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A Comprehensive Review on AI-Enabled Drone-Based Railway Track Inspection, Safety and Fault Detection

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Abstract—

Railway track is a major enabler of economic development in that it provides an effective means of moving both people and goods. The maintenance of safe track and reliable infrastructure is of course fundamental and this requires a huge amount of inspection. In the case of large scale rail networks, this inspection is a major challenge. The traditional methods of inspection (manual inspection, robotic rovers, inspection trolleys) are all limited in terms of access, coverage and the ability to provide continuous monitoring. In response to these limitations, the use of drones in conjunction with AI and computer vision for the inspection of rail infrastructure has been proposed as a very viable solution. This paper presents a comprehensive review of AI-enabled drone based inspection, monitoring and fault detection for railway track. It looks at the use of drones for the acquisition of railway images and the identification of track defects, structural damage, obstructions and potential safety hazards. A range of deep learning and computer vision techniques are considered including YOLO based object detection, Convolutional Neural Networks, semantic segmentation, transformer based detection and multi-object tracking. Specific attention is given to RT-DETR for object detection, Slicing Aided Hyper Inference (SAHI) for small object detection and ByteTrack for tracking the objects of interest across video frames. The review also considers vision-LiDAR sensor fusion, real time processing, environmental challenges and the current limitations of the existing inspection systems. It concludes with a discussion of the research gaps and future directions for the development of reliable, intelligent and efficient drone based rail inspection systems.

Keywords— Railway Inspection, Drones, Artificial Intelligence, Computer Vision, RT-DETR, SAHI, ByteTrack, Fault Detection, Railway Safety.

I. INTRODUCTION

Railways are one of the most important forms of transport in terms of linking the towns and villages together and enabling the movement of both people and goods.As the rail network continues to expand it is becoming increasingly difficult to maintain every section of track in a safe and sound state. Regular inspection is of course essential in order to detect any cracks, damaged components, obstructions etc before they become a serious problem [11]. The traditional methods of inspection (manual inspection, robotic rovers, inspection trolleys etc) are all limited in terms of the area they can cover and the extent to which they can get to areas where there is damaged track or physical obstructions [12].

Drone based inspection is a valid solution to some of the problems with the traditional inspection methods. The drone can fly above the track and so provide images of both the track and the trackbed. When combined with AI and computer vision those images can be used to detect defects and potential safety issues. There's been a fair bit of work in this area previously with for example YOLO based railway defect detection [3], [7], railway track detection and segmentation [6] and machine vision based intrusion detection [8]. Other work has looked at vision Lidar fusion for track anomaly detection [2] and edge AI for faster railway fault detection [4].

Despite the improvements these methods have made to the monitoring of the rail system there are still a number of problems. Small defects in the high resolution images can be very difficult to spot and object detection in the video sequence is only as good as the tracking of the objects that you're detecting. To deal with these issues the paper looks at the combination of three techniques: RT-DETR for object detection [10], Slicing Aided Hyper Inference (SAHI) for the detection of small objects [9] and ByteTrack for the tracking of the objects across the video frames [1]. All three together form a very solid basis for the analysis of rail images and video.

The paper's key contributions are a review of drone based railway inspection techniques, a look at the most recent advances in object detection and tracking and a discussion of the challenges and potential of AI for railway safety and fault detection.

II. COMPARATIVE ANALYSIS OF REVIEWED STUDIES

The Studies examined various methods for improving railroad inspection, defect detection and safety monitoring. Some were drone based image acquisition, others were based on deep learning, object detection, tracking and sensor fusion. Table I summarises the selected studies, their approaches and their contributions to railway inspection.

TABLE I. COMPARATIVE ANALYSIS OF REVIEWED STUDIES

Ref.	Method / Technique	Main Contribution	Identified Limitation
[1]	ByteTrack	It tracks multiple detected objects from frame to frame.	Does not perform its own defect detection.
[2]	Semi-supervised learning and Vision-LiDAR fusion	Detects anomalies on the rail via fusion of visual and LiDAR data.	Requires multiple sensor inputs and good data registration.
[3]	Drone based YOLO detection	Enables real time railway monitoring and defect detection via drone.	Detection ability is a function of image quality and object visibility .
[4]	FPGA based Edge AI	Enables faster detection of rail faults via hardware based processing.	Hardware resources and implementation complexity are very likely to be the limiting factors.
[5]	UAV imaging and deep learning	Capable of identifying railway tracks and floodwater from UAV imagery.	Focused on the railway and floodwater scenarios.
[6]	Connected-ERFNet	Performs railway track detection and real-time tracking.	Primarily focused on track detection rather than a range of different defect types.
[7]	Improved YOLOv3	Uses image processing to detect a range of railway track defects.	The small and hard to see defects are still a challenge.
[8]	Machine vision based intrusion detection	Looks at the various intrusion detection methods and the safety issues that are associated with them.	Mainly concerned with intrusion detection rather than the detection of track faults.
[9]	SAHI	Image slicing and fine-tuning for improved small object detection.	Incurs additional image processing and computational cost.
[10]	RT-DETR	Transformer based architecture for real time object detection.	Performance is very much dependent on the model config and how much compute you have available.

The comparative analysis shows that the various studies look at different facets of the railway inspection process and none of the techniques actually cover the whole range of requirements. Drone based imaging provides the most extensive coverage of the inspection, deep learning is used to identify the defects and safety issues but there are still significant problems with small object detection, object tracking and processing efficiency. SAHI can assist with small object detection, RT-DETR provides the detection framework and ByteTrack helps with the tracking of the objects in the video. That combination would be a possible route to a more complete drone based railway inspection system.

III. RESEARCH GAPS AND CHALLENGES

There have been a number of studies looking at AI for railway inspection and yet there are still a number of issues that need to be addressed. The detection of small cracks, damaged fasteners and the like is a particular problem when looking at high resolution drone images. Detection accuracy is affected by lighting, shadows, weather, and camera angle variations. Another problem is to keep track of the same object from one frame to the next, especially if the object is partially visible or is at a different distance.

Real time processing is also a major issue as the drone based inspection systems in question have very limited computational capability and are going to be looking at a very large volume of visual data [13]. Much of the existing work is focused on individual tasks (defect detection, track segmentation, object tracking etc) rather than trying to put them all together into a single inspection system. Adding other sensing modalities like cameras and LiDAR also increases the complexity of the system [14].

To deal with these challenges, combining RT-DETR with SAHI and ByteTrack is a promising avenue for future work. RT-DETR provides the object detection capability, SAHI provides the ability to detect small objects via image tiling and ByteTrack provides the ability to track objects across frames. The main challenge that remains is to have robust detection, accurate tracking and efficient processing under different rail and environmental conditions.

IV. CONCLUSION

Drone based railway inspection in conjunction with AI and computer vision is a very promising avenue for improving the monitoring of rail tracks, for safety and for fault detection. This review looks at the various techniques that have been used in the existing literature, namely YOLO based detection, deep learning, semantic segmentation, sensor fusion and object tracking. The comparative analysis has highlighted the shortcomings of the current approaches in particular with respect to the detection of small defects, accurate object tracking and real time processing.

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