UNIVERSITY OF NEBRASKA-LINCOLN

DEPARTMENT OF MECHANICAL & MATERIALS ENGINEERING

MECH 446/447

SENIOR DESIGN I/II

FINAL REPORT

Shingle Handling Robot Module

University of Nebraska-Lincoln

Dr. Carl Nelson

Prepared for Mr. Kurt Palik

Instructor of Mechanical Engineering

University of Nebraska-Lincoln

By: Carter McCormick, River Kramer, Brandon Kusek, Isaac Klar, Victoria Nelson

Date Due: May 6th, 2022

Date Received: May 5th, 2022

<u>**Table of Contents**</u>

Executive Summary

Every year, dozens of people die from accidents that are directly related to roofing a building. The Electronic Library of Construction Occupational Safety and Health, or eLcosh, determines that an overwhelming majority of these accidents come from falls off of the roof.

Our Faculty and Project Sponsor, Dr. Carl Nelson came to us at the beginning of the semester and informed us that he would like a prototype of an autonomous roofing robot to be designed, built, and tested. What we have since created is a functional prototype of an automatic roofing system that will serve as a module for a Roomba style robot. This design requires a human to load shingles and nails into it, and the robot will autonomously and accurately cover a standard gabled roof with shingles, up to a 40 degree pitch.

This device is capable of isolating a shingle, sensing the correct positioning, moving the shingle into place, and nailing into a framed roof. The final design found a balance of cost, safety, and ease of use. We wanted the system to be as user friendly as possible. The easier the use, the quicker the system can be deployed. The intended target for this product was commercial use, or for people to rent and roof their house by themself.

There are various designs that have been considered and ruled out, succeeded by our final concept. Accompanying this concept are a bill of materials, cost breakdown, a testing plan with criteria, our future timeline, and various sheets of solidworks drawings.

Background

I. Sponsor & Motivation for the Project

Our sponsor and faculty advisor for this project is Dr. Carl Nelson, a professor of Mechanical and Materials Engineering at the University of Nebraska-Lincoln. Dr. Nelson has years of experience in the fields of Mechanical Engineering and Robotics. Due to his expertise in these fields and his awareness of how dangerous roofing can be, he wanted to design and build a solution to the dangers of roofing. Through talking to Dr. Nelson, we were tasked with designing and building a module for a roofing robot that can store multiple bales of shingles, isolate one shingle from the stack, align and position the shingle into the correction orientation, and nail the shingle to a roof.

Through researching for this project, we found that the number of nails required per shingle depends on where you are located in the United States. For the majority of the United States, only four nails per shingle are required with the exception of the first row requiring five nails. Southern states with higher winds and risk of hurricanes require five nails per shingle across the whole roof. Due to this, we have decided to design the robot to fit the majority of houses (four nails) with there being an option to add a fifth nail when it is required. We have also found that roof pitches vary greatly in the United States, but we will not be required to roof at an angle greater than 45 degrees for this project. For safety and ease of use, the robot will not be laying the first row of shingles. This is to ensure the robot does not fall off the roof by being close to the edge and it allows for a consistent starting point for the robot.

Problem Statement

Roofing accidents occur far too often and should be eliminated. The overall goal of this project is to help eliminate roofing accidents. According to the Electronic Library of Construction Occupational Health and Safety, roofing accidents account for 51 total deaths each year. Most of these deaths are from falling. Clearly something must be done to keep roofers safe and off of roofs. The specific goal of this project is creating a robot to store, place, align shingles on the roof, and nail them down.

Customer expectations have also been incorporated into the design, with ease of use, and limited time on the roof being key factors in the design process.

Project Scope

I. Deliverables

We set out to produce a functioning prototype that is able to effectively place, orientate, and nail asphalt shingles onto standard pitch roofs. The hopper of the robot should be able to hold three bales, or 66 shingles. The accuracy of the positioning and final nailing of the shingle should be within ⅛" of an inch. While the larger movement of the robot is not within the scope, it should be able to attach easily to a robot capable of guidance. Some bonus deliverables that we will try to implement would be an automatic orienting device that can accept any type of packaged shingles (alternating direction), a safety harness proof of concept, and a new type of quick release mechanism for mounting and disassembling the robot.

II. Design Constraints

While the overall goal is to come up with a design to increase the safety of roofing through an automated roofing system, there are a few design constraints that limit the project as well as set specific goals that must be met. One of the first goals is to keep the project under $1,000. This number was later expanded to $1500 after manufacturing had begun. This cost does not include the costs of the nail guns for the project. The $1,500 budget does however include all other parts, raw materials, manufacturing processing, assembly costs, and testing necessary for the creation and testing of a prototype. This budget is subject to change if this product ever went to market, with some temporary materials being replaced with longer lasting parts. The next constraint for the design is to comply with all applicable codes or OSHA requirements. The only applicable codes found were to nail a total of four nails through the shingle to attach it to the roof. The next constraint is to create a design that can be fit onto a ladder lift. Ladder lifts have a platform that is approximately the size of a person standing. This means that the final design must be about the same size or be able to be easily disassembled to fit onto the ladder lift. Most ladder lifts have a ladder lift maximum lifting capacity of about one or two people (approximately 400 lbs). The final product weighed less than our maximum designated weight, which makes taking it apart and moving the pieces even simpler than expected.

Project Timeline

The time constraints for this project were confined down to two semesters, both roughly 16 weeks in length. This can be seen in the Gantt in Appendix I: Figure 1. The first semester was primarily used to do an overall design package for the entire robot. This includes CAD modeling as well as constructing circuit diagrams for total operation of the robot. This was wrapped up by ordering of parts to kick off second semester; this is where the real assembly and manufacturing of the robot occurred. Throughout the final 16 weeks, many tasks were performed in manufacturing, assembly, testing, and redesign. This was primarily done entirely on our own as a team in order to save on cost and budget. This timeline was followed very closely as followed and was a successful and complete pace to follow for any other similar projects related to this robotic design.

Design Concepts

The goal of this project was to create a design that was as safe and efficient as possible to use. With these main criteria in mind, other criteria were needed to be taken into consideration when designing the prototype. Cost, weight, complexity, and ease of use are the other constraints, although not as important as safety and efficiency.

The driving issue for this prototype to solve is the deaths of roofers and other roofing accidents. Safety must be the forerunner in this design in order to maximize the effectiveness of the prototype in solving this issue. Safety was weighted in the design process as the highest. Concepts were graded with regards to moving parts, pinch points, accessibility of parts, and redundancies. Having an automated system around with nail guns certainly requires caution, but with the correct safety features set in place, can be more of an asset than a liability.

The second highest weighted criteria for the designs is the accuracy, or efficiency of the product. Roofing crews have their craft down to a science and muscle memory, so any product that will compete with this will need to move quickly, and not fumble over itself. Concepts were graded based on shingle handling time, accuracy of shingle placement, consistency, and cycle time.

The third highest weighted constraint to the prototype is the ease of use of this product. As stated before, the targeted customer is not only the commercial industry, but for homeowners who want to rent this product. For this to be accomplished, the product must be able to be used by people with little to no construction knowledge. Concepts were graded on how easy it was to replace consumables that the device used, ease of maintenance, and operation.

The fourth constraint of the device's design was the complexity of the concepts. This goes along with the ease of use of the prototype, but to the internal workings. The less moving parts, less parts overall, and smoother and simpler movements of the device were preferred and graded higher than concepts that seemed to be too complicated. We also took into consideration our own manufacturing prowess into complexity.

The two final weighted constraints to this prototype were the cost and the weight of the device. Since this project is only in the prototype phase, these two were weighed the least out of the bunch. This product does need to get onto the roof of someone's house at some point, but it was an initial goal to be able to quickly come apart and come together in order to get up a ladder lift. The cost of this prototype was also discounted, as cost is saved by using materials and manufacturing methods that are not feasible with a final product.

The scale that we ranked each parameter on ranges from one to five. We decided to use that on the weighted decision matrix as we did not feel comfortable with having ten degrees of severity. For us, it was easier to lump each concept onto a broader scale of one to five. The minimum, or the worst option, was ranked at a one, and the best option was ranked at a five.

I. Nail Gun Rail Design

For the module to properly set a shingle on the roof the shingle must be nailed in place. To accomplish the task of nailing the shingles two concepts were created and analyzed with a decision matrix. The first concept created would use 4 nail guns simultaneously. These would be mounted to a rail where they could be moved in unison to nail the shingle to the roof. The other concept created was to use a single nail gun that would run on a slide and nail at the desired intervals. The design matrix, shown below, has each part weighted by its importance and each concept is given a rating between 1-5 for the criteria. The extra parts for the single gun rail are shown to outprice the parts for the multi-gun rail. The safety of the multi-gun rail is less than the multi-gun rail with the addition of the moving parts. In both concepts the nail guns would have no air to them until they were lowered to nail the shingle. The ease of use is another short fall for the single gun system. The time between reloading of the guns for a single gun would be 1/4th the time of the multi-gun design and would not line up with the reload interval for the shingles. While the addition of 3-4 other nail guns will add weight the system is modular and can be disassembled for easy relocation. The use of 4 nail guns allows for the operator to have more hands on ability to set the spacing between the nail guns for a more accurate placement of the nails. With each shingle being adjusted, the accuracy of the nail could be adjusted with the single gun system. The downfall of that is the software and interface to allow for this based on the budget given to the project. The simplicity of the 4 gun rail system proved to be the better option for the project given the design constraints. With the nailing system decided on 4 guns, the holding rail had to be designed. The rail was made from the same square tubing the frame will be made out of, 1.00” x 0.065” walled tube. The tube will have a 0.25” key stock welded to one face of it to assist with the rotational movement from the gun mounts on the bar. The bar will be capped off with a nut welded to the inside of the cap. This will allow the attachment of the end caps and the gun mounts to be slid on and off the shaft. This assembly has to be moved toward and away from the roof to allow for the rest of the machine to complete its task of placing the shingle. The method of creating the movement was between a pneumatic cylinder and a linear actuator. This was easily decided with 2 criteria. The first was the speed at which the actuator could move the assembly. The second was the reaction it would have to repeated opposing shock loading. The linear actuators had issues with speeds and the power screw inside it would have issues with the shock loading from guns firing.

With the decision made for the pneumatic cylinder, a new issue arises. The issue was how to use the cylinder to move the rail. The initial thought was to use a 4 bar system to allow for the rail to move vertically. The issues with the 4 bar design were space constraints and complexity to use pneumatic cylinders. The new design would mount the cylinder to the frame vertically and have rails on each end to assist with the moment on the rail from the nail guns hanging on it. The cylinders will move the rail vertically up and down and bearings would move along the rails and help center the assembly throughout the motion. The rail would be connected to the bearings with bolts. The nail guns and the cylinders will be controlled with electronic valves. This will allow for control of the cylinders and the air to be shut off, adding to the safety of the module.

Nail Guns			
Factor:	**Weight**	**1 Nail Gun**	**4/5 Nail Guns**
Safety	40	2	4
Cost	5	2	2
Weight	5	3	1
Accuracy	25	3	5
Ease of Use	15	3	4
Complexity	10	1	4
Total: (500)	100%	235	400

II. Rollers and Slide Design

In order to have proper placement of the shingle so that the nailing module can operate precisely and place the nails where needed, a module must be designed to bring the shingle down from the hopper into place without the shingle being placed at an angle or without it making it to the front of the device where the actuating fingers can push it into proper positioning. In order to achieve this, four different ideas were conceptualized and placed into a decision matrix. The first concept used the idea of mounting a robotic arm beneath the hopper which could reach up to the hopper slot, grab the base of the shingle, rotate, and place the shingle in the appropriate position needed. This module would remove the shingle from the hopper and be able to place it fairly accurately all with the use of one assembly. Both of the next modules took into consideration using sensors to set the shingle into proper placement. The first would use a mechanical sensor type which would read the position of the shingle based on small switches or levers placed at the bottom to find how square the shingle sat within the frame. Opposed to this, the second concept would implement non-contact sensors of some type whether they use light or photo-imagery to read the location of the shingle compared to where it needs to lay. Finally, a module was proposed that the shingle would drop in out of the hopper and roll down the slide with shafted wheels and slide into slots at the bottom that would press the shingle into its proper location. Another design matrix is put together below; once again it is rated on a scale from one to five. Module selection was based on the following.

The final module listed above ended up coming in last out of our four concepts. From a safety standpoint, there are not many moving parts within the slide module itself. With only the shingle sliding down into place however, especially with the tar texture on the back, the shingle would get stuck constantly and would cause jams within the machine all of the time. With this in mind, there would be a large requirement for the user to reach into the machine where many moving parts exist, hence its very low safety rating. Cost and weight would be saved greatly using this method however due to its low complexity and the slide already being a part of the two other designs. Again because of the constant jams from the shingles texture and wanting to turn sideways, the accuracy and ease of use take very low rankings.

The next step up for the overall design of this module was decided on as a robotic placing arm. This would be a very safe module due to the only necessary danger being the introduction of moving parts within the frame. Along with a large safety factor, this method would also give a very high accuracy due to the advancements in robotics modern day. However, when it comes to the cost and weight of systems like this, the rating is very low due to the cost of extra equipment needed on board to program and determine. Another part of the system would involve the programming which is not a simple process especially for the overall motion we needed to obtain. With all of these extra calculations, this would not be an ideal module design.

The final modules were both a sort of sensor alignment. These came in a tie for the best alignment systems. Both modules were able to obtain the highest safety rating of all modules. This is due to the ability to tuck the sensors away out of place where they will only see the shingle be placed and not misread any other motions if the robot is interfered with. Newer technologies have also caused the cost and accuracy of these systems to come in at a very high rating. For the several sensors between the two types considered, complexity and ease of use are both interchangeable as programming is required for both.

One will use computer learning programming to help it increase accuracy where the mechanical sensors would not need to learn but could be more complex in usage where weather and other outside elements could affect its readings.

With all of the options at hand above, a non-contact sensor will be chosen. This could be chosen as a camera sensor or any other type of non-contacting sensor. By implementing this, some systems will be used along with guide rails to get the shingles in an initial position. By taking the shingle from the hopper in the next module, it can be placed onto a slide with rolling shafts attached. This system overall will get the shingle down to the sensor's position. With the sensors selected for the final design, a series of servos with rack and pinion gears are going to be implemented as the final method of alignment of the shingle using the sensing method.

Shingle Alignment Module					
Factor:	Weight	Automatic Robotic Placement	Mechanical Sensor w/ Guide Rails	Non-Contact Sensor w/ Guide Rails	Slide into Place
Safety	40	4	5	5	1
Cost	5	1	4	4	5
Weight	5	1	3	4	5
Accuracy	25	5	4	4	1
Ease of Use	15	3	3	2	1
Complexity	10	1	2	3	5
Total: (500)	100%	350	400	400	180

III. Hopper Design

Finally, a module is needed to separate individual shingles from each stack. This module must be designed to load shingle bales into and shear one shingle off at a time individually. In order to achieve this, three different separation modules were conceptualized. The first idea looked at using a design matrix was separation using a roller system. This used a roller at the back of the hopper mechanism to press the shingles into and shear them off with gripping wheels. Another proposed idea was to simply let gravity control the shearing of the individual shingles and implement a gate on the hopper to allow once shingle through at a time down into position. The final concept was a combination of these first two modules.

The first module involved taking the hopper on top of the frame and placing two driving shafts at the back with protruding gripping wheels. The actuator within the hopper would push the baled shingles forward into this shaft setup. This individual module concept came in relatively high safety with few moving parts which will be exposed on the back of the entire robot's setup. Cost for this module is relatively equal compared to all other options but would still be a somewhat expensive option due to the usage of chains and motors within. However, by 3D printing some of these parts, it will be a less complex setup as well as having a simple setup causing our ease of use value to go up.

The last two concepts for the hopper can be paired together. Originally, a gravity fed idea was conceptualized. As can be seen in the design matrix below, the factor of safety for this was very low due to the possibility of jams near moving parts as was said in previous design matrix concepts. This also affected the accuracy and ease of use modules on this design. Overall, this was able to keep the weight down as well as the complexity much similar to the roller module. With the cost, accuracy, and ease of use factors completing spiking to a new low, it was decided this idea would just have to be scrapped as an individual module. However, when paired together, both modules combined would give a much better result. By using the rollers to shear the shingles as well as having the gate to control the rate at which they fell, all factors except cost were able to be greatly improved or remain the same. This module of a similar complexity offered a much higher safety factor and gave much higher accuracy and ease of use for the delivery of these shingles.

With all of these factors at hand, both roller and gate concepts paired together will be chosen. This will be done with an actuator with a large pusher slide attached to it to inch the shingles forward one by one at a rate determined prior to movement. Once pressed at a desired force, the gate and rollers can be activated shearing an individual shingle down onto the slide with rollers. Due to the way the shingles will be aligned in the hopper, this should work perfectly with the tar side showing as it will offer a little penetration from the wheels to help grip. This will not damage the shingles and will help to increase the driving force from the motor to the edges of our 3D printed gripping wheels giving the desired torques.

Shingle Separation Module				
Factor:	**Weight**	**Separation w/ Roller**	**Gravity Fed w/ Gate**	**Both Roller and Gate**
Safety	40	3	2	4
Cost	5	3	3	2
Weight	5	4	4	4
Accuracy	25	3	2	5
Ease of Use	15	3	2	5
Complexity	10	4	4	3
Total: (500)	100%	315	235	420

Design Decision Analysis

The decisions for each of the modules are made using the total number of points accrued by each concept. For the nailing module, it was decided that four or five nail guns would be better than one nail gun that moves side to side and is responsible for putting all nails through the shingle. The major reasons for this decision is lower complexity, cost, and safety.

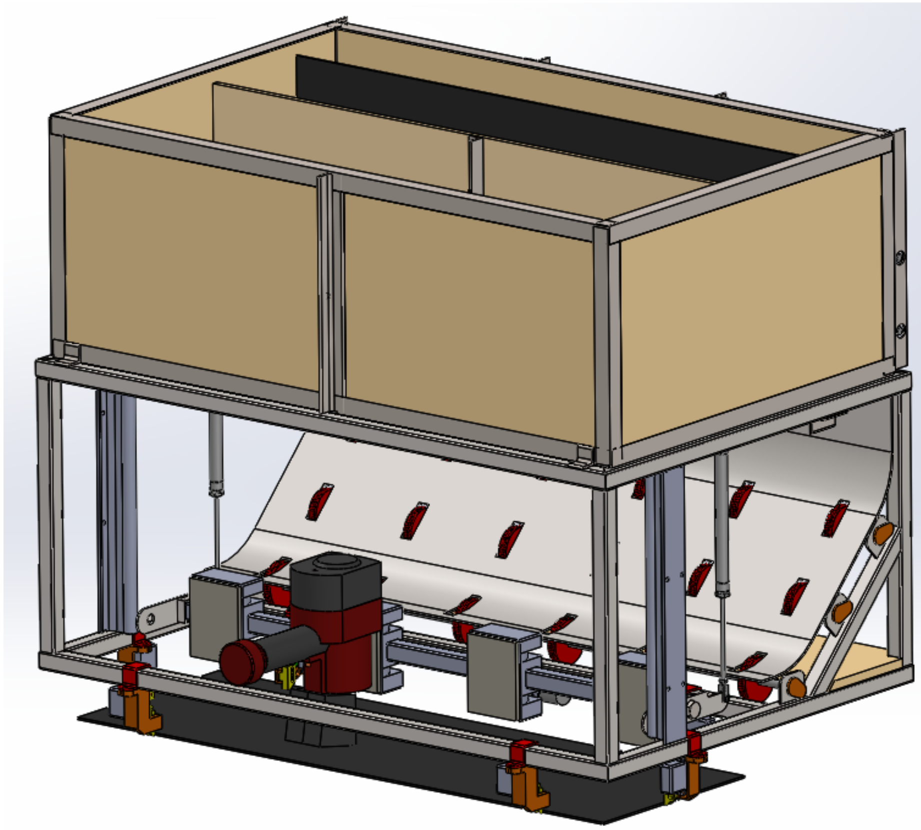
The decision for the shingle separation was made from using gripping rollers or a gate. It was decided that both would likely be necessary to ensure that the shingles both come down from the hopper. It was determined that weight due to gravity would not be enough to shear the shingles from each other. After preliminary testing, It was found that when attempting to shear the shingles from each other resulted in the top shingle being torn apart at seventeen pounds. This means that while this design concept using the gripping roller and the gate will work for shingles simply pressing against each other. Another idea must be used for shingles that are stuck together similar to what may happen in a hot environment.

The decision for shingle alignment was between automatic placement using a physical robotic arm, smaller mechanical arms, non contact sensors, and simply a slide for the shingle to fall into place. Using the totals from the design matrix it was determined that the best design would use smaller robotic arms and noncontact visual sensors to find the correct placement of the shingle and move it into place. The larger robotic arm was determined to be far too complicated and expensive while the simple slide was decided to be inaccurate as well as would not allow for fine placement.

Final Design Concept

The final design concept can be found below. There can be seen all of the design concepts described above from the full rail of multiple nail guns (only one is shown) to the hopper with the rollers and the slide with the rollers. The alignment fingers are also below to do the final positioning of the shingle. These alignment fingers are designed to be manufactured from 3D printed polylactic acid.

The nailing system is to be made out of four standard nail guns, one rail made from square steel tubing, and pneumatic actuators. The frame will be created from the same square tubing. The corners of the frame will be mitered together and welded. The roller system will be created using 3D printed rollers and D-profile shafts. The upper two rollers used to separate the shingles as well as the lower roller is meant to move the shingle into place are all powered using electrically powered motors. The hopper frame is made from angle iron. The shingles are moved forward in the hopper using a linear actuator with a potentiometer.



Final Design Package

The drawings in the Appendices show the final design concept in detail. Each of the designs were created in Solidworks. The design was broken into several subassemblies to organize the design and allow for easier modeling in Solidworks. The subassemblies are the hopper, the nailing equipment, the fingers, and the frame. Each subassembly has a figure to show finer details that are hard to see in the overall assembly view.

An electrical schematic of the robot can be viewed below in the Appendix. This schematic shows how each of the mechanical and electrical devices are intended to interact together. The motors and the linear actuator were driven using motor drivers. The servos were driven directly by the Arduino Uno (chosen microcontroller) using a servo shield to extend its capacity. An LCD screen and a Pixy camera were connected directly to the Arduino Uno. A power converter was used to convert 120 VAC power to 12 VDC power for most of the electronics. A buck-boost converter was used to convert 12 VDC power to 5 VDC power for the servos and the Arduino.

Prototype Manufacturing

In the Appendices, you can find a more detailed spreadsheet of the costs of the prototype. The costs that we have calculated so far sums up to $1456.90. There is still room for budgetary optimization. However, it is growing increasingly difficult to find ways and areas to cut some of the cost without jeopardizing the integrity of the prototype. With this, it is entirely possible that the budget may swell to multiple hundreds of dollars if the prices of raw materials maintain the fluctuations that have been observed.

The budget has been broken down into the following:

- Nail Gun Rail: $281
- Slide and Rollers: $402
- Hopper: $379
- Motors, Sensors, Misc.: $438

The miscellaneous section of the budget is going towards anything that is not solely found in the prototype itself. This cost comes from purchasing shingles, extra fasteners, 3D printed parts, and other expenses that we do not foresee to expect to run into.

Various manufacturing techniques and constraints were present in the design of the prototype as well. These range from saving money on our budget, to safety, to be simple enough for us to build.

The main design constraint that we used in the modeling of the prototype was budgetary. There are several places in the final design that were altered and decided on to save money. One of the places that this can be seen is the design of the hopper. It was originally decided that the hopper would be encased and made out of sheet metal. Upon researching the price of a piece of sheet metal large enough to be made into the hopper, it was quickly decided to build the hopper shell out of oriented strand board and a cheaper alternative, angle iron.

The next design constraint that went into the SolidWorks model was simplicity. As mentioned previously, the original design for the nail gun rail assembly was for the rail to be attached to a four bar linkage, which would provide easier access to reload the nail guns. This was changed to a simpler linear movement that required less parts and analysis.

Another constraint for our parts and model was the manufacturability of the parts that went into the prototype. A decision to only buy a single thickness of sheet metal was made, and a design around that had to be made to ensure that the parts that needed thicker sheet metal, could be produced from the thinner material. An example of this would be the side flanges of the frame that hold the rollers in place. We expect to be able to fold sections of the sheet metal in half and tack weld the sides in order to produce the shape that we need. It is acceptable if these are not folded flat, as a bushing will be placed in a hole drilled through.

Some factors that led us to decide on the certain parts that are put onto the parts list were the cost, availability, and the potential safety of the prototype. Several websites had warnings on their ordering page if they had limited availability or low stock. These were avoided as the parts' arrival needed to be guaranteed. Some parts were also added to the list to boost the safety of the prototype. Several valves for the nail guns and extra metal tubing are to be purchased to aid the structure and the functionality of the nail guns. This prototype has the main goal of being safe to use.

Prototype Testing

I. Test Plan

The testing plan that we had selected for this product not only tests the mechanical workings, but also the initial constraints that were given by Dr. Nelson. To test this prototype, a mock roof would be constructed out of common framing 2x4s and a sheet of oriented strand board. Instead of a robot to effectively move the prototype around, a rolling chassis was constructed out of the same one inch by one inch square steel tubing as the frame. Casters were mounted underneath this assembly and bolted to the sides of the base of the frame.

To begin the testing and to improve the performance of the module, the cameras and integrated image processing needed to be exposed to different types of shingle arrangements. This would create a catalog of images for the robotic system to interpret and choose the most accurate and efficient adjustment for the shingle being placed.

The testing would have started on the testing platform being flat. This will be equivalent to the minimum angle that the prototype will face. From there, various tests will need to be completed.

The first test would be the cyclic testing of the device. Bales of shingles will be loaded into the hopper and the prototype will be allowed to complete all the functions. The guns will be dry fired against the properly placed shingle to avoid accidents. This test will go through multiple bales of shingles to ensure the mechanisms are properly working, or to pinpoint issues in the design.

The next test that will be conducted will be a simulated test. A shingle will be nailed into the platform for the robot to sense off of, and the robot will be wheeled roughly to where the next shingle will need to be placed. This is similar to the robot that the module will be attached to, as the constraint for the robot is to get the module to within one inch of the desired location in two axes.

This module must be able to place hundreds of shingles in a row without fault or failure. In addition to the internal mechanism not faltering, the shingles must be placed in a straight row. If each shingle placed has a constant offset of a half inch, the start and end of the row of shingles can potentially be offset by a foot or more. This is unacceptable for roofing and will cause a huge loss of profit.

For these tests to be determined to be a success, there are very specific parameters that the results must fall under. For the cyclic testing, we estimate that 500 shingles should be run through, start to finish, in order to be deemed a success. For the simulation testing, the robot should be capable of adjusting the next shingles placement based on previous shingles positioning. This must provide a straight line with very little gap or angular difference in reference to the previous shingle.

II. Test Execution

Each subsystem in the module was tested individually and no full system test was completed with the time constraints. Each system test was a proof of concept and functionality instead of an endurance or cyclical test.

For the Hopper and shingle feeding system multiple shingles were dropped down the slide with the assistance of the roller wheels to move it onto the roof for the alignment fingers to align the shingle. We tested the fingers separately from the camera, since it was in learning mode.

The actual testing that was conducted was more “proof of concept” testing. The individual modules were tested by themselves, as opposed to an entire system test. This will still need to be performed, to see how each module interfaces with each other. As of right now, a shingle has not been loaded, placed, and nailed in place at the same time. As of the end of this phase of design and building, we have deemed our smaller tests as success.

III. Test Results/Analysis/Recommendations

Tipping Axis Analysis:

Our initial goal was to have the prototype be able to perform on 12/12 pitch roofs, which sit at a 45 degree incline. This goal fell short by a couple degrees, and it was determined that the maximum operating angle is 40 degrees. Figure 7 in Appendix III shows a geometric analysis of the envelope of the prototype to determine the tipping axis for the two extreme centers of mass. The coordinates of the center of mass were found in SolidWorks mass properties, which give a precise point. The figure drawn in Autocad is to scale. The first line that was drawn was 45 degrees from the axis of tip rotation, located at the very bottom left of the robot. The center of mass was located on the left side of the line, indicating that the center of masses would be on the tipping side of the axis. Another line was drawn corresponding to a 40 degree angle, and both centers of mass were on the right side of the line, indicating that the robot would not tip over when subjected to that corresponding pitch of the roof.

Alignment Finger Analysis:

The max bending stress equation is pulled directly from Shigley’s Engineering Design to find what amount of stress is being applied to the PLA fingers. The provided information of motor rpm and the gear tooth thickness that drive the fingers, coupled with the assumed force required of 5 pounds of force to slide the shingle gives a value that is under the defined yield strength of the plastic.

A FEA analysis of the alignment fingers was also done. The results of this can be seen below in the Appendix. The overall dimensions of the alignment fingers were determined by the constraints to be able to position the shingle one inch. For the sake of simplicity of the gear design, the pitch circle of the spur gear for the fingers was defined at one inch in diameter because the servo can function a total of 180 degrees. This makes the overall travel of the fingers a total of approximately one and a half inches which is more than the stated requirement of one inch of travel of the shingles. Many iterations of FEA tests were done to optimize the design strength and minimize the mass of PLA (polylactic acid). This was done by adjusting dimensions and adding filets to reduce stress concentrations. A safety factor of 3.5 was achieved. This is a relatively high safety factor, but it was deemed effective to reduce localized stresses between 3D printed layers. A displacement analysis was done for the alignment fingers too. This analysis showed that error from displacement from stresses was negligible.

Design Optimization

There are a few areas of interest that need to be optimized in order to unlock the full potential of the prototype. The first area of optimization would be to lower the center of mass in order to achieve the 12/12 pitch roof without tipping. This could be done in several ways, including reducing the weight of the hopper, or reallocating some of the weight to be put towards the bottom of the frame. The electronics and pneumatic controls could be put under the slide to shift the center of mass. Another option would be to change the orientation of the nail guns, to shift that weight away from the tipping axis.

Another way to optimize the prototype would be to construct it out of better materials than what it currently is. The plywood and particle board can be changed out to sheet metal, or even expanded metal in situations where weight saving is crucial. The cardboard slide can also be changed out to sheet metal, as originally designed, to lower the coefficient of friction between the two surfaces. The 3-D printed parts can also be swapped out for machined metal parts, in order to prevent parts breaking, and to avoid excess wear at metal and plastic interfaces.

Another issue that we ran into, which can be easily solved, would be to purchase an additional Pixy camera. This would help improve the accuracy of the placed shingles, and eliminate unwanted gaps.

The main way that this prototype could be improved would be to rewire the robotics, and mount larger motors and servos. This would come at the cost of a higher electrical load, but the converter that has been mounted would have no problem handling the increased load. Improved wiring would be needed as well, since there are some lower gauge wire running in parallel, as larger gauge wire ran out. A new controls system would also be valuable, in order to help simplify the construction. Better motor drivers and a better microcontroller would help eliminate the daisy chained control system. We used what was available, at the cost of simplicity.

Conclusions and Recommendations

The conclusions of this project are below. These conclusions and recommendations would make this project an innovative and potentially marketable and useful device to minimize safety issues of the

1. Continue the project after a redesign
2. Sheet metal should be used instead of a cardboard slide
3. Other more robust microcontroller solutions should be accessed
4. Two Pixy cameras should be used (on opposite corners of the shingle
5. Testing to include other shingle separation (especially for stuck shingles) means should be done
6. This project should be divided into two groups to allow for detailed design of all systems
7. Robust software systems should be made to run each sub-system individually manually as well as automatically run all systems cyclically

References

Budynas, Richard G., et al. *Shigley's Mechanical Engineering Design*. McGraw-Hill Education, 2021.

Causes of roofer deaths. elcosh. (n.d.). Retrieved May 5, 2022, from https://elcosh.org/document/1428/d000491/causes-of-roofer-deaths.html

Travieso-Rodriguez, J Antonio, et al. “Mechanical Properties of 3D-Printing Polylactic Acid Parts Subjected to Bending Stress and Fatigue Testing.” *Materials (Basel, Switzerland)*, MDPI, 22 Nov. 2019, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6926899/.

Individual Contributions

Carter McCormick - First Semester Team Lead, Executive Summary, Design Concepts, Decision Matrices & Evaluation, Final Design Concept, Final Design Package, Prototype Manufacturing, Prototype Testing, Design Optimization/Retest, References

Isaac Klar - Problem Statement, Design Concepts, Decision Matrices & Evaluation, Final Design Concept, Final Design Package, Prototype Manufacturing, Prototype Testing, Design Optimization/Retest

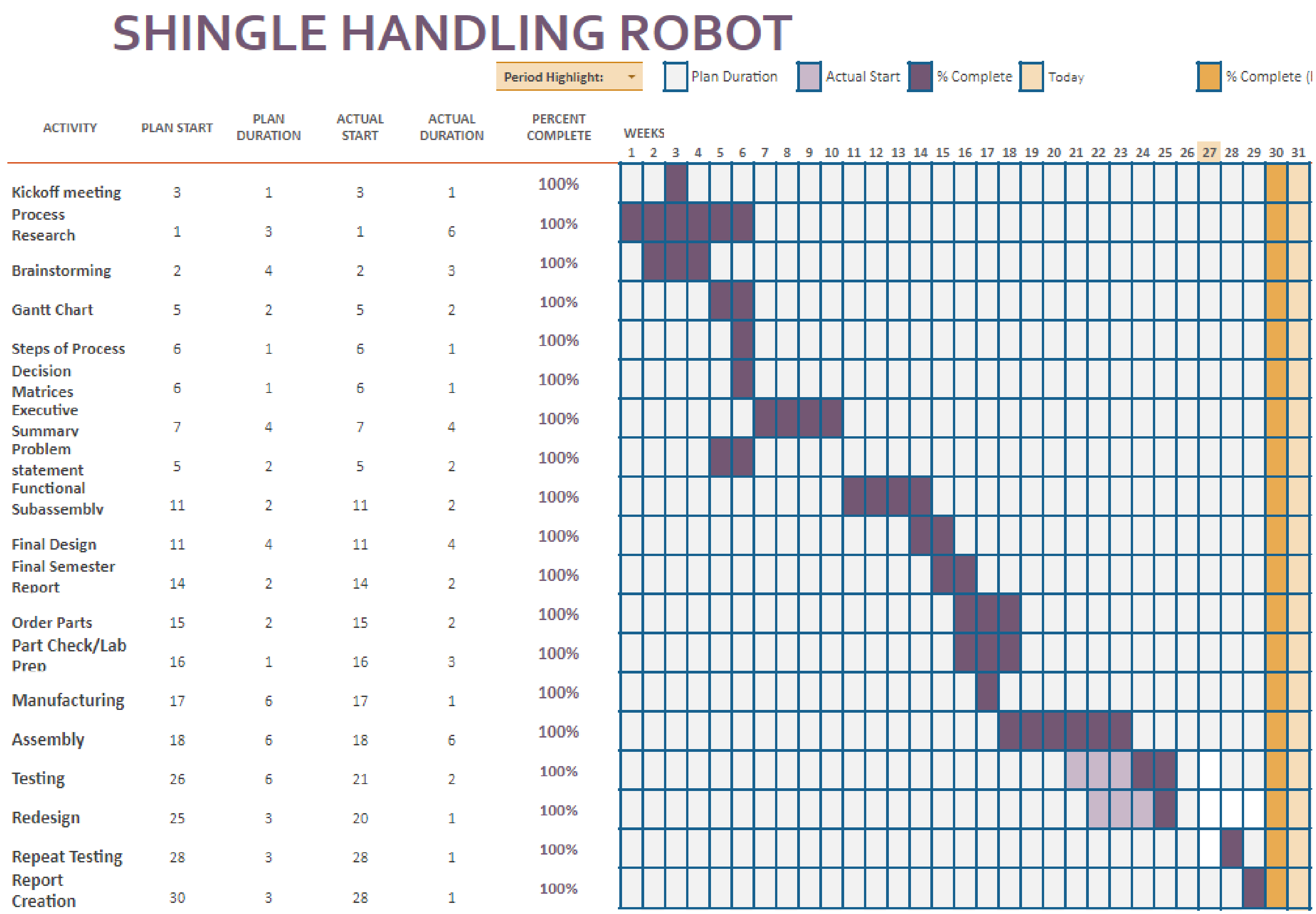
Brandon Kusek - Design Concepts, Decision Matrices & Evaluation, Final Design Concept, Final Design Package, Prototype Manufacturing, Prototype Testing, Design Optimization/Retest

River Kramer - Second Semester Team Lead, Background, Project Timeline, Design Concepts, Decision Matrices & Evaluation, Final Design Concept, Final Design Package, Prototype Manufacturing, Prototype Testing, Design Optimization/Retest, References, Appendices

Victoria Nelson - Design Concepts, Decision Matrices & Evaluation, Final Design Concept, Final Design Package, Prototype Testing

Appendices

I. Appendix I (Gantt Chart)



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Kickoff meeting	3	1	3	1	100%
Process Research	1	3	1	6	100%
Brainstorming	2	4	2	3	100%
Gantt Chart	5	2	5	2	100%
Steps of Process	6	1	6	1	100%
Decision Matrices	6	1	6	1	100%
Executive Summary	7	4	7	4	100%
Problem statement	5	2	5	2	100%
Functional Subassembly	11	2	11	2	100%
Final Design	11	4	11	4	100%
Final Semester Report	14	2	14	2	100%
Order Parts	15	2	15	2	100%
Part Check/Lab Prep	16	1	16	3	100%
Manufacturing	17	6	17	1	100%
Assembly	18	6	18	6	100%
Testing	26	6	21	2	100%
Redesign	25	3	20	1	100%
Repeat Testing	28	3	28	1	100%
Report Creation	30	3	28	1	100%

Figure 1: Shingling Robot Module Project Timeline for Fall 2021/Spring 2022

II. Appendix II (Final Design Package & Costs)

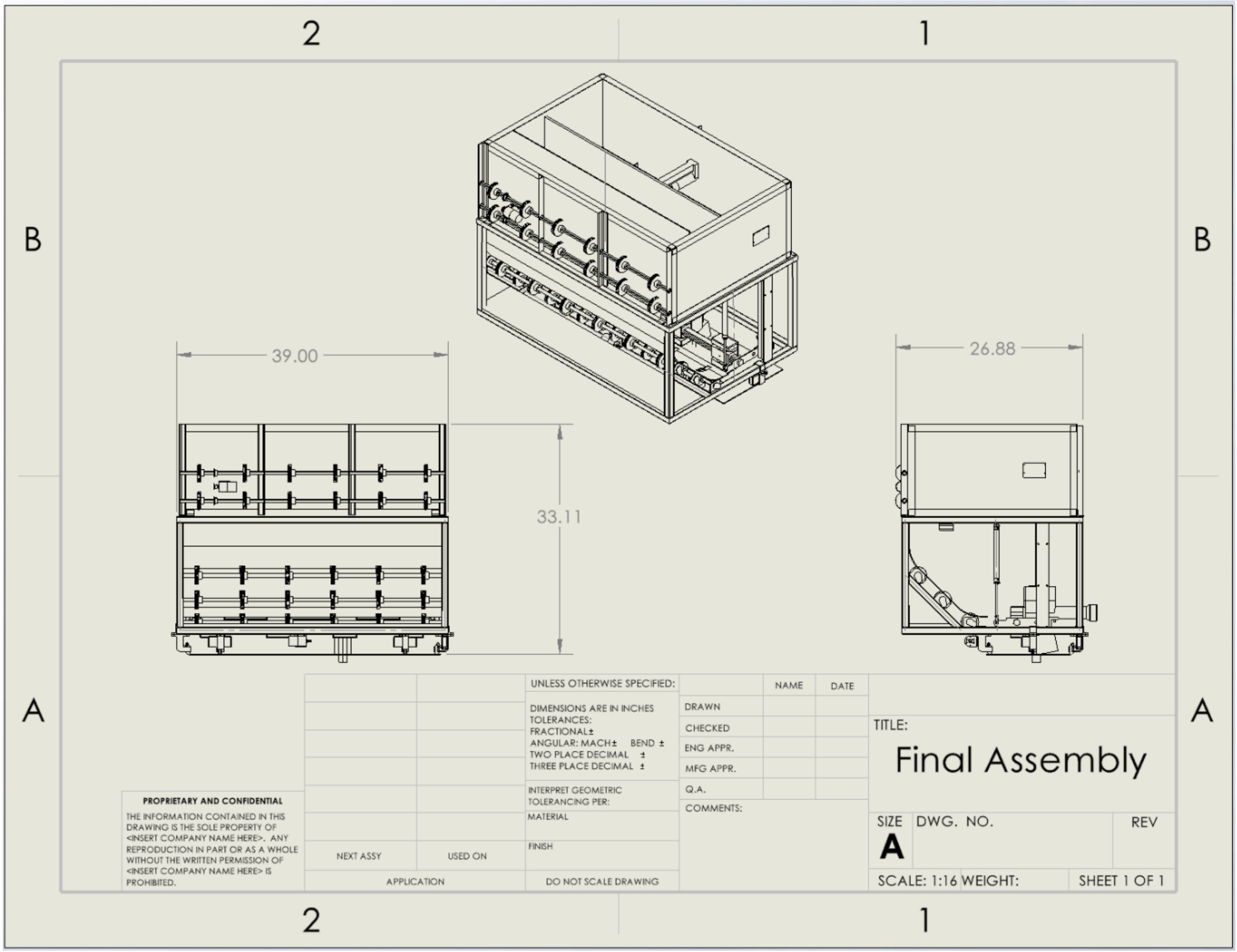


Figure 2: Complete Final Assembly of Shingling Robot Module

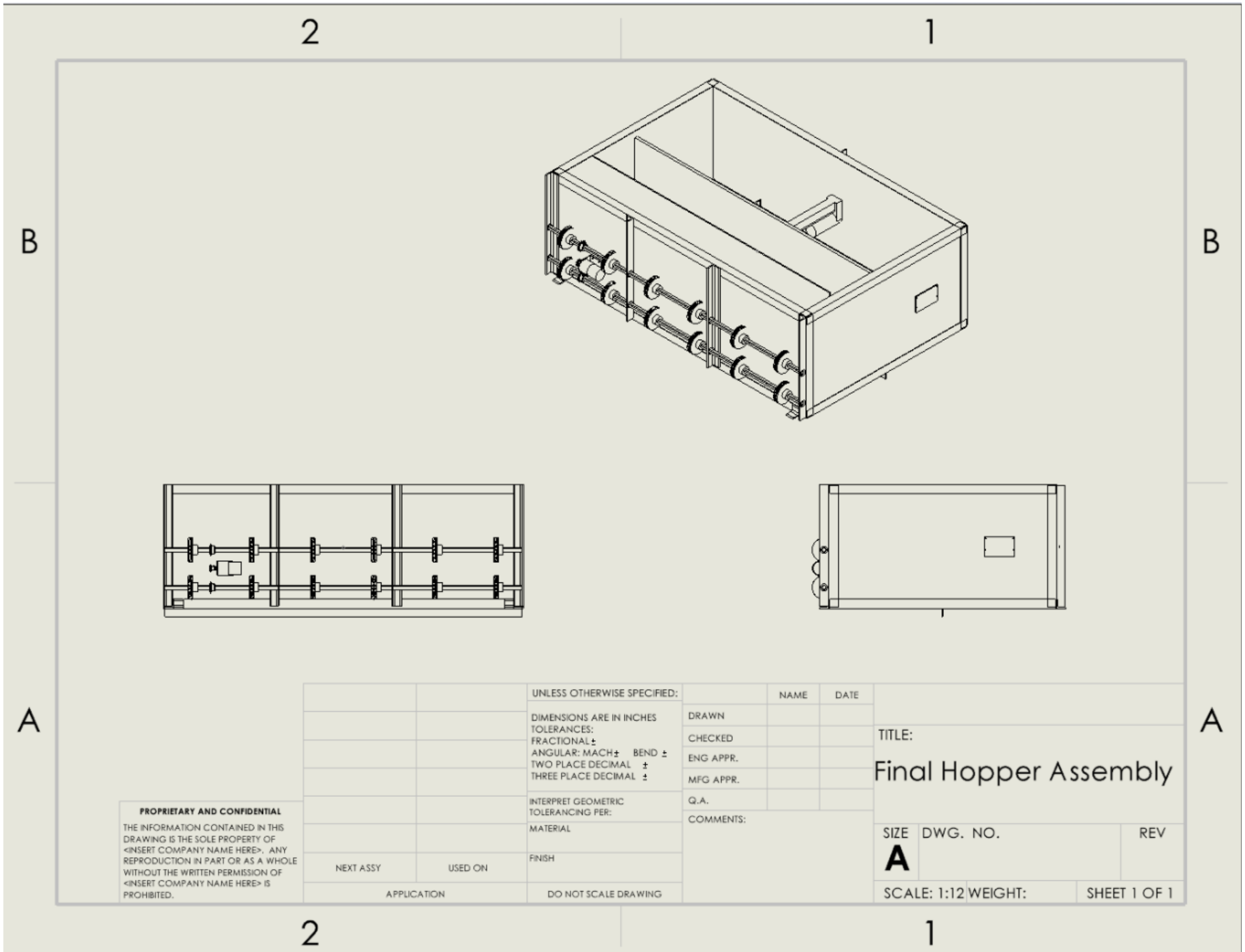


Figure 3: Final Hopper Assembly of Shingling Robot Module (Top Module)

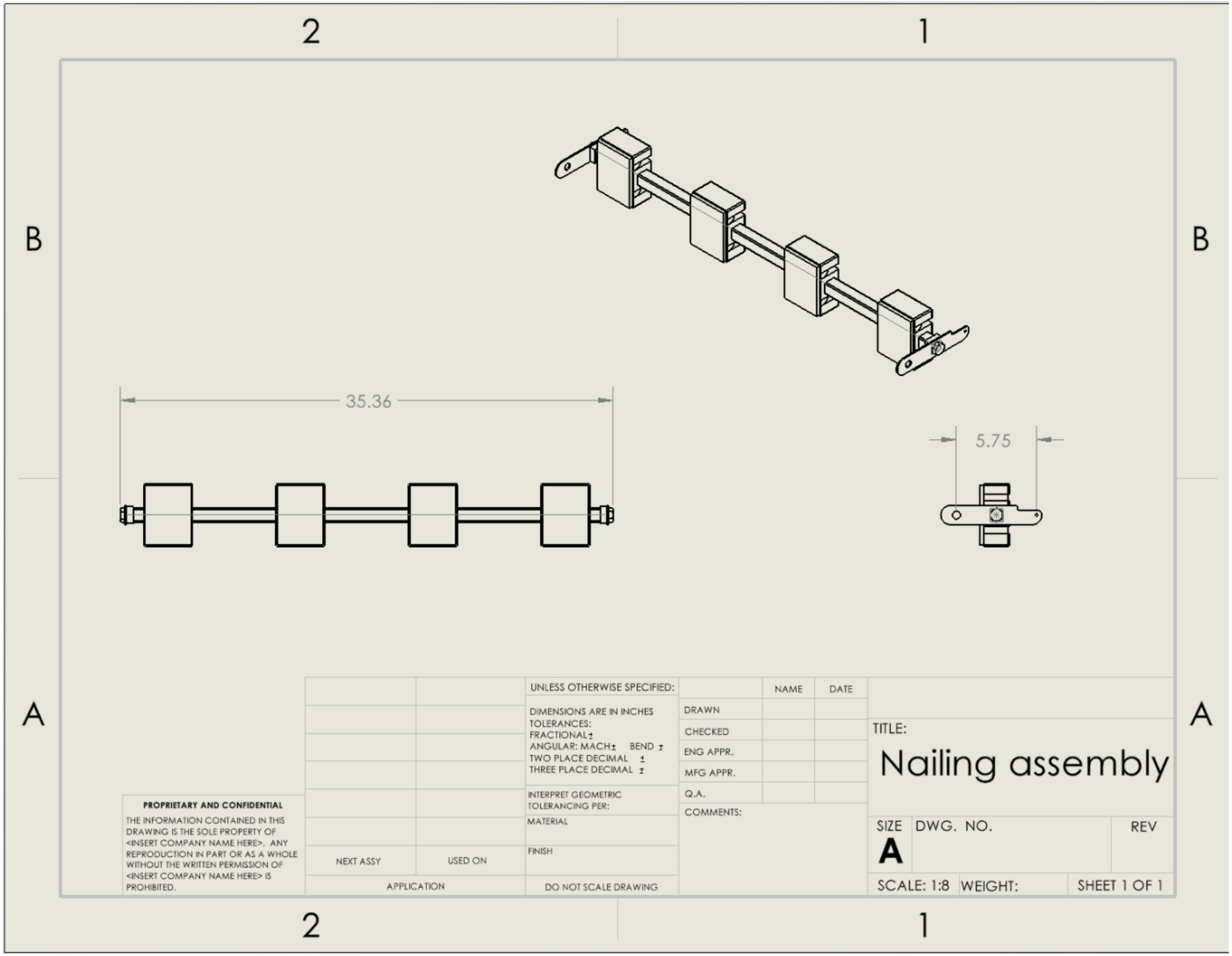


Figure 4: Final Nailing Assembly of Shingling Robot Module (Within Lower Module)

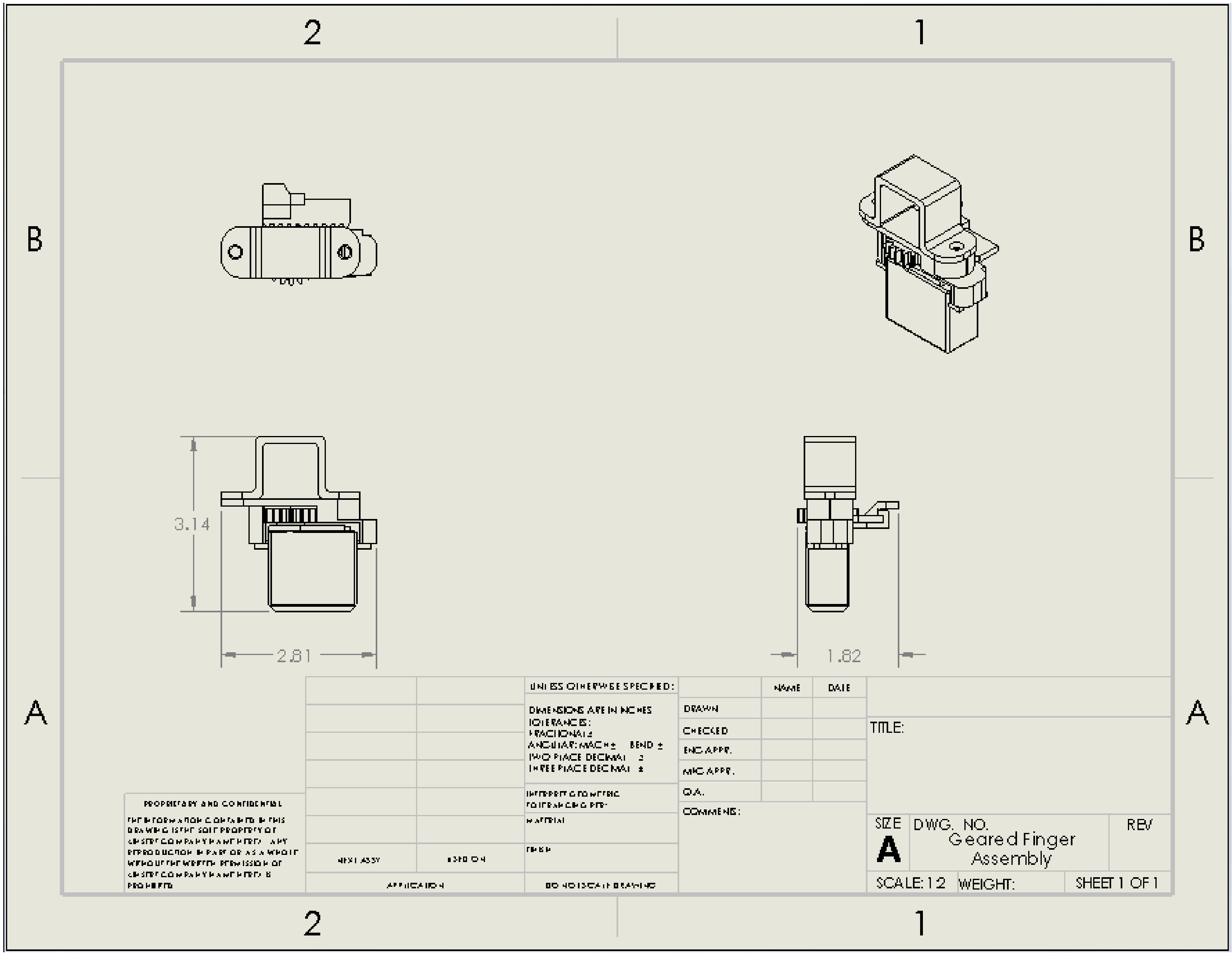


Figure 5: Final Finger Assembly of Shingling Robot Module (Attached to Lower Frame Module)

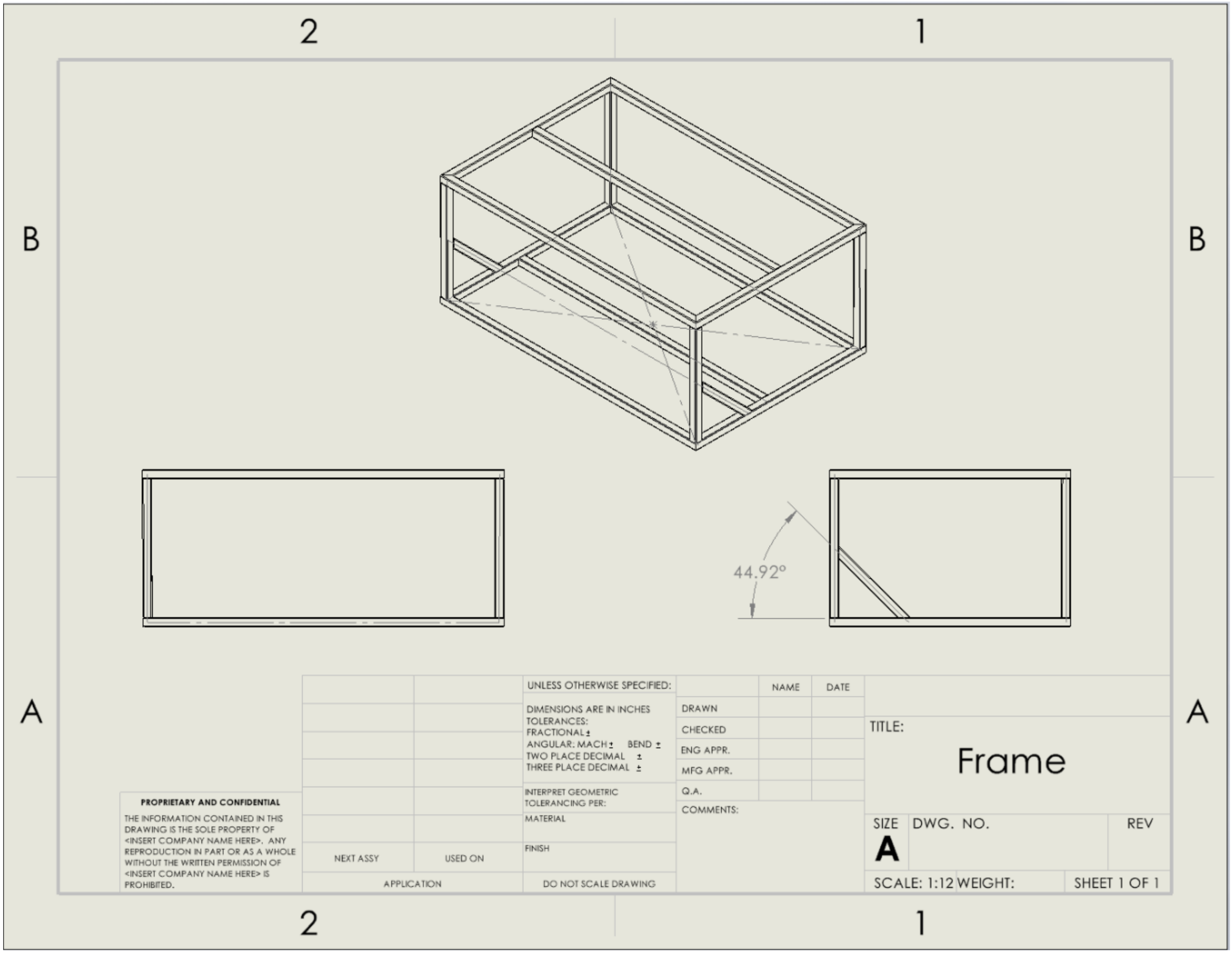


Figure 6: Final Frame Assembly of Shingling Robot Module (Lower Module)

Part:	Supplier:	Part #	Part Link:	Quantity	Cost per Unit	Total Cost:	Order Status/Location:
Cylinder	Amazon		https://www.amazon.com/Tailonz-I	2	$17.99	$35.98	Arrived/Assembled
Gun Valve	Amazon	AOMAG 3/8"	https://www.amazon.com/AOMAG	1	$28.99	$28.99	Arrived/Assembled
Cylinder Valve	Amazon	TAILONZ 4V310-10 *(12V w/ 3/8 fitting)	https://www.amazon.com/Pneuma	1	$18.99	$18.99	Arrived/Assembled
Linear Slides	Amazon	SBR12-39.37in *(Style: 2-SBR12 UU)	https://www.amazon.com/Mssoom	1	$80.99	$80.99	Arrived/Assembled
1x1 Square Tubing (6 ft)	McMaster Carr	6527K174	https://www.mcmaster.com/catalo	7	$22.38	$156.66	Arrived/Assembled
Hopper Actuator	Amazon		https://www.amazon.com/Zoom-In	1	$67.95	$67.95	Arrived/Assembled
Drawer Slides	Amazon		https://www.amazon.com/YENUO	1	$13.90	$13.90	Arrived/Assembled
Gate Servos	Polulu		https://www.pololu.com/product/28	2	$4.25	$8.50	Arrived/Assembled
Gate Rack and Pinion	Digikey		https://www.digikey.com/en/produ	2	$6.74	$13.48	Arrived/Assembled
25 Chain (10 ft.)	Amazon		https://www.amazon.com/PGN-Ro	1	$16.70	$16.70	Arrived/Assembled
Upper Roller Motor	Amazon		https://www.amazon.com/Grea	1	$14.99	$14.99	Arrived/Assembled
Lower Roller Motor	Amazon		https://www.amazon.com/Greartis	1	$14.99	$14.99	Arrived/Assembled
D-Shafts	McMaster Carr	8632T11	https://www.mcmaster.com/rotary-	5	$32.86	$164.30	Arrived/Assembled
Sprocket	McMaster Carr	2737T1	https://www.mcmaster.com/2737T	2	$11.48	$22.96	Arrived/Assembled
Sprocket	McMaster Carr	2737T107	https://www.mcmaster.com/2737T	3	$13.29	$39.87	Arrived/Assembled
1/4 x 1" Bolt and Nut	Home Depot		We will pick these up ourselves			$0.00	Arrived/Assembled
2.5 mm x 20 mm Bolt and Nut	Home Depot		We will pick these up ourselves			$0.00	Arrived/Assembled
1/4" x 2" Bolt and Nut	Home Depot		We will pick these up ourselves			$0.00	Arrived/Assembled
Pixy Camera	Amazon		https://www.amazon.com/gp/produ	1		$0.00	Arrived/Assembled
Power Converter			https://outriggeroutdoors.com/proc	1	$39.99	$39.99	Arrived/Assembled
LCD Display	Adafruit		https://www.adafruit.com/product/7	1	$19.95	$19.95	Arrived/Assembled
Roller Motor Mount	Amazon		https://www.amazon.com/Mountin	2	$8.99	$17.98	Arrived/Assembled
3" Casters	Caster HQ	24CS314PPU34Z-02	https://www.casterhq.com/3-Inch-I	4	$9.89	$39.56	Arrived/Assembled
Motor Drivers (2 pc)	Amazon		https://www.amazon.com/BTS796	1	$13.99	$13.99	Arrived/Assembled
Finger Servos	Amazon		https://www.amazon.com/Control-	2	20.99	41.98	Arrived/Assembled
3D Printed Wheels	3D Print	2 Spools PLA		25-30	$99.95	$99.95	Arrived/Assembled
				Budget Spent:	$1,452.54		

Figure 7: Final Bill of Materials and Budget Spent

III. Appendix III (Final Design Analysis)

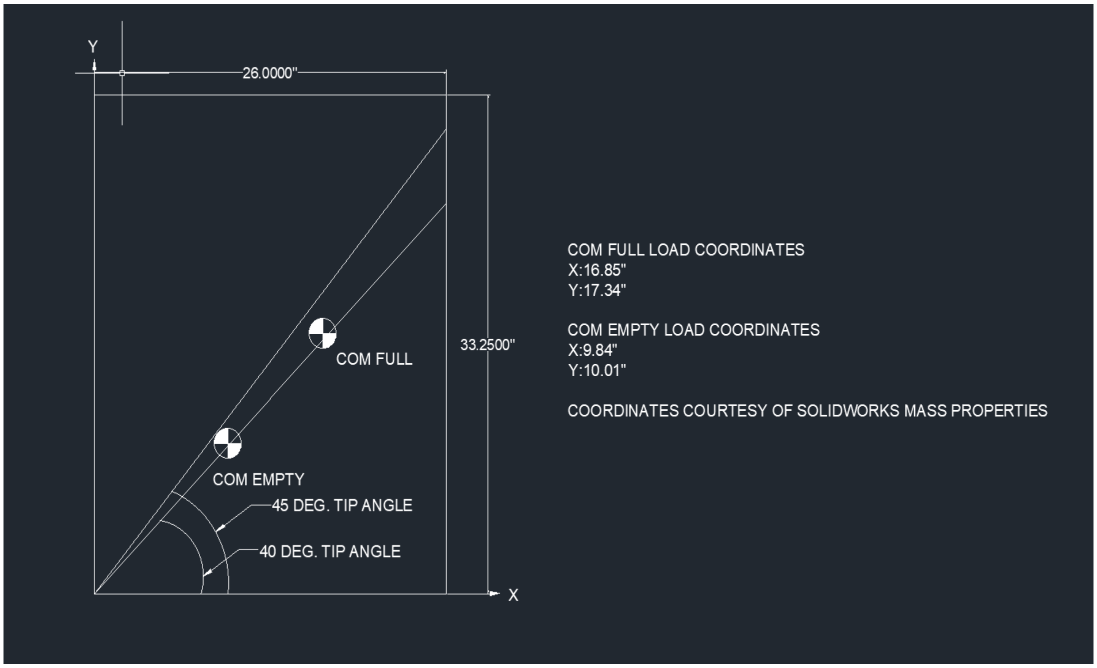


Figure 8: Shingle Robot Center of Gravity Tipping Axis Analysis

$$\sigma_{\max bending} = \frac{Tangential\ Force * Dynamic\ Factor * Overload\ Factor * Distribution\ Factor}{Geometry\ Factor * Module * Tooth\ Width}$$

Where: $Module = \frac{Pitch\ \phi}{n}$ $\quad$ $Tangential\ Force = \frac{2\tau}{\text{Pitch}}$

Where: $\tau = \frac{60 * p_o}{2\pi * rpm}$ $\quad$ Rpm = 46.8 (from specifications)

Where $p_o = \frac{2p}{\pi a}$ =83 psi $\quad$ a = width of half of a tooth = .0379 in

So: $\tau = 1.425\ lbft$ $\quad$ and Tangential force = 24.05 lbf

Resulting in $\sigma_{\max bending} = 8245.71\ PSI/2$ Servos = 4122.85 PSI/tooth

Which is approximately 45% the yield strength of PLA

Figure 9: Shingle Robot Rack/Pinion Gear Fingers Stress Analysis

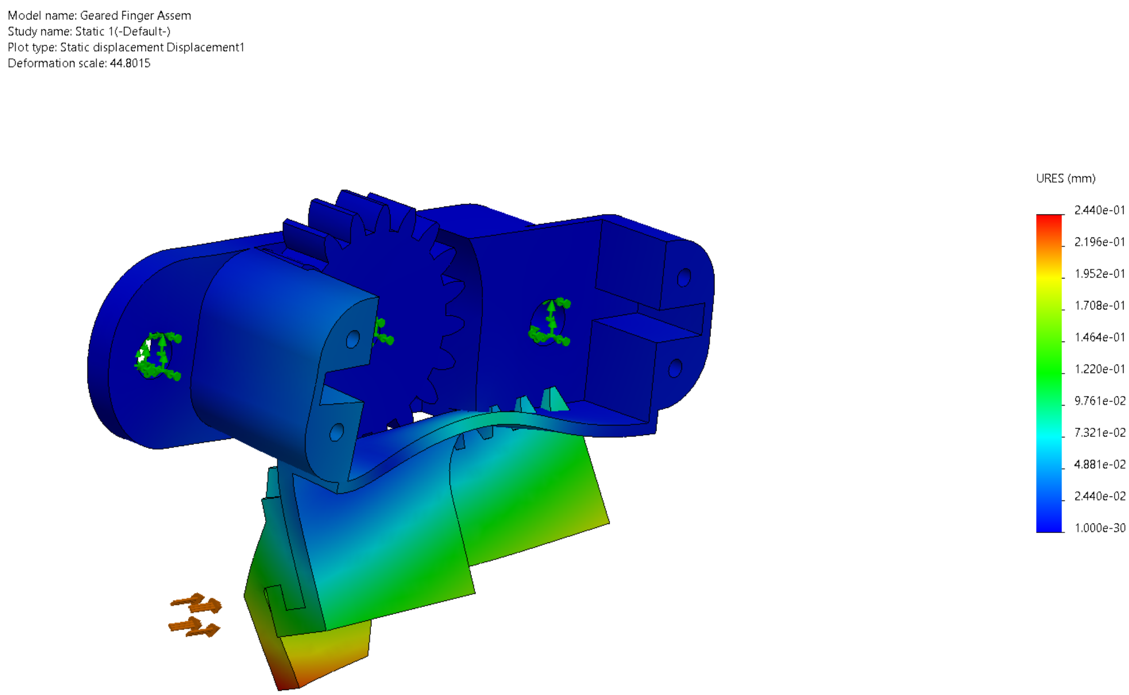


Figure 10: Shingle Alignment Fingers Displacement Analysis

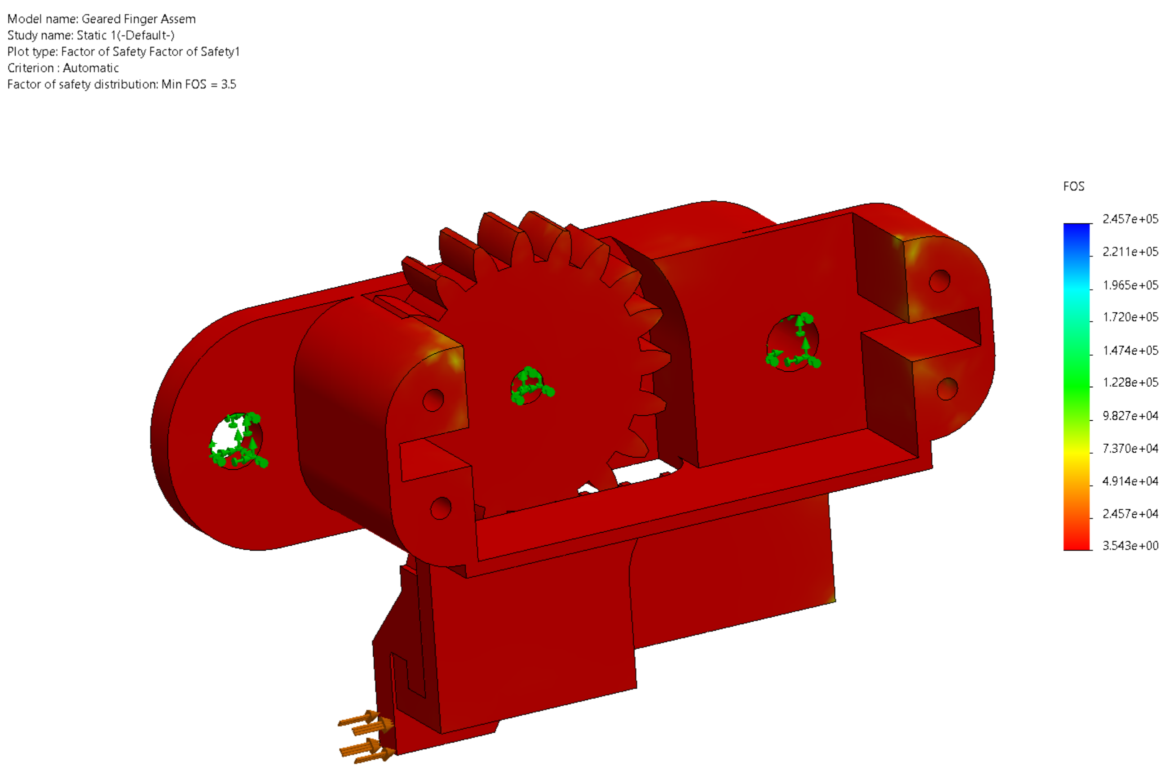


Figure 11: Shingle Alignment Fingers Factor of Safety Analysis

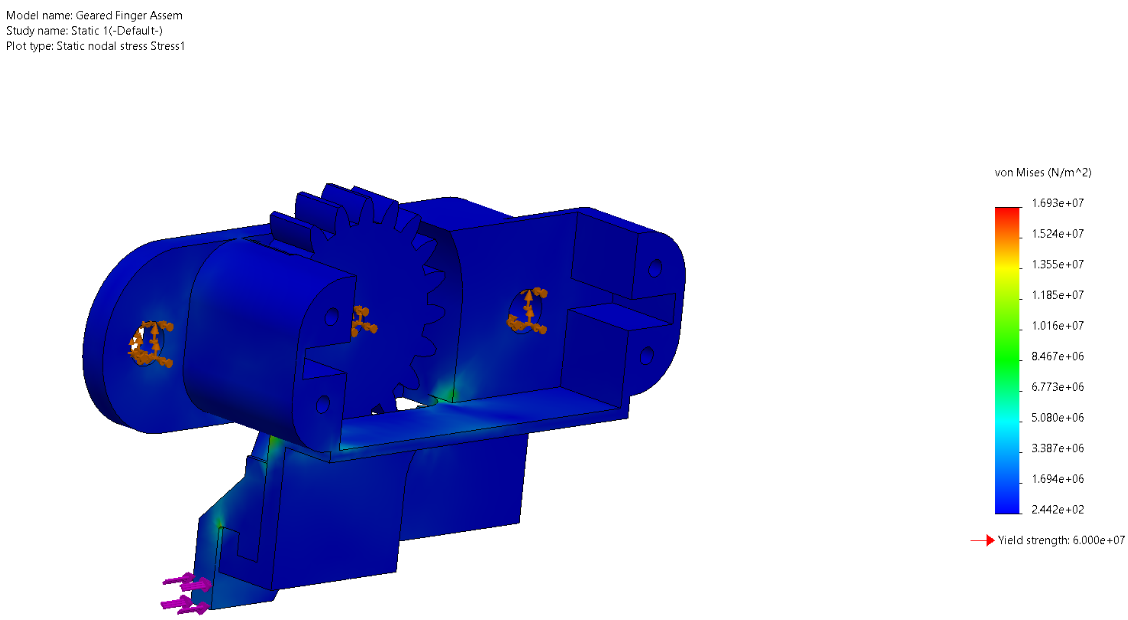


Figure 12: Shingle Alignment Fingers Von Mises Stress Analysis

IV. Appendix IV (Electrical Diagrams/Programming)

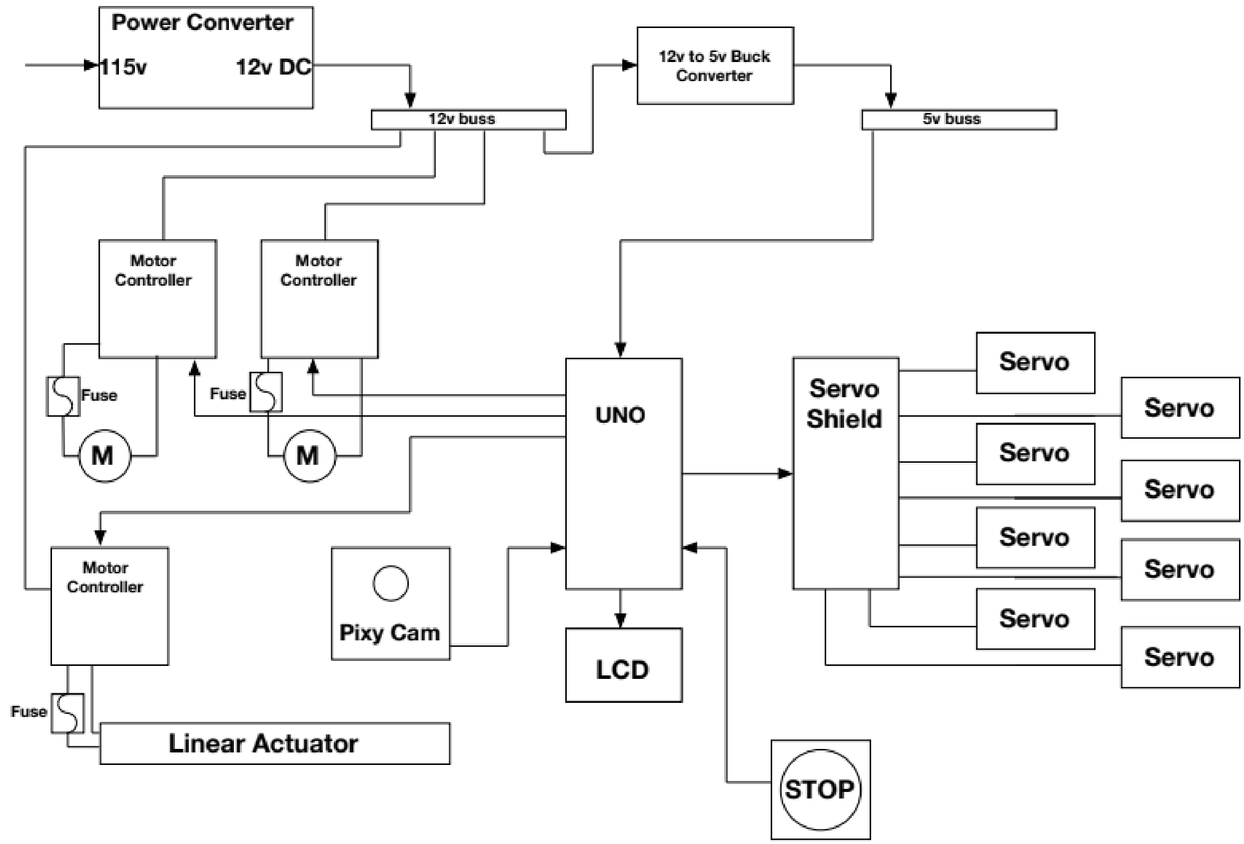


Figure 13: Shingle Alignment Robot Full Wiring Diagram for Electrical Operation

```
#include <SPI.h>
#include <Pixy2.h>
#include <Servo.h>

Pixy2 pixy; //This is the main Pixy object

Servo myservo1; //create servo object to control a servo
Servo myservo2; //create servo object to control a servo
Servo myservo3; //create servo object to control a servo
Servo myservo4; //create servo object to control a servo
Servo myservo5; //create servo object to control a servo
Servo myservo6; //create servo object to control a servo
Servo myservo7; //create servo object to control a servo
Servo myservo8; //create servo object to control a servo

int motor1aPin = 5; //for top motor
int motor1bPin = 6; //for top motor
int motor2aPin = ; //for bottom motor
int motor2bPin = ; //for bottom motor
int solenoid1Pin = ; //for solenoid for nail gun
int solenoid2Pin = ; //for solenoid for nail gun
int linearActuatorA = 7;//for linear actuator
int linearActuatorB = 8;//for linear actuator

void setup()
{
  pinMode(motor1aPin, OUTPUT); //for top motor
  pinMode(motor1bPin, OUTPUT); //for top motor
  pinMode(motor2aPin, OUTPUT); //for bottom motor
  pinMode(motor2bPin, OUTPUT); //for bottom motor
  pinMode(solenoid1Pin , OUTPUT); //for solenoid
  pinMode(solenoid2Pin , OUTPUT); //for solenoid
  pinMode(linearActuatorA, OUTPUT); //for linear actuator
  pinMode(linearActuatorB, OUTPUT); //for linear actuator
  myservo1.attach(); //attaches the servo on pin _ to the servo object
  myservo2.attach(); //attaches the servo on pin _ to the servo object
  myservo3.attach(); //attaches the servo on pin _ to the servo object
  myservo4.attach(); //attaches the servo on pin _ to the servo object
  myservo5.attach(); //attaches the servo on pin _ to the servo object
  myservo6.attach(); //attaches the servo on pin _ to the servo object
  myservo7.attach(); //attaches the servo on pin _ to the servo object
```

```
  myservo8.attach(); //attaches the servo on pin _ to the servo object


  Serial.begin(9600);
  pixy.init();
}

void loop()
{

  pixy.ccc.getBlocks(); //grab blocks! for shingle
  pixy.ccc.blocks[Target].m_x > 140
  pixy.ccc.blocks[Target].m_y > 95

  // gate opens
  myservo1.write(180); //values between 0 and 180
  delay(100);

  // top motor on
  digitalWrite(motor1aPin, 255); //values between 0 and 255
  delay(100);

  // linear actuator pushes then stops
  digitalWrite(linearActuatorA, LOW);
  digitalWrite(linearActuatorB, LOW);
  delay(100);
  digitalWrite(linearActuatorB, HIGH);
  delay(3000);
  digitalWrite(linearActuatorB, LOW);
  delay(100);

  // top motor off
  digitalWrite(motor1aPin, 0);
  delay(100);

  //gate closes
  myservo1.write(0); //values between 0 and 180


  // bottom motor on
```

```
    // bottom motor on
    digitalWrite(motor2aPin, 255); //values between 0 and 255
    delay(200);

    // fingers allign
    myservo1.write(180); //values between 0 and 180
    myservo2.write(180); //values between 0 and 180
    myservo3.write(180); //values between 0 and 180
    myservo4.write(180); //values between 0 and 180
    myservo5.write(180); //values between 0 and 180
    myservo6.write(180); //values between 0 and 180

    // bottom motor off
    digitalWrite(motor2aPin, 0); //values between 0 and 255
    delay(200);

    // 4 bar actuator down
    digitalWrite(solenoid1Pin, HIGH);// turn solenoid on
    delay(200);

    // nail gun on and off
    digitalWrite(solenoid2Pin, HIGH);// turn solenoid on
    delay(200);
    digitalWrite(solenoid2Pin, LOW); //turn solenoid off
    delay(200);

    // finger servos home
    myservo1.write(0); //values between 0 and 180
    myservo2.write(0); //values between 0 and 180
    myservo3.write(0); //values between 0 and 180
    myservo4.write(0); //values between 0 and 180
    myservo5.write(0); //values between 0 and 180
    myservo6.write(0); //values between 0 and 180
    delay(100);

    // 4 bar up
    digitalWrite(solenoid1Pin, LOW); //turn solenoid off
    delay(200);

  }
```

Figure 14: Shingle Alignment Robot Full Software Code for Servo/Actuator/Piston Operation