Condition Monitoring System for Wind Turbine Lightning Protection System

Team 27
Sponsored By Siemens Gamesa

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Executive Summary

Threat of Lightning to Wind Turbines
Wind turbines have been modernizing and continue to improve how energy is harnessed while simultaneously avoiding emissions. With towers ranging from 65-165m (213-541ft) in height, and blades ranging 40-108m (131-354ft) in length, turbines can stand as tall as 240m (787ft) from top to bottom. To keep the wind turbines compliant with national and international regulations, maintenance needs to be performed at several locations of the wind turbines. For this project, the team focused on maintenance of the lightning protection system (LPS), which serves as a grounding path for lightning once it strikes the wind turbine. Lighting strikes can vastly damage a turbine if the lightning is not correctly routed to the ground by the LPS.

Current LPS Maintenance Practice
Currently, maintenance sessions for the LPS are conducted about once a year. Additional maintenance sessions can take place if there is suspected damage to the turbine from adverse weather. With current equipment, maintenance sessions can take up to 1.5 days to fully ensure the functionality of the LPS system. These sessions require two highly skilled technicians to rappel down the outer part of the blade and test the continuity between the tip receptors (steel objects along the blade which attract lightning strikes) and several other parts of the blade using an ohmmeter. If the technicians find evidence that the blade is damaged, they must go through an exhaustive trial and error process to locate the fault by testing multiple locations throughout the blade until they narrow in on the location. Utilizing multiple highly trained technicians and turning off the turbine for an extended period of time makes the LPS continuity measurement process expensive.

Team Solution
After learning of the challenges involved with ensuring the integrity of the LPS, the team, along with Siemens Gamesa representatives, decided that the solution would focus on verifying the integrity of the LPS ground cable located within the inner part of the blade. Furthermore, the team pursued a portable solution that could be used in multiple blades. The team developed an innovative solution to check the LPS cable condition throughout the parts of the blade that are inaccessible to humans.

This system consists of an autonomous vehicle that drives down the length of the blade and pulls a temporary conducting cable that will lay on top of the embedded LPS ground cable. The team chose to use a time domain reflectometer (TDR) for determining continuity because it allows a single-point measurement to be taken, this would decrease the time it takes to discover faults significantly as one technician will be able to determine continuity from the entrance of the blade. For the team to utilize the TDR in the project design, there needed to be two conductors that are mechanically parallel. By introducing the temporary cable to the system and using a TDR device, the system is able to immediately locate any faults or damages in the LPS cable.

Procedure
The overall procedure for implementing the system requires a technician to rotate and lock the blade into a horizontal orientation. Then, they will place the autonomous vehicle on the web structure, which is the floor seen in Figure 1. The technician will unwind the secondary cable from a reel to allow the autonomous vehicle to pull the cable approximately 35 meters down the length of the blade. Once the vehicle traverses the length of the blade, it will release the secondary cable and the technician will make a single-ended measurement using the TDR. This measurement will indicate if the LPS system has been damaged up to the 35m mark, it can also be compared to previous healthy and damaged LPS systems. After the measurement, the vehicle will return to the entrance of the blade, where the technician will retrieve the vehicle.

Figure 1: Final product inside grounded wind turbine blade


**Lightning Protection System (LPS)**

The damages caused by lightning to wind turbines can disrupt normal operations or physically ruin the blade. To keep wind turbines safe from lightning, they are equipped with a lightning protection system (LPS), whose main purpose is to ground the electrical energy from lightning without causing damage to the blade structure. The LPS is divided into 10 different subsections, seen in Figure 2, which form the path for the electric current throughout the turbine. This project specifically focuses on the ground “down” cable region, which is the second part of the LPS. Once lightning strikes one of the tip receptors located throughout the outer surface of the blade, the next part of the path is the ground cable which is embedded in the blades, highlighted in yellow.

The ground cable runs along the entire length of the blade, connecting with the tip receptors and ending in the root terminal. It is essential for this cable to be undamaged so there is a safe path for the energy to dissipate. If the cable becomes damaged, the energy from lightning strikes cannot be dissipated from the blade and will damage the blade itself as it exits back to the cloud through the blade’s laminate surface.

**Maintenance of LPS**

Current maintenance on this system is considered expensive because of the need for two highly skilled technicians to perform the operation. Technicians need to rappel down the blades of the wind turbines and check for continuity between the tip receptors and the root terminal. Because lightning is most likely to damage both the tip receptors and the ground cable, technicians must ensure that both systems are working properly. If there is no continuity, it can be assumed that the ground cable has been damaged. In order to locate the fault, technicians need to test the ground cable continuity at multiple points throughout the blade through a trial and error process until the damage has been located. This process is time-consuming and therefore expensive. In Figure 4, the difference between a damaged ground cable (left) and a healthy one (right) is shown.
Siemens Gamesa is seeking an alternative to their current methods of determining LPS damage. The current process costs the company a substantial amount of both time and money. Two highly skilled technicians must be employed to conduct time-intensive testing up to multiple times per year. Siemens Gamesa has approached the team to develop a condition monitoring system that can automate much of the lightning cable measurement process such that the integrity of the LPS could be verified by a single technician in a relatively short amount of time.

**Project Goals**

**CONTINUITY**
Solution shall verify continuity of accessible LPS ground cable

**FAULT LOCATION**
Determine location of discontinuity within the blade using a measurement device

**TECHNICIAN**
Allow a single technician to make this continuity measurement

**Design Obstacles**

Through the design iteration process, the team continued to learn more about what a feasible solution might be as well as what would not work. This was a learning experience for the team as they were challenged to design a solution without having seen a turbine blade up-close. During the design iteration process, the team uncovered quite a few obstacles, both internal and external to the blade. Some of these obstacles are shown below in Figures 5, 6, and 7. The inside of the blade also poses a challenge due to its small interior geometry. Technicians are not able to internally access the blade farther than 25m due to size constraints. Additionally, a solution that would be permanently installed in the blade would jeopardize the international electrical certifications and be costly to implement. Therefore the final solution needed to be transportable and reusable.

Figure 5: External obstacle, the blade is not completely smooth due to add-ons
Figure 6: External obstacle, complex blade geometry
Figure 7: Internal obstacle, weighted blocks and slippery fiberglass material
Initial Concept Generation Ideas

Figure 8: Telescoping Arm
This idea was limited by the overall diameter of the wind turbine tower

Figure 9: Modify Blade Technician Robot
This idea was limited by the various external blade add-ons

Figure 10: Drone
This idea was limited due to the high wind locations of turbines and the cost of pilots

Figure 11: Installed Track for Robot
This idea was limited due to the poor aerodynamic performance a blade would have

The Final Solution

The team’s final solution consists of an autonomous vehicle that will navigate down the blade, shown in Figure 12. The team chose to use a time domain reflectometer (TDR), shown in Figure 13, for determining continuity over an ohmmeter because it allows a single-point measurement to be taken. This device would allow one technician to determine continuity from the entrance of the blade. By using a TDR device, the solution is able to immediately locate any faults or damages in the LPS cable. A temporary conducting cable needed to be placed along the embedded LPS cable to use the TDR. The details of deploying the vehicle are outlined below.

1. Rotate and lock turbine blade in the horizontal position
2. Place the autonomous vehicle on the web structure internal to the blade
3. Enable autonomous navigation to 35m, the vehicle will release the temporary cable
4. Use a TDR to make a single-ended measurement of the LPS
5. The technician will begin to coil the temporary cable and the vehicle will return to the entrance of the blade
Autonomous Vehicle
The team’s final solution consisted of a vehicle that can autonomously traverse down the length of the blade to about 35 meters. A technician is not able to easily access this far into the turbine due to the confined space and using this small vehicle allows for more of the LPS system to be measured. This vehicle tows a secondary conducting cable and an emergency retrieval cord. The vehicle is autonomously navigated and centered along the blade by onboard control systems. This allows the vehicle to lay the secondary conducting cable on top of the embedded LPS cable that is centered in the blade.

1 LiDAR Scanner
A LiDAR scanner is used to collect a 360-degree scan of the vehicle’s surroundings. This data provides precision situational awareness for autonomous navigation.

2 Custom Electronics Housing
The electronics housing is 1/4 in thick acrylic designed to mount the electronics hardware. This housing extends over the back of the vehicle and provides additional surface area for mounting. The custom design allows enough space for all of the necessary electronics and prevents short-circuiting.

3 Electronics
The electronics handle power, navigation, and secondary conducting cable deployment. The vehicle utilizes an Odroid-XU4, Arduino Mega, RoboClaw Motor Controller, two DC-DC converters, power distribution block, servo motor, and two 11.1 V batteries. The batteries are stored within the vehicle assembly.

4 Emergency Retrieval Cable
At the back of the vehicle, an emergency cable has been attached so the technician may retrieve it at any time. If the vehicle gets stuck on the weighted blocks or a technician needs to leave a turbine quickly due to safety concerns, the vehicle can be retrieved promptly.

5 Cable Release Servo
The release servo is mounted on the back of the vehicle. The secondary cable needs to be released before the vehicle returns to make sure the vehicle does not get caught up on the cable.

6 Polulu 6WD All-Terrain Chassis
The independent motor of each wheel and all-terrain suspension allows the vehicle to navigate over sizable obstacles while towing the necessary payload. Additionally, the vehicle chassis has numerous mounting points for customization. Larger wheels are used in the front of the car to better navigate the weighted blocks.
**Autonomous Vehicle Navigation**

It is essential that the temporary conducting cable is parallel with the LPS cable. To maintain the parallel deployment of the temporary conducting cable, an autonomous navigation method providing precision vehicle positioning was developed. The navigation method continuously auto-corrects and centers the vehicle as it traverses the blade. This guidance method is based on the CU Robot Automation lab’s Ohradzansky et al. Bio-Inspired Reactive nearness control research. This research analyzed insects’ visuomotor systems and modeled their flight path centering method. This system utilizes an RPLIDAR A1 sensor which generates a 360 scan of distances ranging 0.15-12 meters encoding the output in a vector. The LiDAR scan is sent to the CPU, an Odroid XU4 single-board computer, which is outfitted with Linux ROS packages running the code containing the centering algorithm. The centering algorithm is contained within C++ code that subscribes to the LiDAR scan topic, runs calculations to determine the core correction required for centering, and publishes motor control commands that the Arduino can subscribe to via ROS serial.

The Arduino then receives the control command signals, filters them to ensure proper operating ranges, and pushes them to the motor driver continuously. This system allows for the robot to autonomously navigate many environments, especially a narrow relatively uniform environment such as the blade interior. The robot is controlled using Secure Shell Protocol (SSH) through an ad-hoc Wi-Fi network between the Odroid and any other device’s terminal via a wireless Wi-Fi module. This network protocol eliminates the need to physically connect to the robot to operate it. Operation begins by SSH-ing through the Wi-Fi network to run the program and enable controls. This will start the vehicle’s motion and guide it down the blade along the centerline. When the robot reaches the end of the accessible portion of the blade, a safety box feature is activated. The walls will activate the safety box at a distance of 18cm on all sides. The vehicle then stops, releases the TDR cable, and waits for further commands. When the test is complete, SSH-ing an enable reverse command will initiate guidance back to the technician to allow the robot’s retrieval.

### DATA FLOW IN AUTONOMOUS VEHICLE

<table>
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<th><strong>1</strong></th>
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<tr>
<td><strong>LiDAR Sensor</strong>&lt;br&gt;• The sensor spins continuously to allow robot to “see” its surroundings.</td>
<td><strong>Odroid XU4</strong>&lt;br&gt;• The Odroid takes in the scans of the LiDAR and processes them to compute how to drive in the center of the blade.&lt;br&gt;• Receives a run command from the computer terminal.&lt;br&gt;• Sends data to Arduino.</td>
<td><strong>Arduino MEGA</strong>&lt;br&gt;• Receives commands from Odroid and “tells” motor driver to send power to wheels.&lt;br&gt;• Also controls servo in the back of vehicle that releases temporary cable.</td>
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<tr>
<td><strong>Motors/ Servo Motor</strong>&lt;br&gt;• Receive direction and speed commands from Motor Driver to move vehicle forward.&lt;br&gt;• Servo motor receives a command from Arduino to open/close and release cable.</td>
<td><strong>Motor Driver</strong>&lt;br&gt;• Receives commands from Arduino.&lt;br&gt;• Sends direction and speed commands to individual motors on every wheel of the vehicle.</td>
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Project Components

Time Domain Reflectometer

A Time Domain Reflectometer (TDR), is a single-point measurement device where only one end of a cable is needed to test its continuity. The TDR sends a low voltage pulse into the LPS cable being tested. As the pulse propagates down the cable, any change in the characteristic impedance of the LPS cable results in a reflected signal seen on the TDR. The TDR outputs a trace of the system that demonstrates the reflection coefficient ($\rho$) vs. distance. This reflection is due to some of the incident signals reflected back to the TDR. The reflected signal on the TDR will be positive if the impedance change was greater than the instantaneous impedance of the LPS cable as shown in Figure 15 below. The reflected signal will be negative if the impedance change is less than the instantaneous impedance of the LPS cable as shown in Figure 16.

Motivation for Use Over an Ohmmeter

Currently, the continuity of the LPS cable is measured by an ohmmeter. The Ohmmeter leads are physically connected between two points along the LPS cable for every measurement. Those two points are usually the tip receptor and a common point further down the ground path. This process requires highly skilled technicians to externally measure the resistance between points along the LPS cable. This is a very time-consuming and expensive process. On the other hand, a TDR is a single-point measurement device and hence it does not require technicians to access the blade tip or test at multiple locations throughout the blade. The technician can measure the LPS continuity from the root terminal. Moreover, the TDR has the ability to identify fault location on the LPS cable. The TDR used in this project, a Megger TDR2010, can store up to 100 traces; those traces can be used in future trace analysis and comparison to aid in fault location.

Need for a Second Conductor

To utilize the TDR technology, there must be two conductors that are mechanically parallel and electrostatically coupled. Unfortunately, the LPS cable is a tinned copper braided cable that does not have a second conductor or a sheath. When TDRs are used in other industry settings, this additional conductor or sheath eliminates the need for deploying another cable. However, this setting requires a temporary cable to create a return path for the reflected signal. The temporary cable needs to be carefully deployed as it could impact the ability to identify potential faults on the LPS cable. The autonomous navigation method was chosen to deploy the temporary cable with precision.

Factors That Affect the TDR Measurement

While there are several factors that affect the TDR measurement, the most important is the distance between the center of the LPS cable and the temporary cable. If the cables are randomly spaced, the characteristic impedance will change along the LPS cable. This consequently affects the ability to determine if this change in the impedance is due to the distance between the cables not being uniform or if it is because of a damaged LPS cable. The autonomous navigation centers the cable directly above the LPS cable to remedy this.

TDR Traces

The actual appearance of the TDR traces will not match the traces in the figures above, as seen in the test results section, because the characteristic impedance along the system is not constant. However, the team will still be able to determine the continuity of the LPS cable using the TDR. While the traces taken by the team show impedance variation (and look noisy) before the end peak, the end of the cable can still be identified from the high impedance spike.

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Initial TDR Testing

The purpose of the initial TDR test was to confirm that TDR technology will work for the team’s application, as this tool has not been used to measure continuity in wind turbines before. TDR is mainly used to determine the characteristic impedance of metallic cables such as coaxial cables. Those cables usually have two conductors or at least a single conductor with a sheath. The distance between the two conductors in those metallic cables is usually uniform and within the range of a few inches. However, the LPS cable is a tinned copper braided cable that does not have a second conductor or a sheath which would provide a uniform return path for the signal. Hence, the team introduced a temporary cable. This preliminary test determined how far away the secondary cable can be deployed and still have the TDR signal propagate down the LPS cable. The initial TDR testing was conducted at CU Boulder's Engineering Center. The team used Eric Bogatin’s TDR, a professor in the Electrical and Computer Engineering department.

Blade Tip TDR Testing

The temporary cable was first placed directly above the embedded LPS cable, shown in blue in Figure 17. Then, the temporary cable was placed about 25 cm from the LPS cable, shown in red. The TDR readings are also shown in Figure 17.

In the figure below, the y-axis represents the reflection coefficient, \( \rho \), and the x-axis represents the time it takes the signal to travel from the TDR and back. The resultant trace from the “close cable” is illustrated by the blue trace (it might not be seen at the beginning because the red, blue, and green traces are overlapping each other). Every time the TDR signal travels down a joint, there is a bump on the trace like that seen at time 19 ns. The signal propagated down the LPS cable and identified the end of the cable, seen at t~51 ns. To determine whether the TDR could still identify the end of the cable with a larger separation distance, the temporary cable was placed about 25 cm from the LPS cable as previously mentioned. The resultant trace is illustrated by the red trace (far cable), showing the signal still traveling down the cable and identifying the end of the LPS cable. The red trace shows that the cable now has a higher impedance given the distance between the LPS cable and the temporary cable increased. From these TDR traces, the team was able to verify that the TDR technology will work using a temporary cable and the LPS system. Additionally, this test showed that even with a small distance added between the two conducting cables, the end of the cable can still be identified.

Figure 17: Initial TDR test set up on blade tip and resulting TDR traces, LPS cable is located directly below the dotted blue line.
Final Test Results

Final NREL TDR Testing Using Vehicle
A final test with a grounded 49m turbine blade was conducted. The team was looking to confirm that the traces captured by the TDR would verify the status of the LPS cable by either identifying the far end of the cable or a fault mimicked on the temporary cable. First, the team deployed the temporary cable using the autonomous vehicle to collect baseline traces of the blade up to 35m from the root with the temporary cable. Then, the team deployed the temporary cable as done previously, but with a mimicked damage. This "damaged" cable had a 1 megaohm resistor spliced between two sections of cable and should be measured as a discontinuity by the TDR at 19m.

The results of this test are shown in Figure 18, the y-axis represents the reflection coefficient, $\rho$, and the x-axis represents the distance of the cables. By comparing the light blue (healthy cable) and the dark blue trace (damaged cable), the location of the end of each cable was seen on the TDR traces. At about 21m with the dark blue trace, there is a positive spike indicating an open circuit (damaged LPS cable) whereas the actual length of the LPS cable is at 35m as indicated by the positive spike on the light blue trace. The location of the fault was 19m and the TDR identified it to be located at 21m. Even though the TDR has a resolution of 0.1 m, there was some margin of error; the reason for this inaccuracy is the small variations in the deployment of the temporary cable.

Temporary Cable Location
While on-site, the team conducted additional testing to determine the limitations of the TDR based on the distance between the LPS and temporary cable. During one test, the cable was resting fully on the left side of the web about 0.75m from the center. The TDR results were still readable and the end of the cable was located.

Final NREL Vehicle Testing
The final testing verified that the autonomous vehicle worked as intended inside of the blade. The vehicle did not have any major issues while traversing the blade and the obstacles within. With the modification of bigger wheels in the front of the vehicle, the vehicle was also able to overcome the weighted blocks when centered between them. Additionally, the system successfully released the secondary cable once the vehicle traversed the blade and before the TDR measurement was taken.

![Final TDR Test Results from NREL](image)

Figure 18: Final TDR traces from grounded turbine blade (Disclaimer: This data has been clipped to clearly demonstrate the end of the cable for the purpose of this white paper and would usually have additional data past the end seen.)
Conclusion

The team met all of their initial design goals and successfully designed an autonomous vehicle to determine LPS continuity within 35m of the blade root. The size of the blade limited the vehicle’s ability to determine continuity any further. The team was able to test the vehicle functionality multiple times on two different grounded blades. The resulting TDR traces have been analyzed to start making a library of healthy LPS system baselines for future use. The current solution is capable of determining continuity within the LPS system using a single-point measurement device, determining the location of discontinuity within the system, and only requires one person during the vehicle deployment and TDR measurement.

Future Steps

In the next design iteration, there are multiple options that could be implemented to further this project. The team believes there would be a benefit with both furthering the vehicle design and looking at a TDR with additional functionalities.

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<th>IMPROVE THE TIRE TREAD</th>
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<tr>
<td>Search for tires with more aggressive tire tread to grip the fiberglass inside blades and prevent slipping.</td>
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<th>USE A WEDGE</th>
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<td>Implement a wedge under the front and back sides of the vehicle to help it move over the weighted blocks.</td>
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<th>USER MANUAL</th>
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<td>Create a user manual for technicians to learn how to use the product. Use LPS baseline TDR traces to see if cables are healthy or not.</td>
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<th>DECREASE SIZE</th>
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<td>Develop a vehicle with similar navigation but smaller, to make measurements further down the blade.</td>
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<th>ADD A CARRYING HANDLE</th>
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<td>Attach a carrying handle to allow a technician to carry the vehicle with one arm, to more easily travel inside the turbine.</td>
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<th>UPGRADE TDR</th>
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<td>Use a more advanced TDR to see if this technology is capable of determining faults when the temporary cable is further away.</td>
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A huge thank you to all of the team’s mentors and support staff throughout this project.
Meet Team 27

Adrian Gutierrez Project Manager - Adrian is graduating in May with a B.S. in Engineering Plus with an emphasis in Mechanical Engineering and a concentration in Engineering Management. He has worked over the past two summers for an industrial automation company in Mexico and is currently a Teacher’s Assistant for GEEN 3400- Invention and Innovation. He is currently looking for an engineering full-time position in the US.
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Stryker Holland Logistics Manager - Stryker is graduating in May with a B.S. in Mechanical Engineering. He currently works for Seagate Technology and will be starting a full-time position upon graduation. Stryker works on mechanical components of Seagate cloud data storage solutions. Stryker gained an in-depth knowledge of programming robot autonomy using Linux ROS throughout the project and plans on working with autonomous robotics in the future.
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Faraj Abdelgilil Electrical Engineer - Faraj is a senior in the Electrical and Computer Engineering Program. In May, Faraj will receive a Bachelor of Science in Electrical Engineering with a minor in Energy Engineering and will also achieve EIT status upon graduation. Afterward, he plans to find a rewarding job as an electrical engineer, pursuing his interests in power and energy systems and working towards earning licensure as a Professional Engineer.
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Erick Quintanilla Financial Manager - Erick is graduating in May with a B.S. in Mechanical Engineering. He has had an important role in the Inspired Dreamers club and took part in the Society of Hispanic Professional Engineers (SHPE). He gained programming experience through this project, and got exposure to coding in C++, working in Arduino code, python, and through virtual machines in Linux OS. Erick is currently looking for a full-time position in engineering.
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Mia Miller Systems Engineer - Mia is graduating in May with a B.S. in Mechanical Engineering and a minor in business. She is the president of CU Boulder’s Society of Women Engineers (SWE) chapter and a student apprentice for MCEN 2000: Mechanical Engineering as a Profession. She is passionate about the renewable energy industry and will pursue her master’s degree with a focus in simulation and optimization in the upcoming academic year at CU.
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Miles Wright Test Engineer - Graduating in December with a B.S. in Mechanical Engineering, Miles expanded his working knowledge of C++, ROS, time-domain reflectometry, autonomous navigation, and appropriate test design with such a multifaceted project. He’s worked as an assistant in a research lab assessing metrics of right heart blood flow obtained through MRI as they relate to heart function. He is passionate about renewables, biomedical devices, and imaging.
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Mohamed Adil CAD/Manufacturing Engineer - Mohamed is a senior majoring in Mechanical Engineering and a minor in Engineering Management. He has been working in the Mechanical Engineering Research Lab as a research assistant over the past year, focusing on the computational methods that will aid in predicting the pressure drop versus flow rate relationship.
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