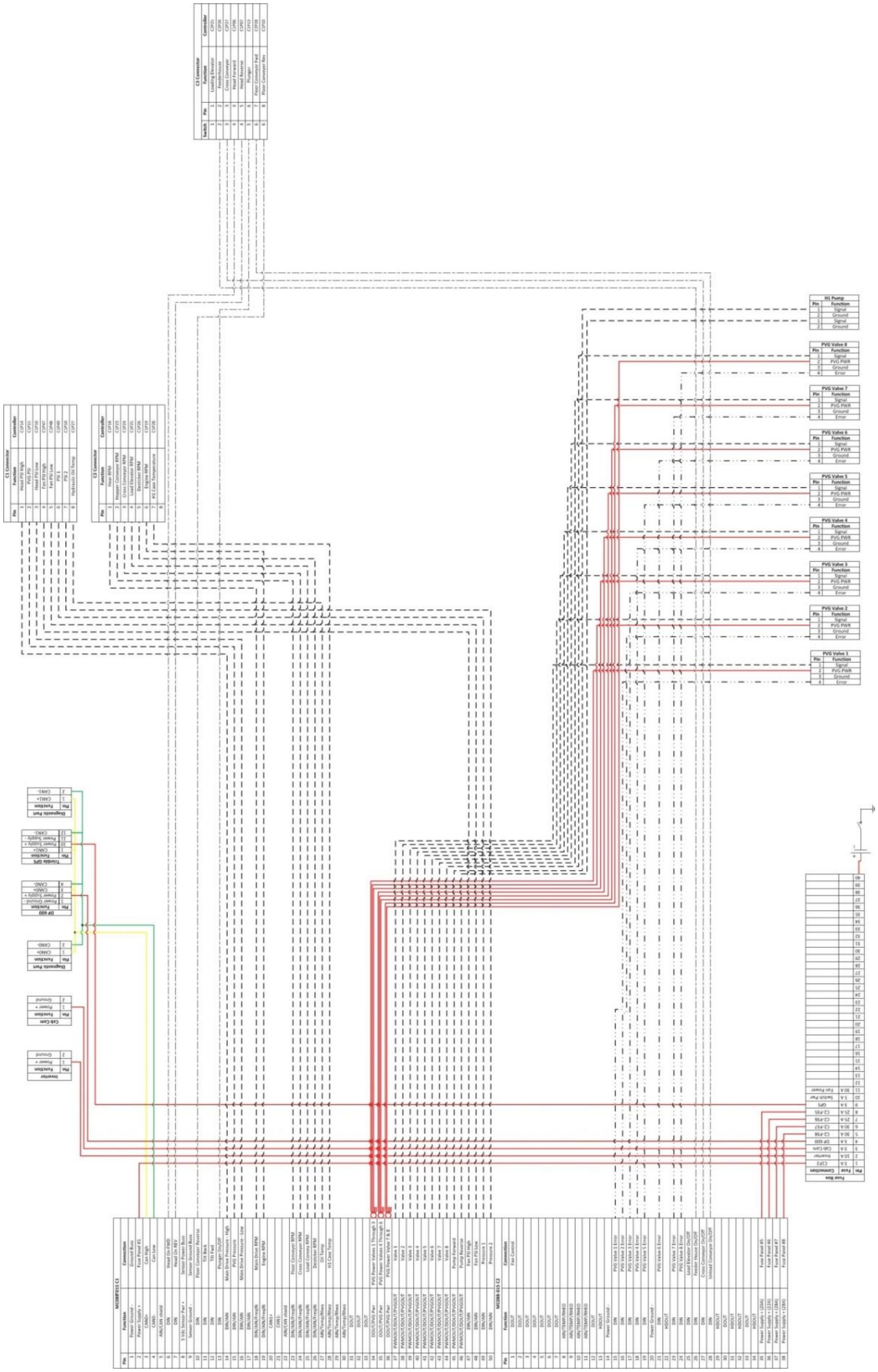


Figure A-1: Full Electrical Schematic for the Harvesting System

Table A-2: Hydraulic System Component List

Reference Number	Descriptopn
1	Hagie STS10 Hydraulic Oil Resivor
2	Oil Suppply Flter
3	Danfoss Series 45 Open Circuit Pump, Model J51B, Displacement = 51cc/rev
4	Danfoss H1053 Closed Circuit Pump, Displacement = 53cc/rev
5	Danfoss 157B5914 Pump Side Module, Pressure, Tank, Load Sensing Ports
6	Danfoss PVG32 Valve Vlock, 8 157B6530 Modules
7	Char-Lynn 18.7in^3 Motor
8	Thermal Transfer Products MFR-30 Oil Cooler
9	Danfoss 11044548 Pressure Sensor
10	Danfoss 1090173 Temperature Sensor
11	Char-Lynn 5.9in^3 Motor
12	Oxbo Cleaning Fan Assembly
13	Char-Lynn 2.8in^3 Motor
14	Char-Lynn 5.9in^3 Motor
15	Delta Power HPR-23 Five-Section Rotary Flow Divider Valve
16	2.5,6,1.25 DA HYD CYL W250060-S
17	Char-Lynn 2.8in^3 Motor
18	Prince Manufacturing RD1400 Locking Valve
19	2X4X1.125 DA HYD CYL HEAVY DUTY CLEVIS
20	Prince Manufacturing RD1075SM Sequence Valve
21	Dynamic 11.6in^3 Motor
22	Prince 2.5x30x1.125 Hydraulic Cylinder B2503000ABAAA03B
23	H1T053 Internal Charge Pump

Table A-3: Field Capacities and Efficiencies at Various Unloading Times

Harvest Speed (mph)	Field Capacity (ac/hr)	Harvest Time (min)	Unloading Time (min)							
			0		2		5		10	
			Field Efficiency and Actual Field Capacity							
			%	(ac/hr)	%	(ac/hr)	%	(ac/hr)	%	(ac/hr)
0.50	0.61	60.00	0.98	0.59	0.94	0.57	0.90	0.55	0.84	0.51
1.00	1.21	30.00	0.95	1.15	0.90	1.09	0.82	1.00	0.72	0.88
1.50	1.82	20.00	0.93	1.69	0.85	1.55	0.75	1.37	0.63	1.15
2.00	2.42	15.00	0.91	2.20	0.81	1.97	0.70	1.69	0.57	1.37
2.50	3.03	12.00	0.89	2.69	0.77	2.35	0.65	1.97	0.51	1.55
3.00	3.64	10.00	0.87	3.16	0.74	2.69	0.61	2.20	0.47	1.69
3.50	4.24	8.57	0.85	3.61	0.71	3.01	0.57	2.41	0.43	1.81
4.00	4.85	7.50	0.83	4.04	0.68	3.31	0.54	2.60	0.39	1.91
4.50	5.45	6.67	0.82	4.45	0.66	3.58	0.51	2.76	0.37	2.00
5.00	6.06	6.00	0.80	4.85	0.63	3.83	0.48	2.91	0.34	2.08

Table A-4: Seasonal Field Capacities

Harvest Speed (mph)	Seasonal Field Capacity (Acres/Week)					Seasonal Field Capacity (Acres/Year)				
	Theoretical Capacity	Unloading Time (min)				Theoretical Capacity	Unloading Time (min)			
		0	2	5	10		0	2	5	10
0.50	5.09	4.97	4.81	4.59	4.27	244	238	231	220	205
1.00	10.18	9.70	9.12	8.37	7.36	489	465	438	402	353
1.50	15.27	14.21	13.00	11.53	9.70	733	682	624	553	465
2.00	20.36	18.51	16.51	14.21	11.53	977	889	793	682	553
2.50	25.45	22.63	19.71	16.51	13.00	1222	1086	946	793	624
3.00	30.55	26.56	22.63	18.51	14.21	1466	1275	1086	889	682
3.50	35.64	30.33	25.30	20.27	15.22	1711	1456	1215	973	730
4.00	40.73	33.94	27.77	21.82	16.08	1955	1629	1333	1047	772
4.50	45.82	37.40	30.04	23.20	16.81	2199	1795	1442	1114	807
5.00	50.91	40.73	32.15	24.44	17.45	2444	1955	1543	1173	838

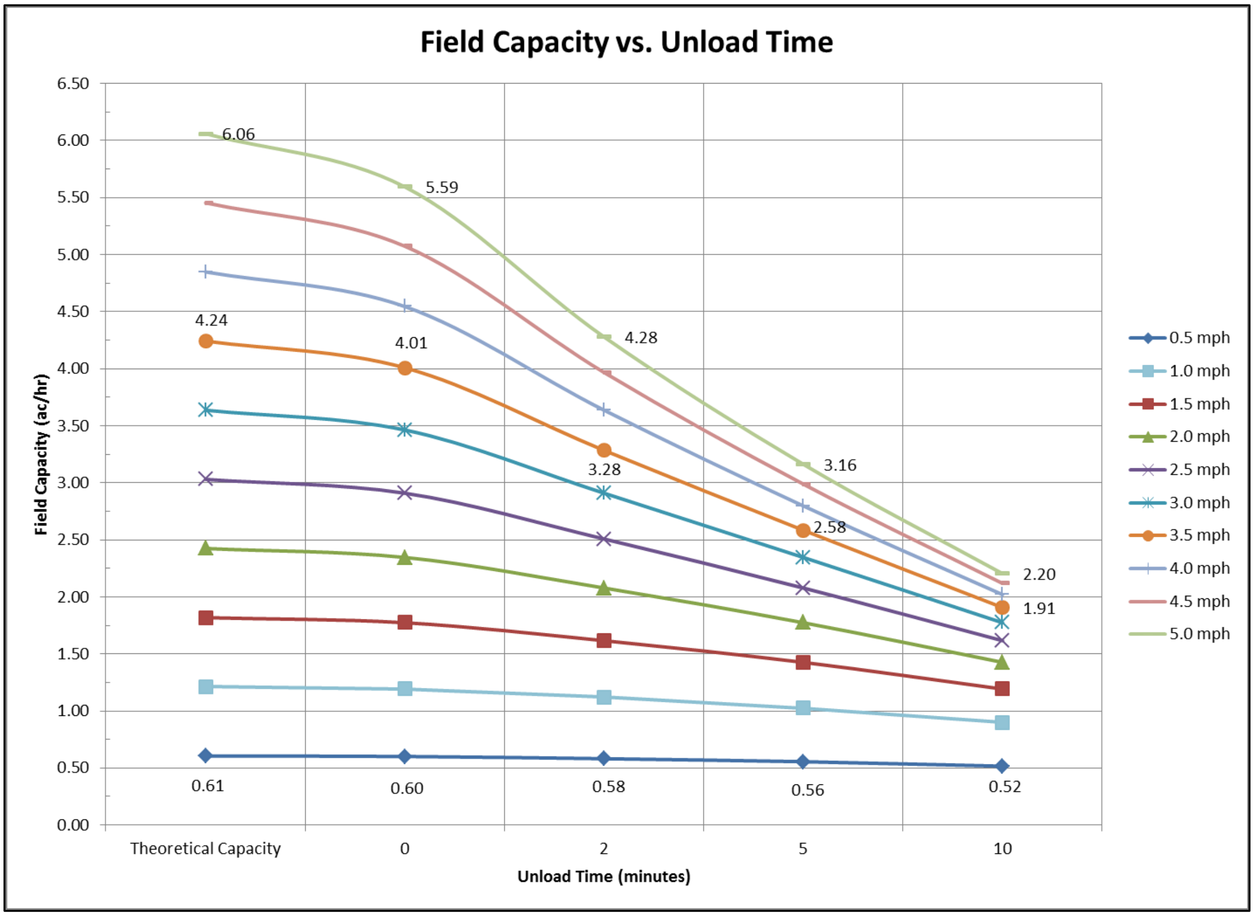


Figure A-2: Harvester Field Capacity Compared to Unloading Time

Table A-5: Hand Harvest Test Yield Results

Hand Harvest Test Yield Results (Pounds/Acre)

	Weekly Harvest			Biweekly Harvest		
	Total Yield	Actual Yield	Overmature Yield	Total Yield	Actual Yield	Overmature Yield
9/4/2013	192	152	41	N/A	N/A	N/A
9/11/2013	465	373	92	663	486	177
9/18/2013	1069	914	155	N/A	N/A	N/A
9/25/2013	1992	1556	436	3348	2420	928
10/2/2013	400	354	46	N/A	N/A	N/A
Totals	***4118***	***3347***	***770***	***4011***	***2906***	***1105***

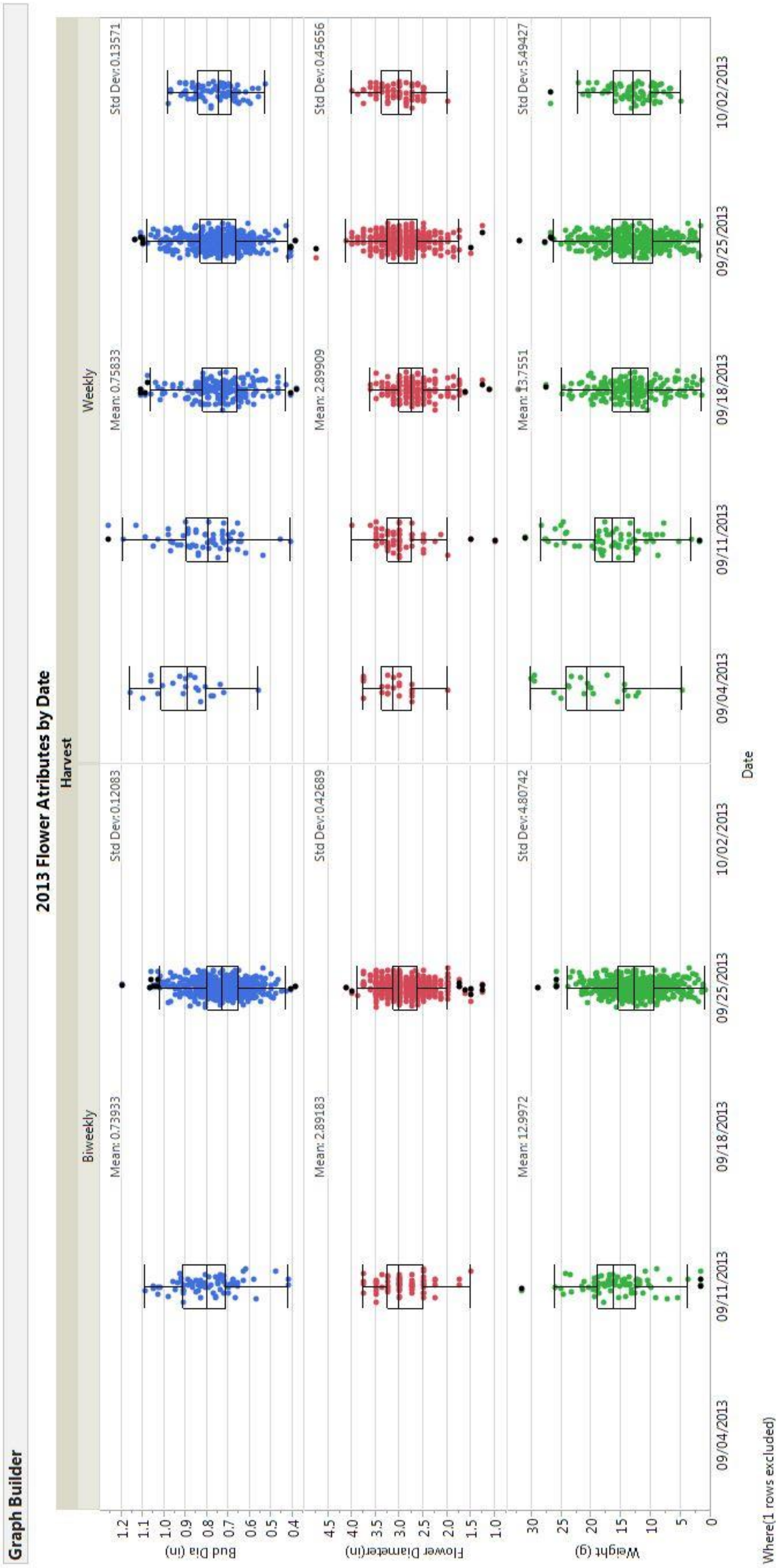
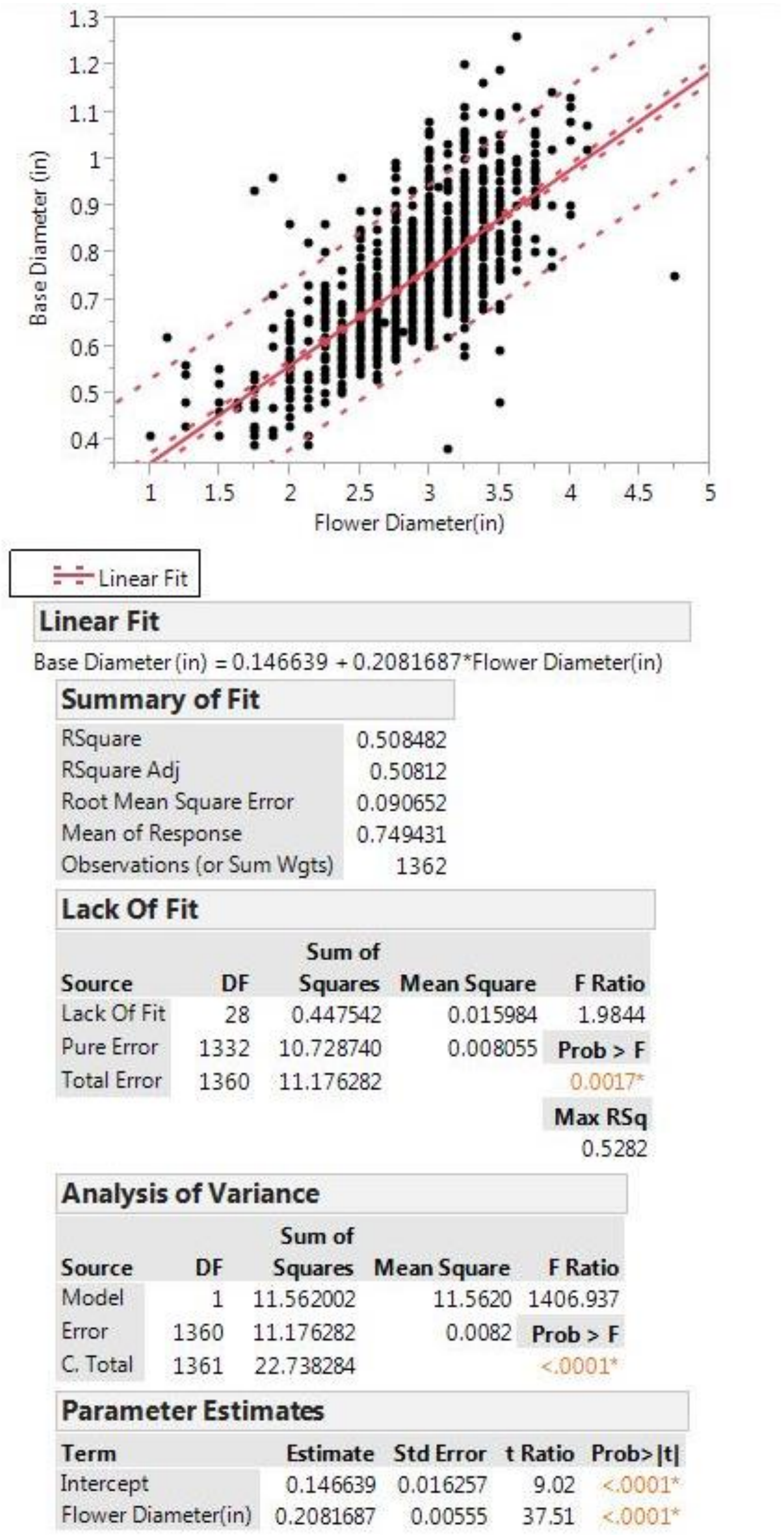


Figure A-3: Hand Harvested Flower Attribute Test Summary



Linear Fit

Base Diameter (in) = 0.146639 + 0.2081687*Flower Diameter(in)

Summary of Fit

RSquare	0.508482
RSquare Adj	0.50812
Root Mean Square Error	0.090652
Mean of Response	0.749431
Observations (or Sum Wgts)	1362

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	28	0.447542	0.015984	1.9844
Pure Error	1332	10.728740	0.008055	Prob > F
Total Error	1360	11.176282		0.0017*
				Max RSq
				0.5282

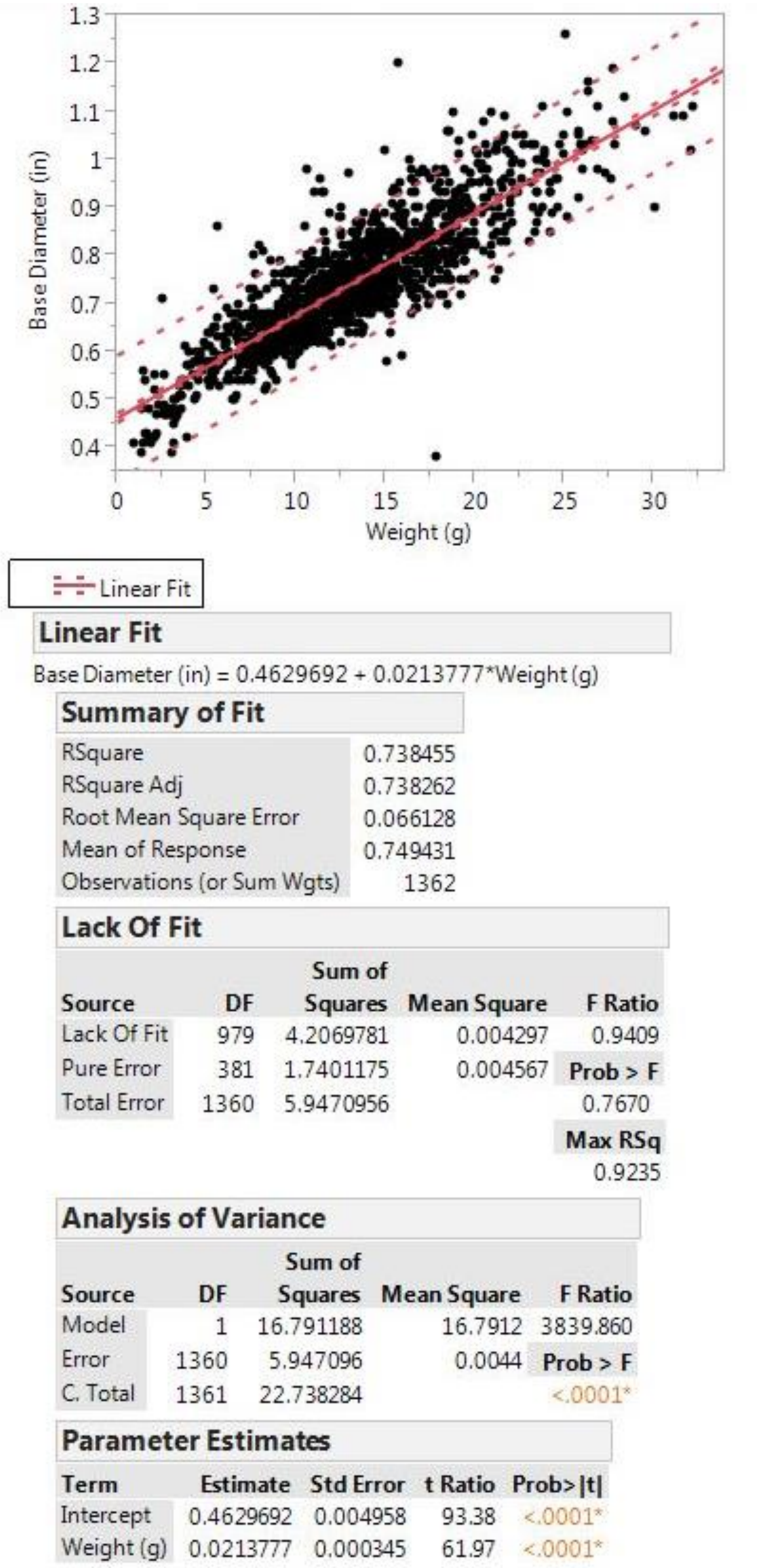
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	11.562002	11.5620	1406.937
Error	1360	11.176282	0.0082	Prob > F
C. Total	1361	22.738284		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.146639	0.016257	9.02	<.0001*
Flower Diameter(in)	0.2081687	0.00555	37.51	<.0001*

Figure A-4: Regression Model of Flower Diameter and Base Diameter



Linear Fit

Base Diameter (in) = 0.4629692 + 0.0213777*Weight (g)

Summary of Fit

RSquare	0.738455
RSquare Adj	0.738262
Root Mean Square Error	0.066128
Mean of Response	0.749431
Observations (or Sum Wgts)	1362

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	979	4.2069781	0.004297	0.9409
Pure Error	381	1.7401175	0.004567	Prob > F
Total Error	1360	5.9470956		0.7670
				Max RSq
				0.9235

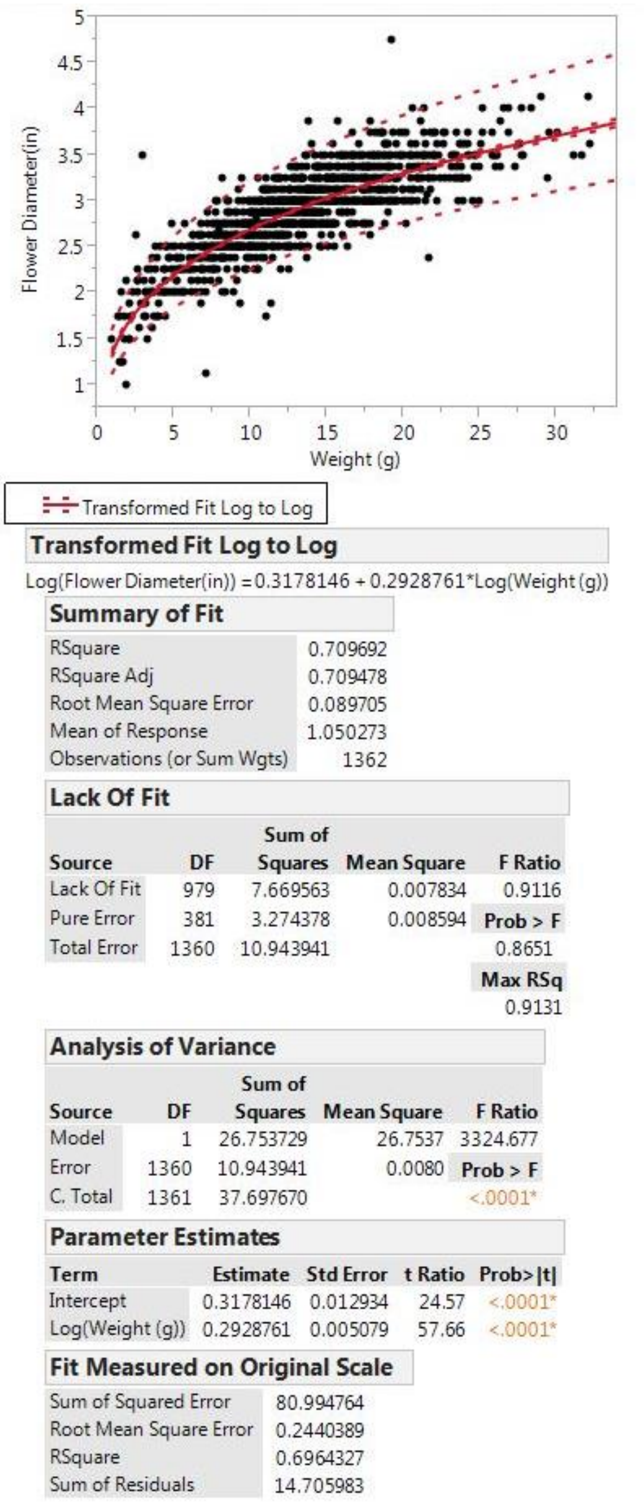
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	16.791188	16.7912	3839.860
Error	1360	5.947096	0.0044	Prob > F
C. Total	1361	22.738284		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4629692	0.004958	93.38	<.0001*
Weight (g)	0.0213777	0.000345	61.97	<.0001*

Figure A-5: Regression Model of Flower Weight and Base Diameter



```
Transformed Fit Log to Log
Log(Flower Diameter(in)) = 0.3178146 + 0.2928761*Log(Weight (g))

Summary of Fit
RSquare                        0.709692
RSquare Adj                    0.709478
Root Mean Square Error         0.089705
Mean of Response               1.050273
Observations (or Sum Wgts)         1362

Lack Of Fit
                       Sum of
Source          DF    Squares  Mean Square   F Ratio
Lack Of Fit    979   7.669563     0.007834    0.9116
Pure Error     381   3.274378     0.008594  Prob > F
Total Error   1360  10.943941                 0.8651
                                             Max RSq
                                              0.9131

Analysis of Variance
                      Sum of
Source       DF      Squares  Mean Square   F Ratio
Model         1    26.753729      26.7537  3324.677
Error      1360    10.943941       0.0080  Prob > F
C. Total   1361    37.697670               <.0001*

Parameter Estimates
Term              Estimate  Std Error  t Ratio  Prob>|t|
Intercept        0.3178146   0.012934    24.57   <.0001*
Log(Weight (g))  0.2928761   0.005079    57.66   <.0001*

Fit Measured on Original Scale
Sum of Squared Error     80.994764
Root Mean Square Error   0.2440389
RSquare                  0.6964327
Sum of Residuals         14.705983
```

Figure A-6: Regression Model of Flower Weight and Flower Diameter