Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 4.15
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.4.15

Advances in Pantograph and Overhead Line Monitoring in Light Rail

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Abstract

This paper presents the development and implementation of three innovative products: OLESense, OLESight, and OLESurvey, aimed at enhancing Overhead Line Equipment (OLE) monitoring. These systems are designed to improve the efficiency, accuracy, and safety of railway operations by integrating advanced sensor technologies, computer vision, and data analytics. The paper outlines the background, problem statement, design concepts, development processes, data collection methodologies, results, and future work directions. The effectiveness of these systems has been evaluated through testing and validation on the Blackpool Tramway, demonstrating significant improvements in OLE monitoring and maintenance.

Keywords: overhead line, pantograph-catenary system, trams, removable sensors, autonomous sensor, computer vision, data analysis, predictive maintenance.

1 Introduction

Overhead Line Equipment (OLE) is critical for the operation of electrified railways, providing the necessary power supply to trains. The maintenance and monitoring of OLE, however, pose significant challenges due to the complexity and dynamic nature of railway environments. Traditional methods often rely on manual inspections, which are time-consuming, labour-intensive, and prone to human error. This paper introduces three products—OLESense, OLESight, and OLESurvey—developed by Digital Transit Limited to address these challenges. These systems leverage modern technologies to automate and enhance the monitoring process, ensuring higher accuracy and reliability. The implementation of these systems aims to reduce maintenance costs, improve safety, and increase the operational efficiency of railway networks.

2 Literature Review

The evolution of railway monitoring systems has gained significant traction due to the need for enhanced safety, reliability, and efficiency in railway operations. Several studies have focused on the development and deployment of advanced technologies to monitor and diagnose faults in railway infrastructure. This literature review examines recent advancements in railway condition monitoring systems, highlighting key developments and their implications for the OLESense, OLESight, and OLESurvey projects.

Aydin (2018) presented a new contactless fault diagnosis approach that employs non-invasive techniques to monitor railway systems. This method utilises advanced sensors and signal processing algorithms to detect anomalies without physical contact with the railway components, thereby minimising wear and tear and improving maintenance efficiency [1]. Similarly, Granström and Seden (2008) emphasised the importance of a system and stakeholder approach in identifying condition information for railway infrastructure. Their study highlighted the need for collaboration among various stakeholders to develop comprehensive monitoring systems that cater to the diverse needs of railway operations [2]. Aurisicchio et al. (2017) explored the use of advanced monitoring technologies for railway catenary systems. They proposed a condition monitoring framework that integrates various sensors and data analysis techniques to monitor the health of catenary wires, which are crucial for the operation of electric trains [3].

The integration of inertial measurement units (IMUs) and time-of-flight (ToF) sensors in monitoring systems has been pivotal in providing accurate real-time data on the condition of railway infrastructure. These sensors measure various parameters such as acceleration, height, and displacement, which are critical for assessing the health of overhead lines and pantographs. Additionally, the application of machine vision systems in railway monitoring has enabled the detection of minute changes in the condition of overhead lines and pantographs. Systems like OLESight employ advanced image processing techniques to track wire thickness, stagger, and height, providing detailed visual data that can be used for predictive maintenance [4] [5].

The integration of cloud computing and big data analytics has revolutionised railway monitoring. Data collected from various sensors and cameras are transmitted to cloud servers where they are processed and analysed. This approach allows for the storage and real-time analysis of vast amounts of data, facilitating the early detection of potential faults and the scheduling of maintenance activities [6] [7].

Despite significant advancements, several challenges remain in the implementation of comprehensive railway monitoring systems. These include the integration of different sensor technologies, the management of large data sets, and the development of robust algorithms for data analysis. Future research should focus on addressing these challenges through the development of more sophisticated sensor fusion techniques and the application of artificial intelligence for predictive maintenance. Additionally, there is a need for standardisation in the design and deployment of monitoring systems to ensure compatibility and interoperability across different railway networks. Collaborative efforts among industry stakeholders, including railway operators, technology developers, and regulatory bodies, will be essential in achieving these goals.

The literature reviewed highlights the critical role of advanced monitoring technologies in enhancing the safety and efficiency of railway operations. The development and deployment of systems like OLESense, OLESight, and OLESurvey represent significant strides in the field of railway condition monitoring. By integrating state-of-the-art sensors, machine vision, and cloud computing, these systems provide comprehensive solutions for monitoring and maintaining railway infrastructure. Future research and development efforts should continue to build on these advancements, addressing existing challenges and exploring new opportunities for innovation in railway monitoring technology.

3 Background

The demand for reliable and efficient railway services has grown, driving the need for advanced maintenance solutions. Traditional OLE inspection methods, though somewhat effective, are labour-intensive and can be inaccurate due to human error. Automated monitoring solutions are increasingly being explored to overcome these limitations. The ATTUNE project plays a pivotal role in this context by providing a framework for the development and testing of advanced OLE monitoring systems. The project is focused on enhancing the reliability and safety of railway infrastructure through innovative technological solutions.

The ATTUNE project involves multiple stakeholders, including railway operators, technology providers, and research institutions, working collaboratively to develop and validate new monitoring technologies. Digital Transit Limited, as part of the ATTUNE consortium, has developed three complementary systems—OLESense, OLESight, and OLESurvey. These systems integrate sensor technologies, computer vision, and data analytics to provide comprehensive monitoring capabilities.

4 Problem Statement

Ensuring the OLE remains in optimal condition is essential for the safe and efficient operation of electrified railways. However, traditional inspection methods face several challenges:

1. Time-Consuming Inspections: Manual inspections require significant time and resources, leading to high operational costs.
2. Safety Risks: Maintenance personnel are exposed to various safety risks during manual inspections, especially in harsh and dynamic railway environments.
3. Accuracy and Reliability: Human error can result in inaccurate inspections, leading to undetected faults and subsequent operational issues.
4. Environmental Conditions: Railway environments are subject to varying weather conditions, which can affect the reliability of inspection results.

To address these challenges, the objective is to develop a comprehensive monitoring solution that leverages advanced technologies for real-time OLE monitoring, with accuracy and efficiency.

5 Design Concept

The design of the three products—OLESense, OLESight, and OLESurvey—focuses on integrating multiple technologies to achieve comprehensive OLE monitoring.

Device	**Contact Forces**	**Contact Wire Uplift / Height Exceedances**	**Arcing / Contact Loss**	**Carbon Strip Wear**	**Accelerations on Panto Head**	**Contact Position / Wire Stagger / Dewirement**	**OCL Geometry**	**Worn Contact Wires**	**Reporting to Train**	**Pantograph-Catenary Imagery**	**Debris in OCL**
OLESight	0	1	1	1	0	1	1	0	0	1	0
OLESense	1	1	1	0	1	1	1	0	0	0	0
OLESurvey	0	0	0	1	0	1	1	1	0	0	0

Table 1: Device capabilities

5.1 OLESense

OLESense is a sensor-based system designed to measure pantograph height and stagger, and detect anomalies. It utilizes:

- 9-axis Inertial Measurement Units (IMUs): A 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer provide detailed movement data of the pantograph, looking for clunks and high acceleration events.
- Time of Flight (ToF) Sensors: For measuring the height of the pantograph and detecting excesses in the stagger of the overhead line.
- GNSS (Global Navigation Satellite System): To provide precise location data, allowing the mapping of detected anomalies to specific track locations.

5.2 OLESight

OLESight is a vision-based system that employs high-resolution cameras and advanced computer vision algorithms to monitor the overhead line geometry. It is designed to:

- Detect Pantograph Height and Stagger: Using machine learning models trained on vast datasets as well as machine vision techniques to identify anomalies in pantograph height and OLE geometry.
- Process Real-Time Video Feed: To capture detailed images of the pantograph and overhead line, which are processed to extract relevant monitoring data.
- Integrate with Existing CCTV Systems: With small adjustments, the machine learning model is effective when connected into existing pantograph camera systems installed onto trains.

5.3 OLESurvey

OLESurvey is a camera system temporarily fitted to the pantograph to provide data on wire thickness and stagger. It is designed to be:

- Easily Deployable: Can be quickly installed and removed, allowing flexible use across different locations and scenarios.
- Integrated with OLESense and OLESight: Can be used as part of a comprehensive monitoring ecosystem or independently in a pick-and-mix approach.
- Data-Driven: Provides detailed data on wire thickness and stagger, which is critical for maintaining the optimal condition of OLE.

These systems are designed to be flexible, allowing railway operators to use them as a comprehensive suite or select individual components based on specific needs. The options table below summarises the usage modes of each system.

5.4 Standards Compliance

The systems developed in this project comply with the relevant standards, including:

- BS EN 50317:2012: Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line .
- BS EN 50367:2020: Criteria to achieve technical compatibility between pantographs and overhead contact line .

5.5 Options Table

System	**Description**	**Usage Mode**
OLESense	Sensor-based system for measuring pantograph height, stagger, and detecting anomalies.	Integrated/Standalone
OLESight	Vision-based system for monitoring overhead line geometry and detecting wire thickness and stagger.	Integrated/Standalone
OLESurvey	Camera system temporarily fitted to pantograph for wire thickness and stagger data collection.	Integrated/Standalone

Table 2: Options Table

These options provide flexibility for railway operators to select the best combination of systems based on their specific monitoring requirements and operational constraints.

6 Development and Build

The development process of OLESense, OLESight, and OLESurvey involved several stages, from initial concept design (see figure 1) to prototype testing and final implementation. The systems were developed using a combination of in-house resources and collaborations with external partners, supported by the ATTUNE project.

6.1 Initial Concept Design

The requirements for the OLE monitoring system were gathered from consultations with railway operators and maintenance personnel, as well as consulting existing literature including a case study identifying contact wire and pantograph failure modes, their detection priority and detectability [2]. The original concept envisaged using only a vision system to collect all data and detect all potential failure modes. After some initial development, it was determined that one system would not be the most effective way to collect the data, and thus a concept of operations was developed that considered three separate systems to achieve the desired monitoring capabilities.

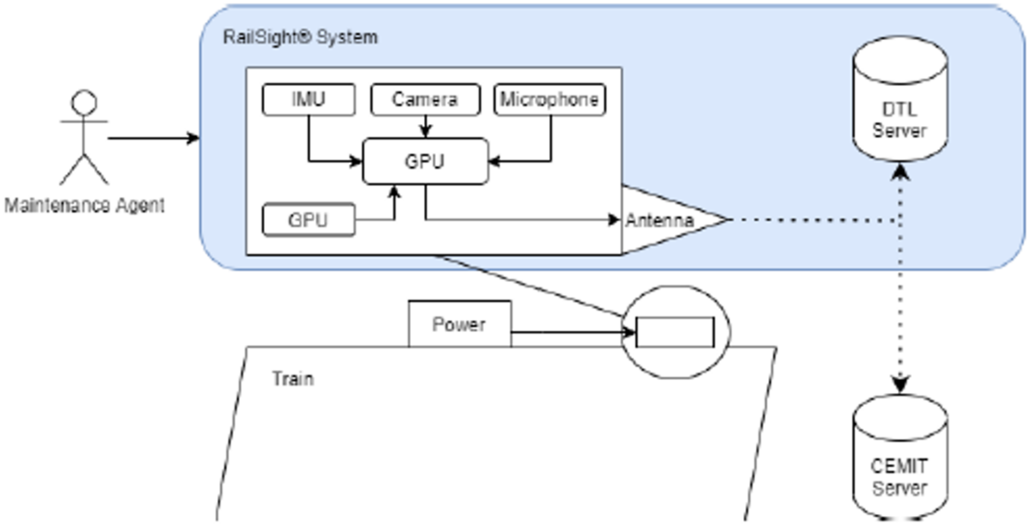

Figure 1: Initial Concept Design

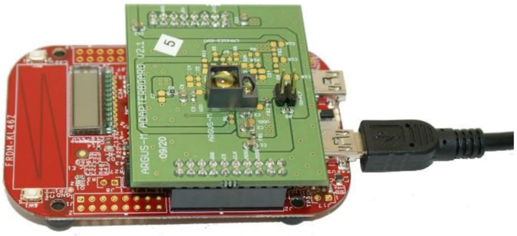

Figure 2: Evaluation Board used for Testing

6.2 Prototype Development

For prototyping the OLESense devices, it was first considered which sensors would be most effective at tracking the overhead line. Lab tests were performed using both ultrasonic and ToF laser sensors. The ToF sensors were found to be more reliable at detecting the passing overhead line than the ultrasonics, which often missed the presence of the line entirely. The ToF could not provide a measurement of the line as it passed, but a detection could be made due to changes in the amplitude of the received signal. An enclosure was designed that allowed the sensors to be mounted to the pantograph itself. An evaluation board was used for this testing (see figure 2).

The OLESight system was prototyped by using GoPro cameras. These cameras were secured to the top of trams to collect footage of the pantographs in service. Some of this data was used for training the convolutional neural network (CNN) to detect the pantograph, and some was used for validation and testing. The OLESurvey system was also prototyped with GoPro cameras, attaching them to the pantograph itself to provide a close-up view of the overhead line. This footage was found to not

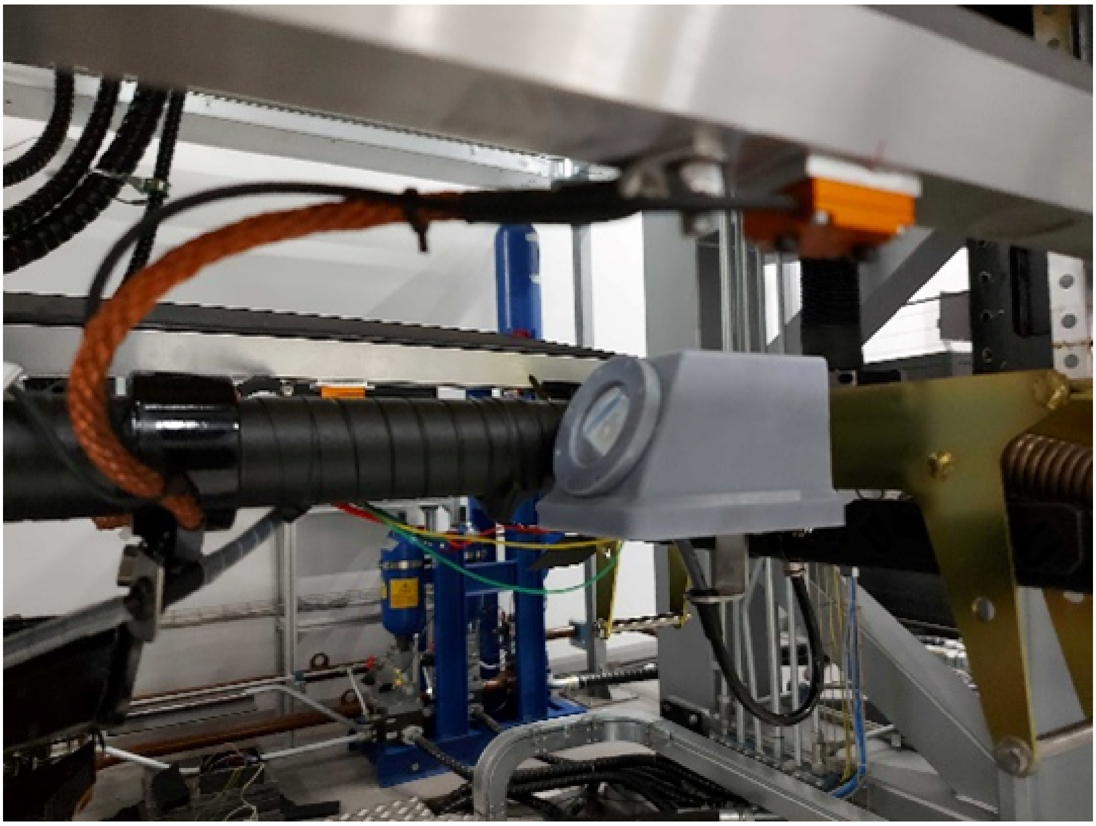

Figure 3: OLESense Enclosure Mounted on PANTHER

be high-quality enough for the machine vision algorithms to distinguish the overhead line from background noise. Thus, machine vision cameras with lenses specifically designed to blur out the background were employed for future trials.

6.3 Testing and Validation

DTL conducted extensive field tests in cooperation with Blackpool Transport Services Limited (BTSL) on Blackpool Tramway to validate system performance. This included:

- Installing the systems on trams and pantographs.
- Collecting data on pantograph movements, wire heights, and stagger deviations.
- Evaluating the accuracy and reliability of the systems under various environmental conditions.

Some refinement of the hardware and software components occurred based on test results. One major refinement was a redesign of the OLESense enclosures. The initial design involved individual electronic modules connected via wires and packed into an enclosure. This led to regular issues with the system not functioning correctly.

Figure 4: Collection of Data at IRR Huddersfield University

A new design allowed simple insertion and removal of all components, as well as implementing a single board for mounting the majority of the system's components.

The software for the OLESight system was updated throughout the project to ensure accurate and low-latency measurements of the pantograph height could be performed. Initially, the CNN ran on a Jetson Orin AGX, and now the software can run at an acceptable frame rate on a Jetson Orin Nano, reducing requirements for weight and power for the system.

The devices underwent extensive testing and calibration on the 'PANTHER' full-scale Pantograph Test Rig at the Institute of Railway Research (IRR), at the University of Huddersfield (see figures 3 and 4). The instrumented test rig provided acceleration, height and stagger data that could be compared against the data collected by our system. Ensuring the data correlated allowed us to be confident that the sensors were collecting accurate measurements. This calibration ensured the accuracy and reliability of recorded data under controlled conditions.

7 Data Collected

Extensive data collection was conducted during the testing phase to evaluate the performance of the developed systems. High-resolution video footage was captured, containing images of pantograph and overhead line interactions, and used for training and validating machine learning models. When using GoPro cameras to collect footage,

Figure 5: GoPro attached to Tram Roof with Extended Battery

256GB SD cards were used for storing data, allowing 8-12 hours of footage to be captured. The main limiting factor was battery life, which varied depending on the settings used. At 1080p30, the battery lasted approximately 2 hours, reducing to 1.5 hours at 1080p60.

Initially, to mitigate this, the cameras were turned on remotely via phone at the latest possible moment before the tram left the depot, to capture as much footage as possible. The connection between the phone and GoPro was unreliable, and the total journey time from the depot to the end of the tramway and back could often exceed two hours – therefore the entire overhead line could not be captured. To remedy this, battery-pack cases were purchased that extended the battery life up to 6 hours (see figure 5). At room temperature, these cases caused the GoPro to overheat and shut off, especially when running at 1080p60. However, when mounted to the top of the tram, it was given sufficient airflow to remain cool and successfully captured the entire journey.

Sensor data was collected from IMUs, ToF sensors, and GNSS, providing detailed information on pantograph movements, wire heights, and stagger deviations. The IMU operated at 200Hz, the ToF sensor at 10Hz, and the GNSS at 1Hz. The data was captured and saved to an SD card at regular intervals to capture the whole length of the tramway in both directions. It was determined that the default rate of 10Hz was too slow a data rate for the ToF lasers, and thus this was increased to 20Hz. Additionally, to provide better geo-location estimates, the GPS hardware was upgraded from a 1Hz model to a 10Hz model.

The data collected from the trams is uploaded to a digital twin hosted in AWS via a 4G router every time the tram returns to the depot. Due to the limited capabilities of the AWS software development kit for the Arduino platform, this upload process was tricky. Large uploads would consistently fail, and determining why an error had occurred was difficult because of the opaqueness of the upload process. To solve this, files are saved onto the SD card in 200kb chunks. When the OLESense device makes a connection to the 4G router, a request header is made and sent to the AWS server. Once accepted, each file is sent sequentially. The file is sent in 1024-byte chunks, and if any of these transfers fail the upload is re-attempted. After 5 attempts, the system moves onto the next file, and then tries again once all other file uploads have been attempted.

This digital twin enables real-time monitoring and analysis, providing insights into the condition of the OLE. Blackpool Transport Services Ltd (BTSL) receives immediate alerts if a serious problem is detected and a short report overnight highlighting any trends or anomalies.

8 Results and Conclusion

The testing and validation of OLESense, OLESight, and OLESurvey on the Blackpool Tramway demonstrated significant improvements in OLE monitoring.

The OLESight camera system was able to determine the stagger of the overhead line to an accuracy of $\pm 20mm$ and precision of approximately 10mm (see figure 6). This accuracy could be improved by using a more specialized machine vision camera and lens, rather than a GoPro camera – providing a better quality of image and with more pixels/mm for determining where the overhead line is located.

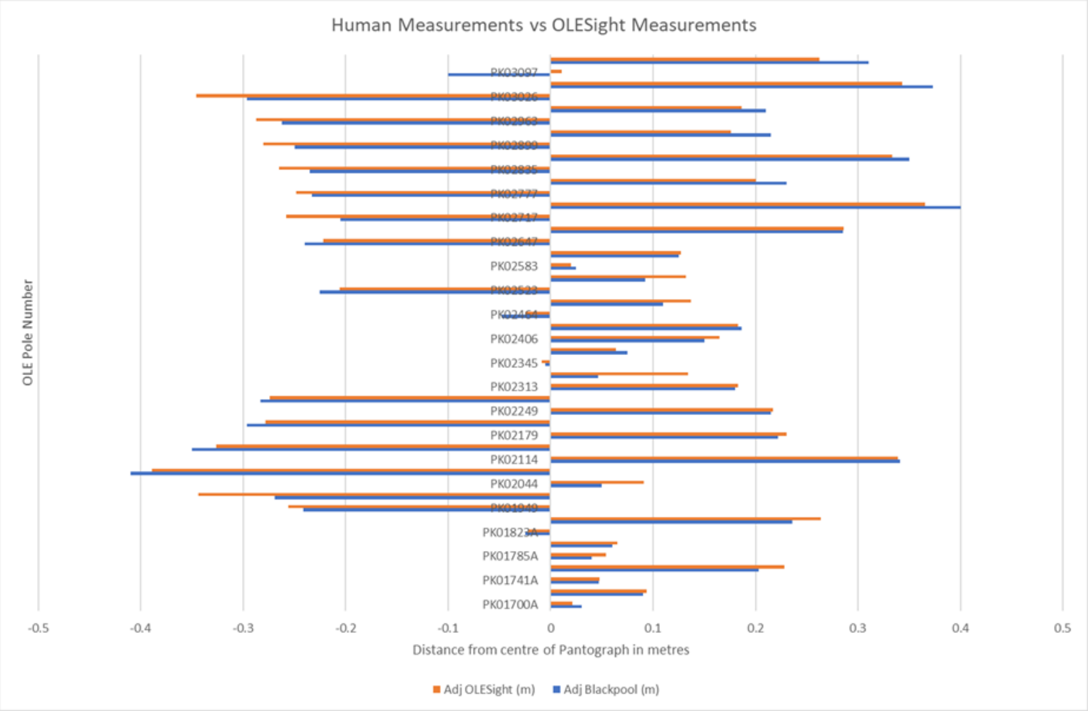

Figure 6: Graph showing variance between human and automated measurements

The IMU picked up several large ‘clunks’ during the test run of the tram, which would need to be verified by repeat testing. Additionally, two different IMUs were used during the test run, one of which provided a systematic error. Data cleaning was performed to remove this systematic error; however, it still creates uncertainty about the validity of these results, and it would again benefit from additional test runs with the more reliable IMU model.

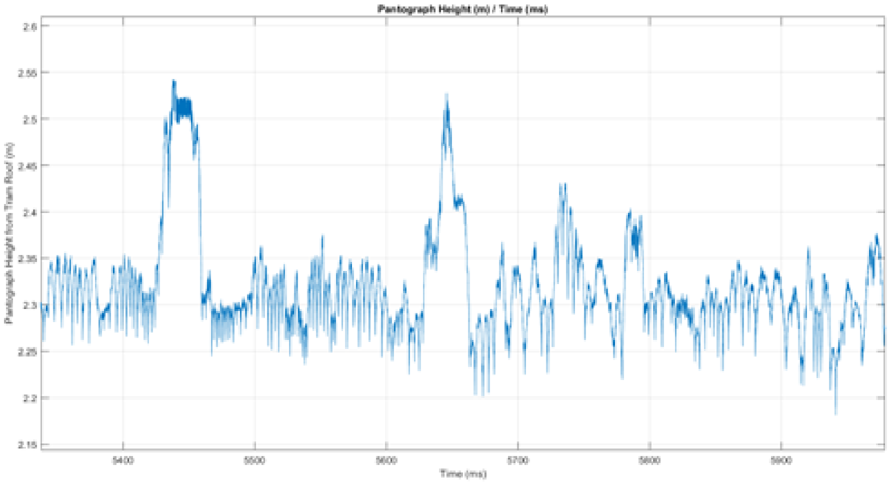

Figure 7: Pantograph Heigh over Time

The ToF laser provided many readings where only a very brief detection was made. Additionally, some of the detections had a high amplitude, and others a low one. Where a continuous, high amplitude detection was made, it could be concluded that the stagger of the overhead line had exceeded its regular operating area. This data could be verified using the OLESight data that was collected at the same time, correlating via the GPS data that was collected.

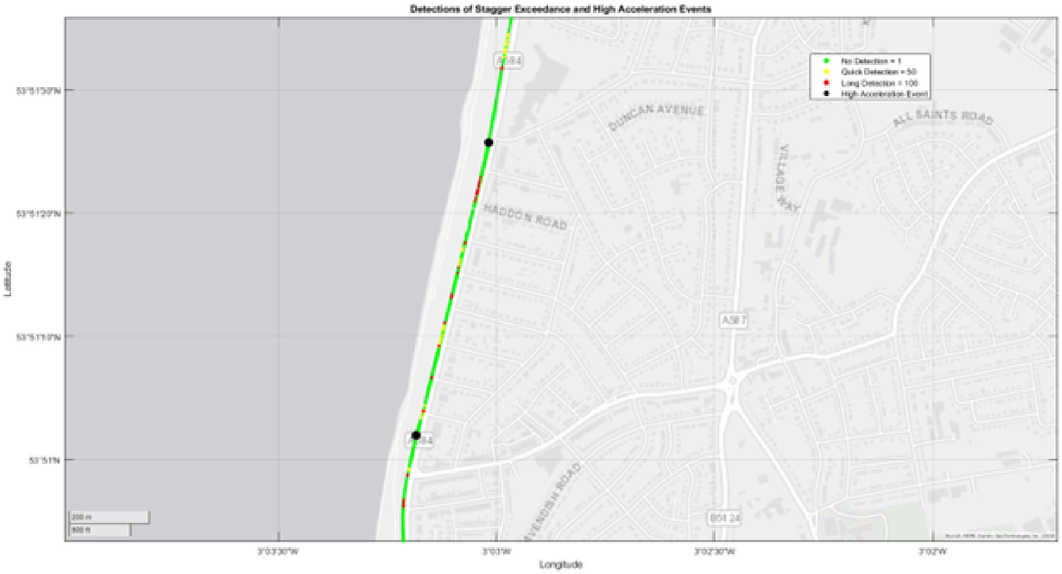

Figure 8: Detection of Acceleration events and stagger exceedances on Blackpool Tramway

Regarding the GNSS data, the entirety of the Blackpool tram route had GPS coverage making it very reliable. It allowed for additional data such as the speed of the tram to be collected, as well as make clear the direction the tram was traveling when a detection was made.

The OLESurvey data was useful for identifying potential future work. The current detection algorithms struggled to detect the overhead line with the GoPro camera footage.

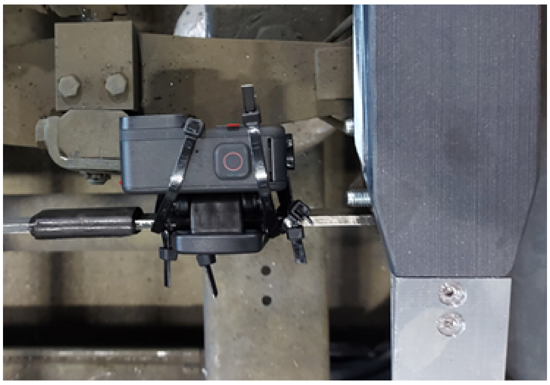

Figure 9: GoPro Camera attached in OLESurvey Configuration

The integration of multiple technologies ensured robust performance and provided comprehensive monitoring capabilities. The results indicate that these systems can greatly enhance the efficiency and safety of railway operations.

9 Further Work

Future work will focus on enhancing the scalability and adaptability of the systems for deployment across different railway networks.

9.1 OLESense

The key to further development of OLESense is to reduce the size and weight of the sensor housing mounted to the pantograph. While the size should not affect the dynamics of the pantograph at the low speeds of a tram, DTL aims to get this equipment on high-speed trains in the future. The key to reducing the size of the box is to integrate the separate electronic modules onto a single board, while finding a way to have the lasers pointing at the correct angles.

9.2 OLESight

OLESight has been successfully tested and is simple to integrate into an existing CCTV system. However, currently, it relies on a small amount of manual labeling for new use cases. By introducing some automated unsupervised machine learning into the software, OLESight could be deployed to a new use case and automatically update its model, reducing time to have the system up and running.

9.3 OLESurvey

OLESurvey will be further tested using machine vision cameras designed specifically to keep only the foreground including the OLE in focus. The difficulty with using machine vision cameras is they are primarily designed for indoor, controlled environments, and thus must be adapted and put in IP-rated enclosures to protect them from the elements. Additional ideas considered include adapting the software to instead work at night, illuminating the overhead line and leaving the background in darkness. This could create a high-contrast video output where the overhead line is easier to detect.

Continued collaboration with industry partners will be essential to ensure the systems meet the evolving needs of the railway sector. By leveraging the support of the ATTUNE project and other stakeholders, these systems can be further developed to provide even greater benefits to railway operators.

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