University of Arkansas – CSCE Department
Capstone I – Preliminary Proposal – Fall 2023

Brain Ballast Sensor

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Project Sponsors: Dr. Michelle Lee Barry, Mr. Ben Davis

Abstract

The Brain Ballast Sensor project addresses a critical issue involving railroad ballast and the maintenance of railroad tracks. Ballast is the small rocks that sit below and support railroad tracks. Over time the pressure applied from the trains and the environment wear this ballast down (Reference:13, 2023). To confront this problem, our goal is to develop a sensor that can accurately detect and measure localized core water pressures within the ballast, which is one of the leading causes in faulted ballast (Reference:9, 2014). Our goal will include testing this said sensor in different conditions in a laboratory environment with a specific device designed to apply pressure to a ballast sample. The focus is to create a sensor system that is small in size, powered wirelessly and capable of transmitting data wirelessly from within the interior ballast. The project's approach involves evaluating different types of sensors that already exist to find which one fits our needs best. We will then investigate different ways to improve on the chosen device which will ultimately be used as part of the "Brain Ballast" prototype. The significance of this project involves increasing railroad safety by providing important data so that railroad maintenance crews can tell the quality of the ballast without having to dig anything up. Additionally, this will decrease the spending needed by the railroad industry to monitor the quality of the ballast. Which will benefit both the railroad industry and public safety.

1.0 Problem

Railroads play a big role in today's modern infrastructure. They are a large contributor to economic activities and in connecting our country with supplies. For the United States to continue to use our network of railroads, the railroad industry is continuously needing to make repairs. There are many problems involving railroad maintenance, but one of the biggest challenges involves the ballast beneath the tracks (Reference:13, 2023). The railroad ballast that sits underneath railroad tracks helps with the track geometry and weight distribution. The pressure applied from the loads on the track and deterioration from the environment wear this ballast down and the result is what is known as "fouled ballast". Which, "refers to the condition when the ballast layer changes its composition and becomes much finer in grain size distribution." (Reference:9, 2014). There is a significant danger in the railroad safety involving fouled ballast since it causes instability of the tracks and, in severe cases, derailments (Reference:10, 2009). There are a couple of existing solutions, but all are too costly, timely, or disruptive. Currently there is no way to detect inner faulted railroad ballast without digging up all the exterior first or by using large scale equipment that scans the ballast from the exterior.

The consequences of such can be maintenance on ballast that has not yet fouled, additional time needed for repairs, not knowing when ballast has failed, and the need for expensive equipment not available to all parts of the track. The result of which is an increase in expenses for the railroad industry and a decrease in railroad safety. That is why there is an urgent need for a wireless sensor system capable of accurately reading the localized water pressure within the ballast. The Brain Ballast Sensor project's goal is to solve this problem.

2.0 Objective

The objective of this project is to design and implement a wireless sensor that can be placed within the inner ballast that can detect core water pressure and transmit the data wirelessly from within the ballast that sits underneath the railroad tracks. When water pressure builds up within the ballast it becomes a key reason for inner ballast going bad (fouled). Our goal is to create a sensor that can detect this water pressure and transmit the data wirelessly so that we can detect whenever the ballast becomes fouled and needs to be replaced. Additionally, this will help with detecting when the ballast is still of good quality and doesn't yet need to be replaced.

The main objective of this project is to get measurements within a laboratory setting so that we can prove that our proposed idea is possible, and that the device will work properly once in the field. Our primary goal is to adapt an existing device to make it smaller, powered wirelessly, extend the battery life, and for it to produce a strong enough signal to obtain the transmitted data from the device. Before we can start the implementation process, there is a variety of research and discoveries that will be needed. There are a couple of existing devices that are similar in what we are trying to accomplish but these devices are either too large or cannot transmit data wirelessly. Which is why we first need to explore how these devices function and figure out which device best suits our needs. We can then move onto discovering ways to improve upon this existing device. The group will then implement and test the added improvements, which will include a new housing for the device. Once we are satisfied with our improved device our next goal will be to develop enhanced software that will be connected to the sensor to retrieve the data. Currently, both existing devices rely on proprietary software, which we would like to change. Overall, our objective is to find a device to improve upon, learn how the device functions, research ways that the device can be improved, implement those said improvements, test the modified device, and then develop our own software that can improve the way that the device is able to transmit it's collected data. All of which has the goal in mind of improving and decreasing the cost of railroad maintenance.

3.0 Background

3.1 Key Concepts

For the Brain Ballast project, there are many different concepts and technologies, relating to small pore water pressure sensors, such as, ballast hub material and design, wireless and wired implementations, and power production. It is very important to understand the contribution each concept and technology plays in the project as current measurement systems cannot capture localized excess pore water pressure in granular soils and wires are fragile and become damaged easily.

One key technology central to our project is the ballast. The current sensor design is flawed in the fact that it is larger and requires delicate wires to be run through the ballast, as well as finer soil particles can become trapped in the sensor, causing it to become clogged and no longer work properly. The current, flawed design of the sensor cannot capture localized excess pore water pressure in granular soils and still requires delicate wires to be ran, increasing risk of failure. Upgrading to a Bluetooth Low Energy Pore Water Pressure Sensor or Wired Micro-Pore Water Pressure Sensor could alleviate some of those problems.

Additionally, we are leveraging wireless implementations for the sensors. Wireless sensors would allow us to place them in more optimal spots rather than less-than-optimal locations in the ballast. "Recent advances in wireless sensor technologies have resulted in a number of pore pressure and other moisture related sensors that can be packaged with a transmitter and used as individual sensing elements throughout the specimen, or they can be packaged within a Ballast-like particle that includes additional sensor components and a microprocessor such as a Raspberry Pi Zero Wireless" (Reference:12, 2023).

Furthermore, power production will be an integral part of the project. Powering the sensor is necessary to collect the data needed for research. For our purposes, the team is researching piezoelectric generation and compact long-lasting batteries. Piezoelectric generation would allow us to integrate power production directly from the vibrations from the railrod, removing the need for external wires.

In summary, the integration of sensor design, wireless and wired implementation, and power production in our project will allow scientists to better understand the issues with currently implemented ballast sensors.

3.2 Related Work

In the field of ballast optimization, several researchers and developers have made significant contributions. This section aims to provide an overview of their work, highlighting key references, and discussing the challenges or limitations in their implementations that our project, Brain Ballast sensor, seeks to address and improve upon.

Over time, technology has played a crucial role in ballast research. Researchers have achieved notable progress in this area, such as Hai Huang, Erol Tutumluer, and William Dombrow who conducted a study on 'Laboratory Characterization of Fouled Railroad Ballast Behavior' (Reference:7, 2009). Their work focused on using a 'large direct shear (shear box) device' to study different ballast materials and how they fouled in different conditions. The researchers tested and measured the strength and deformation of different conditions of ballast when three different fouling materials (coal dust, plastic clay, non-plastic mineral material) were added to the ballast (Reference:7, 2009). Dr. Barry's lab has a similar device used to apply direct shear force to ballast samples. This device is called 'LS-DSS' (Large Scale-Direct Simple Shere). We will use this device similarly to Huang's research to apply direct shear pressure to a sample of ballast but instead of measuring how the ballast failed we will be using it to test our Brain Ballast device to measure core water pressure while inside of the device.

This research expands upon how ballast can become fouled within a laboratory environment. Our Brain Ballast device on the other hand will focus on another fouling attribute. Water pressure, which can build up within the ballast and cause the ballast to become fouled. The goal of our device will be to detect this pressure, collect the data and transmit the data wirelessly.

Another group of researchers, M. Moaveni, Y. Qian, H. Boler, D. Mishra and E. Tutumluer performed research on "Investigation of Ballast Degradation and Fouling Trends using Image Analysis" (Reference:9, 2014). Their research made use of a type of external image processing device to determine whether ballast has fouled or not. This research is interesting but not applicable to all parts of the American railway. The device they used in their research is costly, complex, and sensitive, making it unable to be used on all parts of a railway. Our device is much more simpler in design and instead of performing a type of image processing, our device takes advantage of the correlation between water pressure within ballast and fouled ballast.

In summary, the prior works in this field have contributed significantly to determining how different ballast becomes fouled in a laboratory environment. However, our project, Brain Ballast sensor, stands out by attempting to create a sensor that can eventually be used within actual railroad lines. With the goal to detect the buildup of water pressure which is one of the leading causes of ballast becoming fouled. Our device will first need to be tested thoroughly within a lab environment, but the end goal of the device is for it to be placed within different sections of railroad tracks to be used to detect when ballast has started to foul. Our device will feature internal power and wireless transmission of data. Another goal of our device will be to create our own software system for the device so that the device that is adapted won't have to rely on proprietary software. This is all with the goal to help aid in the detection of fouled ballast within railroad tracks and to improve the maintenance procedure of fouled ballast.

4.0 Approach/Design

4.1 Requirements and/or Use Cases and/or Design Goals

Requirements

- Research and find the best suitable device to improve upon
- Discover how the selected device's components work together to measure core water pressure and transmit the collected data
- Research the best technology to add to and improve upon the selected device, with the goals being: Improving battery life and extending the wireless transmission range
- Implement said technologies into the device
- Perform testing in laboratory setting to prove that the implementation was successful
- Redesign the housing of the device to match the shape and size to be similar to an average ballast rock
- Research the current proprietary code that the device is making use of
- Design and implement our own open-source code base to be used with the device
- Perform more testing with the now implemented open-source code

Use Cases

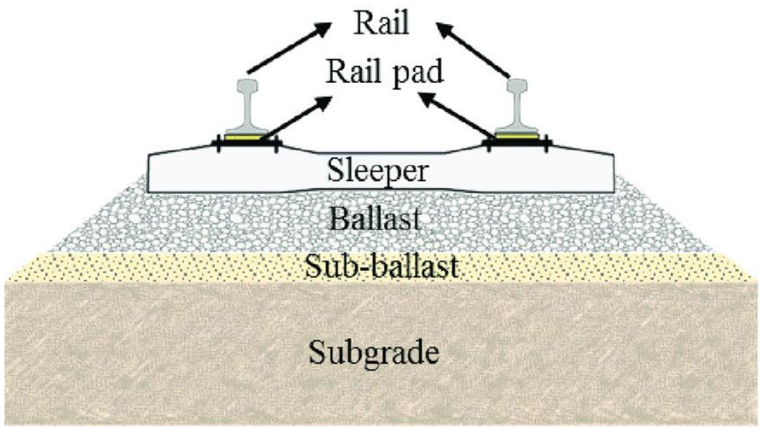
- A wireless sensor will make the distribution of sensors within the ballast easier to accomplish
- Once in place, the sensor will provide accurate core water pressure readings from within the ballast which will provide data about whether the ballast is fouled or not
- Allow a user to collect this data from outside the exterior of the ballast
- Being a small modular device allows for multiple devices to be placed throughout large sections of ballast to get a wide range of data

Design Goals

- Create a new housing for a wireless core water pressure to be smaller and match the shape of an average ballast rock
- Improve on the battery life and the transmission range of the selected core water sensor
- Redesign the software sensor that is in place on the current sensor so that it will be open-source and the device can be changed to match the specific needs of different scenarios

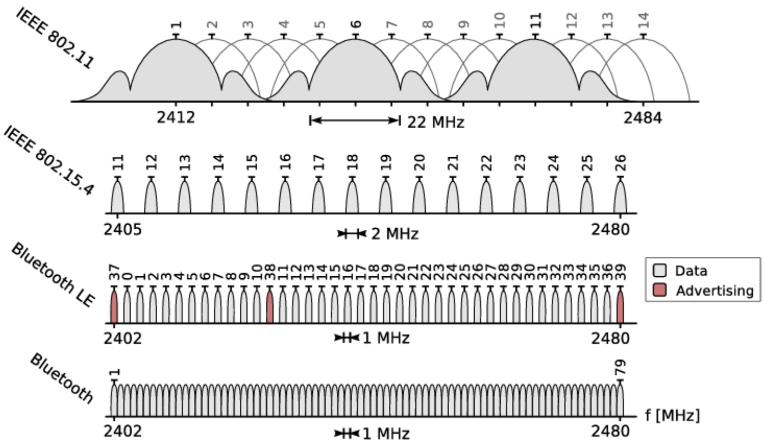
4.2 Brain Ballast sensor Architecture

The Brain Ballast sensor overall goal is to be able detect core water pressures from within the center of railroad ballast. There are a few different devices on the market that can measure core water pressures currently but each of the devices we have found have problems. Either they are wired devices that need to be powered through an external source outside of the ballast or are wireless sensors that are too large and disrupt the distribution of the ballast rocks. We want to adapt one of these on-the-market sensors to better fit our needs. Which means that the sensor will need to be able to transmit the core water pressure data from within the middle of the ballast and be small enough so that the ballast still operates as intended. Not only that, but we also need to ensure that once the sensor is placed within the ballast that it will have a long enough lifetime so that it does not need to be replaced frequently. This is all with the intention to detect when ballast has fouled. Ballast can foul because of a build of water pressure within the rocks. Replacing such ballast is an expensive yet essential task to ensure that the quality of rail lines does not depreciate. To replace internally fouled ballast all the exterior ballast must first be dug out. An image of the cross section of a railway can be seen below.



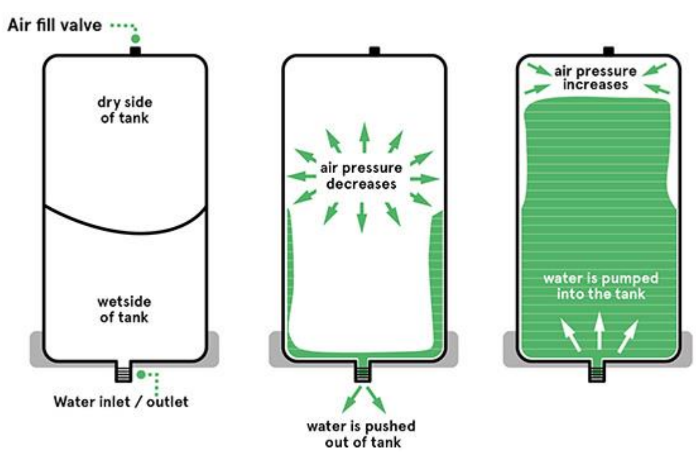
(Reference:8, 2019)

For our project we will first select an existing core water pressure device and improve upon it. Which will require us to first get a comprehensive understanding of how these different devices work and the components that are being used within them. A large section of our project will include improving the way the sensor transmits data. Most of the current sensors transmit data through a Bluetooth connection paired to a phone outside of the ballast. But when covered in too dense material or submerged in water the Bluetooth connection tends to fail. We are currently exploring different modes of wirelessly transmitting data but as of now are researching the possibility of sending the data through a Wi-Fi connection. A Wi-Fi connection will allow the connection to operate at a higher frequency than Bluetooth (2.4 GHz vs 3.6/5 GHz) and operate at a higher bandwidth (800 Kbps vs 11 Mbps) (Reference:2, 2023).



(Reference:14, 2016)

Another large section of the project will be redesigning the housing of the core water pressure sensor to better match the average size and shape of a ballast rock. These sensors are typically housed in a metal exterior with all the components held inside. However, we want to design a new housing that will be smaller than most existing devices and be more unsymmetrical in shape. This may prove to be difficult because we don't want to hinder the quality of the device and need to ensure that all the components can still fit inside the new housing. There will still need to be a way for water to enter the device for the components to get a proper reading of the pressure within the ballast. A diagram is shown below that depicts how a general water pressure sensors works.



(Reference:12, 2023)

4.3 Risks

Risk	Risk Reduction
Device will not transmit through water	Test to correctly assess which transmission mode will allow for transference through water with minimum voltage
Battery life is insufficient	Ensure components use the components use the minimum voltage necessary, incorporate capacitors and appropriate battery technology, and test whether piezoelectric power generation can be employed.
Components require a housing too large for application	Testing different components to select ones that will fit into a housing that is the size of a typical ballast particle and has all the functionality desired.

4.4 Tasks

1. Discover what core water sensor will be best to adapt and improve upon
2. Once selected research that specific device to understand how all the components work together to measure core water pressure, transmit data, and how the device is powered
3. Research different solutions to improve upon data transmission and battery life
4. First implement a new battery solution that will extend the life of the device
5. Test the device's battery life to ensure improvements were made
6. Document our findings and redesign if not up to standards
7. Then work on improving how the device transmit the data, specifically need a way to transmit data through dense materials and water
8. Test the improved device with the 'LS-DSS' machine provided within our sponsors laboratory
9. Document our findings and redesign if not up to standards
10. Once the device is confirmed to be working better than before we will move onto redesigning the housing of the device
11. Research the different ways that we can manufacture the new housing for the device, whether it be from machine milling utilizing CNC or through one of Dr. Barry's advanced 3-D printers
12. Create several different designs for the sensor housing to make it smaller and better match the shape of an average ballast rock
13. Evaluate which design will best suit our needs and will be able to house all the required equipment
14. Manufacture the new design with help from one of our sponsors Mr. Davis
15. Rebuild the sensor inside of the new housing
16. Test the new design in the same 'LS-DSS' machine to prove that the new design does not hinder the devices capabilities
17. Document our findings and redesign if not up to standards
18. Research the current software the device uses to collect and transmit data
19. Design a new system that is open-source and modifiable that can execute in a similar way as the proprietary software
20. Implement this software onto the device

21. Retest the device to ensure that the new software system can collect and transmit data to the same or better standards as the proprietary software
22. Document our findings and redesign if not up to standards

4.5 Schedule

Task and Description	11/27-01/08	01/08-01/29	01/29-02/12	02/12-02/26	02/26-03/11	03/11-03/18	03/18-04/08	04/08-04/22
1. Discover what core water sensor will be best to adapt and improve upon	Task 1							
2. Once selected research that specific device to understand how all the components work together to measure core water pressure, transmit data, and how the device is powered	Task 2							
3. Research different solutions to improve upon data transmission and battery life	Task 3							
4. First implement a new battery solution that will extend the life of the device		Task 4						
5. Test the device's battery life to ensure improvements were made		Task 5						
6. Document our findings and redesign if not up to standards		Task 6						
7. Then work on improving how the device transmit the data, specifically need a way to transmit data through dense materials and water			Task 7					
8. Test the improved device with the 'LS-DSS' machine provided within our sponsors laboratory			Task 8					
9. Document our findings and redesign if not up to standards			Task 9					
10. Once the device is confirmed to be working better than before we will move onto redesigning the housing of the device			Task 10					
11. Research the different ways that we can manufacture the new housing for the device, whether it be from machine milling utilizing CNC or through one of Dr. Barry's advanced 3-D printers	Task 11							
12. Create several different designs for the sensor housing to make it smaller and better match the shape of an average ballast rock				Task 12				
13. Evaluate which design will best suit our needs and will be able to house all the required equipment				Task 13				
14. Manufacture the new design with help from one of our sponsors Mr. Davis					Task 14			
15. Rebuild the sensor inside of the new housing					Task 15			
16. Test the new design in the same 'LS-DSS' machine to prove that the new design does not hinder the devices capabilities						Task 16		
17. Document our findings and redesign if not up to standards						Task 17		
18. Research the current software the device uses to collect and transmit data	Task 18							
19. Design a new system that is open-source and modifiable that can execute in a similar way as the proprietary software							Task 19	
20. Implement this software onto the device							Task 20	
21. Retest the device to ensure that the new software system can collect and transmit data to the same or better standards as the proprietary software								Task 21
22. Document our findings and redesign if not up to standards								Task 22

4.6 Deliverables

- Design Document: Contains a listing of each major hardware and software component and how the hardware is utilized, as well as design specifications and implementation details.
- Transmission protocol that allows for transmission through water and has a sufficiently low voltage to ensure long battery life.
- Power system that allows the device to function self-sufficiently for up to a year.
- A housing that can fit all necessary components and is small enough to reflect that of a typical ballast particle.
- An open-source software application built for the needs of the research community to analyze findings.
- Final Report: a report detailing the Brain Ballast device and how it fulfilled the objectives set forth in the project.

5.0 Key Personnel

Students

Drew Stull – Stull is a senior computer science major in the Computer Science and Computer Engineering Department at the University of Arkansas. Drew is a member of the Scholarship for Service program at the University of Arkansas. Drew has also been employed by a variety of IT jobs at the University of Arkansas, which ranges from an IT help desk worker to a network technician.

Clayton Warstler – Warstler is a senior computer science major in the Computer Science and Computer Engineering Department at the University of Arkansas. Clayton has had an internship at JB Hunt as an Application Development Intern. Clayton has also started up a small business repairing computers and electronics, using his past electronics and programming classes he gained before transferring to the University of Arkansas. Clayton will be working on the key concepts and related work on this project.

Andrew Murphy – Murphy is a senior computer science major in the Computer Science and Computer Engineering Department at the University of Arkansas. Andrew has an internship at NCR Corporation as an Information Security Intern.

Fernanda Caero – Caero is a senior in Computer Science/Computer Engineering at the University of Arkansas, has experience in diverse programming projects, including an internship at Jalasoft Software Company. As an international student with English as a second language, Fernanda will handle key project components like the presentation, project objectives, and problem analysis, contributing her valuable skills to the team.

Braeden Morgan – Morgan is a senior Computer Science major at the University of Arkansas. He is a research assistant for the Computer Vision and Image Processing laboratory under Dr. Khoa Luu. He has worked on RazorFace, an application built to assist researchers at UAMS in the early detection of Autism. His current area of research is the application of machine learning for quantum computing. He will be working on risk assessment and deliverables.

Project Sponsors

Dr. Michelle Lee Barry – Dr. Barry is professor here at the University of Arkansas in the Civil Engineering (CVEG) department. Dr. Barry has a wide range of work and research interests at the university. But most of it is focused on granular materials and behavior. Her research varies from multi-scale granular material behavior, experimentally validated discrete element method (DEM) models, laboratory testing of granular material, granular soil behavior in multi-directional simple shear, and applications of engineering in Historic Preservation Practice (Reference:5, 2023). Dr. Barry also has a PhD student that is an additional sponsor of our project.

Ben Davis – Mr. Davis is a PhD student under Dr. Barry and additionally is the lab manager of the labs where Dr. Barry conducts research. Mr. Davis has been crucial to helping our team with a lot of the hands-on learning of our project. Specifically, how the existing sensors work and how to test them in the laboratory.

Dr. Matthew Patitz – Dr. Patitz is the class instructor for our senior design class called capstone. Dr. Patitz is an associate professor at the University of Arkansas in the Computer Science and Computer engineering department. He will help answer general questions about the project and set the scope for what needs be accomplished. Additionally, he will help with resolving communication issues that arise throughout the project and guidance with challenges that occur.

6.0 Facilities and Equipment

To implement and test our sensors Dr. Barry is graciously letting our group make use of one of her lab areas. This lab area is specifically designed to test railroad ballast and has a couple of different devices designed specifically for such. One such device that our group will make the most use of is called 'LS-DSS' (Large Scale-Direct Simple Shere). This device was specifically designed to apply different types of pressure to a sample of ballast to study the effects. We will use this device to test our created sensors in a lab environment. In the laboratory environment there are several different samples of ballast that range from small to large. This will allow us to test our sensors with a variety of different scenarios of ballast.

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