IMPLEMENTATION AND EFFICIENCY OF ELECTRIC MOTORS IN LYGUS BUG VACUUMS FOR STRAWBERRIES

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ABSTRACT

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Further automation of the agricultural industry and an increase in organic fruit production are needed to address labor shortage and increased demand. The move to an autonomous bug vacuum is easier if the equipment is electric, and not powered by a tractor’s PTO (power take-off) shaft. The main objective of this project was to design a set of lygus bug vacuums to go on a robot that meets industry standards while using electric power instead of hydraulic. The frame of the vacuum was designed using the industry standard. While hydraulic systems have been a very effective power source for vacuums until now, electronic motors with VFD (variable frequency drive) control allow for a cost effective, precise control, of the lygus bug vacuums with less failures. This also allows a robot type system to be able to run the vacuums using a preexisting power source without the addition of a bulky hydraulic system.

Keywords: lygus bug vacuum, electric power, VFD, hydraulic
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1. INTRODUCTION

One of the largest issues that California strawberry producers face today is the negative impact of lygus bugs on their crop. The lygus bug attacks the fruit of the strawberry crop causing it to deform and limit its growth. This has caused farmers to lose revenue from deformed berries that have cat-faced. The lygus bug also causes the berries to become further stressed during growth which causes smaller berries to be produced as more energy is spent on survival of the fruit. These deformed strawberries do not meet the standards for the California fresh food market.

Over the years there have been various strategies developed to help deal with the lygus bug issue. The most popular for the longest time was the use of chemical pesticides to kill the lygus bugs. However, as regulations have become stricter, and organic berries desired, certain chemicals in these lygus bug pesticides have become illegal and no longer a viable option. Of the ones remaining, they can’t be used on organic crops, or they are becoming less effective as the lygus bugs adapt to survive. Another method that has been implemented is called trap cropping. Typically, a row of alfalfa is planted near the strawberries to help attract the lygus bugs away from the strawberry plant. Within these trap crops there are other pests that are predators of the Lygus bug. This method, however, has proven to be less effective as well. In more recent years however, the development and use of the lygus bug vacuums has seen an upturn as the solution to the lygus bug problem.

The lygus bug vacuum in general has proven to be quite effective in dealing with lygus bugs on strawberry plants in comparison to pesticides. There have been many
variations of the lygus bug vacuums over the years such as different single barrel and double barrel models covering one to three beds at a time. One of the grower standards today being used is a single barrel vacuum made by C&N tractor that is hydraulically driven from a pump off the PTO shaft of a tractor. This vacuum was developed with the help of the Cal Poly Strawberry Center using a design similar to that already in use with lettuce fields. The main issues that come with this design, however, are the hydraulic components failing and a lack of efficiency. There is also a lack of automatability and micro adjustments that can be made with a hydraulically controlled system. To address these issues, we look towards a redesign of the main power system of the vacuums to an electric motor with variable frequency drive (VFD) controls. In this study a test in efficiency between a, grower standard, C&N lygus bug vacuum that is hydraulically driven and a, new design, electrically driven lygus bug vacuum are compared. The comparison of wind speeds at the intake, collection testing, and power usage will all be the factors for determining the efficiency of the new electric vacuum design.
2. LITERATURE REVIEW

2.1 Lygus Bugs

Lygus bugs, also known as the tarnished plant bug (Lygus Hesperus), are a hemipteran insect with piercing sucking mouthparts (Dara, 2015a). While there are many scientific stages of life for the lygus bug, there are three main stages used by the Cal Poly Strawberry Center when counting them. They look for small nymphs, large nymphs, and adults. Lygus bugs feed on flowers, leaves, and seeds by puncturing the plant tissue and injecting digestive enzymes (Wickwar, 2023). These digestive enzymes lead to damage and deformities in the plant and fruit, such as premature bud, flower and fruit dropping. Shrivelining and deformation of the seeds can also occur. The most notable deformation that can be seen with strawberries is called Cat-facing. Cat-facing is when there are rough corky areas of the fruit where the fruit has dried out causing a deformed fruit as the healthy part of the fruit grows more rapidly around the damaged part (Anthon 1993).

Figure 2.1 - 6 Major Stages of Lygus Bug Growth (excerpted from “Role of lygus bug and other factors in strawberry fruit deformity – Surendra Dara,” 2015)
There are many hosts to the Lygus bugs other than fruit bearing ones. One of the most notable that has actually been used as a way of pest management for Lygus bugs is alfalfa. Alfalfa has shown to attract Lygus bugs and could possibly be used as a strategically placed trap crop in fields (Hagler, 2018). Within these trap crops different bugs and arachnids were placed that would attack and kill the Lygus bugs that were lured into the trap crop. Lygus bugs are a major pest in California strawberries and are the cause of a significant yield loss for farmers (Dara, 2015a). They are an everlasting issue that continues to get worse as the means for dealing with them dwindle. Hence, it is very important that a viable solution to the problem be found to help farmers.

Figure 2.2 - Examples of Lygus Bug Damage vs Other Defects (excerped from “Role of lygus bug and other factors in strawberry fruit deformity – Surendra Dara,” 2015)
2.2 Problems With Pesticides

One of the major problems with pesticides currently is the number of restrictions and bans being placed on them. There are several laws and issues with a very commonly used pesticide, that helps to deal with lygus bugs, known as neonicotinoids.

Neonicotinoids can present a danger to honeybees and other pollinators (DPR, 2023). While they were initially shown to be not as harmful as previously used insecticides, new research is showing that they have a major ecological impact (Xerces, n.d.). Even though strawberries are a self-pollinating crop and do not require pollinators, the application of neonicotinoids on strawberries for lygus bugs can still affect the pollinators in very harmful ways. Since neonicotinoids are absorbed into plants, they can be present in the pollen and nectar that is produced (Xerces, n.d.). This has led to the ban of neonicotinoids.
being used during the bloom stage of crops and then the quantities allowed to be used at all to be restricted (DPR, 2023).

Figure 2.4 - Widespread Effects of Neonicotinoids (excerpted from “Understanding Neonicotinoids – Xerces Society,” n.d.)
Another major reason that pesticides are becoming less and less a solution is that they are becoming less effective against lygus bugs over time. When the lygus bug population is increasing, it has been seen that it is difficult to achieve an acceptable control with only a single application of any of the most commonly used insecticides available (Crow, 2020). Lygus bugs continue to adapt and evolve as chemical restrictions become stricter. Chemical pesticides have been the traditional method for dealing with the bugs, but recently bug vacuums have increased in popularity (Dara, 2015b). As restrictions become tighter and pesticides become less effective the need to use more of and improve on the lygus bug technology increases. Many strawberry producers agree that relying solely on traditional methods such as insecticides are not efficient long term due to regulations, pest resistance and secondary pest outbreaks (Pickel et al., 1995). This is especially seen when looking into organic strawberries at farms such as the one tests were conducted at. Due to the nature of organic strawberries and their need for alternative, non-chemical, treatment the lygus bug vacuum is perfect for the Betteravia test farm’s needs.

2.3 Previous Lygus Bug Vacuums
The earlier stages of lygus bug vacuums were successful in reducing amount of lygus bug damage as compared to pesticide treatment, but the damage was still found to be very high. (Pickel et al., 1995). Early vacuum designs found to remove a very small percentage of the lygus bugs in the rows.
Figure 2.5 - Early Single Bed Lygus Bug Vacuum Design (excerpted from “Vacuums Provide Limited Lygus Control in Strawberries – Pickel, et al.,” 1995)

Figure 2.6 - Early 3 Bed Lygus Bug Vacuum Design (excerpted from “Vacuums Provide Limited Lygus Control in Strawberries – Pickel, et al.,” 1995)
A later design covered three beds and showed a much more promising development in damage control of lygus bugs when compared to the previous models (Pickel et al., 1995). Further testing was conducted in a lab to test just how effective the vacuums could be on the lygus bugs. To prove the efficacy of the vacuums, they needed to conduct more tests on the behavior of the bugs when around it (Vincent et al., 2000). Some of the main tests done in these studies was what height to run the vacuums at. The results of which showed that the vacuum being run at a lower height in the plant was more effective. Since the strawberry plant have a less rigid architecture than most other crops, it allows for this lower ride height in the plants without causing much apparent damage (Vincent et al., 2000).

The improvements of the vacuums continued over time. This led to the development of a prototype vacuum from the Cal Poly Strawberry Center. This was done by taking a vacuum designed for lettuce fields and retro fitting it to work with strawberry row crops. Once the vacuum was retrofitted, there was a series of tests conducted between the newly designed vacuum and the conventional one. This model was more than twice as effective at removing the lygus bugs as the conventional model (Wells et al., 2020). This was achieved in the later design by adding an elimination baffle just before the screen at the top of the vacuum. By reducing the amount of backpressure into the vacuum from the top screen this allowed for much higher windspeeds inside the vacuum. The bugs were killed because they couldn’t change direction with the air flowing out of the riser and would continue at high speeds into the serrated screen.
2.4 Electric Motor and VFD Control

One of the main problems seen with the early bug vacuum designs was issues with the hydraulic system. Pump failure, fluid leaks, and inconsistent pressures and speeds are just some of the commonly occurring issues. Due to these issues, there can be a much higher power demand when it comes to hydraulics, on top of the already higher cost of hydraulic components. Electric motors also have their costs associated. Though not as expensive in most cases, they have a very poor power density, making them large and heavy in order to produce more power (Berkner, 2008).

The power savings and longevity of the AC motors alone are enough to offset the weight cost of using them. This can especially be seen when the AC motors are paired
with a PLC, (programable logic controller), and or a VFD, (variable frequency drive). Using these systems along with an AC motor can further reduce power consumption, reduce motor starting current, and reduce mechanical stress on the motors (Khalid, et al., 2021). While a VFD can add more cost to the design, it does allow for more possibilities with automation while helping to assure a constant electric motor speed.

![Delta Variable Frequency Drive](image)

Figure 2.8 - Delta Variable Frequency Drive (excerpted from “Design and Implementation of Constant Speed control System for the Induction motors Using Programmable logic Controller (PLC) and Variable Frequency Derive (VFD) – Khudier, et al.,” 2021)
3. MATERIALS & METHODS

3.1 Frame Design and Construction Methods

The bulk of the design and first model construction of the vacuum frame design was done by Andros Engineering in junction with TRIC Robotics prior to the start of the research project. The design followed the single barrel principles laid out by the Cal Poly Strawberry Center research. It took many of the design principles from grower standard at the time, C&N Tractors, hydraulic, fiberglass, vacuum. No additional adjustments were made to the framework of the vacuum other than the overall size to allow for lower rotational speeds and height to accommodate for the size of the ac motor.

Figure 3.1 - C&N Tractor Hydraulic Lygus Bug Vacuum At Betteraiva Farm
Figure 3.2 - Solid Works Model of Electric Lygus Bug Vacuum

The main barrel and transitional piece were both lengthened to accommodate the height of the ac motor and fan blade. A circle to rectangle transition piece was used just like in the C&N vacuum to create more uniform wind speeds across the intake of the vacuum. The uniformity increase was found be helping to eliminate the dead zones in the center of the circle. This was created using a series of compound bends on sheet metal to make two halves that were then welded together using a circle and rectangle flange. The vacuum was to be mounted to an I beam frame, so two supports were added to the transitional piece with a mounting plate welded between them. An inlet guard similar to that of the C&N vacuums was designed to be bolted onto the bottom of the vacuum to
protect against larger objects that could damage the fan blade from being sucked up such as sprinklers and strawberry clam shells. The total open space was 78%, which is within the recommended range to prevent a large loss of airflow at the intake.

Figure 3.3 - Solid Works Model Of Lower Intake Debris Guard
A riser was also developed using the research that the Cal Poly Strawberry Center conducted. It was set to raise the elimination baffle 6 inches, which showed the best improvement of windspeeds. This helped to reduce the back pressure in the vacuum by allowing air to escape with an open area of about 75%. The elimination baffle itself was made out of a perforated sheet material that had a hole diameter of 0.156in and an open area of 63%. Each one of the slates on the elimination baffle was angled at 22.5 degrees which was found to be the optimum angle for the slates by the Cal Poly Strawberry Center. Rubber sections were added to both sides of the vacuum intake guard that hung down beside the plants in the row. This was made using a rubber conveyer type material so as to not cause any damage to the strawberry plants or the mulch covering the beds. This portion of the vacuum helps to create a pocket around the strawberry plants and prevent pulling air up from the furrows between the beds which could cause damage crops as well as reduce the effectiveness of the vacuum.
One difficulty encountered was figuring out the best way to mount the AC motor. It was far larger and heavier than the traditional hydraulic motors and still needs to be in the center of the barrel so that the fan blade for direct couple. AC motors can either be
face mounted or rigid mounted using a base plate attached to the motor housing. After some simulated tests with the face mounted motor it was determined that it would be too unstable and caused issues with back pressure in the vacuum as the size of the mount would fill too much of the barrel cross sectionally. The conclusion was to go with the rigid mounted version using a piece of ¼ in plate bolted to the square tubing supports of the barrel. This, however, caused another problem in early designs as the mount acted as a major disruption in the cyclone of air movement through the vacuum. To remedy this in future models a large area was opened up in the center of the motor mount in order to avoid high and low spots of air movement caused by the disruption of the mount face.

![Figure 3.7 - Electric Lygus Bug Vacuum Dropped Into Frame At Andros Engineering](image)

The vacuums were designed to mount to a sub frame in the center of the TRIC robot frame between two I-beams. This allowed for the vacuums to have their height
adjusted in the field independent of the main frame height. This was important as research from the Cal Poly Strawberry Center had shown that due to the drop off in windspeeds, riding as close to the plants as possible was crucial. Each vacuum was dropped into the frame using a crane attachment for a forklift prior to final. Once mounted to the frame each electric motor was first configured for 480V 3 phase power and then wire nuts were used to connect a four conductor 14 gauge cable.

![Figure 3.8 - Wiring Of AC Motor in Lygus Bug Vacuum at Andros Engineering](image)

*Figure 3.8 - Wiring Of AC Motor in Lygus Bug Vacuum at Andros Engineering*
The high-speed fan blade was attached directly to the keyed shaft of the AC motor leaving a 0.75 inch clearance between the tips and the side of the barrel. To attach the fan blade a quick connect tapered coupler was used that bolted to the fan blade and collapsed down into the hub of the fan blade. A set screw was then used to lock the fan blade in place at half of an inch from the top of ac motor shaft. This allowed for enough clearance so that the hub of the fan blade did not ride on the face of the ac motor.
3.2 Fan Blade and Electric Motor Selection

Determining what fan blade to use was the first task when re-designing the main air flow system for the lygus bug vacuums. The size of the fan blade that was settled on was 36-inch diameter, this was to both make sure that the same CFM, (cubic feet per minute), could be hit in the vacuum while only running at no higher than 1800 RPM, (rotations per minute), since most AC, (alternating current), washdown motors max out at 1800 RPM. The other reason for this was to get as much coverage over the 48 inch bed
with a single barrel. Multi-Wing makes the fan blades for the C&N vacuums and trial
Strawberry Research Center vacuums, also made a 36-inch version with 6 blades. This
fan blade had the exact same profile with a 30 degree pitch made out of the same
materials which made certain assumptions possible when calculating.

Figure 3.11 - 36 inch Diameter High Speed Fan Blade

The first step in the analysis of what hp, (horsepower), motor to select in order for
the vacuum to hit the minimum requirements of the farmer by making sure that the same
1767 CFM (Appendix A) could be met by the vacuum. To do this the total cubic inch
volume of the fan blade was calculated. Then for the C&N vacuum CFM was calculated
using the speed given by Strawberry Center of 3000 RPM. Given the cubic inch
volumetric profile of the 36-inch fan blade, it was found that the minimum speed the
electric vacuum would need to run at would be 1333 RPM (Appendix A). This fell under
the necessary requirements of being under 1800 RPM, so the fan blade was confirmed to work for the desired use. The next step was calculating the necessary hp of the AC motor required to overcome the drag force created by the fans profile at these speeds. This assumed standard air density of 1.225 kg/m^3 and a drag coefficient of 0.05 due to the fan blades pitch and profile. With these assumptions in place and in addition an assumed motor efficiency of 85%, an 8.24 hp was found to be necessary. The next closest nominal size that met this requirement was a 10 hp ac motor (Appendix A).

![Figure 3.12 - 10 HP Washdown AC Motors](image)
Once the power requirement of the AC electric motor was calculated, the motor was sourced. The next step was to find a VFD that could run the motor as needed. The VFD needed to be able to handle the 10 hp demand at 480 V 3-phase power. The other main requirement was that the fan blade needed to be spun counterclockwise in order to create a suction force, so the VFD needed to have a reverse function. One was found and sourced from Automation Direct, GS23-4010 DURApulse, that met all of the necessary requirements along with the bonus add in of being able to further along the automation of the vacuum with an ethernet cable expansion port.

Figure 3.13 - 10 HP 480V 3-Phase Variable Frequency Drives

[Image of variable frequency drives]
3.3 Materials

Design, construction, and initial testing of the initial vacuum frame took place at the Andros Engineering R&D Department. The design of the vacuum followed the same principles already laid out in the C&N vacuum as well as the research done by the Cal Poly Strawberry Center which is described more in the literature review. The key specifications of the frame design were as follows:

- Perforated plate sections angled at 22.5 degrees (1)
- 6in Raised baffling before screen on top to help with airflow (2)
- Circular barrel for fan/ motor housing (3)
- Circular to rectangular transition for more even inlet air speeds (4)
- Slotted inlet guard to prevent sucking up sprinklers and clam shells (5)
- Rubber drapes to help cradle row for better air flows (6)

*Figure 3.14 - Final Vacuum Components*
Testing of the vacuums after the initial wind speed tests at Andros Engineering took place at a Betteravia Farms location. Additional wind speed tests, as well as collections tests were conducted using the following materials:

- Bluetooth wind speed anemometer
- Mesh collection screens
- Large 18 in by 36 in collection containers
- Small 3 cups volume collection containers

3.4 Testing Methods

The tests conducted during this study were conducted at an organic strawberry farm located in Los Almos California owned by Betteravia Farms. The farm bed size and soil type are similar to that of most of the Santa Maria area where this vacuum was designed to run. On site the farmer already had a three-vacuum manifold on a tractor from C&N tractor.
Figure 3.15 - C&N Tractor Driving in Collection Trials at Betteravia Farm

Figure 3.16 - Air Speed Sample Map
The initial tests conducted with the fans was a wind speed test at various points across and distances from the intake of the vacuums. The intake speeds necessary for different stages of the plants to extract the lygus bugs range from 40 to 50 mph directly at the intake, as stated by Cal Poly Strawberry Center. For these tests, 50hz, 55hz, and 60hz frequency were all tested with the electric vacuum. A grid pattern design was used for measuring the windspeeds at various points across the intake. These measurements were used to plot the wind speeds vs distance from the intake manifold. The distances were measured using a set height gauge attached to the wind speed anemometer. The distances measured were 0, 3, 6, and 12-inches from the manifold to simulate different points down a plant that the vacuum will reach. A wireless WeatherFlow brand wind speed propeller style anemometer was used to take the wind speeds data and was all recorded for both the C&N and electric vacuum models. The anemometer was held at each position for 5 seconds to collect an average wind speed at that point.
The second set of tests conducted was a series of lygus bug collection tests using each vacuum. A mesh screen was used for the collection process by placing it below the intake manifold and using a bungie strap to hold it on. The vacuum was then driven through the field and left on until ready for collection on the opposite end of the row. The electric vacuums were held at 60hz frequency for this portion of testing. Once the collection bin was ready, the vacuum was turned off, allowing the screen and all of its contents to be dropped into the collection bin. These bins contents were put into labeled containers and sent off to the lab for the entomologists to count the number of bugs.
trapped and the stage of lygus bugs collected. These tests were repeated for each vacuum across different sets of rows, at different times of day, on different dates so that a range of comparative data can be analyzed between the vacuum designs. The collection data once received back from the lab was then used to run statistical anova tests on the comparison between the vacuum type results and the effects of day and night.

Figure 3.18 - Mesh Collection Screen on Electric Lygus Bug Vacuum at Betteravia Farm
The third test was to test the power usage efficiency and compare between the hydraulic and electrical systems. Since the hydraulic system is 3 vacuums in parallel, the electric vacuum system was measured with 3 vacuums turned on. The Kw of power use was measured directly off of the generator control panel that reads off of the alternator. The Kw was measured before and after the 3 vacuums were turned on and then
subtracted to find the Kw of power used for 3 vacuums. Kw were then converted into HP for comparison. For the hydraulic system the system pressure, fan motor speed, and motor displacement are known. With this the required system GPM could be calculated. Once the system pressure and flow were known, the mechanical horsepower with a motor efficiency factor or 90% could be calculated.

3.5 Limitations

These tests' limitations are mostly constrained to equipment availability and not inflicting with farm operations. As the company did not own the C&N vacuums and were just working with the farmer to run the vacuum for testing when needed. There was also constant harvesting of berries happening in the field. At times, organic pesticides were being sprayed at night, restricting, even further, the times that testing was allowed. To combat these issues, we were in constant communication with the farm manager and worker manager so that we could make sure that the C&N vacuums are always available when we need to do testing. We also were being updated on what days that block that we were doing testing on would be picked so that we could make sure that we were not in the way of their regular operations. As the spraying schedule was set with the farmer before we began testing, we were also being flexible to be out of the way of those workers when they were in the field. Good communication was the key to our testing running smoothly without interfering with regular farm operations.
4. RESULTS

The final product of the construction process was six galvanized vacuums with 10 hp washdown ac motors. The vacuums fit well into the frame of the robot and met the height requirements of the Santa Maria style beds. Initial testing of the power systems went well. The motor was able to start the vacuums spinning in the suction direction at the set point frequency of 55-60 hz and a speed of 1300-1600 RPM.

Figure 4.1 - Fully Assembled Electric Lygus Bug Vacuum
The first set of data collected on the two different vacuums was the windspeeds and can be seen in Figure 4.2. We can see that the electric powered vacuum proved to have higher wind speeds than the hydraulically driven vacuum at both 60Hz and 55Hz frequencies. Once dropped down to 50Hz frequency we begin to see a larger increasing drop off in speeds. As the target windspeeds at the intake of the vacuum is 45 to 50 mph we can see the 55Hz frequency is the optimal frequency to run the electric vacuum at. Anything over 50 mph begins to be too aggressive on the plants causing healthy leaves and whole plants could be pulled out. Due to the target windspeed, the goal was not to be more power efficient, but to be able to match the goal and drop off in speeds of the grower standard. As can be seen in Figure 4.2 the electric vacuum was able to meet and at some points exceed that of the wind speeds seen by the hydraulic vacuum.

![Wind Speed Drop Off from Intake](image)

*Figure 4.2 - Vacuum comparative wind speeds*
The next round of tests were lygus bug collection efficiency on both the electric and hydraulic vacuums. Collection tests were performed during both daytime and nighttime on multiple rows and days. The comparative results of the collections can be seen below in Figure 4.3 and Figure 4.4, C&N hydraulic vacuum and TRIC electric vacuum respectively. As observed, in most of the tests the electric vacuum outperformed the hydraulic vacuum in amount of lygus bugs collected. Another observation is the electric vacuum seemed to perform better at night than during the day. This was not expected because previous research with the hydraulic vacuums had shown that the hydraulic vacuums were ineffective at nighttime collection.

Figure 4.3 - Daytime Collection Data
Bug collection data was processed by the Cal Poly Strawberry Center to produce a set of collection efficiencies for the separate trials. This shows the percentage of lygus collected, in a singular pass, of a theoretical population based on averages. The C&N vacuum performed as expected from previous trials conducted by the Strawberry Center.
The electric vacuum was on a robot that will run with UV light in the future as well. The vacuums were tested running both directions down the field to see if the generator passing over before the vacuums would influence collections. There do appear to be some differences depending on the direction driven, but it is minimal.

An anova test was used to test the significance of the collection data using IBM SPSS, a statistical analysis software. An anova table was used to test the difference in the data between the two vacuum systems. As seen in Table 4.2, with an F value of 5.6, a significance value of .04 was calculated. As this is below the .05 significance threshold, we can see that the results of the collections test were statistically significant.

**Table 4.2 - Anova Comparison of Lygus Bug Collections Data**

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean Lower Bound</th>
<th>Upper Bound</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIC (Electric)</td>
<td>6</td>
<td>62.1</td>
<td>24.9</td>
<td>10.2</td>
<td>36.0</td>
<td>88.3</td>
<td>25.9</td>
<td>91.3</td>
</tr>
<tr>
<td>C&amp;N (Hydraulic)</td>
<td>5</td>
<td>28.2</td>
<td>22.1</td>
<td>9.9</td>
<td>0.8</td>
<td>55.6</td>
<td>5.0</td>
<td>55.3</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>46.7</td>
<td>28.6</td>
<td>8.6</td>
<td>27.5</td>
<td>65.9</td>
<td>5.0</td>
<td>91.3</td>
</tr>
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</table>

**ANOVA**

<table>
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<tr>
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<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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</thead>
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<td>Total</td>
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The unexpected performance of electric vacuum at night prompted further statistical comparison between night and day effects on lygus bug collection. As can be seen in Figure 4.5, days where collections were done at night and day, the nighttime collection was higher. All collections, however, were done in different rows.

![TRIC Day vs Night](image)

**Figure 4.5 - Electric Vacuum Collections Day Versus Night**

To test the actual significance of night and day testing on the collection results yet another statistical analysis was conducted. As can be seen in Table 4.2, with the electric vacuum with an F value of .01 and a significance level of .91 was found. This is well above the .05 thresh hold and suggests that day and night collections were not the primary explanation for the difference in collection results with the electric vacuum. As can be seen in Table 4.3, with the electric vacuum with an F value of 22.4 and a significance level of .02 was found. This is below the .05 thresh hold and suggests that day and night collections do play a factor in the efficiency of the hydraulic C&N vacuum.
Table 4.3 - Anova Comparison of Lygus Bug Day Versus Night Collections

Descriptives

<table>
<thead>
<tr>
<th>Collections</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Min</th>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Day</td>
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<td>36.0</td>
<td>88.3</td>
<td>25.9</td>
<td>91.3</td>
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<tr>
<td>C&amp;N (Hydraulic)</td>
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<td></td>
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<tr>
<td>Day</td>
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<td>43.3</td>
<td>10.7</td>
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<td>69.9</td>
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<td>0.7</td>
<td>0.5</td>
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<td>11.9</td>
<td>5.0</td>
<td>6.0</td>
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<tr>
<td>Total</td>
<td>5</td>
<td>28.2</td>
<td>22.1</td>
<td>9.9</td>
<td>95% Confidence Interval for Mean</td>
<td>0.8</td>
<td>55.6</td>
<td>5.0</td>
<td>55.3</td>
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</table>

ANOVA

<table>
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<tr>
<th>Collections</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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<td>TRIC (Electric)</td>
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<td></td>
<td></td>
<td></td>
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<td>1718</td>
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<tr>
<td>Total</td>
<td>1948</td>
<td>4</td>
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</tbody>
</table>

With the power efficiency tests measured in the above section, we can compare the power consumption of each type of system. The electric system consumed 19.4 Kw, which comes out to about 26 mechanical HP. With the system flow of 2500 psi and a system flow of 19 GPM we calculate that the required power of the hydraulic system to be about 31 HP. The calculations for both values can be seen in appendix A. The electric
vacuum system and hydraulic vacuum system have similar power consumptions. However, the electric vacuum system is a little bit more efficient which could be explained by less mechanical inefficiencies.
5. DISCUSSION & CONCLUSION

The wind speed data collected during the tests verified that the wind speeds of the electric vacuum performed as expected. The hydraulic vacuum seemed to however have lower wind speeds directly at the intake than expected from previous research. The test was replicated multiple times and came up with the same results even when running at full power. This could be explained by a defect in the hydraulic system of the hydraulic vacuum because maintenance is a big problem for farmers with current models. However, since the speed was still above 40 mph it met the requirements to continue with the collections test. The drop-off of wind speeds on the electric vacuum matched the grower standard drop off speeds seen on the hydraulic vacuum. Other data collected from this test was the confirmation that a higher frequency is available for the electric vacuum for tuning windspeeds. Because vacuum wind speeds over 50 mph is too aggressive on the plants the vacuums will be set at 55Hz instead of 60Hz.

By testing different times of day, different rows, and different days, multiple sets of data were able to be compared between the two vacuums. We can see the difference in collection efficiency of the vacuums. Most of the electric vacuum collection tests were shown to have higher collection amounts on each pass of a row. However, as there were only 6 collections, there is a large amount of unaccounted variability present. A higher number of repetitions is recommended for future research. The collected data was then analyzed for the statistical significance of both night versus day and electric versus hydraulic. Through these statistical tests we can see that there is significant statistical evidence that the difference in vacuum power source does affect the collection amounts of the trials. We also see that though there were higher collections at night than some day
trials with the electric vac, there is not enough statistical evidence to show that night
versus day makes a difference in the collection results of the electric vacuum, but it is still
not advised to use the C&N vacuum at night.

The electrical vacuum is able to hit the required windspeeds and drop off speeds
of the grower standard, as required. There is significant evidence that the efficiency of the
electric vacuum with collections of lygus bugs is higher than that of the grower standard
hydraulic vacuum. It has to be taken into consideration that the electric vacuum during
these tests is running at a higher intake windspeed and is a bigger frame. However, the
hydraulic vacuum achieved the expected collection efficiency of 1-8% removal of lygus
bugs per pass. The electric vacuum showed removal efficiency of 6-19% of the lygus
bugs per pass of a row. Therefore, the collection efficiency of the electric vacuum appears
to be higher than the fiberglass hydraulic lygus bug vacuums.

The main change with these vacuums as compared to previously used vacuums is
the power system. The electric vacuum was designed so that an additional hydraulic
system didn’t have to be implemented on the robots as well as to save on power
consumption. The tests for power efficiency helped to prove this with the electric
vacuum. Though the vacuum is bigger, it is able to run at a lower RPM and maintain a
higher intake windspeed, all while requiring less mechanical horsepower than the
hydraulic vacuums. With this, the goals of the electric vacuum are achieved, less
hydraulic systems on the robot, less mechanical issues to worry about, and lower power
consumption overall. With these results we can conclude that the electric motor
controlled by a VFD is uses power more efficiently while meeting the collection
standards set by the Cal Poly Strawberry Center.
BIBLIOGRAPHY


https://www.xerces.org/pesticides/understanding-neonicotinoids#:~:text=While%20they%20were%20initially%20introduced,beneficial%20insects%2C%20and%20aquatic%20invertebrates
PUBLICATION PLANS

This thesis will be published by California Polytechnic State University, San Luis Obispo at the library and online in the Digital Commons.
APPENDIX

A. Calculations

The fan blade of the Cal Poly Strawberry Center Research Vacuum was made by the $A = \pi r^2$ exact same company and shared the same pitch and profile as the fan blade used in the electric vacuum. The primary difference was that the Strawberry Center Vacuum fan blade was 24 inch diameter and was spun at 3000 RPM, while the electric vacuum’s blade is a 36 inch diameter so that it could be spun at a lower RPM. A basic cubic feet per minute calculation was used to determine the minimum RPM the electric fan blade would be spun at. This was done by first calculating the volumetric profile of the fan blade.

Hydraulic Vacuum:

$$Volumetric \ Profile = \frac{\pi(24in)^2}{4} \times 2.25in = 1017.88in^3$$

Electric Vacuum:

$$Volumetric \ Profile = \frac{\pi(36in)^2}{4} \times 2.25in = 2290.22in^3$$

CFM at Inlet, Hydraulic Vacuum:

$$CFM = 3000RPM \times \frac{1017.88in^3}{1728in^3/ft^3} = 1767.15 \text{ CFM}$$

The volumetric flow of 1767.15 CFM is the baseline target that the electric vacuum needed to be designed to hit so that it would have the same airspeeds at the intake and similar efficiency. With this value known we could next use the same
equation, but rearranged to find the theoretical speed that the larger diameter fan blade would need to spin at.

Theoretical Minimum Speed of Electric Vacuum Fan Blade:

\[
RPM = \frac{1767.15 \text{ CFM} \times 1728 \text{ in}^3/\text{ft}^3}{2290.22 \text{ in}^3} = 1333.33 \text{ RPM}
\]

The fan blade speed of 1333.33 RPM is the theoretical minimum that the electric vacuum fan blade would need to spin at, in order to hit the same volumetric air movement that the hydraulic vacuum produces. This does not take into account efficiency or other additional losses, so the actual speed will be a bit higher. The next step is determining the hp necessary to overcome the drag force created by the profile of the fan blade at this speed. For this, some assumptions are made. With a 30 degree pitch, a drag coefficient of 0.05 is used and air density is set as 1.225 kg/m^3.

Angular Velocity of Fan Blade at Minimum RPM:

\[
\omega = \frac{2\pi \times 1333.33 \text{ RPM}}{60 \text{ sec/min}} = 139.59 \text{ rad/s}
\]

Linear Velocity of the Fan Blade:

\[
v = \frac{18 \text{ in}}{39.37 \text{ m}} \times 139.59 \frac{\text{rad}}{s} = 63.82 \text{ m/s}
\]

Drag Force on Fan Blade at the Minimum RPM:

\[
F_d = \frac{1}{2} \left( \frac{1.225 \text{ kg}}{\text{m}^3} \right) \times (0.05) \times \frac{\pi \left( \frac{36\text{ in}}{39.37\text{ in}} \right)^2}{\frac{m}{4}} \times \left( \frac{63.82\text{ m}}{s} \right)^2 = 81.91 \text{ N}
\]
Torque on AC Motor Shaft Created by Drag Force:

\[ T = 81.91N \times \frac{18in}{39.37in/m} = 37.45 \text{ Nm} \]

Power Required to Overcome Drag Force:

\[ P = 37.45 \text{ Nm} \times 139.59 \frac{rad}{s} = 5227.86 \text{ watts} \]

HP Required to Overcome Drag Force with Motor Efficiency:

\[ HP = \frac{5227.86 \text{ watts}}{746 \text{ watts/HP}} \div \frac{85\%}{100} = 8.24 \text{ HP} \]

The calculated HP, with taking into account motor efficiency, to overcome the drag force of the fan blade at the minimum RPM is 8.24 HP. AC motors come in nominal sizes however. The next closest, higher HP ac washdown motor is 10 HP. Therefore, a 10 HP, 480V, 3-Phase, washdown, motor was selected as the main driving force of the electric lygus bug vacuum.

The calculations for HP of both systems usage were converting from Kw as well as a hydraulic system analysis. The known variables of the hydraulic system were a system pressure of 2500 psi, motor speed of 3000 RPM, and a motor displacement of 8cc. Both sets of calculations are for a set of 3 vacuums.

Kw to HP Conversion:

\[ HP = 19.4Kw \times 1.341 \frac{HP}{Kw} = 26.02 \text{ HP} \]

Hydraulic System Flow:
\[
GPM = \frac{8 \text{ cc}}{\text{Rev}} \times 3000 \text{ RPM} \times 3 \text{ Vacs} = 19.02 \text{ GPM}
\]

HP Required for Hydraulic System:

\[
HP = \frac{19.02 \text{ GPM} \times 2500 \text{ PSI}}{1714 + 0.9} = 30.82 \text{ HP}
\]