Mechanical Engineering
UNIVERSITY OF COLORADO BOULDER

DC DESIGN CENTER COLORADO
DESIGN • BUILD • INVENT

Remote Nacelle Monitoring System

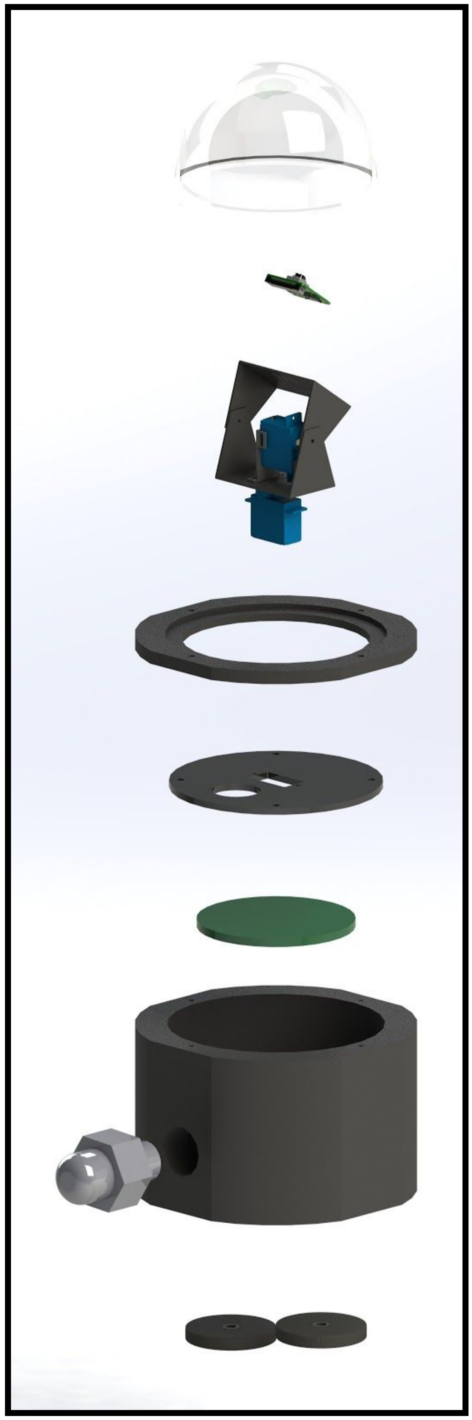
Rachel Adelberg
Ryan Duever
Ryan Henley
Dade McMorris
Jay Neal
Patrick Sherman
Jock Tuttle

Sponsor:

SIEMENS Gamesa
RENEWABLE ENERGY

Director: Gage Froelich

Table of Contents



Background

Wind turbines have multiple interdependent parts and subsystems, meaning these machines need frequent maintenance and supervision. The nacelle is located on top of the tower and houses the majority of the turbine's components including the drivetrain, yaw system, and power electronics. This area facilitates the conversion of mechanical energy from the turning blades into usable electricity. These systems are uniquely difficult to service and maintain as the nacelle can be elevated as much as 80m+ (262 ft) off the ground.

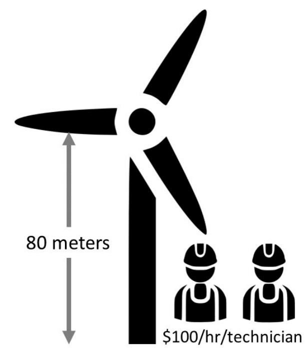
Despite a regular maintenance cycle, subsystems inside the nacelle can malfunction. The next step after a malfunction is diagnosis. Visual diagnostics are often required, either because that component does not have dedicated monitoring and/or potential malfunction needs to be visually verified.

Currently, any visual inspection is performed by a technician. These employees visit a turbine that is scheduled for maintenance or that is malfunctioning in some way. They may be able to solve the issue upon discovery, however, some damages may require unanticipated corrective action to return the turbine to operation.

However, in-person visual inspection is not an optimal solution; dispatching technicians is labor-intensive and costly, and documentation of the issue is left to the discretion of the technicians, which can lead to inconsistent results across multiple inspections.

These issues can be mitigated by implementing a remote monitoring system. That is, to install a camera system inside the nacelle capable of monitoring critical components without requiring a technician to visit the turbine.

Turbine technicians are billed hourly and are required to work in teams for safety. Currently, a visual inspection in the nacelle requires the technician team to do the following:



- Travel to the turbine (can be >45-minutes)
- Shutdown the turbine, resulting in costs due to lack of production
- Ascend the tower
- Perform visual inspection
- Descend the tower
- Travel back to the operations building

If the inspection requires additional troubleshooting or repair work, it can require another trip to bring the correct tools and equipment. These costs can quickly add up over the course of a year and the lifetime of the turbine, which is typically 20-30 years. Integrating a monitoring system within the nacelle can remove these steps making for more efficient working conditions.

A user-friendly, continuously recording, low-cost remote monitoring system implemented in the nacelle has significant potential to significantly increase maintenance efficiency, resulting in decreased maintenance costs and increased turbine up-time.

Finding Inspiration

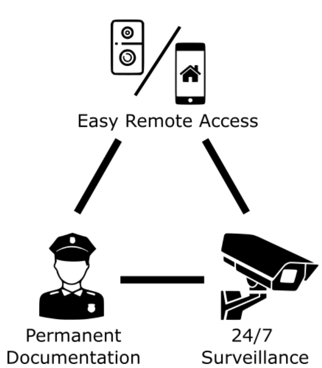
The primary inspiration for the RNMS came from the Ring™ household security system. This product integrates a live video streaming application with a household security system. The features of this system that were preferred by Siemens Gamesa Renewable Energy (SGRE) are:

- Quick access to camera views
- Intuitive User Interface
- Easy navigation between views
- System Modularity

These concepts represent an essential part of the desired user experience.

Figure 1: Ring doorbell User Interface

Apart from home security, there are other industries that use camera monitoring to solve issues that could apply to a wind turbine. Body cameras on police officers yield permanent documentation and accountability. Similarly, Industrial closed-circuit television, or CCTV, systems are common in supermarkets, schools, jails, etc., and allow for 24/7, automated monitoring of an area. However, installing 10+ cameras in every turbine of a wind farm with hundreds of turbines from a third party would be economically impractical. Additionally, these systems can be ill-suited from a connectivity perspective. SGRE's internal network would have issues interfacing with many monitoring cameras due to their custom network.



A viable monitoring system implemented within the nacelles on a wind farm would take the best aspects of the above examples and adapt them to fit the needs of the turbine producer and wind farm owner.

Solution Development Process

To assess all options for a system to remotely monitor the nacelle and reduce technician visits, the team conceptualized multiple design ideas with varying complexity. This yielded four design concepts that were critically assessed and iterated to determine the optimal solution given the requirements. These four designs were distilled into two categories: mobile cameras with a specified range of motion within the nacelle to monitor all subsystems, and stationary cameras monitoring designated subsystems. These categories present different advantages and disadvantages which the design team used to settle on a final design for the RNMS.

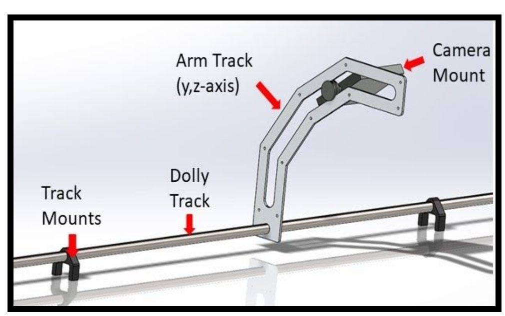


Figure 2: Dolly track design alternative

The culmination of several mobile camera concepts was a system consisting of a robotic camera arm that would be free to move along a dolly track. The aim of the refined mobile camera design was to minimize complexity in the realm of data processing and organization. However, once these designs were initially developed, some major drawbacks were identified.

The most important drawback of mobile cameras is the space required. The nacelle is made to house power generation equipment, and the addition of another system introduces a risk of interfering with the turbine's primary function. These designs also presented a level of mechanical complexity that could increase the amount of maintenance required for the turbines instead of minimizing it. Finally, the development of a mobile camera system was found to be more expensive than the options presented in the stationary camera category.

The stationary cameras developed by the team were originally going to be mounted to brackets, only being able to monitor one fixed frame of view. Implementing this plan presented a challenge due to the large number of systems to monitor. To adequately monitor every component, many cameras were needed which made this plan less cost-effective than the team had originally thought. Actuated cameras were then proposed to remedy this problem, allowing for multiple components of the nacelle to be monitored with one camera unit. To achieve low manufacturing costs, the same base camera housing and related parts were designed for both the fixed and actuated implementations. This cut back the necessary cameras by approximately 20% and significantly reduced the total system cost.

Final Solution

The final design chosen by the team consists of 10 custom cameras and housings, six gimbal-actuated and four fixed, capable of monitoring the 18 critical components within the nacelle.

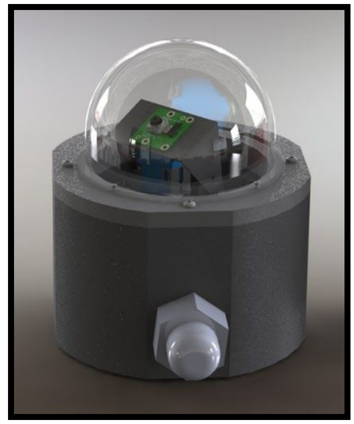


Figure 3: Camera assembly render

A Raspberry Pi 4 computer supports the thermally regulated Central Control Unit as it manages the entire system, in addition to the auxiliary lighting system. Microphones are incorporated into each camera unit to allow for audible detection and diagnosis of things like loose objects or suspicious noises. This RMNS system design has numerous features necessary for adequate monitoring that are not offered by other commercially available surveillance devices. Detailed design descriptions will be laid out in the following subsections.

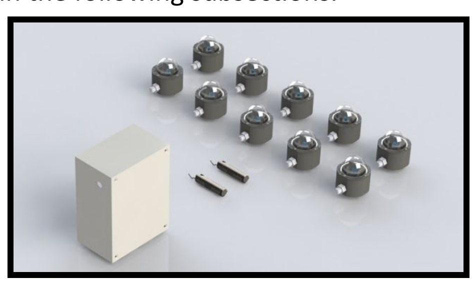


Figure 4: Full product render (excluding lighting)

Electrical Design

To achieve the best camera quality for cost, the team opted to design the camera circuitry in-house. Utilizing the Cypress "CX3" microcontroller Integrated Circuit (IC), the team designed a six-layer circular Printed Circuit Board (PCB) 75mm in diameter to capture images and audio while allowing for motorized control of the camera angle. The Raspberry Pi v2 image sensor outputs 1080p video at 30fps, which requires a super-speed USB 3.0 digital interface to stream in real-time. This meant that many of the interconnects on the PCB had to be designed with controlled impedance and length matching.

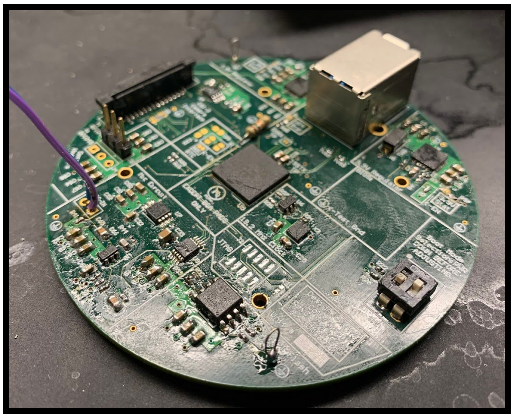


Figure 5: Assembled Camera PCB

Audio capture was handled using an electret condenser microphone, pre-amplifier circuit, and an analog to digital converter (ADC). To minimize the size of the controller board, the team utilized high-density surface mount components as well as utilizing both the top and bottom surfaces for component mounting.

The electronic components for the boards themselves cost around $100 per board, with each PCB adding an additional $66.

To establish independence from the integrated nacelle lighting, the team developed an auxiliary LED lighting system controlled by a smaller mosfet peripheral board. This allows for powerful LED floodlights to be enabled or disabled as needed to monitor components, maximizing image quality while minimizing power usage.

From an electronics perspective, this solution is novel in that there is no motorized USB 3.0 camera available currently on the market. The majority of security camera systems today utilize either ethernet or direct analog video connections. Many companies, however, are moving towards USB 3.0 for machine vision and automation, as the high data rate, power delivery, and flexibility of USB 3.0 offer many potential improvements over typical imaging systems.

Central Control Unit Design

The Central Control unit consists of a Raspberry Pi 4 computer, Samlex SEC-1223BBM power supply, Lead-Acid backup battery, Powered USB 3.0 Hub, thermoregulation components, and the aforementioned peripheral board. The CCU allows for centralized video processing and network access, reducing the processing power required by each individual camera. All components are housed in a compact Crum/Rittal electrical cabinet, protecting the CCU components from physical or water damage. The Samlex works in conjunction with the backup battery to allow the monitoring system to remain functional in case of a power fault in the turbine. To accommodate deployment in a wide variety of locations and climates, the CCU is capable of self-thermoregulation via heating elements and cooling plates.

<u>Software Design</u>

Another novelty of the system is its software interface. The highlight of this software is the customization available to the user. Not only does the software support expansion made possible by the electrical design, but data is stored in a way that allows for unlimited cameras and camera angles to be supported. Likewise, the software must support the many configurations that provide so much functionality, such as the lighting group, the designation of the camera as articulating or stationary, and the access to an onboard microphone.

This customizable approach is accomplished by creating two distinct partitions. The first partition is the separation of installation of a new camera module from the processes necessary to retrieving actual media during operations.

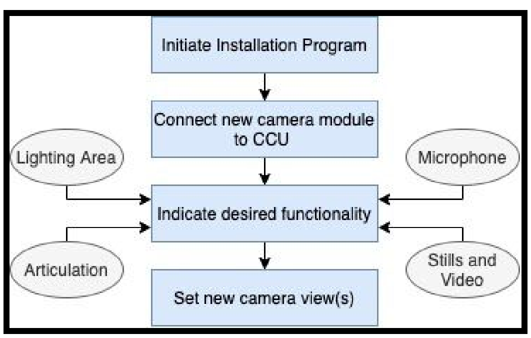


Figure 6: Installation procedure flow diagram

This method of organization allows for expansion down the road and creates a data structure that is resilient to corruption. This data structure is then more efficiently accessed by the operations application and helps make power budgeting and other behind the scenes processing possible. It also establishes the relationship of the microcontrollers used in the camera modules as simply a means of converting an image sensor into a USB camera device, with the additional benefits of Serial Peripheral Interface (SPI) communications with microphones, and control over two servos motors for positioning.

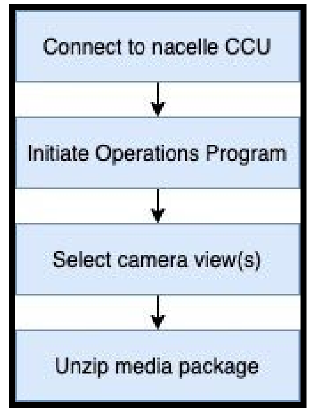


Figure 7: Operations procedure flow diagram

The second partition is this separation of the CCU from the camera module. The CCU covers all oversight, and aside from controlling its own climate, organizes the data representing each camera position and angle upon installation, and sends requests for imaging and articulation to the CX3 microcontrollers that coordinate with internal applications relating to their functionality. The CX3s also are simply a central collection point for the media requested; all data formatting into video, image, and audio files takes place at the CCU.

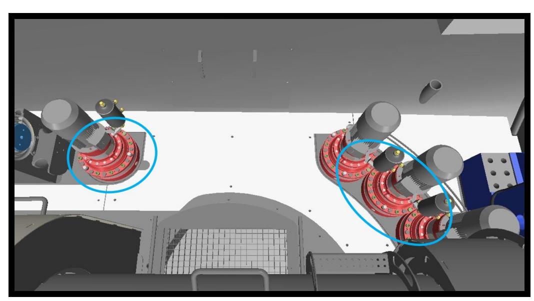


Figure 8: Simulated camera view for a camera unit, monitoring grease reservoirs (circled)

Mechanical Design

The Mechanical components of the 10 cameras can be broken down into six main parts, each detailed below. Delrin was chosen for exceptional machinability but could be easily substituted for injection-molded plastic in a production environment. Collectively, one camera unit costs $340 when all components are accounted for, which is both less expensive and higher quality than the majority of motorized cameras on the market.

- *Protective Domes:* The protective domes are hemispherical and made of polycarbonate.
- The domes are affixed to the mounting lid with Loctite 771 primer and Loctite 401 adhesive.
- *Gimbal Assembly:* This assembly consists of steel mounting brackets, pre-purchased from Sparkfun Electronics, and two sub-micro servos (actuated Cameras only).
- *Mounting Ring:* The mounting plate is a circular ring machined from Delrin. It is fitted to the top of the outer housing with M3 screws.
- *Mounting Plate:* The mounting plate is a circular disc machined from Delrin. It is fitted to the inside of the outer housing with M3 screws on a counterbore.
- *Outer Housing:* This black outer housing is manufactured out of 5.5-inch diameter Delrin stock.
- *Cable Gland:* To prevent the intrusion of dust and water droplets into the housing, the cable hole in the outer housing was fitted with a watertight, IP67 cable gland.
- *Magnetic Mounts:* The entire camera assembly is fitted to the steel nacelle through the use of SGRE standard magnets.

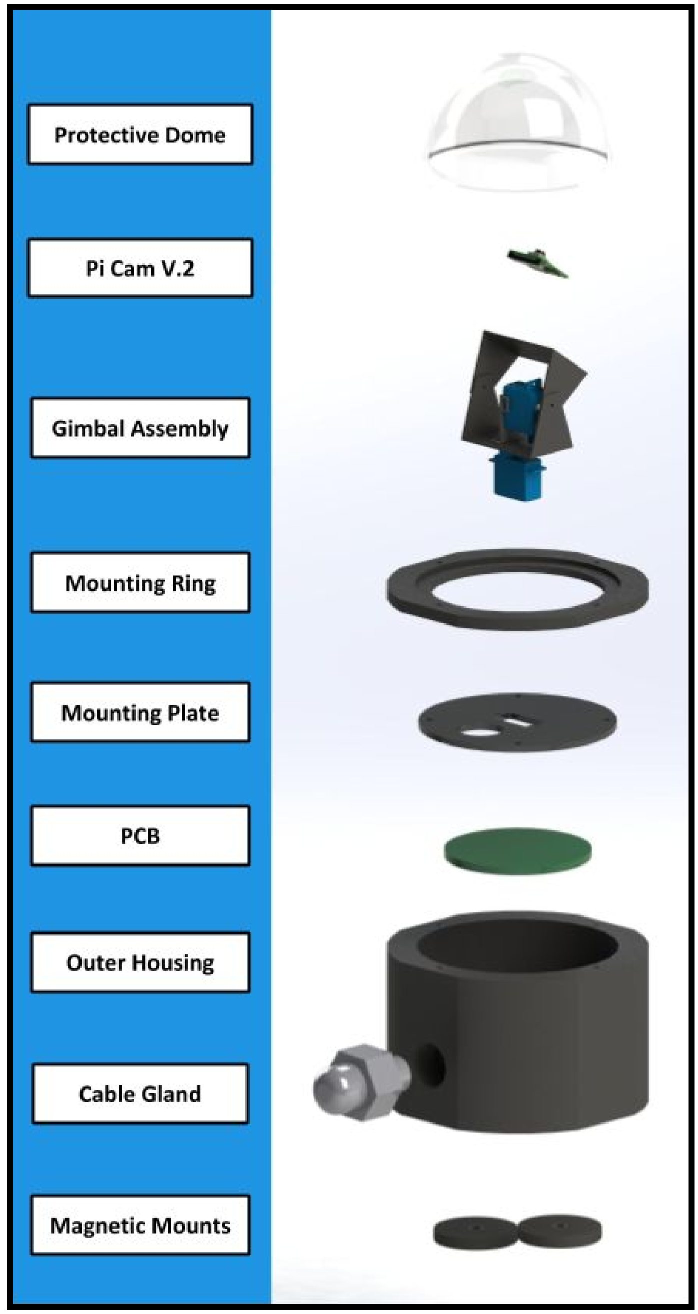


Figure 9: Camera module exploded view

Reflection

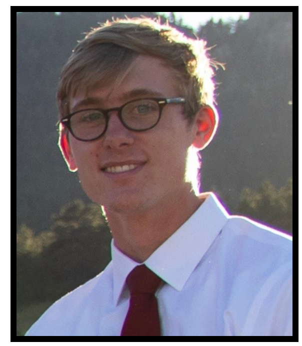
Siemens Gamesa Renewable Energy and the remote nacelle monitoring system team share unified goals as well as independent, symbiotic goals. Siemens Gamesa seeks to develop an internal visual monitoring system for the nacelle of the turbines. The design team shares these design goals and hopes to develop a concept to reliably and consistently monitor the critical components of the nacelle. The success of this design goal can be gauged by factors such as system response time, turbine fault independence, resilience to the environment of the nacelle, and the clarity of each component view.

These design goals were kept in mind throughout the system design and development and the final product has served to provide a foundation for which Siemens Gamesa can complete and scale the project. The team is proud to have developed the framework for a system that accomplishes these design goals.

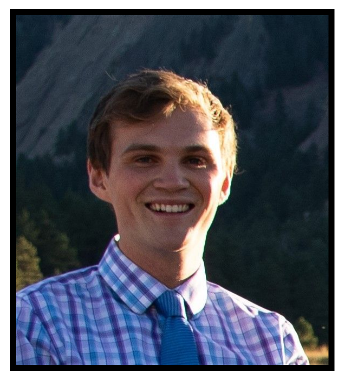
The Remote Visual Monitoring team set out to produce a meaningful project that makes a tangible impact and enables them to gain experience and connections in the RE industry. Above all else, the team hopes to approach all challenges with a unique and collaborative mindset so that at the end of the project duration, all project stakeholders are proud of both the end product and the growth they have made throughout the duration of the project.

Team Biographies

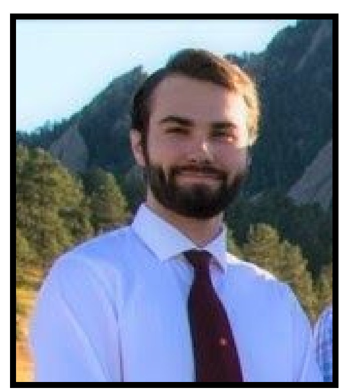
Rachel Adelberg
B.S. in Mechanical Engineering, May 2020
Rachel Adelberg served as the manufacturing engineer for this project. Her primary role was making sure all the physical components designed in SolidWorks could be machined and taking a lead in the manufacturing process. She hopes to pursue a job in the renewable energy industry.



Ryan Duever
B.S. in Engineer Plus (Mechanical), May 2020
Minor in Energy Engineering
Certificate in Sustainability
Ryan Duever served as the logistics manager for the RNMS project. His primary technical role was leading software development, specializing on the CCU and UI. He plans to remain in Boulder to pursue full-time employment in energy engineering.



Ryan Henley
B.S. in Mechanical Engineering, May 2020
Minor in Energy Engineering
Ryan Henley served as the test engineer for this project. coordinated all testing procedures and documentation. His primary goal was to ensure that the system could survive within the unique environment of a wind turbine nacelle. He also worked on the software development to configure the camera chips on the PCB. He hopes to work in the sustainable energy field after graduation.



Dade McMorris
B.S. in Electrical Engineering, August 2020
Dade McMorris served as project manager for the RNMS project, as well as the resident Electrical Engineer. Born and raised in Colorado, he is a third-generation CU Alumni. His primary contributions were the 6-layer camera PCB, documentation, and general management of the project schedule. He intends to stay in Colorado to pursue full-time employment in Mechatronics/ PCB Design.

Jay Neal
B.S. in Mechanical Engineering, May 2020
Jay Neal served as the CAD engineer for the RMNS project. He was responsible for approving all CAD models, controlling and documenting each revision, and ensuring all parts were completely manufacturable given a CAD drawing. He hopes to pursue a career in renewable energy.

Patrick Sherman
B.S. in Mechanical Engineering, May 2020
M.S. in Mechanical Engineering, December 2021
Minor Evolutionary Biology and Ecology
Patrick Sherman served as the systems engineer for the RMNS project. He was responsible for ensuring the interfaces of the project were compatible. He had his hand in many different aspects of the project including software development, testing, and mechanical design. He will stay in Colorado to finish his Graduate School Degree in Mechanical Engineering.

Jock Tuttle
B.S. in Mechanical Engineering, May 2020
Minor Energy Engineering
Jock Tuttle served as the financial manager for the RNMS project. His primary contributions were compiling and maintaining the project bill of materials and budget, managing all component procurement and manufacturing of mechanical components. He plans to stay in Colorado after graduating to pursue full-time employment in the renewable energy industry.