Winter 5-2017

Safer Sweep Auger Operation Using Robotics

Nathan A. Wulf

University of Nebraska - Lincoln, nwulf45@gmail.com

Follow this and additional works at: http://digitalcommons.unl.edu/mechengdiss

Part of the Computer-Aided Engineering and Design Commons, and the Electro-Mechanical Systems Commons

http://digitalcommons.unl.edu/mechengdiss/116

This Article is brought to you for free and open access by the Mechanical & Materials Engineering, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Mechanical (and Materials) Engineering -- Dissertations, Theses, and Student Research by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
SAFER SWEEP AUGER OPERATION USING ROBOTICS

By

Nathan A. Wulf

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Mechanical Engineering and Applied Mechanics

Under the Supervision of Professor Shane Farritor

Lincoln, Nebraska

May, 2017
This thesis presents a remotely controlled robotic solution for those who must sometimes enter agriculturally confined spaces in attempts to assist with grain bin cleanout, particularly by manipulating the sweep auger. In 2015 alone, there were at least 47 documented incidents that occurred in agriculturally confined spaces, of which more than half were fatal. While there have been several advancements in the quality and effectiveness of sweep augers, there have been very few that offer the safety and adaptability of the robotic solution proposed. This robotic solution is a four-wheeled, skid-steering style robot with camera and lighting attachments that allow the user to operate from outside of a grain bin. The intended use of this robot is to manipulate the sweep auger by providing forward advancement assistance via an interfacing front-end attachment. Testing has shown that this robot is capable of generating over 500 lbs of assistive force and can also provide assistance even in situations with poor traction with the aid of an integrated thrusting mechanism. This thesis details the design process, provides a description of the testing methods employed, and results obtained.
# TABLE OF CONTENTS

CHAPTER 1 BACKGROUND AND PROBLEM STATEMENT ........................................... 1  
  Background ................................................................................................................... 1  
  Problem Description ................................................................................................. 3  

CHAPTER 2 EXISTING SOLUTIONS ............................................................................. 7  
  Products on the Market ............................................................................................. 7  

CHAPTER 3 SURVEYING DATA ..................................................................................... 13  
  Survey .......................................................................................................................... 13  
  Interpreting the Results .............................................................................................. 15  
  Problems Encountered ............................................................................................... 16  

CHAPTER 4 THE GRAINBOT ....................................................................................... 17  
  Design Constraints ...................................................................................................... 17  
  Design Features ........................................................................................................... 19  

CHAPTER 5 TESTING IN GRAIN BIN ......................................................................... 49  
  Static Pull Test .............................................................................................................. 50  
  Dynamic Pull Test ........................................................................................................ 52  
  Aeration Floor Pull Test ............................................................................................... 54  
  Maneuverability/Communication Effectiveness ......................................................... 55  
  Results and Discussion ............................................................................................... 58  

CHAPTER 6 SIMULATED GRAIN BIN ENVIRONMENT TESTING ............................... 60
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verification of Load Cell Accuracy and Consistency</td>
<td>63</td>
</tr>
<tr>
<td>Static Testing</td>
<td>64</td>
</tr>
<tr>
<td>Dynamic Testing</td>
<td>69</td>
</tr>
<tr>
<td>Thrusting Mechanism Testing</td>
<td>73</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>75</td>
</tr>
<tr>
<td>CHAPTER 7 CONCLUSIONS AND FUTURE WORK</td>
<td>99</td>
</tr>
<tr>
<td>Future Work</td>
<td>101</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>104</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>106</td>
</tr>
<tr>
<td>A. Classification of Hazardous Locations [10]</td>
<td>106</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1-1: A carry-in sweep auger. .................................................................4

Figure 1-2: A side access door of a grain storage structure, seated a few feet above
ground [4]. ........................................................................................................5

Figure 2-1: Hutchinson-Mayrath’s sweep end-wheel replacement for Klean Sweep augers
[5] ......................................................................................................................8

Figure 2-2: The Grain Handler Inc.’s Buzz-Saw double reduction drive wheel [6]. .......9

Figure 2-3: Hutchinson/Mayrath NexGen 2000 commercial sweep auger [7] .............10

Figure 2-4: Daay Bin paddle sweep [8] ................................................................11

Figure 2-5: Mack Robotics’ Bin Bot solution [9] ....................................................12

Figure 4-1: Front and rear views of the Grainbot as modeled in SolidWorks. ............19

Figure 4-2: Front and rear views of the fully assembled Grainbot. ............................20

Figure 4-3: Swivel attachment (top) and rigid plow (bottom) as modeled in SolidWorks.
......................................................................................................................23

Figure 4-4: Hammering mechanism as modeled in SolidWorks, shown with and without
the front cover plate. .......................................................................................24

Figure 4-5: Advancement stage shown from the front and back sides. .......................26

Figure 4-6: Phase 1 of hammering process. ..........................................................26

Figure 4-7: Phase 2 of hammering process. ..........................................................27

Figure 4-8: Detailed view of phase 2 of hammering process ....................................27

Figure 4-9: Detailed view of the section gear engaging the rack. ...............................28

Figure 4-10: Phase 3 of hammering process. .........................................................28

Figure 4-11: Phase 4 of hammering process. ..........................................................29
Figure 4-12: Adjustment collar (left), assembly exploded view (center), and cam (right).

Figure 4-13: Section view of cam collar assembly demonstrating the groove fit of the collar on the cam.

Figure 4-14: Depiction of spacing dilemma for motors.

Figure 4-15: Torque-speed curve.

Figure 4-16: Pan/tilt fixture for mounting the camera to the Grainbot.

Figure 4-17: The prototype controller, as designed in SolidWorks.

Figure 5-1: Test setup in a GSI grain bin in Grand Island, NE.

Figure 5-2: Results of the static testing performed at the GSI grain bin.

Figure 5-3: Average of the results of the static testing performed at the GSI grain bin.

Figure 5-4: Results of the dynamic testing performed at the GSI grain bin.

Figure 5-5: Average of the results of the dynamic testing performed at the GSI grain bin.

Figure 5-6: Photo of Grainbot driving on the aeration floor next to a Hutchinson/Mayrath NexGen 2000 commercial sweep at the GSI testing facility.

Figure 5-7: Sequence of stills of the robot maneuvering around the far obstacles (tires) inside of the grain bin.

Figure 5-8: User interface with tripod mounted video display located outside of grain bin door.

Figure 5-9: Plot showing the times at which the signal was lost from outside the grain bin. A value of 1 represents the signal was lost.

Figure 6-1: Simulated grain bin setup located at UNL.
Figure 6-2: Load cell fixture as modeled in SolidWorks, front (left) and rear view (right). ..............................................................61

Figure 6-3: Exploded view of load cell fixture assembly including adjustable height mount (bolts not shown). ..........................................................61

Figure 6-4: Front (left) and rear (right) isometric views of the load cell fixture assembly. .............................................................................62

Figure 6-5: Side view of the load cell fixture assembly with the left figure showing a section view. ........................................................................62

Figure 6-6: Results of initial testing of the Interface load cell. ......................64

Figure 6-7: Grainbot shown making full contact with fixture before engaging at full power.................................................................................65

Figure 6-8: Combined plot of static testing with tractor tires on concrete. ...........66

Figure 6-9: Combined plot of static testing with tractor tires in 1 inch of grain.........67

Figure 6-10: Combined plot of static testing with tractor tires in 3 inches of grain. ....67

Figure 6-11: Combined plot of static testing with snow tires on bare concrete. ........68

Figure 6-12: Combined plot of static testing with snow tires in one inch of grain. ....68

Figure 6-13: Combined plot of static testing with snow tires in three inches of grain. .....69

Figure 6-14: Combined plot of dynamic testing with tractor tires on concrete. ..............70

Figure 6-15: Combined plot of dynamic testing with tractor tires in one inch of grain. ...71

Figure 6-16: Combined plot of dynamic testing with tractor tires in three inches of grain. ........................................................................71

Figure 6-17: Combined plot of dynamic testing with snow tires on concrete. ..........72

Figure 6-18: Combined plot of dynamic testing with snow tires in one inch of grain. ....72
Figure 6-19: Combined plot of dynamic testing with snow tires in three inches of grain. 73
Figure 6-20: Combined plot of impactor testing on concrete. ................................. 74
Figure 6-21: Combined plot of impactor testing in one inch of grain. ...................... 74
Figure 6-22: Combined plot of impactor testing in three inches of grain .................... 75
Figure 6-23: Highest forces produced during each test. ........................................... 76
Figure 6-24: The two attachments shown side by side. ............................................. 77
Figure 6-25: Average plot of static testing with tractor tires on concrete. ................. 80
Figure 6-26: Average plot of static testing with tractor tires in 1 inch of grain. .......... 80
Figure 6-27: Average plot of static testing with tractor tires in 3 inches of grain. ........ 81
Figure 6-28: Average plot of static testing with snow tires on bare concrete. .......... 81
Figure 6-29: Average plot of static testing with snow tires in one inch of grain. ...... 82
Figure 6-30: Average plot of static testing with snow tires in three inches of grain. ... 82
Figure 6-31: Average plot of dynamic testing with tractor tires on concrete. ............ 83
Figure 6-32: Average plot of dynamic testing with tractor tires in one inch of grain. ... 83
Figure 6-33: Average plot of dynamic testing with tractor tires in three inches of grain. 84
Figure 6-34: Average plot of dynamic testing with snow tires on concrete. ............... 84
Figure 6-35: Average plot of dynamic testing with snow tires in one inch of grain. ... 85
Figure 6-36: Average plot of dynamic testing with snow tires in three inches of grain. .. 85
Figure 6-37: Average steady state forces produced by each test, listed in descending
order. .......................................................................................................................... 86
Figure 6-38: Comparison of each test with different attachments, including average force.
........................................................................................................................................ 88
Figure 6-39: Comparison of the average dynamic forces with the two different tire treads.

Figure 6-40: Impact force plot on concrete with impact magnitude displayed for test 1.

Figure 6-41: Impact force plot on concrete with impact magnitude displayed for test 2.

Figure 6-42: Impact force plot on concrete with impact magnitude displayed for test 3.

Figure 6-43: Impact force plot on concrete with impact magnitude displayed for test 4.

Figure 6-44: Impact force plot on concrete with impact magnitude displayed for test 5.

Figure 6-45: Impact force plot in 1 inch grain with impact magnitude displayed for test 1.

Figure 6-46: Impact force plot in 1 inch grain with impact magnitude displayed for test 2.

Figure 6-47: Impact force plot in 1 inch grain with impact magnitude displayed for test 3.

Figure 6-48: Impact force plot in 1 inch grain with impact magnitude displayed for test 4.

Figure 6-49: Impact force plot in 1 inch grain with impact magnitude displayed for test 5.

Figure 6-50: Impact force plot in 3 inch grain with impact magnitude displayed for test 1.

Figure 6-51: Impact force plot in 3 inch grain with impact magnitude displayed for test 2.

Figure 6-52: Impact force plot in 3 inch grain with impact magnitude displayed for test 3.
Figure 6-53: Impact force plot in 3 inch grain with impact magnitude displayed for test 4.

Figure 6-54: Impact force plot in 3 inch grain with impact magnitude displayed for test 5.
CHAPTER 1
BACKGROUND AND PROBLEM STATEMENT

Background

Agriculturally confined spaces often impose several threats to the persons occupying them. According to Purdue University’s 2015 Summary of U.S. Agricultural Confined Space-Related Injuries and Fatalities, there were at least 47 documented cases of incidents that occurred in agriculturally confined spaces [1]. These documented cases were comprised of the following: 24 grain entrapments, six falls into or from grain storage structures, six equipment entanglements (including augers), four asphyxiations, four drownings and three cases in which the victim was struck or pinned by a heavy object while working in an agriculturally confined space. Of all these cases, 25 were fatal.

To date, the highest number of documented confined space-related cases are from grain entrapments (1,143 cases), falls (196 cases), asphyxiation/poisoning (195 cases), and equipment entanglements (186 cases). These numbers represent the number of reported cases since the early 1960’s. It is important to note that these numbers only represent the number of cases reported. It is estimated these numbers represent approximately 70% of the total cases that have actually occurred annually in the Corn Belt [1].

It is not unusual for farmers and their employees to put their safety at risk in an attempt to expedite their tasks. In grain storage structures, grain is fed to the center of the structure via a sweep auger, where another auger receives the grain and transports it
under the floor to the outside of the structure. From there, it is met with another auger which transports the grain to a trailer. Each of these augers present serious entanglement and amputation hazards. With these augers in operation, grain dust can also become a serious hazard. This is amplified if an employee is present inside the structure shoveling the grain, which is not uncommon.

Grain dust is a complex mixture of husk particles, cellulose hairs and spikes, starch granules, spores of fungi, insect debris, pollens, rat hair, and approximately 5 percent mineral particles [2]. When dispersed in the air and provided an ignition source, this can be a recipe for disaster. Grain dust explosions are often severe, involving loss of life and substantial property damage. There have been over 500 explosions in grain handling facilities across the U.S. over the last 35 years, killing more than 180 people and injuring more than 675 [3].

In addition to the threat of explosion, there are severe health risks associated with the inhalation of grain dust. Exposure to grain dust causes “grain fever,” wheezing, chest tightness, productive cough, eye and nasal irritation, and symptoms of chronic respiratory disease. In addition to grain dust, hazardous gases can also be emitted by spoiling grain or fumigation. Workers may be exposed to unhealthy levels of airborne contaminants, including molds, chemical fumigants (toxic chemicals), and gases associated with decaying and fermenting silage. Exposure to fumigants may cause permanent central nervous system damage, heart and vascular disease, and lung edema as well as cancer [3].

With all these hazards presented, it is quite clear that the solution should be to keep farmers and their employees removed from grain storage structures as much as
possible. In the past years, several attempts have been made to greatly reduce the risk of danger associated with entering grain storage structures. These attempts include safety training to raise awareness of the dangers present, as well as improvements to the machinery used in transporting the grain. In addition, the Occupational Safety and Health Organization (OSHA) has also implemented several regulations and associated fines in order to protect employees from being placed in dangerous situations.

**Problem Description**

Perhaps the best way to prevent a person from putting themselves in dangerous situations is to remove the need to do so in the first place. A variety of tools and modifications for sweep augers have been developed over the past years which are intended to do just that. Before discussing these, it will be helpful to discuss the cleanout process, the sweep auger’s purpose, how they work, and why they sometimes do not work.

When a grain storage structure is full and it is time to empty it, the cleanout process begins. Beneath the floor of grain storage structures is a single screw conveyor which transports grain from the center of the bin, through a large grated hole in the floor (known as a sump), to outside the structure. When the structure is very full, gravity is a sufficient driving force to draw the grain into the sump where it can be carried away. However, once enough grain has been removed, gravity is no longer sufficient and grain is left piled high all around the perimeter, while it is very shallow at the center. At this point, a sweep auger is used to aid with the remainder of the cleanout process.
A sweep auger, or “sweep”, is a screw conveyor used to transport grain from one location to another within a grain bin and can be seen in Figure 1-1. It receives this name due to the fact that it sweeps around the entire base of the storage structure, removing grain along the way.

![Figure 1-1: A carry-in sweep auger.](image)

On the sides of grain storage structures is an access door. This door sits a few feet above the floor so that farmers can enter the bin without grain spilling out, if there is grain still present inside the structure. A side access door can be seen in Figure 1-2. It is through this door that a sweep auger must be carried in so that it may be installed. The sweep, which gets pinned at one end at the center of the grain storage structure, is powered by a single motor which is fixed to the end of the sweep located at the center of the structure. At the opposite end of the sweep is a wheel that is rigidly attached to the sweep, meaning the wheel turns at the same rate as the auger. This wheel is what drives the sweep in a circular motion around the entire base of the grain storage structure. As the sweep is driven forward, it engages the large piles of grain while simultaneously conveying the grain towards the center of the structure. From there, the grain is transported out of the structure via a second conveyor.
Figure 1-2: A side access door of a grain storage structure, seated a few feet above ground [4].

While this seems like a very simple solution for transporting the grain, there are several pitfalls. Because the drive wheel is rigidly attached to the spinning auger, it is very common for the wheel to slip and lose traction. In addition, grain can easily be sucked under the wheel and essentially act as ball bearings. When the drive wheel is not getting proper traction, it is not driving forward and thus not engaging the piles of grain which ultimately leads to inefficient grain flow. Another common issue associated with the sweep is that it may sometimes get buried in grain, either by engaging the pile with too much force or from avalanching grain. When this happens, the grain does not flow well into the auger and it can get stuck. One other common issue is when the sweep gets high-centered and cannot move because its drive wheel is elevated off the floor, while the spinning auger is caught on debris or chunks of grain.

Given all these factors which can lead to inefficient grain flow, it is easy to see why assistance may be necessary. When any of these issues arise, someone must be there
to manipulate the sweep so that it may continue to remove grain at optimal efficiency. Due to the fact that the power switch for the sweep is located outside the grain bin, and the difficulty associated with entering and exiting a grain bin, it is not uncommon for the operator to leave the sweep active while they manipulate it. Manipulation can include kicking the sweep, lifting the sweep, prodding it with a shovel, or other techniques. This is a clear violation of OSHA regulations, as one of their regulations states that all powered equipment associated with the bin, including augers used to help move the grain, must be turned off and locked out prior to entering the bin. This is for good reason, as being in a confined space with an active auger exposes individuals to extreme safety hazards.
CHAPTER 2

EXISTING SOLUTIONS

After discussing the major issues that arise from the sweep, one can begin to imagine a variety of ways to improve the process of moving grain. As mentioned in the previous chapter, a variety of tools and modifications for sweep augers have been developed over the past years which are intended to improve the efficiency of sweep augers. These modifications come mainly in the form of gear-reduction sweep end-wheel replacements, powered tractor attachments, remotely controlled robotic tractors, and paddle sweeps.

Products on the Market

Hutchinson-Mayrath Sweep End-Wheel

Hutchinson-Mayrath is an agricultural industry leader that specializes in engineering and manufacturing grain handling equipment. One of their current products is a sweep end-wheel replacement, which can be seen in Figure 2-1. This end-wheel utilizes an 8.5:1 reduction inside the wheel to maintain a proper advancement pace of the sweep. Its tread is also designed such that the grain is pulled towards the auger, away from the wall, as the wheel rotates. This also helps to keep grain from being trapped beneath the wheel, causing it to slip. Another unique feature of this wheel is that portions of the wheel can be replaced as wear occurs. While this is indeed a great improvement for sweep augers, it can only be used with Hutchinson-Mayrath Klean Sweep augers. Thus, this is not a viable solution for many failing sweep augers, without replacing the entire sweep auger system.
Figure 2-1: Hutchinson-Mayrath’s sweep end-wheel replacement for Klean Sweep augers [5].

**Buzz-Saw Double Reduction Sweep Drive Wheel**

The Buzz-Saw is a sweep end-wheel replacement option from The Grain Handler Inc., a manufacturer of flat storage grain handling equipment. Like Hutchinson-Mayrath’s sweep end-wheel replacement, this product is intended to aid the sweep auger by providing better traction and utilizes many of the same features. The Buzz-Saw, which can be seen in Figure 2-2, is much larger in diameter than most sweep-end wheels, which is made possible due to its offset receiver for the auger’s drive shaft [6]. This large diameter, in conjunction with the 32:1 planetary gear reduction, allows the drive wheel to rotate at a much slower rate and helps to prevent accelerated wear and increases traction. The tread design, as implied by its name, resembles that of a buzz-saw blade and is made of a replaceable, abrasion resistant molded urethane. However, like Hutchinson-Mayrath’s sweep end-wheel, this product is again only usable with specific sweep augers and is not a viable solution for all failing sweep augers.
Hutchinson/Mayrath NexGen 2000 Commercial Sweep

Another product from Hutchinson/Mayrath is the NexGen 2000 Commercial Sweep, which is seen in Figure 2-3. This product is an incredibly powerful option for moving grain, and is more commonly used in commercial grain bins. Because this sweep auger is intended to move a larger amount of grain, a very powerful propulsion system is utilized. Essentially, a tractor type device is rigidly mounted to the sweep auger and is propelled by four solid drive wheels powered by electric motors providing a total of 40 HP [7]. Again, this product is an entire sweep auger replacement system and is not a very adaptable solution.
Daay Power Sweep

The Daay Power Sweep, produced by Daay Manufacturing, is a sweep auger alternative and is meant to entirely replace a sweep auger system. The Daay Power Sweep, which can be seen in Figure 2-4 is a paddle sweep which utilizes rubber paddles on a chain drive system [8]. The paddle sweep system is a much safer alternative to auger-based systems as it greatly reduces risk of entanglement and also causes less dust to be tossed into the air. In addition to being safer, it is also much more efficient in the sense that it can completely clean the floor of a grain bin in only one or two passes, whereas an auger may require several passes with someone sweeping or shoveling the grain as well. The drive wheel is also driven by the paddle chain, meaning that a second motor is not needed to propel the sweep.

Unlike most sweep augers which are installed only after the grain has been mostly emptied from the bin, the Power Sweep is designed to be fully submersed in grain and can even unbury itself from a grain avalanche. However, this is almost a necessity as the

Figure 2-3: Hutchinson/Mayrath NexGen 2000 commercial sweep auger [7].
Power Sweep is significantly heavier than sweep augers of comparable size. The Power Sweep can weigh up to 100lbs per 5 foot section, whereas a standard auger will weigh on average approximately 30lbs per 5 foot section. For this reason, it will take much more man power or lifting equipment to transport this sweep between grain bins.

Figure 2-4: Daay Bin paddle sweep [8].

**Mack Robotics Bin Bot**

Mack Robotics, Inc. is company based in Leola, South Dakota that emerged in 2010 with their grain bin clean out solution, the Bin Bot [9]. The Bin Bot, seen in Figure 2-5, is a remotely controlled skid-steering electric robot that is intended to enter grain bins in place of humans to assist the sweep auger with the clean out process. The Bin Bot is small in size, being only 6’ x 2’ x 2’, which allows it to fit into any grain bin, and weighs in at 550lbs. There is little information available for the Bin Bot in terms of technical specifications, but they do advertise a dust proof heavy-duty metal body,
optional camera and lighting attachments, and the ability to push, pull, or lift the sweep and knock down a wall of grain. In addition, the Bin Bot is rated to operate in a Class II Division I Group G grain dust environment. This classification can be viewed in detail in Appendix A.

While the Bin Bot offers several advantages, the drawbacks must not be overlooked. First, the Bin Bot is a corded solution, meaning it is powered by an external power source using a long power cable. This could be an issue if the cord were to get tangled up in the auger, or if it were to catch on anything else and be synched off the bot. Additionally, because the Bin Bot is so heavy, it must be lifted into the bin using heavy lifting equipment. This increases difficulty of loading and unloading and increases the likelihood of injury to those assisting with the process.

Figure 2-5: Mack Robotics’ Bin Bot solution [9].
CHAPTER 3  
SURVEYING DATA

Survey

An online survey was approved by the University of Nebraska-Lincoln Institutional Review Board to research the reasons for entering grain bins to assist with sweep auger operation. Participants were recruited through industry contacts provided by Garner Industries. Emails were used to advertise the survey and reach a broad audience throughout the United States in a short period of time. Many of the participants were from the Midwest region (i.e. Nebraska, Iowa, Kansas, Minnesota, and Illinois). The survey consisted of 10 multiple choice answer questions, in which the order of the answers were randomized to remove bias. A total of 236 participants answered questions in the survey. This survey, and its responses, are listed as follows.

1. What percentage of time does a sweep auger get buried, high-centered or otherwise stalled?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never (0%)</td>
<td>5%</td>
</tr>
<tr>
<td>Rarely (Less than 10%)</td>
<td>28%</td>
</tr>
<tr>
<td>Sometimes (&gt;10 to 50%)</td>
<td>42%</td>
</tr>
<tr>
<td>Often (&gt;50 to 95%)</td>
<td>21%</td>
</tr>
<tr>
<td>Almost Always (&gt;95 to 100%)</td>
<td>4%</td>
</tr>
</tbody>
</table>

2. When emptying a grain enclosure, how often do workers need to enter the enclosure to assist a sweep auger to empty that enclosure?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never (0%)</td>
<td>5%</td>
</tr>
<tr>
<td>Rarely (Less than 10%)</td>
<td>19%</td>
</tr>
<tr>
<td>Sometimes (&gt;10 to 50%)</td>
<td>30%</td>
</tr>
<tr>
<td>Often (&gt;50 to 95%)</td>
<td>26%</td>
</tr>
<tr>
<td>Almost Always (&gt;95 to 100%)</td>
<td>20%</td>
</tr>
</tbody>
</table>
3. What are the reasons the sweep auger needs assistance (multiple answers possible)?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried under grain</td>
<td>50%</td>
</tr>
<tr>
<td>High-centered, can’t move</td>
<td>29%</td>
</tr>
<tr>
<td>Slipping on debris</td>
<td>41%</td>
</tr>
<tr>
<td>Stalled, can’t move</td>
<td>48%</td>
</tr>
<tr>
<td>Other issue</td>
<td>18%</td>
</tr>
</tbody>
</table>

4. How is a sweep auger manipulated to make it operational (multiple answers possible)?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pushing</td>
<td>70%</td>
</tr>
<tr>
<td>Pulling</td>
<td>30%</td>
</tr>
<tr>
<td>Lifting</td>
<td>28%</td>
</tr>
<tr>
<td>Clearing debris</td>
<td>40%</td>
</tr>
<tr>
<td>Other</td>
<td>10%</td>
</tr>
</tbody>
</table>

5. After the sweep auger begins operating, when does the sweep auger first need assistance?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>As it begins</td>
<td>32%</td>
</tr>
<tr>
<td>At the first-quarter</td>
<td>19%</td>
</tr>
<tr>
<td>At the first half</td>
<td>2%</td>
</tr>
<tr>
<td>At three-quarters</td>
<td>2%</td>
</tr>
<tr>
<td>Near completion</td>
<td>3%</td>
</tr>
<tr>
<td>All of the above</td>
<td>42%</td>
</tr>
</tbody>
</table>

6. Where is the sweep auger most often located when it starts sweeping the enclosure?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>2%</td>
</tr>
<tr>
<td>In line with the door</td>
<td>31%</td>
</tr>
<tr>
<td>Slightly in front of the door</td>
<td>24%</td>
</tr>
<tr>
<td>Slightly behind the door</td>
<td>40%</td>
</tr>
<tr>
<td>Away from the door</td>
<td>3%</td>
</tr>
</tbody>
</table>

7. What type of grain enclosure is the sweep auger more likely to need assistance?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement floor</td>
<td>13%</td>
</tr>
<tr>
<td>Metal vented floor</td>
<td>30%</td>
</tr>
<tr>
<td>Doesn’t matter (no difference)</td>
<td>48%</td>
</tr>
<tr>
<td>Do not know</td>
<td>9%</td>
</tr>
</tbody>
</table>

8. What type of grain most often requires sweep auger assistance? (multiple answers possible)

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>61%</td>
</tr>
<tr>
<td>Wheat</td>
<td>19%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>60%</td>
</tr>
<tr>
<td>Rice</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>13%</td>
</tr>
</tbody>
</table>
9. How many employees are present during normal sweep auger operation?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 person</td>
<td>17%</td>
</tr>
<tr>
<td>2 people</td>
<td>58%</td>
</tr>
<tr>
<td>3 people</td>
<td>22%</td>
</tr>
<tr>
<td>4 people</td>
<td>3%</td>
</tr>
</tbody>
</table>

10. How many employees help when the sweep auger needs assistance?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 person</td>
<td>22%</td>
</tr>
<tr>
<td>2 people</td>
<td>48%</td>
</tr>
<tr>
<td>3 people</td>
<td>26%</td>
</tr>
<tr>
<td>4 people</td>
<td>4%</td>
</tr>
</tbody>
</table>

**Interpreting the Results**

The survey results identified that it is not uncommon for problems to occur during sweep auger operation, and that once these problems occur workers must enter the grain enclosure. The auger can experience problems at any time during operation and on both vented and cement floors. There are a wide variety of reasons that the sweep auger needs assistance, necessitating a robust design for the robot. Problems with sweep auger operation are encountered primarily in corn and soybeans. It is believed that soybeans will be much more problematic due to traction problems on the spherical shaped grain.

Key findings related to the successful design of a robot for operating inside of grain bins were also identified. “Pushing” the sweep auger was identified in the survey results as the most common method to provide assistance (70%). Because sweep augers contain a drive wheel, it was originally believed that helping the sweep auger along by pushing would be the most common form of interaction. This suggests that workers may be violating OSHA regulations.

The survey results also suggest that inserting the robot into the grain bin through a side door should be feasible because 95% of the participants indicated that the sweep
auger begins operation near the side door. Beginning operation at this point will remove grain from near the side door to allow for insertion of the robot into the grain bin. The results further indicated that typically at least two people are present during normal sweep auger operation. The proposed robot could reduce the number of necessary personnel during sweep auger assistance.

**Problems Encountered**

There were a few limitations encountered in the survey administration and results. Many of the survey requests were lost in email spam folders. An alternative approach would be advertisement of the survey using local, regional and national grain production board contacts. Another problem occurred with the wording of the questions 9 and 10. The intent was to illustrate the amount of personnel present during normal sweep auger operations, and to identify the increase in personnel when the sweep auger requires assistance. However, the results suggest that some participants interpreted the final question as “how many additional people are needed” and some participants interpreted the final question as “how many total people are needed”. The result was a mixed representation, and is evidenced by the fact that more participants responded that only “1 person” is needed when the sweep auger requires assistance, which is fewer than during normal operation. It seems that some participants believed they were responding that one additional person is needed. Also, it is safe to conclude that additional people are needed for assistance when the sweep auger isn’t functioning properly.
Prior to the design phase of this prototype, a previous prototype had already been designed, constructed and tested by a group of graduating senior mechanical engineering students at UNL. This prototype was created as part of a senior design project and was used in determining further design aspects.

Design Constraints

Interfacing with the Sweep Auger

According to the survey results, pushing the sweep auger is the most common method to provide assistance when the auger is stuck. Therefore, the robot should have this capability. This then poses the question, how can the robot safely and effectively interface with the auger so that harm is not brought upon the robot or the auger? Sweep augers have a metal shield on their backside which prevents grain from escaping and also protects humans from becoming entangled, should they be near when it is active. Interfacing with this metal shield is likely going to be the best option for manipulating the sweep.

Terrain Type

Maneuvering easily throughout the grain bin is a must. In order to achieve good maneuverability, the terrain must be considered. The floor type in most grain bins are either cement or vented metal, both of which are very smooth. Combine this with the grain dust that accumulates on the floor, and gaining traction can be very difficult. Also, as the sweep auger advances around the base of a grain bin, a layer of grain is commonly
left behind due to the auger not being flush with the ground. Depending on the auger, and the levelness of the floor with respect to the auger, this layer can be over an inch thick.

One must also consider the areas which the auger has not yet reached. Because the auger starts at a single point along the perimeter and works its way around, there will be very high piles of grain behind the auger at the point where the auger started. If the robot were to accidentally run into one of these piles of grain, the robot would need the capability to free itself. This could also occur if crusted grain that has adhered itself to a wall should collapse and spill onto a cleaned portion of the bin floor and form a mound of grain which the robot could run into. If the grain avalanches over the auger, this could also form a mound of grain which the robot would need to traverse.

**Bin Entry**

The safest and easiest method of entering the grain bin is through the side access door. The side access door is typically located a few feet above ground level, so driving the robot directly into the bin may not be possible. In addition to the door’s location, its size is also another constraint. The side access door may be as narrow as 25 inches. Therefore the robot must meet a width requirement of no more than 25 inches wide. To load the robot, it will either need to be light enough that it can be carried in by hand, have a ramp system which can allow it to drive in, or be easily loaded using a heavy lifting device such as a tractor or forklift.
Remotely Controlled

The main goal of this robot is to keep farmers outside of grain storage structures. Therefore, the robot must be remotely controlled. While a corded connection could be used for control, it would be far easier and safer to use a form of wireless control. Ideally, the operator should be able to control the robot from outside the grain bin with no line of sight to the robot with the side access door closed. This means a camera and lighting system must be installed on the robot so the operator can know what is happening inside the bin.

Design Features

So far, several design constraints have been discussed which shall apply to a robotic solution. Based on these constraints, a proposed solution was designed and modeled in SolidWorks and is depicted in Figure 4-1. The remainder of this chapter will focus primarily on the design process and features of this robotic solution which shall be referred to as the Grainbot.

Figure 4-1: Front and rear views of the Grainbot as modeled in SolidWorks.
Wheels

One of the main influences on the design of this robot was maneuverability inside the grain bin. This was one of the major challenges, as poor traction is one of the main reasons the sweep auger gets stuck in the first place. The floor of grain bins are typically cement or vented metal, both of which are very smooth surfaces and offer little in terms of traction. When grain dust is introduced, gaining traction can become even more difficult. For this reason, special care was taken when considering the mode of vehicle propulsion.

In order to obtain the best traction, two scenarios were considered. The first scenario would be where the wheels are able to dig down to the floor by displacing the grain. Doing so would mean the traction would then be a matter of friction between the wheels and the floor. The second scenario would be a case where the wheels rely less on friction with the floor, and more on pushing off the grain. This second scenario would be analogous to how paddle tires function. Paddle tires, typically seen on dune buggies or other off road vehicles, are very wide and are intended to dig into the surface of the
terrain with wide paddles. Thus, instead of relying on traction with the ground to provide a forward motion, they essentially push off the material they dig up. A third option that was also considered was a continuous track, or tank tread.

Given these two scenarios, it was determined that it would be better for the tires to dig down to the floor and gain friction with a hard surface. This was determined based on a few factors. Grain, particularly soy beans and corn, is packed very loosely and is not very dense. Thus, as the paddles turn through the grain, not much force would be generated in terms of resistance for forward motion. Also, paddle tires need to be wide in order to generate as much resistance as possible. This is especially true in the case of traversing grain, as it is low density. Therefore, with a width requirement of less than 25 inches, it was not feasible to use paddle tires.

After ruling out the paddle tires, the two remaining options were to use a narrow tire with a desired tread pattern or use a type of continuous track. Tank tread is very good at generating traction, particularly on soft terrain. However, one of the main advantages of a continuous track propulsion system is its ability to distribute weight evenly across the surface of the terrain so that it does not sink. This would not be advantageous when trying to traverse a thin layer of grain, which would be the case with an auger that does not sit close to the floor. In this case, the grain would likely act as ball bearings (especially in the case of soy beans) and would simply roll under the tracks, reducing traction.

Finally, the decision to use narrow rubber tires with a desired tread pattern was made. In order to get the best traction, there needs to be contact between the wheels of
the robot and the floor. In order to get optimal traction, two different tread patterns were determined to likely give the best results and were tested in a traction test. These tests will be covered in detail in Chapter 5.

**Manipulating the Sweep Auger**

In order to manipulate the sweep auger, some sort of bumper/attachment must be implemented onto the front end of the robot that can safely and effectively interface with the auger’s shield. Because there are a variety of sweep augers and a variety of shield types, the attachment must be adaptable. For this reason, two attachment options were designed, each with a different function. The first attachment that will be discussed is a swiveling attachment intended to adjust to the angle of the auger and provide a uniform force distribution on the shield. This attachment can be used in conjunction with a thrusting mechanism. The second attachment is a rigid plow that is designed to be closer to the ground and is ideal for ramming into the auger. These two solutions can be seen in Figure 4-3.
The swivel attachment was designed so that it can be attached via a pinned connection. This design was selected so that if the robot were to approach the sweep at a non-perpendicular angle, the attachment can adjust so that full, flat contact can be made with the sweep’s shield. Doing so will prevent damage to the shield which could result from forceful contact with the edge of a rigid attachment.

In addition to interfacing well with the sweep’s shield, this attachment is also used to provide small bursts of force produced by a spring-loaded hammering mechanism mounted within the Grainbot. This hammering mechanism allows for the Grainbot to simulate ‘kicking’ the shield, but in a safer and more controlled manner. This means that the Grainbot can produce a forward thrusting force, even if it has poor traction, by utilizing its own inertia. This hammering mechanism is depicted in Figure 4-4.
An important aspect that was considered when designing this mechanism was the prevention of damage to the sweep’s shield. Providing an impulsive force to an object with an impact can cause damage to one or both of the objects. To prevent this, a two system impact was designed. These two systems consist of the hammering system and the advancement system.

In the hammering system, the hammering mechanism is used to generate a large potential energy in the form of spring energy. This mechanism is essentially a rack and pinion system with a partially toothed spur gear, otherwise known as a section gear. This system consists primarily of the aforementioned rack and pinion, a hammering rod, a spring, four linear bearings, two guide rails, and a housing. As the section gear turns it
engages the rack, pulling the hammering rod backwards, which in turn compresses the spring. Once the final tooth of the section gear disengages from the rack, the compressed spring releases its stored energy by thrusting the hammering rod forward at a very fast rate. At the front end of this hammering rod is a steel block (referred to as the hammer head), which will transfer its kinetic energy to the advancement system.

The advancement system, depicted in Figure 4-5, consists primarily of a long rod, a hammer plate, a small spring, two linear bearings, a coupler, and the bumper attachment. This system transfers the energy from the hammering system directly to the sweep auger’s shield. When the robot engages the shield, the small spring which keeps the bumper extended is depressed. This brings the advancement system’s hammer plate within reach of the hammering system’s hammer head. When the hammer head strikes this hammer plate, the kinetic energy is transferred and the bumper attachment is thrust forward. Because the bumper attachment is already in full contact with the shield, the force is distributed equally and simultaneously across the surface area in contact with the shield. A depiction of this process can be seen in the following section.
Figure 4-5: Advancement stage shown from the front and back sides.

Hammering Mechanism Detailed Walkthrough

Figure 4-6: Phase 1 of hammering process.
Figure 4-6 shows the hammering mechanism in its unloaded state. As the section gear is rotated, the pin extruding from the section gear comes in contact with the face of the cam profile.

Figure 4-7: Phase 2 of hammering process.

Figure 4-7 shows the section gear beginning to engage the rack, and the pin extruding from the section gear leaves the cam’s surface.

Figure 4-8: Detailed view of phase 2 of hammering process.
In Figure 4-8 it is shown that due to the cam attachment, the teeth of the gear align perfectly with the teeth on the rack. Axial adjustments of the cam with respect to the rack can be made via the adjustment collar to achieve proper alignment as needed.

Figure 4-9: Detailed view of the section gear engaging the rack.

Figure 4-9 shows a detailed view of the teeth drawing back the hammering mechanism by engaging with the rack.

Figure 4-10: Phase 3 of hammering process.
In Figure 4-10, it can be seen that the hammering rod is fully drawn back and the last tooth on the gear is about to slip off the rack.

Figure 4-11 depicts the final phase of the process where the hammering rod is accelerated forward and impacts the hammer plate with the hammer head, driving the front attachment forward. The guide rods ensure the hammer head will align perfectly with the hammer plate.

**Further Design Aspects of the Hammering Mechanism**

The hammering mechanism was a challenge to design due to the fact that special care had to be taken to ensure the teeth on the section gear would properly mesh with the teeth on the rack. Due to the high torque capabilities that may be needed of a motor to draw the hammering rod back, it is possible that irreparable damage would be inflicted on the system if they did not mesh properly. To ensure a proper mesh, an adjustable cam collar assembly was implemented on the hammering rod so the teeth would mesh...
properly every time. This cam collar assembly and its components can be seen in Figure 4-12.

Figure 4-12: Adjustment collar (left), assembly exploded view (center), and cam (right).

The cam collar assembly consists of two main components that were custom milled out of steel: the cam and the adjustment collar. The adjustment collar prevents the cam from sliding forward and backward on the hammering rod by seating itself in a circumferential groove around the end of the cam. This collar is also threaded so that finely tuned adjustments can be made to the axial position of the cam relative to the hammering rod. The cam component also has a groove at its base which allows for a key to restrict its motion to linear motion only, so that it cannot rotate on the hammering rod. Once the cam is set in the correct place, two set screws are then used to secure the cam so that minor twists and sliding due to clearances are avoided. A section view of this assembly can be seen in Figure 4-13.
When designing the cam component, careful design had to be performed to ensure that the proper height and angle were selected so the teeth of the section gear and the rack would properly mesh. This design process was accomplished in SolidWorks using an iterative process where several different angle and height combinations were tested until a proper mesh was achieved. To account for clearances that would exist due to tolerances and to allow for easier assembly, the adjustment collar was introduced. The adjustment collar would also allow for adjustments to be made over time as wear occurs.

**Motors/Power Source**

As was mentioned earlier, care must be taken to ensure that there are no ignition sources within the grain bin. Because brushed motors can produce arcs of electricity, it was decided that the use of brushless motors was the more appropriate choice. In total, five brushless motors were used for the Grainbot: one for each of the four wheels and one for the hammering mechanism. The main criteria for selecting motors were physical size, torque output, and speed.
When determining the power source for the motors, the best options available based on the constraints would either be via battery, or a corded power supply. A corded power supply, such as from a standard 120V power outlet, is a possibility, but would not be preferred. A cord could potentially get tangled in the auger, causing damage to itself or to the auger. Additionally, the robot could potentially run over its own cord and could result in damage to itself. Ideally, the robot should be totally self-contained. For this reason, batteries are the most preferred option for powering the motors. Before selecting specific batteries for this application, the required motor traits must be determined. Based on the required motor traits, it will be known if batteries are a feasible option.

*Physical Size*

One of the primary limiting factors of the motor selection for the wheels is the space available inside the robot. As mentioned earlier, the width of the robot is being limited to 25 inches. When one considers the width of the tires, which are approximately 5 inches wide each, the available width is nearly halved due to the fact that the motors must be mounted on the interior side of the wheels. Doing this only leaves 15 inches of available space inside the robot between the wheels on the left and right sides. This does not include the space that will be required for coupling the motor shafts with the tires, and also the bearings for mounting the shafts to the robot. Assuming this takes up at least 2 inches of space, this leaves only 11 inches of space for the motors. If the motors are in-line axially, this distance is again halved. This results in only 5.5 inches of space for each motor, which would also mean the motors are end-to-end with no space between them.
which could cause issues when trying to install them. This dilemma can be viewed in Figure 4-14 for better understanding.

![Diagram of motor spacing dilemma](image)

**Figure 4-14: Depiction of spacing dilemma for motors.**

In order to overcome this issue, one possible alternative is to stagger the motors by using a chain-drive system. Rather than mounting the motors directly in-line with the wheel axes, the motors can be mounted on brackets located above the wheel shafts. The motors and wheel axles can then be outfitted with sprockets, allowing the motors to drive the wheels via a chain drive. Doing so will allow the motors to be offset, giving them the entire interior width of the robot. For the hammering mechanism, physical size of the motor is not as important due to the fact that the height of the robot can easily be adjusted with no drawbacks. Therefore, physical size is not an important factor for the hammering mechanism’s motor.
**Torque Output**

Determining a minimum torque requirement for the drive wheels of this robot can be simply calculated, provided the required information is known. If the torque requirement were to be solely based on the force desired for advancing the sweep auger, the torque can easily be calculated using Equation 1.

\[ \tau_m = \frac{1}{4} \times F \times r \]  

(1)

In Equation 1, \( \tau_m \) is the torque requirement of one motor, \( F \) is the force required to advance the auger, and \( r \) is the radius of the tire. The force in the equation is divided by four due to the fact that there are four tires producing traction, assuming equal traction is attained on all four tires. Because of the difficulty associated with measuring the force required to advance an active sweep auger, this force will be approximated based on the weight of the auger. Thus, the target force required to advance the auger will be approximately the weight of an auger. This is a safe and conservative approximation because it is unlikely that a coefficient of friction higher than unity would be present between the auger and the floor. In fact, due to the smooth surfaces present in grain bins, it is likely that the coefficient of friction will be much lower than unity, and there is also the drive wheel which is constantly producing a force to advance the auger. If there is more resistance than the robot is capable of overcoming through static driving force (not ramming into the auger or utilizing the impactor), it is likely that it is due to the auger engaging the pile of grain. In this case, it is not necessary to further advance the auger.
To apply Equation 1, it will be assumed that the maximum weight of an auger is around 100 lbs., which is approximately the weight of a 16’ sweep auger. Using this value for $F$ and using 8 inches as the radius of the tire, the torque requirement is calculated to be 200 in-lbs., or about 22.6 Nm. Therefore, this should be the target motor torque desired.

When determining the torque requirement of the hammering mechanism, one must simply know the spring constant of the spring in use, as well as how far the spring will be compressed. This is of course assuming that friction and damping forces of the bearings are neglected, which should be very small. The equation used for this calculation is shown in Equation 2.

$$\tau_m = k \times (x_o + \Delta x) \times r_p$$ (2)

In Equation 2, $k$ is the spring constant of the spring being used (33 lbs./in), $x_o$ is the initial displacement of the spring (2.125 inches), $\Delta x$ is the additional distance the firing rod is drawn back (4.25 inches), and $r_p$ is the radius of the pitch circle of the gear (1 inch). To draw back the firing rod, the motor selected must be able to output enough torque to compress the spring. Based on the spring selected in an earlier section, the torque requirement can be calculated using Equation 2, and is found to be 210.375 in-lbs., or about 23.77 Nm. So, for a motor to be able to draw back the firing rod, the motor should be able to output at least 24 Nm of torque.
Speed

As the torque capabilities of a motor increase, the speed decreases. Because of this relationship, shown by a torque-speed curve in Figure 4-15, the speed requirement must be considered when selecting a motor. For the wheel motors, speed is not as important as torque capabilities or the physical size, but it does play a role in the overall functionality and user-friendliness of the robot. One of the key objectives of the Grainbot is to expedite the clean out process, and the faster it can do this, the better. Due to the large size and weight of this robot, low speeds should be maintained to allow the user proper reaction time in order to prevent accidental collisions. So, while it is difficult to say exactly what the minimum speed requirement of the robot should be, the target speed will be about half that of a human walking pace, or around 1.5 mph (4.4 ft/sec).

Figure 4-15: Torque-speed curve.

Based on a linear speed of 4.4 ft/sec, and with the tire radius known, the required angular velocity of the motor can be calculated using Equation 3.

$$\omega = \frac{v}{r_{tire}}$$  \hspace{1cm} (3)
In Equation 3, \( \omega \) is the angular velocity of the motor, and \( v \) is the linear velocity of the robot. Thus, for a linear velocity of 4.4 ft/sec and a tire radius of 16 inches, the required angular velocity is calculated to be 31.5 rpm.

For the hammering mechanism, one revolution of the motor corresponds to one firing of the hammering mechanism. Therefore, the desired rpm can easily be determined based on the desired frequency of impacts. For safety reasons, and because the firing mechanism should not be needed at a high frequency, the target angular velocity will be at most 15 rpm. This angular velocity will result in one impact every four seconds. Having a low angular velocity will help to prevent the user from accidentally firing multiple times when not intending to.

**Motor Selection**

Based on the criteria determined thus far, an appropriate brushless DC motor was selected from Maxon Motor. In addition to these motors, a corresponding gearbox was also selected. The key parameters of these motors and gearboxes can be seen in Table 4-1. The length of these two combined is 172.1 mm, or about 6.78 inches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EC40 Brushless DC Motor</th>
<th>GP 52 C Planetary Gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Input</td>
<td>24 V</td>
<td>Max Cont. Torque</td>
</tr>
<tr>
<td>Nominal Speed</td>
<td>9120 rpm</td>
<td>Max Cont. Input Speed</td>
</tr>
<tr>
<td>Max Cont. Torque</td>
<td>165 mNm</td>
<td>Gear Ratio</td>
</tr>
<tr>
<td>Efficiency</td>
<td>89%</td>
<td>Efficiency</td>
</tr>
</tbody>
</table>

Table 4-1: Wheel motor and gearbox key parameters.

Based on these parameters, when the motor is coupled with the planetary gearbox, a max continuous speed of 16.9 rpm and a max continuous torque of 35.2 Nm are
achievable. However, the gearbox is only rated for a max continuous torque of 30 Nm. To ensure that damage is not brought to the motor or the gearbox, current will need to be limited to the motor. This is easily done using the programmable motor drivers that Maxon also offers.

To calculate the required current to produce a maximum torque of 30 Nm, the torque input to the gearbox from the motor is first calculated as shown in Equation 4.

$$\tau_m = 30 \, Nm \times \frac{1}{N} \times \frac{1}{\epsilon_{gb}}$$

In Equation 4, $N$ is the gear reduction (353) and $\epsilon_{gb}$ is the efficiency of the gearbox (0.68). After plugging in the corresponding values, the motor torque is determined to be 0.1250 Nm. The current required to achieve this torque value with the motor is found using Equation 5.

$$I = \frac{\tau_m}{T} + I_{no\,load}$$

In Equation 5, $T$ is the torque constant (23.2 mNm/A) and $I_{no\,load}$ is the no load current (0.385 A). Again, plugging in the corresponding values results in a current of 5.77 A. Therefore, to prevent damage to the motor or gearbox, the maximum current supplied to the motor should not exceed 5.77 A. Doing so should provide a torque output from the gearbox of 30 Nm. With 30 Nm (265.52 in-lbs) of torque being exhibited at each 8 inch radius tire, this should result in a maximum forward driving force of 132.76 lbs.

For the hammering mechanism, the motor selected was an EC45, 250 Watt, brushless DC motor, as well as a corresponding gearbox. The planetary gearbox selected for this motor provides a 236:1 gear ratio. The length of these two combined is 248 mm,
or about 9.76 inches. The key parameters for this motor and gearbox can be seen in Table 4-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Input</td>
<td>24 V</td>
<td>Max Cont. Torque</td>
<td>50 Nm</td>
</tr>
<tr>
<td>Max Cont. Torque</td>
<td>311 mNm</td>
<td>Gear Ratio</td>
<td>236:1</td>
</tr>
<tr>
<td>Efficiency</td>
<td>86%</td>
<td>Efficiency</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table 4-2: Impactor motor and gearbox key parameters.

The motor selected has a maximum continuous torque of 311 mNm. When coupled with the planetary gearbox, which has an efficiency of 70%, this enables a max continuous torque of 51.38 Nm. This motor offers much more torque than what is required, as before it was stated that only 24 Nm of torque was needed. However, this particular motor/gearbox combination is a standard combination sold by Maxon and does allow for stronger springs to be tested, if needed. In addition, the motor drivers that are used with these motors offer many features for controlling the motors, so torque and speed can easily be controlled or limited.

Battery

In order to power these motors, a sufficient battery must be selected. The highest voltage components run at 24 volts; therefore it was decided to use two 12 V marine batteries in series. This allows for a wide selection of batteries and can power all components without the use of step-up voltage regulators. The selected batteries must be able to provide enough current to the motor drivers, and they must have a sufficient life span to power the robot for several hours.
Deep cycle batteries are particularly good at handling moderate discharges for long periods of time. They are designed with thicker lead plates than those used in automotive starting, lighting, and ignition (SLI) batteries. This means they will provide less current, but will produce the current for a much longer period of time. To determine the lifespan of a battery, Equation 6 can be used.

\[
t_{bat} = \frac{C}{I_{avg}}
\]  

(6)

In Equation 6, \( t_{bat} \) is the lifespan of the battery in hours, \( I_{avg} \) is the average current draw of the system in amps, and \( C \) is the capacity of the battery in amp-hours. The bulk of the battery capacity goes towards powering the five motors. All five motors are only used intermittently, when moving or when manipulating the auger. Due to the comparatively low current draw when the robot is in standby, for this analysis, lifespan will be considered as the time the robot is active. With the Grainbot, the largest current sinks will be the four wheel motors. These four motors will each draw at most 5.77 A of current intermittently. The hammer motor requires similar power, however, it is used infrequently and is therefore considered negligible. If it is for now assumed that other current sinks are negligible in the amount of current they draw, the total current draw would be approximately 23.08 A. For now, this is a reasonable assumption for determining battery lifespan, as other current sinks will only be in the mA range.

If it is assumed that during the cleanout process the Grainbot is only used 50% of the total time it takes to empty the bin, and that it takes approximately 8 hours to do so, then a battery should be selected that will provide at least 4 hours of continuous
operation. In order to have a lifespan of at least 4 hours, the selected battery should have a capacity of at least 92.32 Ah.

**Camera and Lighting**

When the sweep auger is active, the side access door should be closed. There are no lighting systems inside grain bins and there are no windows. In order for the user to know what is happening inside the grain bin, a live-streaming camera and lighting system must be installed on the Grainbot. Controlling the robot will be easiest from a first-person viewpoint, which would be the case of mounting the camera on the robot. The best location for mounting the camera will likely be on the front of the robot so that the user can see what is in front of the robot. This will allow them a proper view when trying to manipulate the sweep auger.

The next step is then to determine how to mount the camera to the robot. Ideally, the user should be able to attain a wide view of the Grainbot’s surroundings without having to completely rotate itself in place. This will help to prevent the Grainbot from accidentally bumping into something when trying to look around, and will also help conserve battery life. To do this, the camera will be mounted on a pan/tilt device that will allow the mounted camera to look in 180 degrees up and down, as well as 180 degrees left and right. This can easily be done with two servo motors and an acrylic mounting fixture. This system was designed and modeled in SolidWorks and can be seen in Figure 4-16.
The camera selected for this application is a Fat Shark PilotHD FPV camera, commonly used by hobbyists in drone applications. Thus, they are very compact and designed for transmitting live video feed. The camera does not have a built-in transmitter, so a separate transmitter must be purchased and installed. The transmitter selected was a Fat Shark 1.3 GHz 250 mW A/V transmitter. To receive and display this video transmission, a 7 inch 5.8 GHz LED monitor was selected.

To provide lighting for the user, headlights must be mounted on the Grainbot. These lights should be selected carefully so that too much heat is not generated which could ignite grain dust. LED lighting is a perfect candidate for this reason, and will also require a low current draw. The lighting should also be distributed in a broad ray, as opposed to a narrow beam of light, in order to provide proper lighting in any direction the camera may look. The lights selected for this application were 15 W LED marine work lights with a 45 degree beam angle.
Control System

The Grainbot consists of several electronic components which include five motors, each with their own motor driver, two servo motors, two headlights, and a camera. To control all these devices, a control system must be implemented. In doing this, the required inputs and outputs of the components must be determined. These inputs and outputs will need to be controlled by a separate on-board microcontroller, which will in turn receive commands from the user via RF communication.

The motor driver used for these motors is the Escon 70/10 servo controller. These drivers use feedback control from hall sensors in the motors to control the rpm of the motor and also provide the ability to limit current to the motors to prevent damage from overheating. While the software provided with these motors offers several other useful features, the area of most concern are the inputs and outputs required of the microcontroller. To control the motors, a speed and direction must be defined. The microcontroller will do this by providing a pulse width modulation (PWM) signal for the speed and a digital signal for the direction. This is easily done with nearly any microcontroller. In addition, because the Grainbot utilizes skid steering, the two motors on the left side and the two motors on the right side can each share the analog and digital signal because the wheels on one side will always be turning in the same direction and at the same rate. This reduces the number of output pins required of the microcontroller and helps to simplify the control system. Thus, four output pins are required for the wheel motors, and two output pins are required for the hammering mechanism. In total, the motors require six output pins on the microcontroller.
The next components to consider are the camera and lighting. The transmission from the camera is already being handled by a transmitter which will only require a voltage input. There is no need to control the transmission (on/off) so it does not need to be integrated into the main control system. However, the two servos which are used in the pan/tilt mounting system will require a voltage input as well as a PWM signal to control the position of the servos. Additionally, the power to the lighting should also be controlled so they are not always on. This can easily be controlled via a transistor with a digital signal. In total, the camera and lighting system will require three output pins on the microcontroller.

The final component which has not yet been mentioned is the RF communicator. Because the user will not receive any feedback from the Grainbot, other than the video transmission which is being handled by a separate communication network, the Grainbot will only need to receive transmission from the user. Therefore, an RF receiver will be mounted to the Grainbot which will receive an RF transmission from the user’s controller. For this application, the nRF24L01+ transceiver module was selected for its ease of use and range capabilities. It also operates at a different frequency than the video transmitter, which will prevent interference. Although this module is a transceiver, meaning it can transmit and receive data, it will only be used for one-way communication to the Grainbot. This module uses serial peripheral interface (SPI) communication, so the selected microcontroller must have this capability as well.

With all of these components considered, a total of nine output pins (five PWM and four digital I/O) are required, as well as SPI communication capabilities. To handle
this, an Arduino microcontroller is an ideal candidate in a prototyping stage. Arduino is an open-source electronics platform. There are several different Arduino boards which all offer unique advantages, but the board selected for this case is the Arduino Mega 2560 R3 microcontroller. It offers all the pins required, plus many more should the need arise for additional pins. A layout of the control system can be seen in Figure X.

To ensure that all these electrical components are safe from moving parts, as well as isolated from each other, an electronics bay was designed. The electronics bay is located inside the lid of the Grainbot and is essentially an acrylic tray with mounting holes for the individual components. Acrylic was selected to ensure the electrical components were electrically insulated from the rest of the robot, as well as from each other.

In addition to the control system that has been discussed so far, a user interface is also required. This user interface comes in the form of a physical controller device. The controller will consist of several buttons, switches, and joysticks which the user will use to send commands to the Grainbot via RF communication. To determine which components are required on this controller, the functions of the robot that are being controlled must first be determined. In general, a digital signal can easily be controlled by a pushbutton or switch, while analog signals will require a joystick or other form of potentiometer.

When selecting input components for the controller, it is important to select components whose functions are intuitive. For that reason, two 2-axis joysticks were selected for controlling the left and right wheels. A 2-axis joystick allows for two
separate analog outputs corresponding to the left/right displacement as well as the up/down displacement of the throttle. Because each wheel set only needs one analog signal, and because the up/down motion is a more obvious input selection, the left/right analog output can simply be ignored.

It is important to note that although the speed of the impactor motor is controlled via an analog signal, there is no need for the user to adjust it. The impactor will be programmed to operate at a specified rate; therefore, the impactor will only require one digital signal from the user. This means either a pushbutton or a switch should be used. Because the impactor will only be used in short bursts, and because there would be no reason to leave the impactor firing constantly, a pushbutton will be the preferred input method.

Because of the potential danger associated with an accidental fire of the impactor, certain precautions must be taken to ensure this doesn’t happen. An accidental fire could happen if the user accidentally, or mistakenly, pressed the impactor button on the controller. To avoid this, two separate buttons on opposite sides of the controller will be required to activate the impactor motor. This should significantly decrease the chances of the user firing the impactor without intending to, as they would need to press the two buttons simultaneously. Because this will require both the user’s thumbs to activate the impactor, thus removing them from the joysticks, the motors will also be programmed to drive forward when both buttons are depressed. This will ensure continuous contact is being made between the Grainbot’s interfacing attachment and the shield.
The final two components which must be controlled are the pan/tilt servos and the headlights. The headlights are very simple to control, as they only require a digital signal to turn them on or off. This could easily be done either with a pushbutton or a switch. To prevent possible confusion with the pushbuttons used for the impactor, a switch will be used. For the pan/tilt servos, a 2-axis joystick is used for controlling both of these with a single component. The left/right displacement of the joystick will correspond to the pan servo, while the up/down displacement of the joystick will correspond to the tilt servo.

Now that all the required components have been determined, the controller itself must be designed. So far, it has been determined that three joysticks, two buttons, and two switches are required. There also must be an on/off switch for the controller as well. To handle all these components, a microcontroller must again be selected. For many of the same reasons as before, the Arduino Mega 2560 R3 is chosen.

An additional function of the case is that it should be able to hold the monitor which is receiving the video transmission. This will make it easier for the user to view the live feed while they are trying to control the Grainbot. Otherwise, the user may have to utilize a tripod or some other mounting device to hold the monitor. This controller prototype, which can be seen in Figure 4-17, was designed in SolidWorks and 3D printed as 4 separate components: the case body, the cover plate, the monitor mount, and a removable battery cover plate.
Figure 4-17: The prototype controller, as designed in SolidWorks.
CHAPTER 5
TESTING IN GRAIN BIN

In order to determine the tractive capabilities of the robot, several pull tests were performed in a grain bin at GSI Engineering in Grand Island, NE. However, non-optimal testing methods were employed during traction testing due to constraints imposed by testing equipment available, as well as by the environment itself. Tests were later performed at UNL in a simulated grain bin environment. These tests will be discussed in detail in the following chapter.

It is also important to note that the sweep auger used in this particular test bin was a Hutchinson/Mayrath NexGen 2000 commercial sweep. This sweep auger performs very well on its own and would not require assistance from a product such as the Grainbot. This particular sweep auger is significantly larger than the type of augers one would find on a typical farm, which is one of the target markets of the Grainbot. The objective of the visit to this test site was not to evaluate the robot’s ability to manipulate a sweep auger, but rather to examine the maneuverability and control of the Grainbot in a grain bin environment in an attempt to see how well it can perform in that environment.

The load cell used for testing was a Dillon EDjunior crane scale with a load limit of 5,000 lbs. and resolution of 5 lbs. In total, 16 separate traction tests were performed. Four individual tests, each with the two styles of tires, performed both on bare concrete as well as in 2 to 3 inches of grain. Additional tests were also performed on a section of aeration floor.
In each pull test, a steel cable was used to tether the robot to a rigid, stationary mounting point located on the center pivot of the auger. It was ensured that this tether was attached so as to be level with the ground, so that no vertical forces were introduced which could increase or decrease traction. The crane scale was placed in line with the tether, so the tension could be measured. This setup can be seen in Figure 5-1. In this figure, the scale is shown sitting on top of a stack of tires. This was done to support the scale so that it would be prevented from bouncing, which could introduce dynamic forces that could ultimately skew the results.

![Figure 5-1: Test setup in a GSI grain bin in Grand Island, NE.](image)

**Static Pull Test**

In the static pull tests, there was initially no tension in the cable and the scale was zeroed. Once the scale read 0 lbs., the robot was driven forward slowly until the slack in the cable was taken up. The robot was then given full power for several seconds until the readings on the scale came to a steady state. The maximum value was then recorded and the process was repeated several times. In this case, the term static is used to describe the
fact that the robot remains in place (does not move) while testing takes place. This data represents the minimum force the robot will be able to output at maximum power based on the terrain (grain, concrete, etc.), such as when the robot is in contact with the auger and attempting to drive it forward. The results of these tests can be seen in Figure 5-2 and Figure 5-3.

![Static Tests From GSI Grain Bin Tests](image)

Figure 5-2: Results of the static testing performed at the GSI grain bin.
Dynamic Pull Test

In the dynamic pull tests, the setup was the same with the cable again left slack initially so that no tension was present. Once the scale was zeroed, the robot was driven forward at full power, accelerating the robot to its top speed before the cable stopped it. Using the scale’s ‘peak’ setting, we were then able to measure the maximum force produced. In this case, the term dynamic is used to describe the fact that the robot is moving and has momentum at the time of the measurement, thus a dynamic force is being measured. This data represents the amount of force the robot can produce by ramming
into the auger at full speed with a rigid plow attachment on its front end. The results of these tests can be seen in Figure 5-4 and Figure 5-5.

![Dynamic Tests From GSI Grain Bin Tests](image)

**Figure 5-4:** Results of the dynamic testing performed at the GSI grain bin.
Aeration Floor Pull Test

In addition to the bare concrete floor, there were also sections of floor meant for aeration of the grain. These sections of floor are metallic and ribbed, offering better traction in one direction and can be seen in Figure 5-6. This floor type is seen in some grain bins to increase air flow to assist in drying the grain, therefore it is important to know how well the robot can gain traction on these sections of flooring. Additional static and dynamic tests were performed on this section of floor to determine its tractive capabilities. Because the aeration floor is ribbed in two different directions, the tests were performed both parallel to the direction of the ribs and perpendicular to them.
Maneuverability/Communication Effectiveness

Once the force testing was finished, the next task was to determine how well the controller could communicate with the robot from outside the grain bin. To do this, four objects (the four tires not in use) were placed on the floor, spread far apart from each other. The grain bin was then evacuated and the doors were shut, leaving only the robot inside. The monitor, which receives the video transmission, was set on a tripod just outside the door. The goal was then to round up all four of the tires into one location using the rigid plow attachment. Doing so would provide an idea of how well the robot can maneuver inside a grain bin, how easy it is to control when you can’t physically see the robot, and how well the controller communicates with the robot from outside the grain bin. This test can be viewed in Figure 5-7 and Figure 5-8.

Figure 5-6: Photo of Grainbot driving on the aeration floor next to a Hutchinson/Mayrath NexGen 2000 commercial sweep at the GSI testing facility.
Figure 5-7: Sequence of stills of the robot maneuvering around the far obstacles (tires) inside of the grain bin.
For safety reasons, the robot is programmed to go into an emergency state in the case that it loses communication from the controller for more than a quarter of a second. In this emergency state, the robot disables power to all of its moving parts, as well as the lights. This is easily reset by turning the controller off and then back on. When the robot goes into its emergency state, it is known that communication was lost for an unsafe period of time. Each time the robot went into this state, the time of occurrence, as measured from the start time, was recorded. The communication was lost a total of 28 times over a period of 15 minutes. This data has been plotted in Figure 5-9 below to show how frequently the signal was lost.
Results and Discussion

Although several tests were performed, it is important to be aware of the potential inaccuracies associated with the corresponding measurements. The main source of error would be due to the steel cable used for tethering the Grainbot, as it was mounted higher on the Grainbot than it should have been. However, this was a requirement in order to keep the cable level with the ground due to the height of the tether point. In order to achieve more accurate results, the steel cable should have been mounted at the same height as the ramming attachment. Because the steel cable was mounted higher than this, a torque was produced about the rear axle which reduces the load on the front wheels while also increasing the vertical load on the rear wheels. Ideally, because the motors all have equal power, the weight should be distributed evenly on all four wheels.

Despite these potential sources of error, several important conclusions can still be derived. First, the overall highest force output by the Grainbot was approximately 535 lbs. This force was generated during the dynamic pull tests using the snow tread tires on bare concrete floor, which had an average force of 491.3 lbs. In the previous chapter, it
had been declared that a safe assumption for the force required to manipulate an auger is approximately the weight of an auger. The types of augers the Grainbot is designed to manipulate will be in the 100 to 200 lb. range, so this result is good news.
CHAPTER 6
SIMULATED GRAIN BIN ENVIRONMENT TESTING

A test bed was built at UNL that adequately simulates the environment of a grain bin and can be seen in Figure 6-1. This test bed is essentially a large enclosed wooden frame that is situated on a concrete floor. A large concrete support pillar is also utilized in the test bed to provide a rigid section of the frame which can be used when taking force measurements. The grain used in this test bed is soy beans.

Figure 6-1: Simulated grain bin setup located at UNL.

For these tests, several improvements have been made. The largest improvement is the load cell that is used. The load cell used for these tests is an Interface model 1200 series precision low profile load cell with a 1,000 lb. capacity. A custom housing was also designed, manufactured, and assembled which allowed for the load cell to be safely
mounted during testing. This custom housing can be seen in Figure 6-2, Figure 6-3, Figure 6-4, and Figure 6-5.

Figure 6-2: Load cell fixture as modeled in SolidWorks, front (left) and rear view (right).

Figure 6-3: Exploded view of load cell fixture assembly including adjustable height mount (bolts not shown).
Figure 6-4: Front (left) and rear (right) isometric views of the load cell fixture assembly.

Figure 6-5: Side view of the load cell fixture assembly with the left figure showing a section view.
Unlike the crane scale used in Grand Island at the GSI testing facility, this load cell provides the ability to perform compression measurements. Because the Grainbot is used to manipulate the sweep auger by pushing with its front end attachment, it is appropriate that the measurements taken should also be measured in this manner. The load cell fixture was thus designed with a broad, flat, steel plate reinforced with triangular ribs that would interface with the Grainbot’s attachments. The force received on this front plate would then be transferred through the load cell to the rear plate, which rests against a rigid surface (in this case, the large concrete pillar). The two housing components are then coupled via two steel cylinders of differing diameter with a slide-fit construction which restricts the relative motion of the two components to linear and rotational motion only. A slot is left open at the top to allow for the wiring to escape.

**Verification of Load Cell Accuracy and Consistency**

The Interface load cell was pre-calibrated by the manufacturer, so no calibration was necessary once it was received. However, to ensure consistency and to verify no faults or flaws existed with the load cell or with the housing designed, known loads were applied to the load cell and the output was recorded. This was done by placing the load cell in its housing and then laying it on the ground vertically. After zeroing the load cell, a 35 lb. weight was placed on top and the output was recorded for three separate iterations of the weight. Three different 35 lb. weights were measured individually first, then combined. These three weights are referred to as #1, #2, and #3. These results are shown in Figure 6-6. These results could then later be used to verify that no drift was occurring in the load cell measurements by again weighing the 35 lb. weights between
sets of Grainbot force measurements. The results indicate that there is a very small standard deviation, even as the load approaches 100 lbs.

Figure 6-6: Results of initial testing of the Interface load cell.

**Static Testing**

When performing static testing, both the swiveling attachment and the rigid attachment were used. When using the swiveling attachment, the load cell fixture was mounted on an adjustable-height mounting fixture that allowed the load cell to be directly in line with the center of the attachment. When using the rigid attachment, the fixture was set on the ground. In both cases, the back side of the fixture was butted up against the concrete pillar.
Once the fixture was in place, the Grainbot was then driven carefully up to the front plate of the fixture. The fixture was adjusted to be centered with the attachment if needed, and then the Grainbot was driven slowly into the fixture until full contact was made. Once contact was established, full power was given to the motors and the output was measured and recorded using software provided with the load cell on a laptop computer. Care was taken to ensure the angle of attack of the Grainbot was as perpendicular as possible with the front face of the fixture. An example photo of one of these tests can be seen in Figure 6-7.

![Figure 6-7: Grainbot shown making full contact with fixture before engaging at full power.](image)

These tests were performed in three different depths of grain: zero inches of grain (bare concrete), one inch of grain, and three inches of grain. These tests were also performed with both types of tires (tractor tread and snow tread). For each test, the test was repeated five times in order to obtain an average. In order to reduce the total amount
of testing required, the steady state force measured during the dynamic testing of the rigid attachment was used as the static value. This will be covered in more detail in the following Dynamic Testing section. The data for these static tests can be seen in the following figures. The data in all of the following figures were obtained using the swiveling attachment.

Figure 6-8: Combined plot of static testing with tractor tires on concrete.
Figure 6-9: Combined plot of static testing with tractor tires in 1 inch of grain.

Figure 6-10: Combined plot of static testing with tractor tires in 3 inches of grain.
Figure 6-11: Combined plot of static testing with snow tires on bare concrete.

Figure 6-12: Combined plot of static testing with snow tires in one inch of grain.
Dynamic Testing

When performing dynamic testing, only the rigid attachment was used. This is due to safety reasons as the swiveling attachment was not designed for ramming into totally rigid objects, and doing so could cause damage to the Grainbot. Therefore, the associated measurements for dynamic testing will apply only to the rigid attachment.

To perform the dynamic tests, the load cell fixture was placed on the ground in front of the concrete pillar and the Grainbot was lined up as straight as possible with the fixture. In order to get the Grainbot up to full speed before impact, the Grainbot began a few feet from the fixture. The Grainbot was then given full power as it accelerated towards its target. It was ensured that the Grainbot was at full velocity prior to impact. The load cell was set to begin recording measurements as soon as a threshold force was
met, then record for three seconds. These three seconds were more than enough time to allow the force to come to steady state. This steady state force was then used as the static force measurement for the rigid attachment.

These tests were again performed in the three different depths of grain. These tests were also performed with both types of tires (tractor tread and snow tread). For each type of test, five tests were performed in order to obtain an average. The data for these tests can be seen in the following figures. The data in all of the following figures were obtained using the rigid attachment.

![Graph of dynamic testing with tractor tires on concrete](image)

Figure 6-14: Combined plot of dynamic testing with tractor tires on concrete.
Figure 6-15: Combined plot of dynamic testing with tractor tires in one inch of grain.

Figure 6-16: Combined plot of dynamic testing with tractor tires in three inches of grain.
Figure 6-17: Combined plot of dynamic testing with snow tires on concrete.

Figure 6-18: Combined plot of dynamic testing with snow tires in one inch of grain.
Figure 6-19: Combined plot of dynamic testing with snow tires in three inches of grain.

**Thrusting Mechanism Testing**

In order to test the thrusting mechanism, the swiveling attachment was connected and the load cell fixture was setup on the mounting fixture to the proper height. The Grainbot is programmed to drive forward at full power while the thrusting mechanism is engaged. This is to help ensure the attachment is fully depressed when the hammering mechanism fires. So, once the Grainbot is properly aligned with the load cell, the thrusting mechanism is engaged and the Grainbot drives at full power into the load cell while the thrusting mechanism fires. For these tests, the load cell was again set to begin recording measurements once a threshold force was met, then record for eight seconds. This test was repeated 5 times and the data can be seen in the following figures.
Figure 6-20: Combined plot of impactor testing on concrete.

Figure 6-21: Combined plot of impactor testing in one inch of grain.
Results and Discussion

The primary goals of this testing were to determine: the highest force the Grainbot can produce by any means, the average force output associated with each testing scenario, the average force output of the thrusting mechanism, the effect of grain depth on the average force output, and which tread style offers better performance. From the results, all of these questions can be answered.
Highest Overall Force Produced

![Graph showing highest forces produced during each test](image)

Figure 6-23: Highest forces produced during each test.

The highest force produced from each test can be seen in Figure 6-23. The forces displayed in this figure represent the single highest recorded value from each type of test. For the dynamic tests (those with the plow attachment), the values shown correctly represent the magnitude of the force that was intended to be measured. However, the other tests, which were performed statically, produced very large forces upon approaching the load cell. These large forces were present only briefly and quickly returned to a much lower steady state value, which was the intended value for measurement.
The key in explaining why these large forces are present is the length of deceleration upon impacting the load cell during the initial approach. During all static tests, the Grainbot began very close to the load cell in order to prevent gaining too much momentum prior to reaching the load cell. This was to help prevent dynamic factors from coming into play. However, despite these attempts, the deceleration upon impact was still large enough that it caused a very high force on impact. The reason for this lies in the attachments and the way they are attached.

Figure 6-24: The two attachments shown side by side.

When looking at the two attachments, shown side by side in Figure 6-24, it can be seen that the plow attachment is essentially a cantilevered steel plate, while the swiveling attachment is a weldment of several steel tubes. Because the plow attachment is so long, the force of the impact is able to deflect the plate appreciably, which in turn acts as a high stiffness spring. The plow was intentionally designed to be somewhat springy in order to prevent damage to the auger’s shield, and to provide some upward lift as the deflected
plate rebounds. Due to this springiness, the Grainbot’s deceleration is distributed over a longer period of time.

When looking at the swiveling attachment, the only source of any momentum absorption comes from the small spring used to keep the attachment protruded. This spring has a very low spring constant (~5 lbs/in), providing very low resistance upon its full depression. Once the two steel retaining cylinders come into contact, the entire momentum of the Grainbot is transferred to the steel frame. This causes the Grainbot to decelerate very quickly, causing a very large impact force.

It is important to note that while this logic is reflected in some of the static testing results, it is not true for all of them. During static testing, care was taken to ensure this impact force was kept low by approaching slowly and from a close distance. However, due to difficulties in maintaining a slow speed and obtaining accurate steady state results, errors did occur where higher impact forces were the result. This is one possible explanation as to why the results are somewhat inconsistent.

While these results are not what were expected, they do provide useful information. For example, even when the Grainbot approaches the auger from a close distance, a very high instantaneous force can be achieved when using the swivel attachment. This force was even higher than the forces produced by the thrusting mechanism. Also, a very interesting trend appears in this data. The top five highest forces were produced with the Grainbot in one inch of grain, the next five highest forces were produced in three inches of grain, and the lowest forces were produced on bare concrete floor. This is counterintuitive to what one might expect, as it would be expected
that the highest forces be produced on bare concrete flooring. However, when comparing the snow tires with the plow attachment in one inch of grain versus the snow tires with the plow attachment on bare concrete, a difference of over 100 lbs. is observed in favor of the one inch of grain. The reasoning for this will be explained in the following section.

**Average Force Output**

Each of static, dynamic, and hammering tests were performed five times in order to obtain an average result. The averages for each of these tests were obtained using MATLAB by taking an average of each of the five data points at each point in time. These average points were then plotted versus time. The impactor averages were handled in a different manner due to the impulses occurring at different points in time. These results will be discussed and presented separately.

Once these average plots had been formed, the steady state values could be determined. The steady state values indicate the force the Grainbot will output purely due to the tractive forces between the tires and the ground, and begin when the output force begins to remain relatively constant. In order to determine when steady state has begun, the plots must be inspected. Upon doing so, it can be seen that plots level off after approximately two seconds. Thus, the steady state value will be defined as the average value of the average output forces for the final one second of the test. These average steady state values are shown on the average plots in the following figures, and are also shown in Figure 6-37.
Figure 6-25: Average plot of static testing with tractor tires on concrete.

Figure 6-26: Average plot of static testing with tractor tires in 1 inch of grain.
Figure 6-27: Average plot of static testing with tractor tires in 3 inches of grain.

Figure 6-28: Average plot of static testing with snow tires on bare concrete.
Figure 6-29: Average plot of static testing with snow tires in one inch of grain.

Figure 6-30: Average plot of static testing with snow tires in three inches of grain.
Figure 6-31: Average plot of dynamic testing with tractor tires on concrete.

Figure 6-32: Average plot of dynamic testing with tractor tires in one inch of grain.
Figure 6-33: Average plot of dynamic testing with tractor tires in three inches of grain.

Figure 6-34: Average plot of dynamic testing with snow tires on concrete.
Figure 6-35: Average plot of dynamic testing with snow tires in one inch of grain.

Figure 6-36: Average plot of dynamic testing with snow tires in three inches of grain.
Figure 6-37: Average steady state forces produced by each test, listed in descending order.

From Figure 6-37 it can be seen that the highest steady state force, 167.0 lbs., occurs with the snow tires while using the swivel attachment on bare concrete. This value exceeds the theoretical maximum forward driving force calculated in the previous chapter was only 132.76 lbs. Assuming there was equal traction on all tires, and that all motors were outputting equal torque, 167.0 lbs. of forward driving force would equate to 37.7 Nm of torque per motor. This torque value is 7.7 Nm more than the rated output value of the gearbox, or 126% of the rated value.
The results of this table are very consistent with what would be expected. The largest forces are now produced on bare concrete, followed by one inch of grain, followed by three inches of grain. This trend is due to the grain being sucked under the wheels as the Grainbot drives forward. The grain acts as ball bearings under the tires and makes it difficult for the wheels to get good traction with the floor. When looking at the force plots, it can be seen that when the Grainbot is in one inch or three inches of grain, there is a period of time in the beginning where the force is rising over time before eventually leveling off at the steady state output. It is during this time that the Grainbot is digging down to the concrete floor. Once that contact is made, the maximum force output is achieved.

The next interesting trend that is noted from Figure 6-37 is that the snow tires consistently outperformed the tractor tires for each depth of grain. For each depth, the snow tires had the largest output force. The only case where this was not true was on bare concrete with the plow attachment. In this case, the tractor tires produced an average force of 148.5 lbs. while the snow tires produced an average force of 138.7 lbs., nearly a 10 lb. difference. However, in the one inch and three inch depths of grain with the plow attachment, the snow tires output nearly 20 lbs. and 30 lbs. more force than the tractor tires, respectively. Based on the average column, the snow tires outperform the tractor tires by 16.9 lbs.

To determine if the type of attachment affects the average output forces at steady state, Figure 6-38 was created. In this table, the average output force of all the tests for each attachment was calculated. Interestingly, while each attachment seems to have an
almost significant advantage in certain conditions, the average force for all these tests differed by only 1.2 lbs. for each attachment. This indicates that regardless of the attachment in use, the steady state force produced simply by driving the auger forward is roughly the same on average.

![Average Steady State Forces Comparing Attachments](image)

Figure 6-38: Comparison of each test with different attachments, including average force.

Finally, Figure 6-39 shows the average forces of the dynamic testing. Again, only the plow attachment was used during dynamic testing, so no swivel attachment data is shown here. Based on this data, the one inch depth of grain produced the highest average dynamic forces, followed by concrete, followed by three inches of grain. This is an
unusual trend, as it would be expected that concrete would also be conducive to producing the highest dynamic force. However, the greater tractive capabilities are actually what limit the impact force on concrete.

When the Grainbot impacts the load cell with the plow attachment, the attachment is appreciably deflected and acts as a spring, bouncing the Grainbot backwards. When on concrete, the traction is good enough that the wheels cannot slip on the ground and the motors thus help to absorb the backwards motion, increasing the duration of the deceleration. This is opposed to being on a thin layer of grain where the traction is not as good and the motors are able to keep the wheels spinning forward, allowing the Grainbot to rebound quicker. This quicker rebound is ultimately what causes the higher impact force.

![Average Dynamic Forces Comparing Tires](image)

Figure 6-39: Comparison of the average dynamic forces with the two different tire treads.
Average Force of Thrusting Mechanism

To determine the average force of the thrusting mechanism, the results of the impact tests had to be carefully analyzed. Using MATLAB, the peak forces corresponding to each of the impactor strikes were found and their magnitude was recorded. Because the Grainbot is driving into the load cell while firing, there is a pre-existing force which must be subtracted from this magnitude in order to determine the pure impact force. This was done by calculating the average forward driving force of the Grainbot for a short period of time before the impact occurred. In the following figures, these average forward driving forces are displayed by a red bar on the individual plots, which also indicate the range of values used to obtain the average. The numbers on these plots correspond to the impact force, which is the difference between the peak force and the average forward driving force prior to impact.

The overall average impact force was calculated to be 46 lbs. and was calculated from the results of 51 different impacts. The highest force produced by the impactor was 84 lbs. which occurred in 1 inch of grain. The highest force produced overall while utilizing the impactor was 266.4 lbs. which occurred on bare concrete.
Figure 6-40: Impact force plot on concrete with impact magnitude displayed for test 1.

Figure 6-41: Impact force plot on concrete with impact magnitude displayed for test 2.
Figure 6-42: Impact force plot on concrete with impact magnitude displayed for test 3.

Figure 6-43: Impact force plot on concrete with impact magnitude displayed for test 4.
Figure 6-44: Impact force plot on concrete with impact magnitude displayed for test 5.

Figure 6-45: Impact force plot in 1 inch grain with impact magnitude displayed for test 1.
Figure 6-46: Impact force plot in 1 inch grain with impact magnitude displayed for test 2.

Figure 6-47: Impact force plot in 1 inch grain with impact magnitude displayed for test 3.
Figure 6-48: Impact force plot in 1 inch grain with impact magnitude displayed for test 4.

Figure 6-49: Impact force plot in 1 inch grain with impact magnitude displayed for test 5.
Figure 6-50: Impact force plot in 3 inch grain with impact magnitude displayed for test 1.

Figure 6-51: Impact force plot in 3 inch grain with impact magnitude displayed for test 2.
Figure 6-52: Impact force plot in 3 inch grain with impact magnitude displayed for test 3.

Figure 6-53: Impact force plot in 3 inch grain with impact magnitude displayed for test 4.
Figure 6-54: Impact force plot in 3 inch grain with impact magnitude displayed for test 5.
CHAPTER 7

CONCLUSIONS AND FUTURE WORK

The purpose of this project was to design, build, and evaluate the performance of a remotely controlled robotic device that is able to enter grain bins and manipulate a sweep auger. A thrusting mechanism was implemented in order to provide additional force in cases of poor traction, and a camera and lighting system were installed to allow the user to have a first-person view of the robot from a remote location. Several tests were then performed with the robot to measure its capabilities.

Testing showed that a maximum force of 303.3 lbs. is achievable. This maximum force was achieved when using the swiveling attachment and was the result of the instantaneous impact when approaching the load cell. Because this force was achieved at such a slow speed, it is indicative that the maximum force could be increased further with a properly designed attachment. Based on the field testing performed in a grain bin in Grand Island, it is known that a force of 535 lbs. is achievable.

The greatest average forward driving force produced by the Grainbot was approximately 167.8 lbs. This force is achievable with the snow tread tires on bare concrete with the swiveling attachment. The snow tread tires performed better than the tractor tires on average with a 16.9 lb. advantage. While this attachment seemed to perform significantly better than the plow attachment in the same conditions with 149.2 lbs. of forward driving force, it was determined that neither of the attachments provide a significant advantage on average when considering all the conditions.
Testing also showed that the ideal terrain for the Grainbot to produce the maximum forward driving force is bare concrete, followed by one inch of grain, followed by three inches of grain. However, this trend is not consistent when considering the dynamic forces. During dynamic testing, it was shown that the largest dynamic forces produced (with the plow attachment) were 302.2 lbs. in one inch of grain, 269.4 lbs. in three inches of grain, and 184.7 lbs. on bare concrete. This unusual trend was explained by discussing the effects of the deceleration rate which is affected by the grain depth.

The results from the thrusting mechanism tests showed that it produced on average 46 lbs. of impact force. When combining the average forward driving force with the average thrusting force, approximately 214.28 lbs. of force is achievable. The maximum recorded impact was approximately 84.00 lbs. of force. Combining this with the average forward driving force and it provides the potential for up to 251.8 lbs. of force.

While there was a great deal of data obtained from testing, it should be noted that more testing should be performed in order to reduce standard deviation and to obtain a better true average for many of these tests. The thrusting mechanism tests are one area where improved testing methods would certainly be beneficial. Ideally, the thrusting mechanism would be removed from the Grainbot and fired directly at the load cell from a rigid, stationary platform. This would remove the need to subtract a pre-existing force induced by the forward driving of the Grainbot.
Future Work

While the testing of this prototype robot has shown very promising results, there is much work to be done before the Grainbot is ready for the market. One of the main concerns with the current prototype is the difficulty in loading and unloading from a grain bin. Weighing in at approximately 415 lbs., the Grainbot must be loaded and unloaded using lifting equipment such as tractors, forklifts, etc. While some weight can be removed with relative ease, such as the tires, batteries, and the front-end attachment, which would lighten the Grainbot by about 130 lbs., it would still be very difficult and dangerous to try and load without the use of lifting equipment. One solution to consider for reducing weight would be to swap out the heavy steel construction for aluminum. This alone should reduce the overall weight by about 90 lbs. Combining this with the removal of the aforementioned items would bring the overall weight down to 195 lbs.

While reducing the weight allows for the robot to be more easily loaded and unloaded, it would also decrease the traction capabilities. Because traction and weight have a direct relationship, higher weight is still desired. To resolve this dilemma, a newer version of the Grainbot should have a lower base weight while providing the ability to add and remove additional weights. Doing so should allow users to more easily load and unload the Grainbot from grain bins, while also allowing ideal traction to be attained.

Another aspect of the Grainbot that will also be improved upon are the attachments and other capabilities. A robotic arm with an end effector will be attached to the front of the Grainbot that will allow it to break up the grain on the opposite side of the
sweep auger and help guide non-flowing grain into the auger. This arm could also have other attachment capabilities that would further broaden its task diversity.

In addition to the robotic arm, a front-end loading style attachment could also be very desirable. This could allow for a bucket type attachment for scooping grain, or a forklift type attachment which could potentially allow the user to safely lift the auger to move it. Because the Grainbot has equal power in both forward and reverse, the option to place such an attachment on the back side can be considered. This would prevent interference with the already existing front end attachments.

The scope of future improvements is not limited to mechanical alterations. During testing from outside the test bin in Grand Island, the control signal was lost a total of 28 times over the course of 15 minutes. This indicates that a stronger transmitter is required, or a repeater station should be implemented at the door of the grain bin. During this testing, it was also noted that controlling the Grainbot was difficult due to not knowing the orientation of the camera. For this reason, some sort of digital overlay should be implemented on the camera feed so the user can know where the camera is looking relative to the robot.

One final improvement that could also be implemented is automated capabilities. Overall the Grainbot has a fairly simple and straightforward task. There is a strong potential that the Grainbot can be programmed, with the utilization of some additional sensors, to simply follow the sweep auger and assist only when it is needed. This would allow the user to be free to go and perform other tasks while the Grainbot ensures the sweep auger is operating efficiently.
Although there are several existing solutions for improving the safety and effectiveness of grain bin clean out, the Grainbot certainly has the potential to be the most universal and adaptable solution. Testing has shown that the Grainbot is capable of producing forces necessary to manipulate a sweep auger, and is able to handle the terrain and environment within a grain bin. With some improvements in regards to additional attachments and features, the Grainbot will certainly be a very useful, desirable, and life-saving device.
REFERENCES


APPENDIX

A. Classification of Hazardous Locations [10]

Class II Locations

Class II locations are defined by the NEC as those locations that are hazardous due to the presence of combustible dusts. Class II locations are grouped according to the specific dust involved: Group E combustible metal dusts or other combustible dusts having resistivity of less than 105 ohm-centimeters; Group F combustible dusts such as carbon black, charcoal, and coal or coke dusts having resistivity greater than 102 ohm-centimeters or less than 108 ohm-centimeters; and Group G containing grain dusts or other combustible dusts having resistivity of 105 ohm-centimeters or greater. Class II locations are further classified as to whether combustible dusts may be present in the air under normal operating conditions (Division 1) or whether combustible dusts are not normally in the air but which may accumulate on or near electrical equipment (Division 2).

Enclosures that can be used for Class II locations:

CLASS II, DIVISION 1

- NEMA Type 9 enclosures
- Pressurized enclosures (subject to approval by the inspection authority having jurisdiction)

CLASS II, DIVISION 2

- Same as those listed for Class II, Division 1
• Dust-tight enclosures listed for use in hazardous locations. Tests for hazardous location dust-tight enclosures are contained in ISA 12.12.01 and UL 1604.

General purpose dust-tight enclosure types as defined by UL 50 and NEMA 250 are Types 3, 4, 4X, 12, 12K, and 13.

• General-purpose enclosures (such enclosures are permitted for some applications by Paragraph 502 of the National Electrical Code if the equipment does not constitute a source of ignition under normal operating conditions)