

Final Report: Automated Shingling Robot

*Team RiPUS: Roboticists Involved in Putting Up Shingles
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1. Problem Description

Roofing is a strenuous and tiring job. It involves repetitive climbing, bending, lifting and nailing. All of these activities performed on a roof lead to a dangerous environment. Taking this into consideration it is no surprise that work-related injuries for roofers are among the highest of all occupations. Many of these injuries prove to be severe and some result in a loss of life. According to the 2010 Bureau of Labor Statistics, falls represented more than 40% of the fatal accidents among roofers. ^[1] The "National Census of Fatal Occupational Injuries in 2011" reported roofing to be the fourth most dangerous job in America. 70 workers involved in roofing died in 2012, a 17% increase from the previous year. ^[2] Figure 1 shows the primary cause of fall fatalities in construction from 2008-2010 compiled by The Center for Construction, Research and Training. Falls from roofs account for one-third of all fatal falls.^[3]

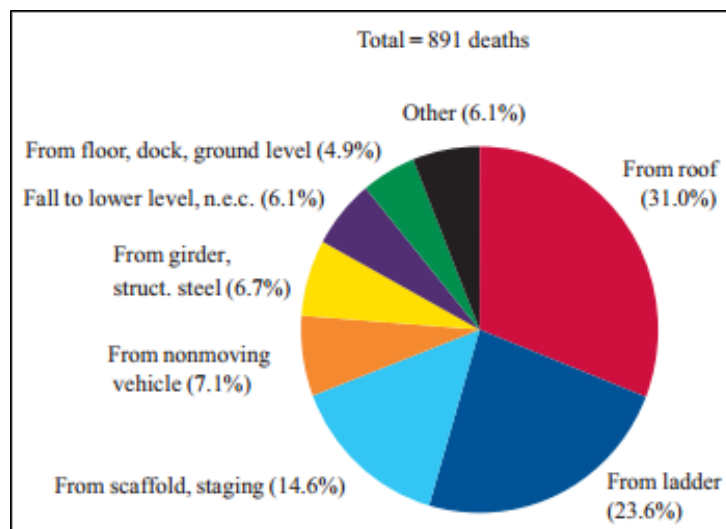


Figure 1 : Falls from roofs accounting for one-third of all fatal falls in construction (2008-2010)

Fatalities have been reduced, thanks to safety measures such as ensuring good condition of safety harnesses and roof barriers, however roofing is still a high risk job. These injuries not only

affect the worker but the company. Economic impact due to accidents in the construction industry is striking. Over 400k working days have been lost in this industry due to injuries or fatalities from 2006 to 2008. [4]

Shingling is a monotonous and dangerous part of the roofing job, it is better suited for a robotic implementation. We aim to build a system that autonomously shingles a roof with minimal human intervention. Place the robot on the roof with access to a stack of shingles and take it off the roof once it's finished shingling! This would not only reduce the risk of injuries, but also result in improved quality and significant savings in cost and time.

2. Use Case

Mr. Smith, a construction and roofing company owner in Pittsburgh, PA, is just about to start his first shingling job with his new automated shingling system from RiPUS. During the first few weeks of ownership, a RiPUS representative familiarized Mr. Smith with safe operation of his new system. The automated shingling system will allow Mr. Smith to send a single employee, who has been trained on the system, to shingle a house. The system is designed to autonomously shingle a roof with standard three-tab asphalt shingles. The system includes a robot and an off-board monitoring system that will allow the employee to monitor progress.

Mr. Smith ensured the roof was covered in roofing felt and all debris was removed from the roof. The roof pitch has been calculated as less than 30-degrees and the roof is a simple rectangle. Mr. Smith has checked the forecast to ensure no inclement weather, such as rain or snow will impact the robot.

The robot is unloaded from the truck and placed at the lower edge of the roof using a fork lift. Mr. Smith loads shingles into the robot's hopper, ensures that the nail slides are full and all personnel are removed from the roof, and the system is attached to his compressor. He presses the 'Start' button, the robot checks its subsystems and the robot illuminates the ready signal on the off-board monitoring system.

The robot begins by determining the roof edge location's with its sensors and lays its first shingle. The shingle is affixed with four nails at each tab corner. The robot continues laying and nailing shingles, moving along the roof and placing shingles with .75" gap between each shingle. When robot reaches the end of the roof it automatically calculates the size of shingle needed to complete the row. The robot cuts, lays and nails the row end shingle. Once the row is completed the robot moves up to the next row and begins laying along the next row. At the end of each row the robot performs the same calculation to size the shingles. Partway through the job the robot senses it has run out of shingles. The robot sends a signal to the off-board monitoring system, informing Mr. Smith shingles need to be added. The robot maneuvers back to the home side for shingles to be placed in its hopper. Once the shingles have been refilled, Mr. Smith sends the 'resume' command to the robot. The robot returns to the shingling position where the last shingle

was placed and resumes the shingling job. Once the roof has been completely shingled the robot sends the 'finished' signal to the off-board monitoring system and returns to the home side.

Mr. Smith is informed by the off board controller the robot has completed the first side of the roof. He then moves the robot to the opposite side of the roof and the same process is repeated to finish the other half of the roof. Once the entire roof has been completed Mr. Smith examines the quality of the roofing job the robot has done. He is satisfied to see the job is of the same quality as one his crew would have created and was completed in a third of the time.

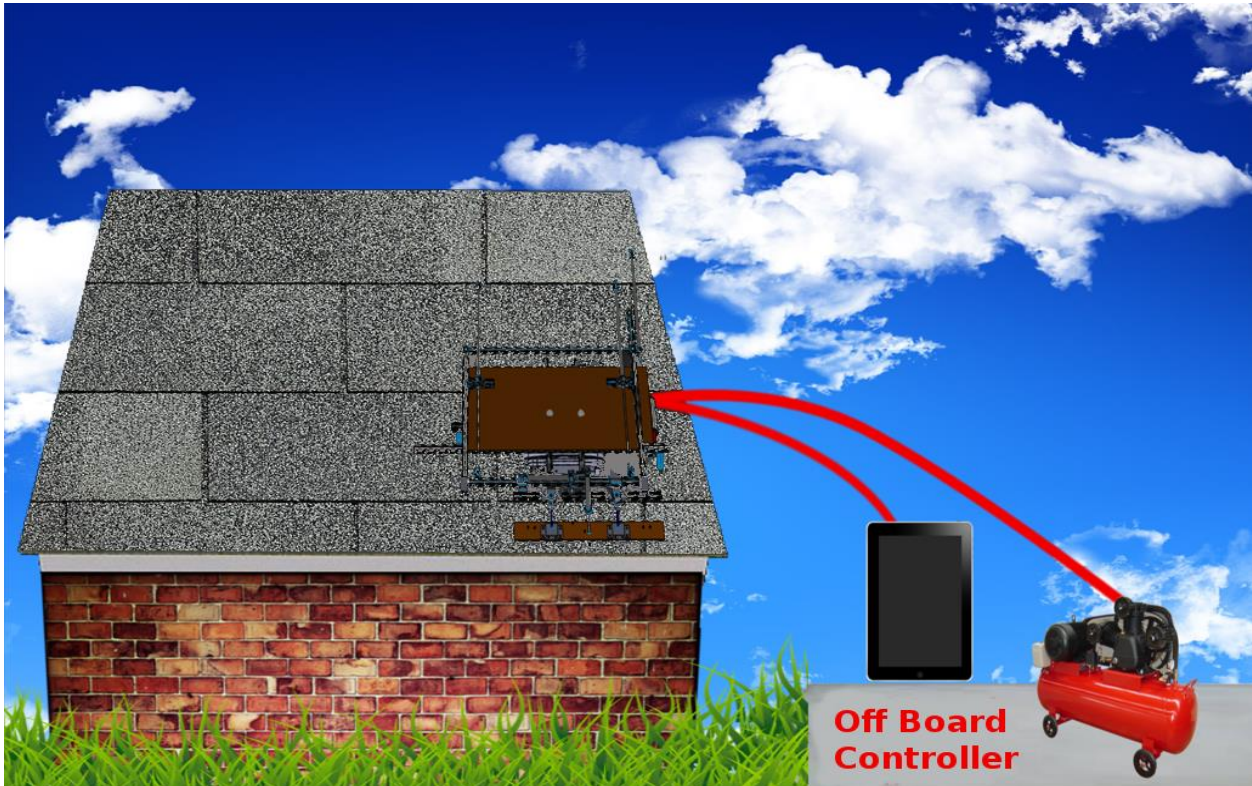


Figure 2: Use Case of RiPUS Autonomous Shingling Robot

3. System Level Requirements

3.1 Mandatory Non-Functional Requirements

3.1.1 Robust Construction

- The robot shall be able to withstand normal operation on the roof without malfunctioning, including but not limited to handling and storage of materials like shingles etc. It also must not lose pieces, like nails for instance, or break parts during operation.

3.1.2 Operate on Roofs with Different Pitch

- The robot shall operate satisfactorily on roofs with a constant pitch of up-to 30°. It must not drive off or fall off the edge. It should also be able to drive in a straight line while maintaining stability.

3.1.3 Industry Standard of Shingling

- National Roofing Contractors' Association, NRCA recommends application of rectangular 12 inches wide by 36 inches long asphalt shingles that have three tabs exposed along the length of the shingle for visual effect. Our robot shall lay these industry standard shingles on an underlayment of felt on the roof-deck. The fixation of these layers one above another is enabled by the usage of velcro for testing purposes.
- The quality of the shingling job shall be as good as or better than that of a manually shingled roof.

3.1.4 Stable Operation on Roof

- The robot shall not fall or drive off the roof at any time during operation. It shall be able to stop correctly at shingle laying locations and roof edges. It shall also be able to move up to a higher row by performing an S-curve motion stably and accurately.

3.2 Mandatory Functional Requirements

3.2.1 Lay shingles accurately on roof

- The robot shall lay 3 shingles on each row by cutting the last shingle to the accurate size at the end of each row.
- The robot shall maintain the standard shingle spacing of 0.75" – 1.75" on either side of each laid shingle
- Maximum alignment difference between consecutive shingles shall be ≤ 1.0 ".
- Distance between top edges of successive shingle rows shall be between 5.75" and 6.25".

3.2.2 Size Shingles at Roof Edges

- The robot shall cut shingles to correct size at roof edge. Length of a cut shingle piece is between 5.75" and 6.25".

3.2.3 Shingles in timely manner

- The robot shall shingle 8 sq ft area of the roof, on an inclined test-bed of 3 shingles wide by 4 shingles tall (i.e. 8' X 4'). Robot will lay 2 rows of shingles in 20 minutes.

3.2.4 Return to be refilled

- The robot shall return to a designated refill position, which is the left edge of the corresponding row, for manual refill of shingles. Once the refill is done, the robot shall wait for the "Continue" signal from the user to resume shingling on the new row.

3.2.5 Notify the user shingling is "Complete"

- Off Board controller shall notify the user that the shingling job has been completed and stays at its place, waiting to be picked up.

3.3 Desired Non-Functional Requirements

3.3.1 Improved Roof Pitch Capabilities

- The robot shall work on roof pitches of up-to 45°.

3.4 Desired Functional Requirements

3.4.1 Attach each shingle with nails

- The robot shall lay 4 nails per shingle with proper spacing and at correct locations on the shingle (i.e. one nail at each edge of the shingle and one placed 1' in from each shingle edge).

3.4.2 Obstacle Avoidance

- The robot shall be capable of shingling around one a 1'x 1' chimney.

3.4.3 Improved Shingling Speed

- The robot shall place 7 shingles in 3.5 minutes.

3.4.4 Automatic Reloading of Shingles

- The robot shall navigate autonomously and reload shingles placed at designated position on the roof.

3.5 Performance Metrics

Req. No.	Operation Specification	Performance Metric
3.1.2	Stable Operation on a roof constant pitch	Pitch up-to 30°
3.2.1	No. of shingles to be laid on each row	3
3.2.2	Length of shingles on 1st row	3' - 3' - 2.5'(after cutting)
3.2.2	Length of shingles on 2nd row	2.5' - 3' - 2.5'(after cutting)
3.2.1	Shingle spacing on either side	0.75" - 1.75"
3.2.1	Length of shingle cut off along the longer edge	5.75" - 6.25"
3.2.1	Maximum alignment difference between consecutive shingles	<= 1"

3.2.1	Distance between top edges of shingles between successive rows	5.75" - 6.25"
3.2.3	Time required to complete laying two rows of shingles	20 minutes

Table 1: Performance Metrics for Spring Validation Experiment

4. Design Concepts and Rationale

Our system is designed to meet the mandatory functional and nonfunctional requirements. This section describes how each design was finalized so as to facilitate integration of all the subsystems easily. The designs were meant to meet the requirements are described below:

4.1 Locomotion System

Previous project by students in the 'Mechatronics class of Spring 2012' provided a fair idea of how the locomotion system should work. However, the said systems handled 1'x1' shingles while the RiPUS system needed to handle standard roofing shingles, 3'x1'. The RiPUS system would also have the ability to cut shingles. The locomotion system needed to be robust because of the the extra weight and size of our more complex system. Several Ideas were brainstormed for the locomotion system and are discussed below.

4.1.1 Tethers

The tether system design was comprised of tethers that would be pulled taut from the top of roof by a set of supporting motors. The motor would pull the system up the roof for each new row of shingles laid. The benefit of this design is that the system would remain stable on the roof, however it could not be made generic for all kinds of roofs. Also, the system would require the user to go up on the roof and install the tether, resulting in a relatively complex setup process and a greater risk of falling. This system violated requirement 3.1.2 but met 3.1.4. This tether system would decrease the weight of the system, but would increase its operational complexity and potential risk of user falling.

4.1.2 Long lead screw mechanism

In the same vein as a tethered system, two lead screws placed across length and breadth of the roof used to move the whole system was considered. The primary issue with this system is that the design does not scale well with the length of roof. As the length and breadth of the roof increases, the length of lead screws required would become longer. This would increase the diameter of the lead screws and result in additional weight. Beyond a certain limit, this would be

impractical because of too much weight being added to the system. This system would also be hard to install and require climbing on the roof, again violating requirement 3.1.4.

4.1.3 Tread Systems

Tracks were chosen over the above two options because the track based system would not limit the size of roof the robot could work on. Also, an untethered system is easy to install in just one go without worrying about the height of roof and length of tether. The complexity of long lead screws was eliminated. Finally, since a 30 degree roof pitch was the target, tracks ensured the system would remain stable by providing extra friction, fulfilling requirement 3.1.2.

The requirement of laying shingles in straight rows was fulfilled by integrating a line-follower system with encoders. The construction of robot depended on the size of the shingles, and by using both the robots size and line following system a PID loop accurately maneuvered the robot on the roof. To ensure the robot did not drive off the edge of the roof, SHARP IR range finders were used to detect the edge of roof.

4.2 Laying System

The laying system is used to move shingles from the robot onto the roof. The system was required to properly handle 3'X1' shingles such that they would not be damaged or misplaced during laying. The system was also required to be lightweight and keep its center of mass low.

4.2.1 Lead Screw

Initially, a lead screw was picked to move the shingles and place them on the roof. The lead screws required several stepper motors, increasing the power requirements for the system. Moreover, these motors required additional power to be controlled. The lead screws needed to be light in weight but this resulted in choosing smaller diameter. The drawback of choosing smaller diameter of lead screw was a decreased thread pitch increasing the travel time for the carriage. Lead screws also require consistent lubrication, demanding more maintenance and increasing potential downtime of the system. The wiring of the whole system would also become cumbersome with motor controllers required for each motor. Furthermore, each motor would add extra weight to the system, which was undesirable.

4.2.2 Pneumatic Systems

The second choice was to use pneumatic pistons to move the laying system. Pneumatics are faster than lead screws. Pneumatics also provided simpler control and require less power to run. The pneumatic cylinders also work at lower pressures and are still faster than a lead screw system. Most of the weight would be carried by slides on 80-20 bars, this allowed the use of cylinders with a small diameter and still provide enough force to move the slides. The only power requirements for the pneumatic system would be each cylinders required solenoid valve, however the valves weight as much as the cylinders. This problem could be solved by strategically placing the valves and forcing the centre of gravity where needed.

The simplicity of control and speed of operation provided by the pneumatics was more important and hence pneumatics were chosen.

4.2.3 Pneumatic Suction Cups

Since Pneumatics were chosen for the laying system we originally decided to use a vacuum pump to lift the shingles from the stack. The vacuum pumps used a venturi meter and a high amount of pressurised air to create a vacuum. The system worked well with a single suction cup; however, the amount of pressurized air needed increased as more vacuum pumps were added. We switched to a larger diameter hose to provide a higher volume of air. The quality of suction was also dependant on the type of material the suction cups were attaching to. Several materials like water based clay, oil based clay and rubber-type gel were tested to improve the suction cup attachment. We believe that the suction cups did not attach to the shingles because the existing lab compressor could not provide the necessary air pressure and volume. Another reason for insufficient suction provided by different materials is because of the porous and rough surface of the shingle. This combined with the weight of the shingle resulted in the shingle peeling of the suction cups when it was lifted.

4.2.4 Magnetic Lifting

Since the pneumatic suction cups failed to lift the shingles properly a new way to lift the shingles was needed. Magnets were chosen as the new lifting method. A stack of magnets were combined with a section of sheet-metal underneath each shingle. The magnets attract to the sheet metal and allows the shingle to be moved from the system to the roof. Magnets were chosen as they require no extra power and the magnetic cups were lighter than the suction cup and vacuum pump systems. This was done under the assumption that sheet metal can later be replaced with magnetic paint or a reformulation of the shingles to make them ferrous.

4.3 Cutting Subsystem

Requirement 3.2.2 was fulfilled by usage of cutter at one side of the robot. The RIDGID cutter was used mainly to provide a professional quality cut. This helped us fulfilling requirement 3.1.3 and also simplify the subsystem design.

4.5 Off-Board Controller Subsystem

The whole system was designed to be controlled by an operator on the ground. To implement this we designed an off-board controller system to enable user to switch the robot On and Off and receive the status of shingle refilling. A touch based, off-board controller was used to fulfill requirement 3.2.5.

5. System Graphical Representation

Our system is a complex mechanical, electrical and software solution to the roofing problem. The top view of the system is shown in Figure 3 and 4. Figure 3 is the CAD design of the system as seen from the top. This figure shows the major components of the system. Figure 4 shows an actual image of the system. It shows the smaller components not shown in the CAD along with a few reference components so that Figure 3 and Figure 4 can be compared. Figures 5

and 6 show the configuration and location of the treads for the system. Figure 6 shows the actual system mounted and the internal construction of the treads.

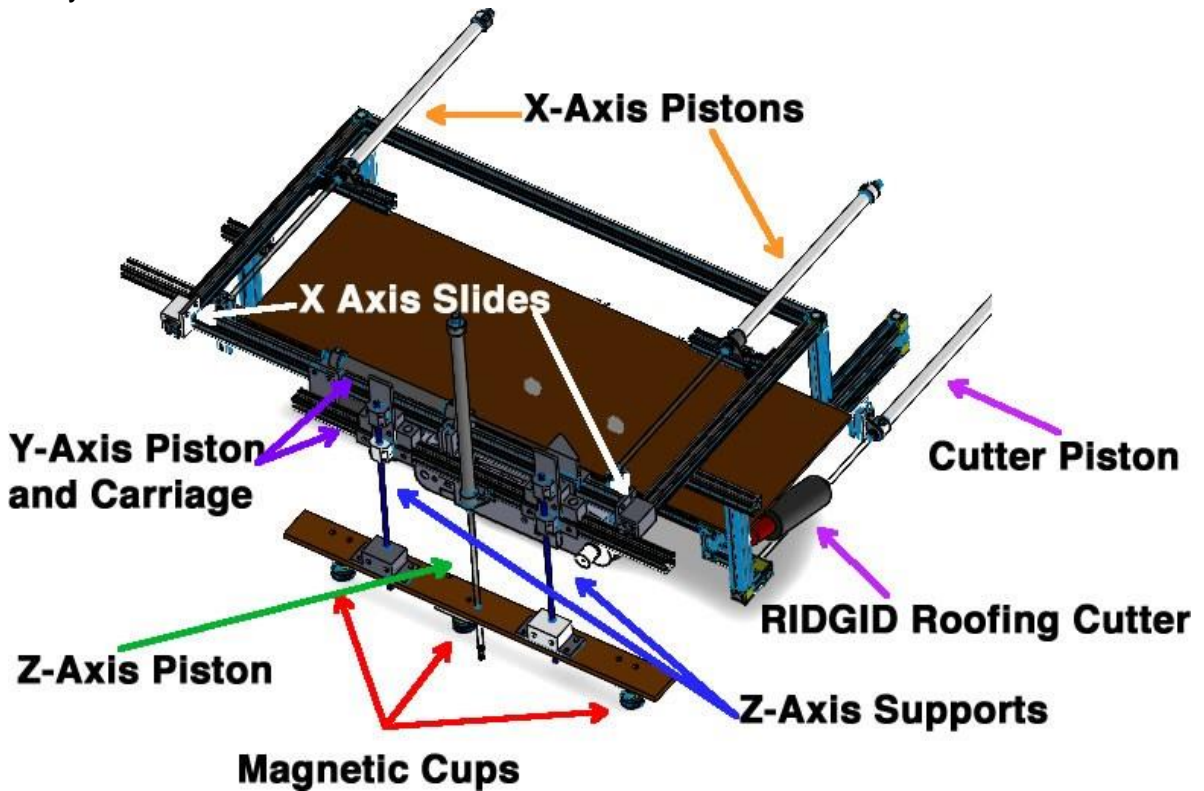


Figure 3: Top View of CAD Model of System With Major Parts Labeled

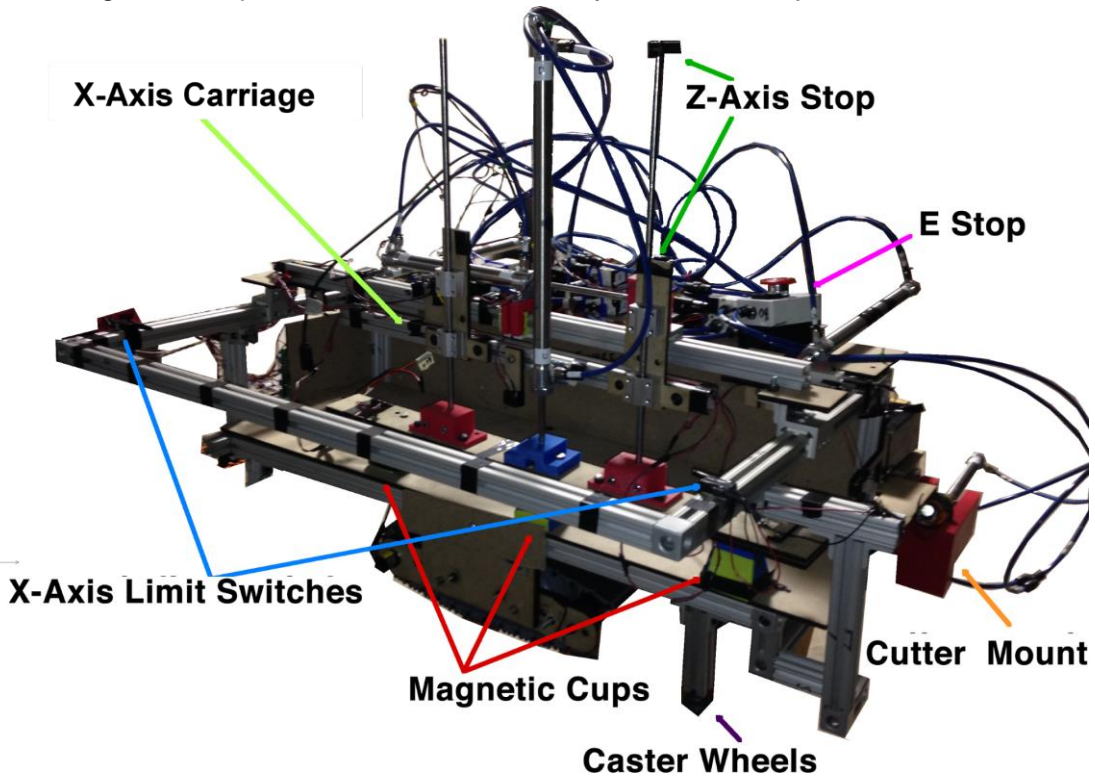


Figure 4: Actual Picture of System

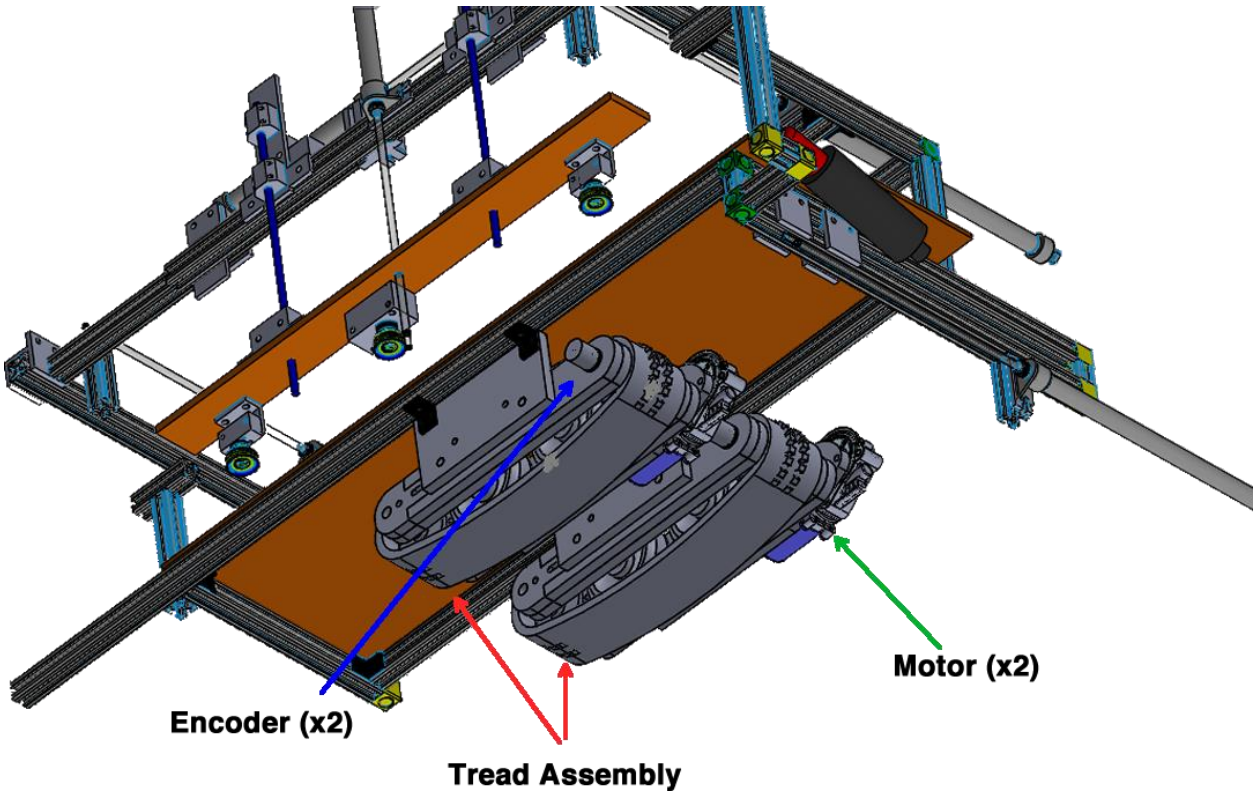


Figure 5: Bottom View of CAD Model Showing Locomotion System

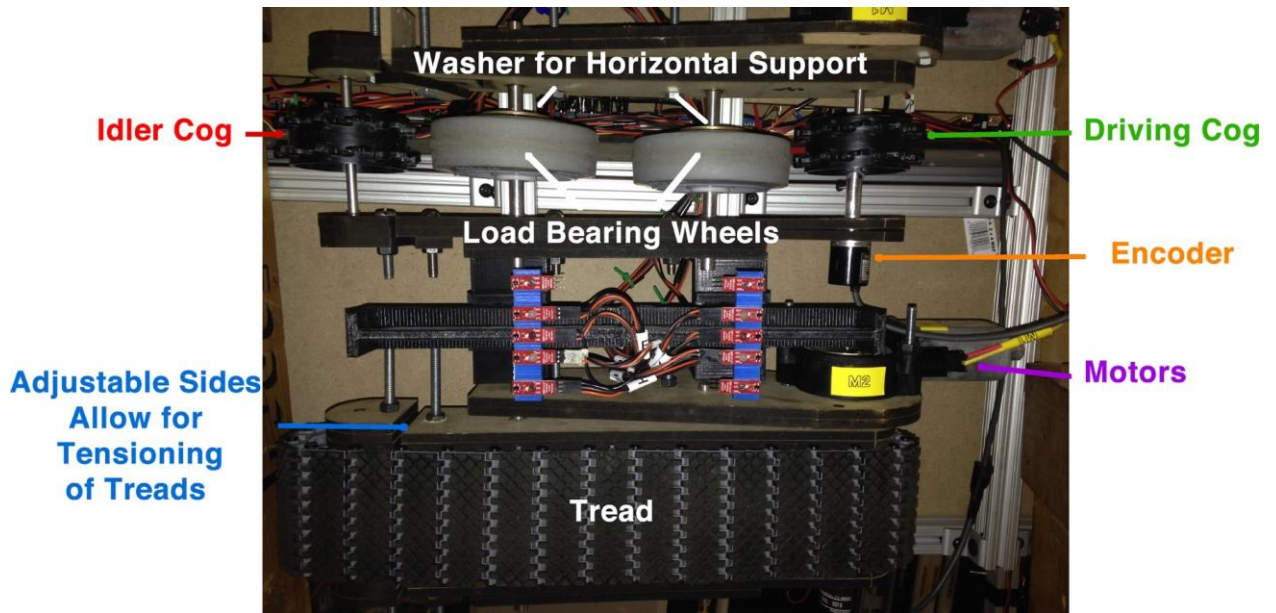


Figure 6: Actual Bottom View of System With Internal View of Treads

6. Functional Architecture

The functional architecture of the system is shown in Figure 7 below. The major functions of our system are localization, locomotion, safety, laying, cutting, power and mechanical. The mechanical functional block abstracts the mechanical support required for various parts. The localization block abstracts the process of keeping track of where the robot is (i.e) the row on which the robot currently is; the number of shingles that have been laid on the current row, etc. The locomotion block deals with all the functions associated with the robot moving on the roof. Safety block abstracts the functions associated with safely and stably operating the robot on the roof. The laying function encompasses the actions of picking up and placing the shingles on the roof. The cutting block depicts the action of cutting the shingles to size at the edge of the roof. Finally, the power system deals with supplying power to the various components of the robot.

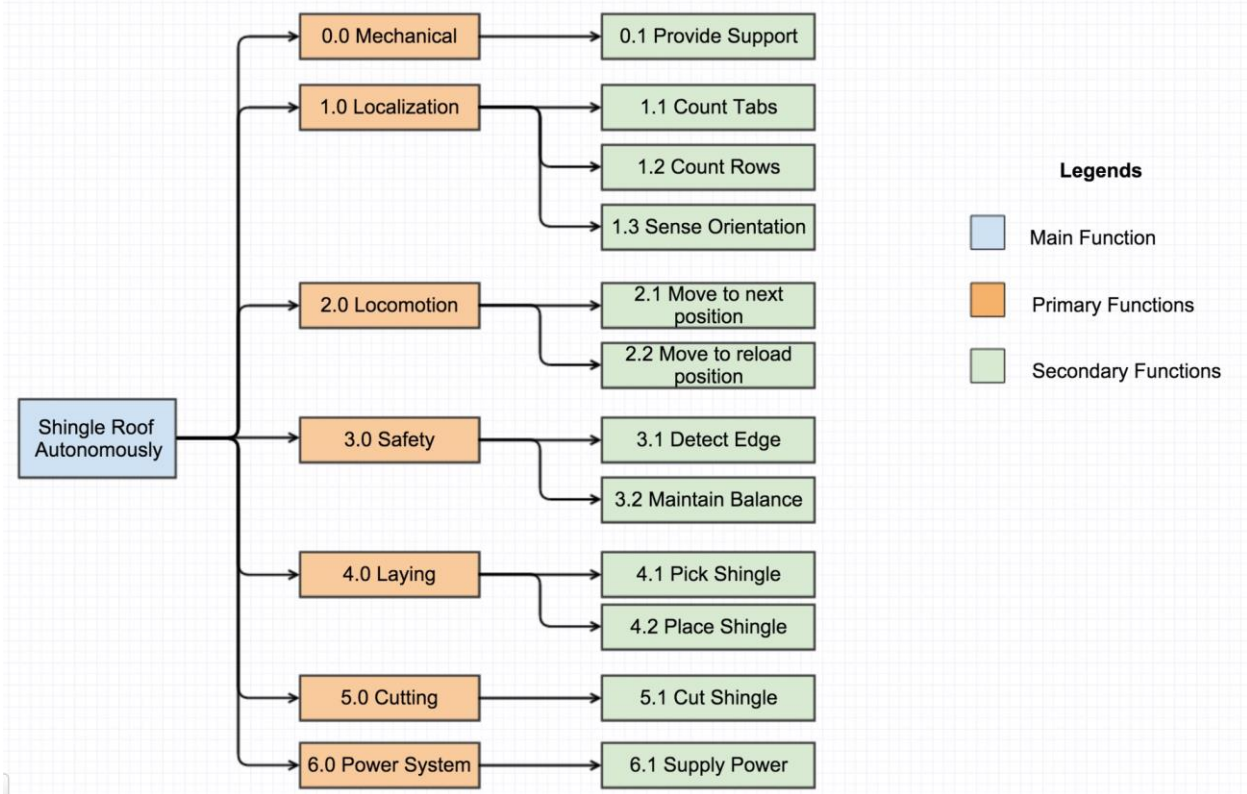


Figure 7: Functional Architecture Diagram

7. Physical Architecture

The Physical System Architecture describes the physical components of the robotic system. The main components comprising each of the major functional blocks are depicted in the

physical architecture diagram shown in Figure 8 below. Also, the flow of power and data / control signals is depicted as colored lines.

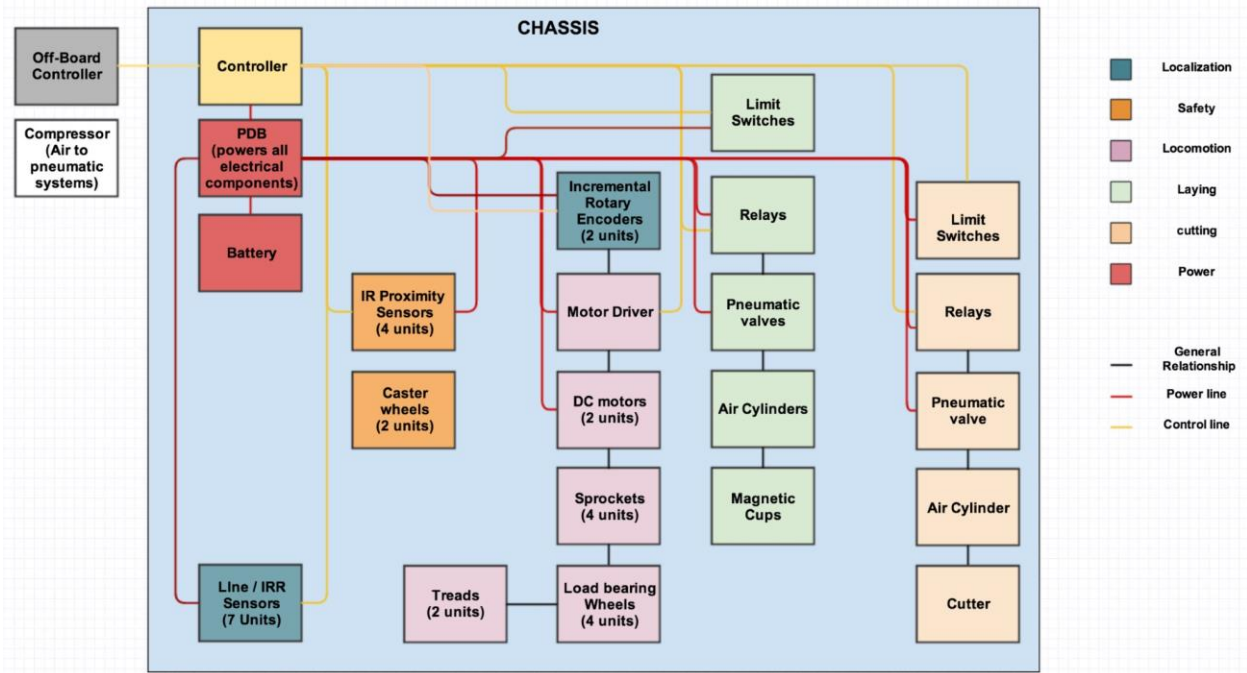


Figure 8: Physical Architecture Diagram

The localization system consists of the line sensors (Infrared reflectivity sensors) mounted onto the chassis between the treads. They draw power from power distribution board and send their output signal to the controller. The encoders are mounted onto the motor shaft through a shaft coupler. They draw power from the PDB and send the output signals to to the controller.

The Locomotion system consists of a pair of treads. Each tread consists of a motor, 2 load bearing wheels, 1 active sprocket and one idler sprocket. These parts are enclosed by the tread links to form the tread.



The Laying system is comprised of limit switches, relays, pneumatic valves and pistons. The relays actuate the pneumatic valves which in turn drive the air pistons. The cutting system is comprised of similar parts except for the additional shingle cutter.

The main components in the power system are the batteries and the power distribution board. Other minor components include the various circuit boards that distribute the power from the PDB.



8. Component Definition

This section defines all the components used in our system - Mechanical Components (Table 8.1A), Pneumatic Components (Table 8.1B) and Electrical Components (Table 8.2A- Table 8.2C). There is a brief description of what each component is and what system it is used in. Each subsystem is described in Section 9.

8.1 Mechanical - Table 8.1A.

	<p>Treads</p> <p>Treads used in locomotion system comprised of small plastic linkages cover in a rubber coating. These links are connected together using nylon rods and plastic rivets. Chosen to provide friction on roof with rubber and some amount of durability. [5]</p>
	<p>Cogs</p> <p>The two separate sprockets are combined using one of the metal hubs shown to create a cog. Two cogs are used in each tread of the locomotion system. They are used as a drive cog, driven by the motor, and idler cog. [6] and [7]</p>
	<p>MDF</p> <p>Medium Density Fiberboard (MDF) is used extensively in our system. It is a rigid material that can be cut using a laser cutter. We used 1/4 in thickness for all our applications of MDF. [8]</p>

I


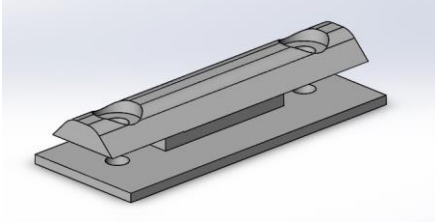
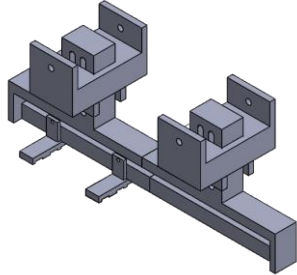

	<p>Bearings</p> <p>Bearings are used in the locomotion system. The fully enclosed Bearing is used to create the idler cog and the open bearing is used to allow free rotation of the encoder shaft coupler. [9]</p>
	<p>Shaft Coupler</p> <p>The shaft coupler is used in the locomotion system to couple the encoder to the drive shaft. [10]</p>
	<p>Load Bearing Wheels</p> <p>Load bearing wheels are using in the locomotion system. They included the shaft bearing used with them. [11]</p>
	<p>80-20 Extrusion</p> <p>80-20 Extrusion is a lightweight aluminum rapid construction material. It is used extensively in our system. It was chosen because of its ease of assembly, it is lightweight and rigid. [12]</p>



80-20 Linear Bearing

80-20 linear bearings are linear bearings design to be used with 80-20 extrusion. They are used in both the cutting system and the laying system to smotly slide along the 80-20 extrusions. [13]

	<p>80-20 L-bracket</p> <p>80-20 L-brackets are used to create 90 degree connections between two pieces of 80-20 extrusion. These are used extensively in our system. [14]</p>
	<p>80-20 Square End Connector</p> <p>80-20 square end connectors are used to connect two or more 80-20 extrusions very precisely. These are used in the laying system to give precise fit for the slides to actuate properly. [15]</p>
	<p>Magnetic Cup</p> <p>The magnetic cups for the system are designed to hold the magnets onto the Z-axis actuation plane. The cups hold 4 ¼ in magnets and 2 ½ in magnets and interact with the metal plates placed on the back of the shingles. These parts were 3D printed.</p>
	<p>Magnets</p> <p>Our system uses ½ in and ¼ in neodymium magnets to lift shingles from the shingle hopper to the roof. [16]</p>
	<p>Z-axis supports:</p> <p>This system supports the z-axis actuation plane while the z-axis piston moves the plane up and down. It is comprised of two linear bearings, a slide, a limit switch trigger and a z-axis plane attachment block.</p>

	<p>RIGID Pneumatic Roofing Cutter</p> <p>The RIDGID roofing cutter is used in the cutting system. This was purchased as a unit and was not modified other than to have the switch tied down.</p>
	<p>IR Range Sensor Mounts</p> <p>3D printed mount used to attach IR range sensors to the 80-20 bar. Two nuts and bolts are used to tighten the mount in place once it is in the 80-20.</p>
	<p>Line Sensor Mount</p> <p>Line sensor mount is 6 3D printed parts used to mount the line sensors. The mount provides vertical and horizontal adjustment capabilities.</p>
	<p>Snap rings</p> <p>Snap rings are used in the locomotions system to hold the idler cog bar and the load bearing wheels in place. [17]</p>

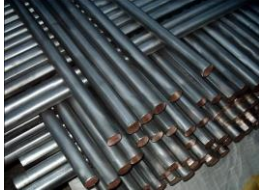
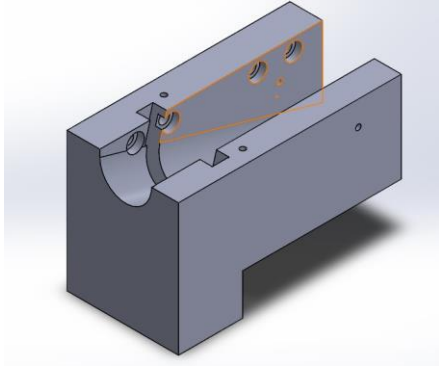

	<p>Bar Stock</p> <p>Steel bar stock was used to create all bars in locomotion system. This includes the motor shaft, load bearing wheels shaft and idler cog shaft. [18]</p>
	<p>Cutter Mount</p> <p>The cutter mount is used to mount the RIDGID roofing cutter to both 80-20 slides and the pneumatic piston.</p>
	<p>Shingles</p> <p>Our system uses standard 3-tab asphalt shingles. The shingles are modified by duct taping steel sheeting to the back in strategic places. This allows the magnetic cups to pick the shingles up. Velcro is then placed over the steel plates to allow the shingle to adhere to the roof.</p>

Table 8.1A) Mechanical Components

8.1.1 Pneumatic Components - Table 8.1B







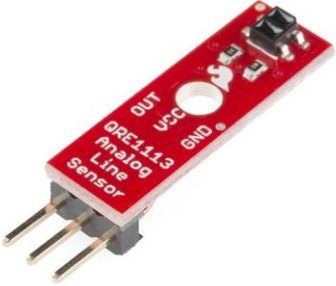



	<p>Pneumatic Pistons</p> <p>Pneumatic pistons are used in both the laying system and cutting system to actuate the shingle laying mechanisms and cutting mechanism precisely. They are attached to pneumatic hose and a compressor.</p>
	<p>One-Way Flow Valve - Meter Out Valve</p> <p>These valves are used in the pneumatic systems for laying and cutting. This valve enables actuation and limiting of the pistons. [20]</p>
	<p>Pneumatic Hose</p>
	<p>Our system uses ¼ in. Pneumatic hose is used in all pneumatic systems. [21]</p>
	<p>Pneumatic valves</p> <p>The pneumatic valves are used to set the positions of pneumatic cylinders. They were all spool based valves that could change the way air flowed in the system. The configuration of valves are 3/2 and 5/2.</p>
	<p>Compressor</p> <p>A 120 psi compressor is used to power the pneumatics in the system. The compressor is off board of the roofing system. [22]</p>

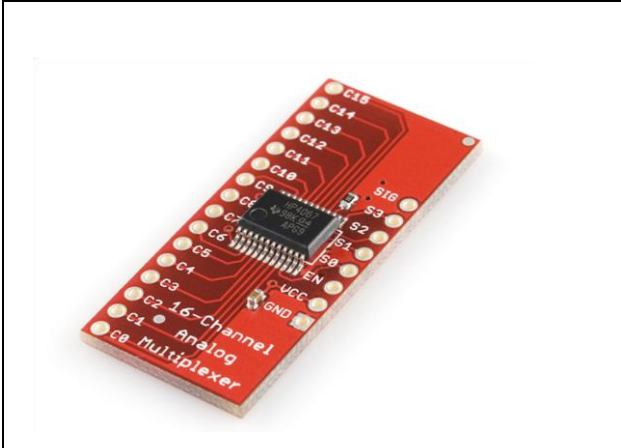
Table 8.1B) Pneumatic Components

8.2 Electrical Components- Table 8.2A

	<p>Encoders</p> <p>Encoders are used to determine the speed of motors from the pulses. The encoder give 200 pulses per revolution</p>
	<p>Line-follower sensors</p> <p>The sensors are infrared reflectivity sensors that give out analog values and can measure accurately a distance under 3mm</p>
	<p>Proximity Sensors</p> <p>The Proximity sensors were selected because of their 20-150 cm range. They are used to detect the edges of roof. The Sharp Proximity sensor can be seen in Figure 32.</p>

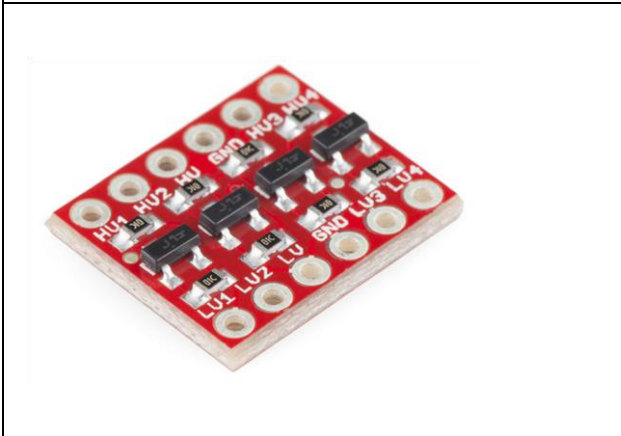
	<p>Limit Switch</p> <p>The limit switches provide feedback to the controller which in-turn controls the valves to actuate the cylinders. A high-level sequencing loop is described in Figure 14.</p>
	<p>Motors</p> <p>The two main driving motors are AME 214-series geared motor that deliver 143 kg cm torque each.</p>

I



Multiplexer

The multiplexer was used to accommodate extra limit switch pins on Arduino Uno of Laying system.



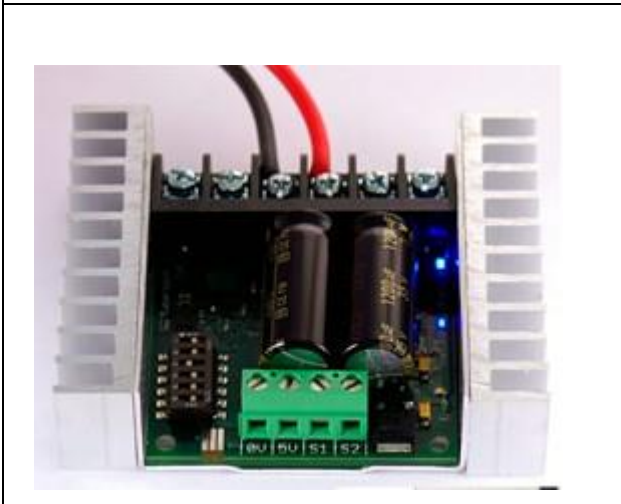
Level Converter

The level converter is used to convert 5V signals from sensors to 3.3 V and provide them to Arduino Due. Also the communication between Arduino Due and Arduino Uno required this logic level conversion.



Relays

Relays are used to activate pneumatic solenoid valves. They require 5.2V to activate and they receive signal from Arduino UNO(laying system).



Motor control

The Sabertooth Driver 2x25 which has overvoltage protection and provides stall current up to 50Amp per channel for a few seconds. This stall current was used to drive the AME 214 Motors in the locomotio system. Also it runs on serial commands, which means it can easily controlled with minimal number of wires.

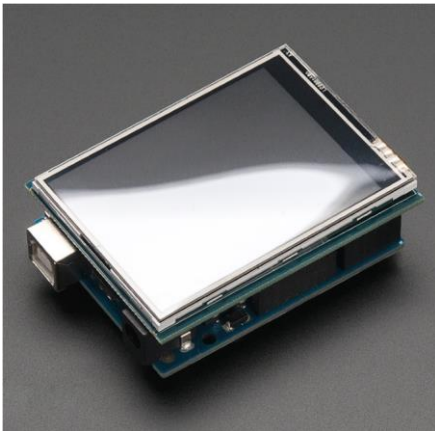
n



Arduino Due was used to control the locomotion system and interface with the other controllers.



Arduino Uno was used to control the laying and cutting system. Another Uno was used in Off-board controller which is explained in next section.



Off-board controller

This is a TFT screen touch based LCD display. It was used as the off-board controller. It has a ready-made shield for Arduino UNO.

Table 8.2A) Electrical Components

Power Distribution Board

The power distribution supplies 9V to Arduino Due (Locomotion System) and Arduino UNO(Laying System). It also supplies 5V to SHARP sensors and line-follower sensors. Table 8.2b shows PDB.

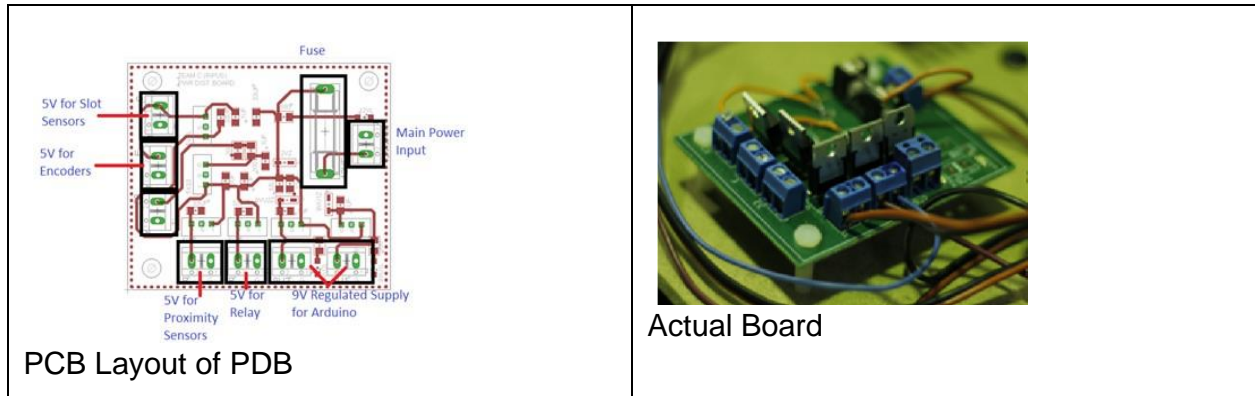


Table 8.2B: Power Distribution Board

Other Distribution Boards

The system has two distribution boards:

1. Proximity sensor distribution board
2. Limit switch distribution board

The inputs to these boards are the sensing elements and outputs are connected to the Arduino, relieving it from hassles of extra pairs of wire from each. Both the boards(Table 8.2C) have similar PCB layout as seen in figure 8.2a.

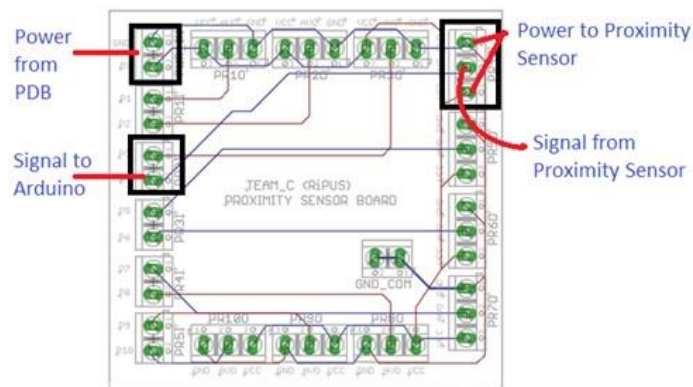


Figure 8.2a) PCB layout for proximity and limit switch distribution boards

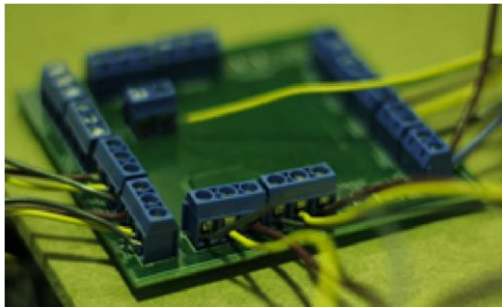
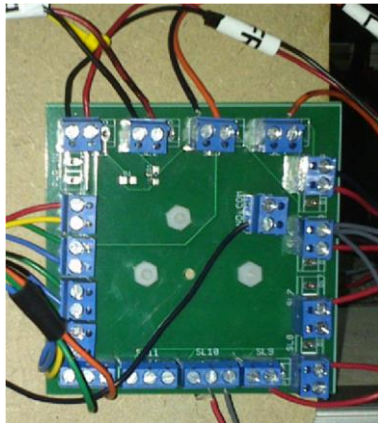
Proximity Sensor Board	
Limit Switch Board	

Table 8.2C) Sensor and Limit Switch Distribution Board

9. Subsystem Descriptions

9.1 Laying System

The laying system lays one shingle at a time, from the stack of shingles on robot onto the roof. The system had 3 axes to execute this task: X, Y and Z. The system uses a gantry design for the X axis and a simple slide bar design for the Y-axis. The Z-axis uses two linear slides to support its vertical movement.

The X-axis throw is 12 inches allowing the shingle to be moved, exactly its width, out onto the roof. The Y axis moves along the length of the shingle 6 inches to place the shingle into the cutting system for sizing. The Z axis moves perpendicularly to the plane created by the X and Y axis, and used to lift the shingles from the stack and place onto the roof. To achieve the correct motions for each axis, pneumatic pistons of following strokes were used: X axis: 12 inch, Y axis: 6 inch, Z axis: 11 inch. The axis directions of movement are shown in Figure 9.

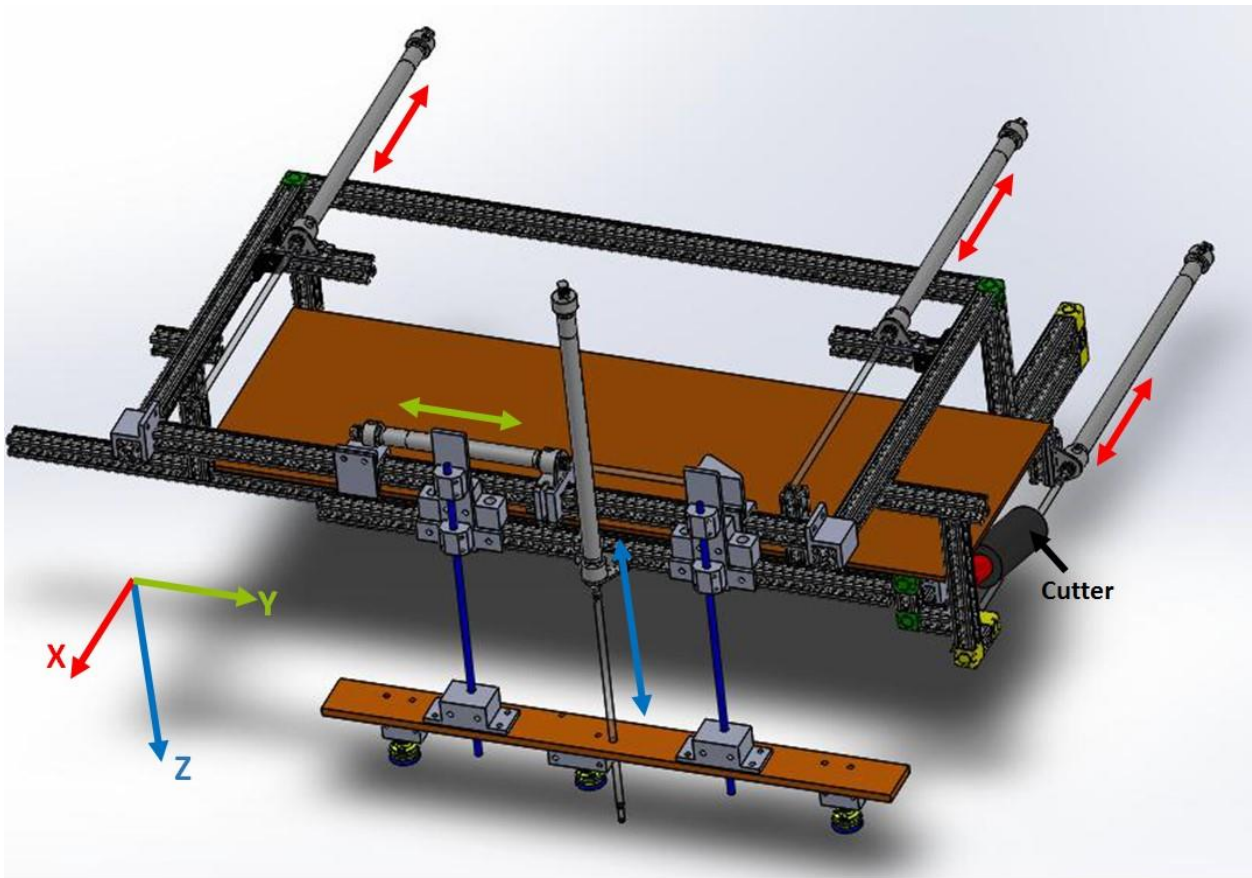


Figure 9: Laying system with axis.

The Z-axis cylinder needed to have the capability of stopping in any position to pick up a shingle and put it on roof correctly. In general, pneumatic cylinders are set to stop only at two positions: fully extended or fully contracted. To make a cylinder stop in any other position, two 3/2 valves were used, to control the end positions of cylinder and two more 3/2 valves controlled the exhaust of the previous pair of 3/2 valves. The valve setup and type of valves can be seen in Figure 10. Two limit switches were placed near the magnetic cups to give feedback when a shingle was collected from the stack. These limit switches were activated when the shingles attached to the magnetic cups. This switch eventually actuated the valves stopping the Z axis cylinder from going further down. To place the shingle, already attached to the magnetic cups, on the roof, another limit switch was placed on one of the Z axis support slides. It signals when the cylinder achieves the correct distance and cuts off the valves. This limit switch can be seen in Figure 4.

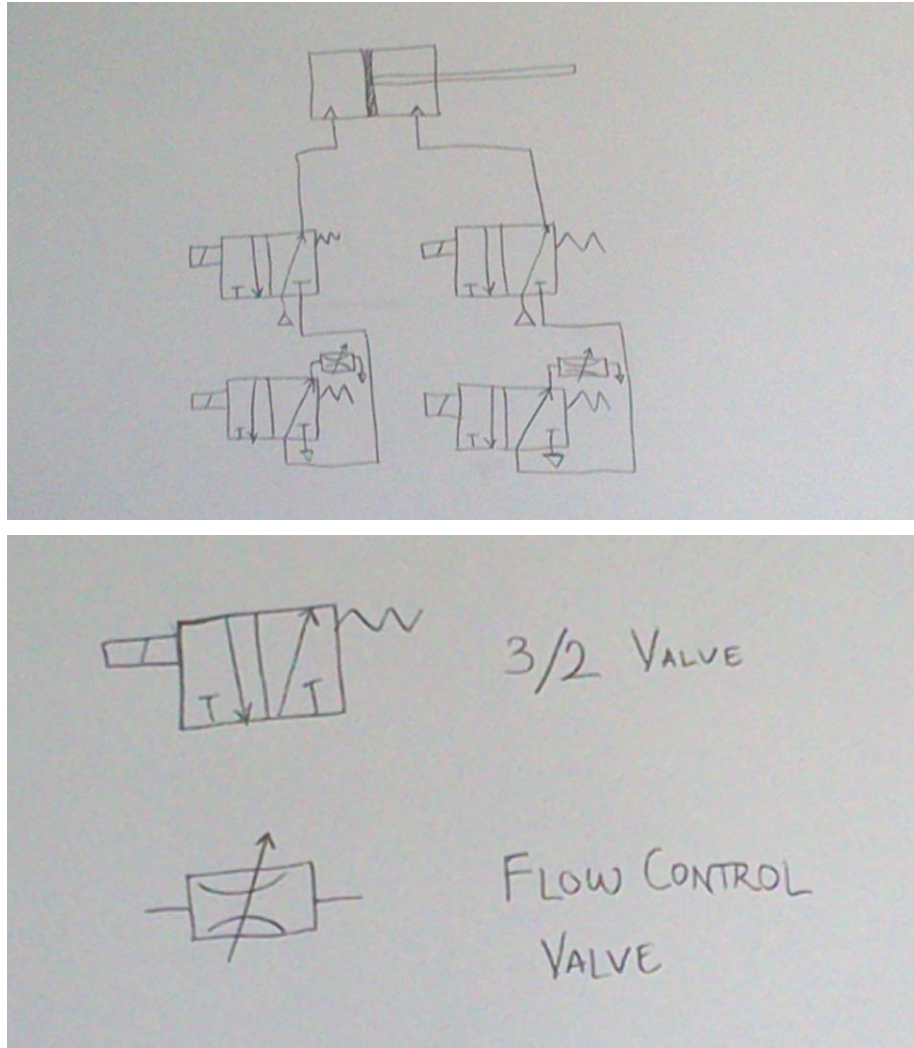


Figure 10: a) Valve setup for Z axis b) Valve description

Table 2 shows limit switches used in the Laying System that provide feedback to correctly execute the sequencing of valves. Table 3 shows the valves used in the pneumatic system.

Axis	Name of Limit Switch in System - Position
X	FR – Front Right
X	BR – Back Right
X	FL – Front Left

X	BL – Back Left
Y	FY – Front Y
Y	BY – Back Y
Z	SS – Shingle Sense
Z	ZB2 – Shingle on Z -2
Z	ZB1 – Shingle on Z -1
Z	ZU – Z Up
X	CR - Cutter Back Sense

Table 2: Limit Switches in laying system

Name in system - Serving Axis
X – Valve X
Y – Valve Y
D – Valve Z Down
U – Valve Z Up
C – Valve Cutter
DE – Valve Z Down Exhaust
UE – Valve Z Up Exhaust

Table 3: The valves used in the pneumatic system

There were two tasks executed by the laying system: Laying and Cutting-Laying. A sequence of valves were required to achieve the motion of each axis. Valves and switches used in the diagram are referred in Table 2 and Table 3 respectively. The sequence diagram for the laying task can be seen in Figure 11. The sequence diagram for the laying-cutting task can be seen in Figure 12.



Figure 11 : Laying sequence

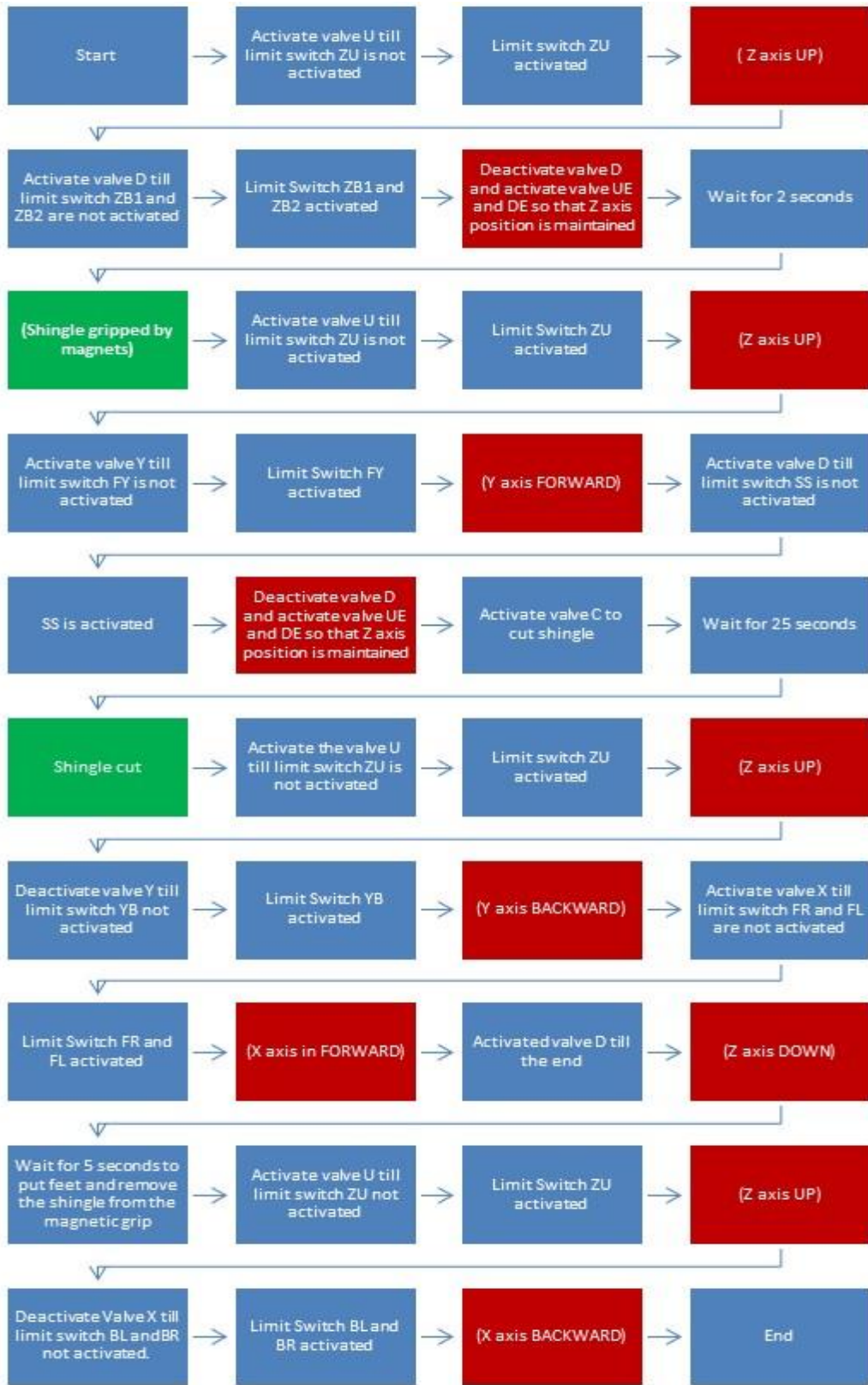


Figure 12 : Laying and Cutting Sequence

Each of the sequence was activated only when it received the correct signal from the locomotion system. During the normal operation, when the locomotion system was following the line, it would send a signal to the laying system to run only the 'Laying' sequence. When the locomotion system encountered the edge it sent the signal for the 'Cutting and Laying' sequence. The two controllers, Arduino Due for locomotion system and Arduino Uno for laying system, communicated via serial port.

A typical flow of signals can be seen in Figure 13.

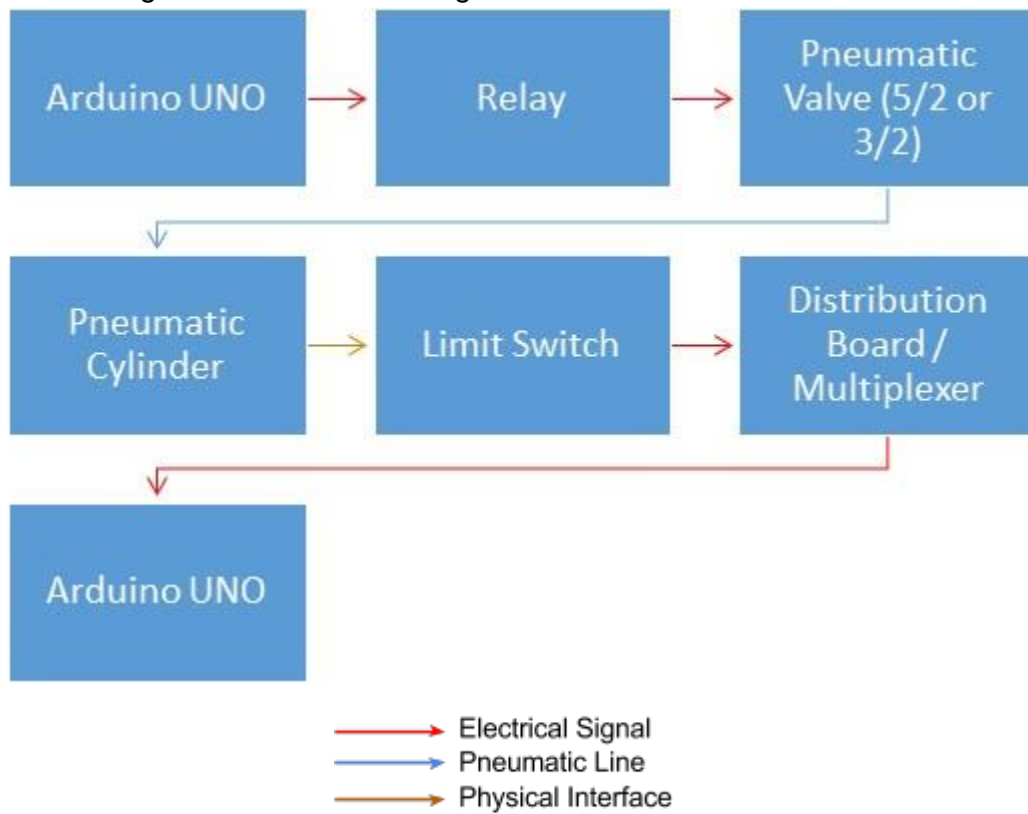


Figure 13 : Signal Flow for Laying

9.2 Cutting System

The cutting subsystem is used to cut the shingle for the end of each row. The laying system is used to hold the shingle in place as the cutter is pulled through the shingle. The cutting system consists of a RIDGID pneumatic roofing cutter, a 14 in pneumatic piston, a 3D printed part to hold the cutter, and two 80-20 slides mounted on the laying system. This is shown in Figure 14.

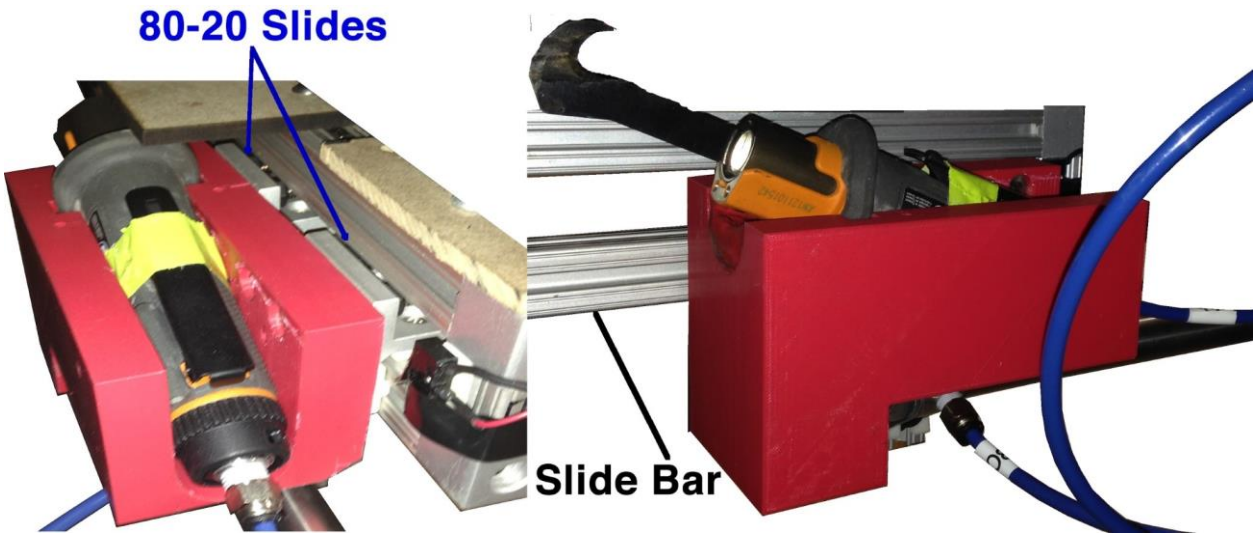


Figure 14: Actual Cutting System Image Showing Slides and Sliding Bar

The roofing cutter is housed in a 3D printed part that allows it to be easily attached to both the pneumatic piston and 80-20 slides. The piston is attached to the cutter mount with a nut which screws onto the end of the piston after it passes through a hole in the mount as seen in Figure 15. The mount is attached to the 80-20 slides using 4 bolts through recessed holes also shown in Figure 15. This mount is moved along the slides to cut the shingle with the pneumatic piston when commanded.

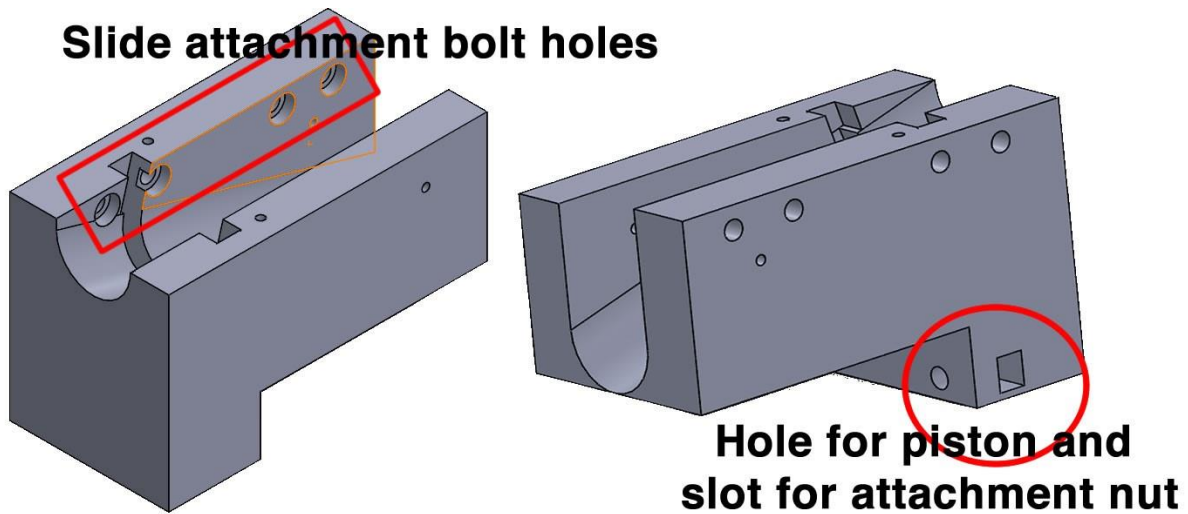


Figure 15: Two Views of Cutter Mounting System Showing Attachment Locations for Hardware

9.3 Locomotion System

The locomotion system is comprised of two treads what are used to keep the system on the roof and driving correctly to lay shingles. Each tread is identical and is comprised of two cogs, a motor, two load bearing wheels, two shaft bearings, two washers, 8 bolts, an encoder, a shaft coupler, three standard bearings, assembled tread and several pieces made from MDF. The motor has a single cog attached to its shaft that is then coupled to the encoder. This is the drive cog of the system. The second cog is attached to a second shaft that is supported in the MDF supported by bearings. This is the idler shaft and provides tension in the treaded system. The cogs are made of plastic and would be unable to support the amount of weight that is exerted by our system so two load bearing wheels are added to the treads. The load bearing wheels are supported on a shaft, and use a shaft bearing to allow them free movement. To keep the load bearing wheels from forcing them selves up the shaft due to the angle of the roof, two washer are placed between the snap ring and wheel.

The treads are placed in parallel with each other and parallel along the roof. This configuration can be seen in Figure 16.

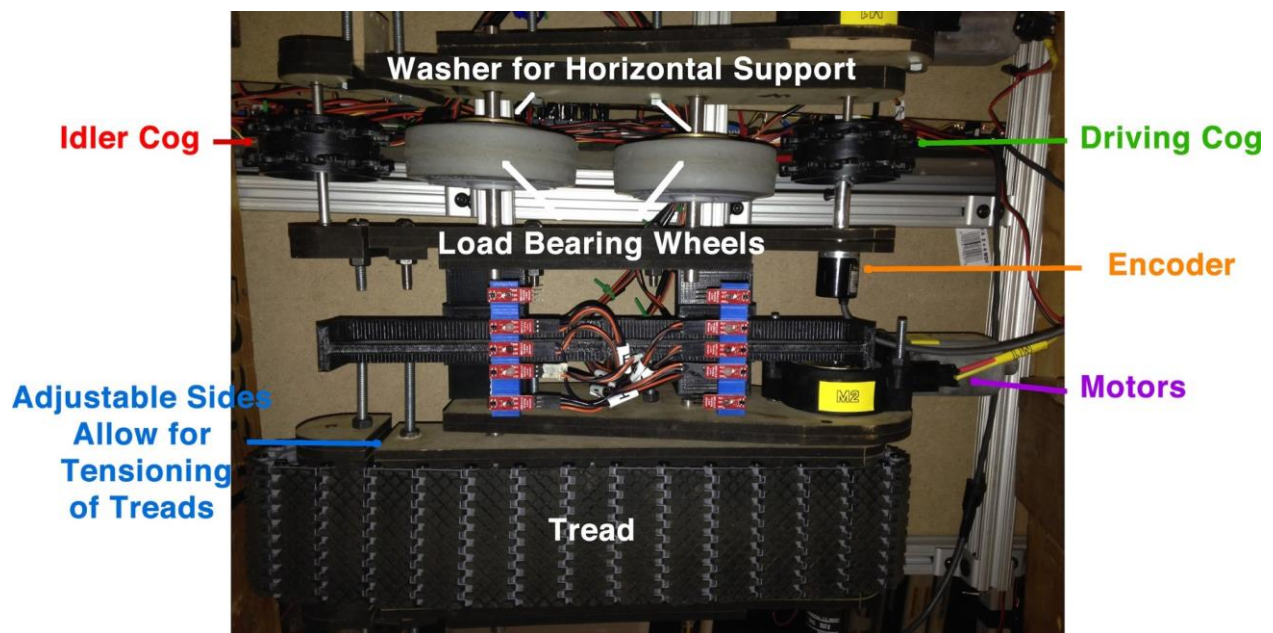


Figure 16: Diagram of Tread Configuration and Identification of Parts of Tread

9.4 Electrical Systems

There were many components on the robot that required 3.3V, 5V, 9V, 12V and 24V supply. SLA batteries were used to fulfill this requirement. We decided to keep separate batteries for each components. Electronic component were supplied from one 12V while another 12V battery

supplied power to the motors. The remaining 24V was used to supply to the valves. Figure 17 shows how batteries were distributed among different components:

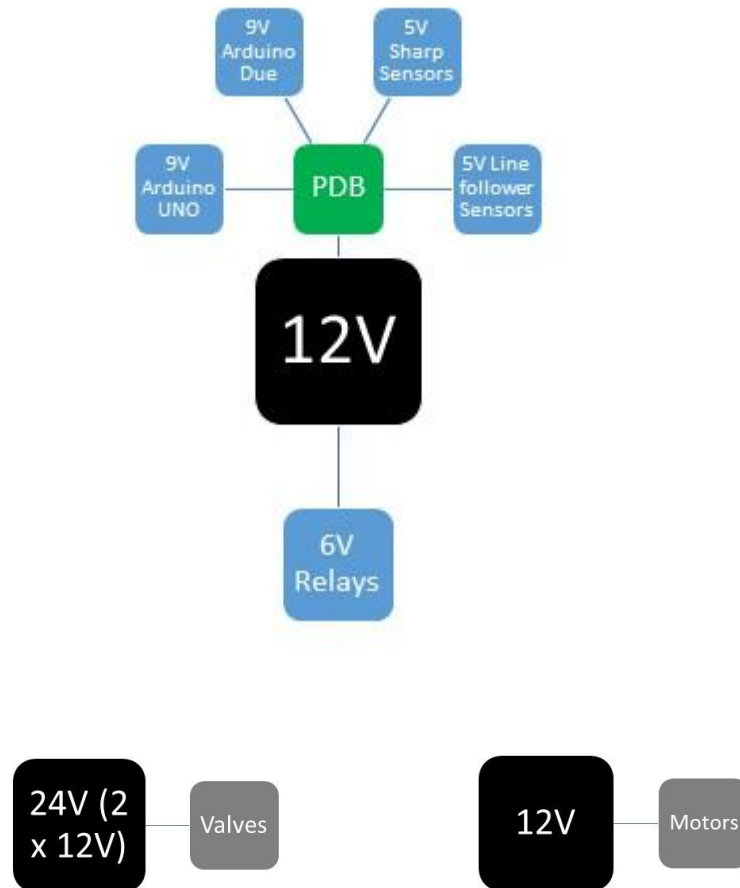


Figure 17: Battery power distribution

9.5 Line Following System

The line following system is used to keep the system properly aligned on the roof and determine when the locomotion system needs to stop and activate the laying system for shingle placement. A combination of encoders with line-follower sensors was used to correctly follow a straight line. Line-follower sensors followed the white line laid on roof at 5 inch distance. To detect the shingle laying position an extra sensor was used. There were white crosses made on the long lines laid on roof and this cross was detected by the added sensor. Encoders provided feedback to this system and the speed of motors was controlled using PWM from the sabertooth motor driver. The feedback from encoders and line sensors was used to correct and control the system. This will be further explained in Software Subsystem 9.6.

The 7 sensors are mounted using several 3D printed parts. Figure 18 shows the CAD of the mounts for the system and Figure 19 shows the sensor integrated into the mounting system.

This mounting systems allows for the sensors to be adjusted both vertically and horizontally as described by the arrows in the figure. This allows for calibration without the need to remake the system every time.

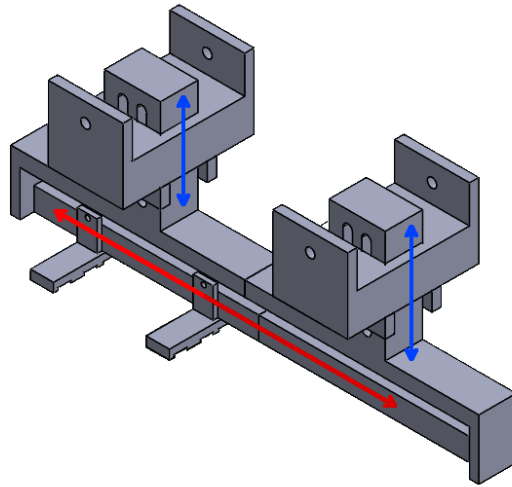


Figure 18: Line Follower Sensor Mounting System

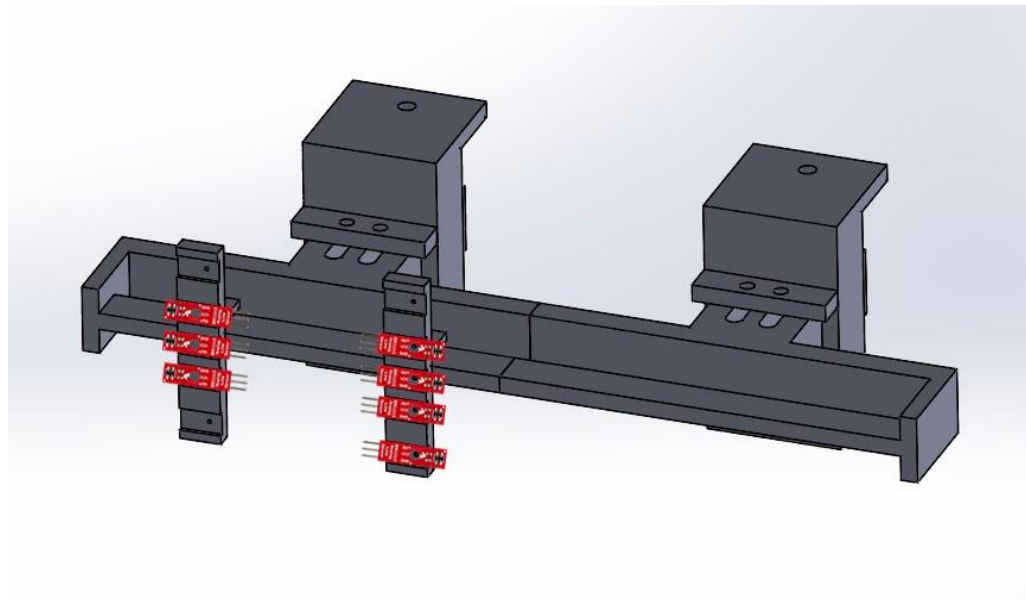


Figure 19: Line Following Sensors Integrated with the Mounting System

9.6 Off-Board Controller



Figure 20: Different displays of the off-board controller depending upon the commands pressed on the touchscreen LCD device by the user. The respective command is sent to the robot's on-board controller via serial communication for its operation.

The off-board controller, with a built-in shield for Arduino UNO, is an Adafruit product with a 2.8" touch-screen display as shown in Figure 20. The device has individual pixel control. The shield is fully assembled and tested. No wiring and soldering is required. It needs to be plugged in to the Arduino and the Adafruit library needs to be loaded. The GUI is programmed such that there would be three commands that the user can send to the on-board Arduino DUE controller (via serial communication) by clicking on either of the three keys created on the device as shown in Figure 20 image 1. These are 'FWD' for forward locomotion of the bot, 'STP' for stopping the robot and 'CON' for resuming operation after restacking of shingles is done. The entire touch-screen consists of 240X320 pixels which can be individually assigned colors. The software puts a background color to the device and creates three rectangular boxes at the bottom of the screen each having each of the above commands. When the user clicks on each of the boxes depending upon the user requirements, the color changes to green, red and yellow respectively for FWD, STP and CON. This has been done to make the controller as user-friendly as possible. The device looks for touch-data, computes the coordinates of the point touched and calibrates it to the touch-screen coordinates. It then checks if the coordinates are within the bounds of either of the boxes and then reports the user that the touch has been registered by changing the color of the box. From Figure 20 Image 2, it can be seen that the user sends the FWD command to the robot and now the robot starts its normal operation. At any time if the user wants to stop the operation, they can press STP as shown in Figure 20 Image 3 and can resume by re-pressing FWD. At any time, when the robot runs out of shingles it comes back to the home-side so that shingles can be stocked manually. The robot lets the user know that this is being performed by displaying the "RESTACK" command on the off-board as shown in the

Figure 20 Image 4. Once restacking is done, the user can resume the robot operation by pressing CON as shown in Figure 20 Image 5.

9.7 Software

This section discusses the software developed as part of the project. At a high level, there are three programs running the entire system:

1. On-board controller program
2. Laying system program
3. Off-board Controller program

Each of these are discussed in detail in the sections below. All the programs were written in the C programming Language using the Arduino IDE to run on the Arduino controllers employed to control the subsystems of the robot.

9.7.1 On-board Controller Program

The on-board controller program (OnCP) runs on the main controller (Arduino Due) and handles the following functions:

1. Locomotion
2. Controlling the Laying System
3. Interfacing with the off-board controller

The OnCP is the main code that controls the robot. It is initialised when the robot is powered on and is responsible for the operation of the robot until the robot completes its task. Essentially, software execution starts and ends with the OnCP.

9.7.1.1 Locomotion

This module handles the navigation and localization of the robot (i.e.) this module is responsible for motor control and line-following. It also handles edge-detection ensuring that the robot does not fall off the roof / testbed.

9.7.1.2 Controls

Motor Control

Our robot has two motors, one in each tread. These motors are controlled by a Sabertooth motor driver. The driver, in turn, is interfaced to the Arduino Due via a serial interface. Two quadrature encoders are coupled to the two motors, one each, to obtain feedback from the motors. The encoders give 1000 pulses per revolution.

The Sabertooth motor driver receives a value between 0-255. Values between 1-127 control the speed of one motor. There are effectively 64 discrete speed settings at which the motors can

be run in each direction using this driver. Values from 1-63 runs the first motor in one direction and 65-127 run the same motor in the opposite direction. Sending a value of 64 stops the first motor. Similarly the second motor is controlled by sending values from 128 to 255. Sending a serial command of 0 stops both the motors.

Each of the motors are run independently by a proportional controller loop. The set-point is determined by the type of motion being executed. Each type of motion has a different setpoint which was determined empirically. The feedback term is obtained by measuring the number of pulses recorded by the encoder in a small time interval (50ms) and multiplied by a scale factor to convert it into speed. The error term is now calculated by subtracting the setpoint from the feedback term. The error term obtained is now multiplied by K_p (proportional gain) to compute the correction term. The control signal supplied to the motor is a sum of the correction term and setpoint value.

Line Following

The robot orients itself correctly and moves in a straight line on the roof by following white lines drawn on the roofing felt. It also determines the exact positions at which the shingles have to be placed by detecting crosses laid on the line.

Straight line motion (forward and reverse) is achieved by employing 2 sensor arrays consisting 3 infrared reflectivity sensors each placed at about a 5 cm offset from the center of the robot. The forward and reverse sensor arrays are used for forward and reverse motions respectively. Initially, the sensor thresholds are calibrated when they are centered on the line. The robot then executes one of 3 motions-- straight, left or right. It corrects itself based on the readings from the sensors. Each of the three motions consists of the left and right motors being independently controlled by a proportional controller as described in the motor control section above.

Stopping for laying is achieved by employing an additional infrared reflectivity sensor in the front sensor array. This sensor is placed at an offset from the center and used to detect the crosses placed on the line.

Edge Detection

Four Sharp IR rangefinders were placed at the four corners of the robot for detecting edges. These ensure that the robot does not fall off the roof / testbed. An averaging filter, that averages the last 5 values, was employed to overcome noise in the signal. The edge was detected when the value returned by any of the sensors was less than the threshold (determined empirically).

Row Switching

Row switching is performed in four steps; the first is a turn step where the robot turns upslope in place till none of the sensors (front or rear) are on the line. Then the robot move straight up the testbed / roof till the front sensors hit the next row. Now the robot turns downslope in place until the rear sensor detects the line. Finally the robot aligns itself and moves to the rear edge by following the line with the rear sensors.

9.7.2 Laying System Program

The laying system controller program (LayCP) is always running on the Arduino UNO, controlling the laying system. It communicates with the Due using a serial interface. The LayCP is always listening on the serial port waiting for a command from the Due. It receives the characters 'X' or 'Y' to perform laying or laying-with-cutting respectively. Depending on the actions to be performed the appropriate valves are actuated in sequence based on the inputs from the limit switches. Once the particular laying sequence is completed, the LayCP returns 'D' on the serial port to indicate that laying actions has been completed.

9.7.3 Off-Board Controller Program

The off-board controller communicates with the Due via a software serial interface. It sends character commands to the Due to control it the robot. It supports start, stop and continue commands. It also listens for status messages from the Due. When it receives the character 'R' it displays a message on the LCD screen to alert the user that the shingles needs to be restacked.

10. System Modeling and Performance

We did some work on analysis of the tread system to ensure that the system would not slide off of the roof. The system was analyzed using trigonometry and the coefficient of friction was determined considering the system would remain put on the 30 degree pitch without slipping. The treads also needed to carry the weight of the system and thus load bearing wheels were included in the tread. However, this proved to not be enough as the motor shaft saw a large amount of stress from both the angle of the roof and the weight of the system. A larger motor shaft would be desirable for this application. Also a center rib down the center of the tread would help with the shifting, down the roof due to force, of the tread. This would help eliminate some of the torque on the motor shaft.

The cutting system used a RIDGID roofing cutter and this was tested on several shingles to judge the force needed to both hold the shingle and cut it. From these test we determined that the force holding the shingle could be applied with the laying system and a pneumatic piston would provide enough pulling force for the cutter.

The ability to pick up shingles was a crucial part of the laying system. We first pick suction cups as the system to pick up the shingle. Originally the suction up worked well with a small amount of clay. However this was only in the small scale, on a single tab of shingle. Once the system was scaled up to a full three tab shingle the suction cups could not produce enough suction, with our small compressor, to hold the shingle. From suction cups we moved to magnets. The magnets were combined with pieces of sheet metal on the other side of the shingle to create a firm hold on the shingle for laying.

Below the system's actual performance is discussed in reference to our requirements and performance metrics. The system fulfilled many of our requirements but none of our desired requirements and thus those are not discussed.

Mandatory Non-Functional Requirements

3.1.1 Robust Construction

- The system was not exceedingly robust however it was able to work for the entire roofing job performed for our spring validation experiment.

3.1.2 Operate on Roofs with Different Pitch

- Our system operated on a 30 degree pitch however in the end our treads could not continuously withstand the forces cause by our system operating on this high of a pich. The pitch was lowered to 15 degrees and satisfactory operation was achieved as this pitch.

3.1.3 Industry Standard of Shingling

- Our system succeeded in using and cutting three tab shingles
- The placement of shingles needs some improvement to be comparable to that of a manually shingled roof.

3.1.4 Stable Operation on Roof

- The robot operated stably on the test bed and was able to complete an s-curve.

Mandatory Functional Requirements

3.2.1 Lay shingles accurately on roof

- Shown in Table

3.2.2 Size Shingles at Roof Edges

- Shown in Table

3.2.3 Shingles in timely manner

- The system shingled a 8 sq ft area of the roof, on an inclined test-bed of 3 shingles wide by 4 shingles tall (i.e. 8' X 4'). Robot will layed 2 rows of shingles in 20 minutes.

3.2.4 Return to be refilled

- We had the system go to the home edge of the roof when it was in need of refilling however we needed to turn the motor off for refilling as our off board controller was not integrated. The “continue” signal was replaced by turning the motors back on.

3.2.5 Notify the user shingling is “finished”

- The off board controller was not completely integrated and therefore the “finished” notification was not completed.

Performance Metrics

Table 4: Actual Performance of the System Versus the Performance Metrics

Req #	Operation Specification	Performance Metric	Actual Performance
3.1.2	Stable Operation on a roof constant pitch	Pitch up-to 30°	Used pitch of 15°
3.2.2	Length of shingles on 1st row	3' - 3' - 2.5'(after cutting)	Length produced: 3'-3'-2.5'
3.2.2	Length of shingles on 2nd row	2.5' - 3' - 2.5'(after cutting)	Length produced: 2.5'-3'-2.5'
3.2.1	Shingle spacing on either side	0.75" - 1.75"	Shingle spaced at - 1 in
3.2.2	Length of shingle cut off along the longer edge	5.75" - 6.25"	Length removed: 6 in
3.2.1	Maximum alignment difference between consecutive shingles	<= 1"	Alignment error: ~1.5 - 2 in
3.2.1	Distance between top edges of shingles between successive rows	5.75" - 6.25"	Shingle spacing: 6 - 6.3
3.2.3	Time required to complete laying two rows of shingles	20 minutes	Completed in 20 min

The system did not fulfill all of the above requirements but we were able to lay six shingles on the test bed including cutting the shingles to size.

11. Lessons Learned

If our group was to redesign this system the first thing that we would change is the use of treads. We would recommend using cables and motors mounted on the edges of the roof to move the system around. The new system would eliminate all of the issues with weight and inclination

faced by the treads. We would also leave more time for integration as the weight of the system and pitch of the roof caused more integration issues than we originally believed we would face. We learned how a tread system should be designed and what would need to be taken into account when building another treaded system. Critical systems should be tested first and test highest risk systems should be tested as quickly as is feasible.

Wiring quality plays a critical role in debugging. We learned that not all crimps fit well with Arduino. This can cause loose connections and eventually to long hours of debugging. We learned that proper planning of electrical design can make system look neat and failed components are easy to replace.

Our team learned a large amount about roofing and how roofers work. We have formed an intimate relationship with shingles and how they work on a roof. We also learned how to create a schedule and realise that the schedule can fall apart and so it is necessary to have some leeway on time. Finally, we learned how to work together in a high pressure team situation.

Finally, the project was a very complex system to build. It involved several unique subsystems. The fact that the system was originally intended to be used on a 30 degree pitch added another level of complexity. The system also needed to accommodate a large shingle which also added to the overall weight. All of these needs created a very hard design problem to a system that would also need to be controlled and localise properly. It was a time exhaustive project that required consistent testing and patience to deal with its untimely breakdown.

12. Future Work

If this system would be used in future project, the first step that would need to be taken is a complete redesign of the locomotion system.

- The tread system does not provided the reliability or accuracy that is necessary to drive correctly on an angled roof. This system could be replaced with a pulley system designed to move the robot across the roof like a plotter. Once the locomotion system is redesigned a nailing system will need to be implemented so the shingles can be affixed to the roof in the correct manner.
- The laying system can be redesigned to reduce weight of the overall system. The system can then be tested for robustness and repeatability of shingle laying. •
Wiring hassles can be reduced by planning fewer circuit boards.

13. References

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