Deep Learning-Enhanced UAV-Based Hardware-in-the-Loop for Infrastructure Inspection in GPS-Denied Environments

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Abstract

Manual inspection is the primary method for detecting tunnel cracks in domestic railways. However, this method needs to meet railway inspection's accuracy and rapidity requirements due to subjective judgment from inspection personnel. Moreover, tunnel images often have complex situations, which challenge traditional image processing methods. Unmanned aerial vehicles (UAVs) have proven effective in identifying structural damage in various infrastructures, but tunnel inspections present unique challenges due to the absence of GPS signals and collision risks. We propose a GPS-free self-localization algorithm that utilizes onboard sensors and a segmentation neural network for precise defect detection to address these challenges. Field tests have affirmed the framework's effectiveness, underscoring its potential for application in tunnel inspections.

Keywords : Tunnel Inspection, Deep learning, Autonomous Navigation, Defect segmentation.

I. Introduction

Conducting tunnel inspections is critical to assessing tunnel safety and establishing maintenance plans. It is crucial to thoughtfully evaluate the technology and methodology employed during inspections, as they significantly impact the accuracy of safety evaluations and the extent of maintenance required [1]. Factors such as environmental elements, inadequate maintenance, and inherent structural weaknesses can contribute to tunnel deterioration over time, with cracks being the most common type of damage. These cracks can progress from minor to severe, resulting in a catastrophic failure [2].

Recently, the utilization of commercially available UAVs for inspections has displayed significant potential in revolutionizing the conventional inspection industry. However, using traditional UAV inspection systems in tunnel environments presents unique challenges, such as the absence of light and GPS signals, which can increase the risk of collisions. These challenges underscore the need for a more dependable and effective method for tunnel inspections [3].

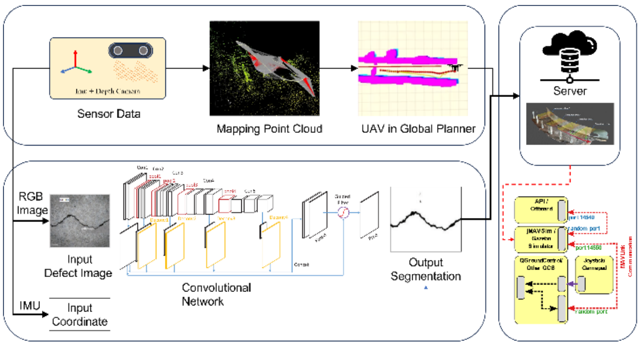

Fig. 1 Overview UAV Defect detection with SLAM architecture.

To address these challenges, a proposed framework utilizes a flying robot with crack-detection capabilities. A GPS-free self-localization algorithm was also developed based on onboard computer, camera, and inertial measurement unit (IMU) data. The system's effectiveness was established through simulations and real-world scenarios, confirming the feasibility of implementing the proposed framework for tunnel inspections.

Ⅱ. Proposed System

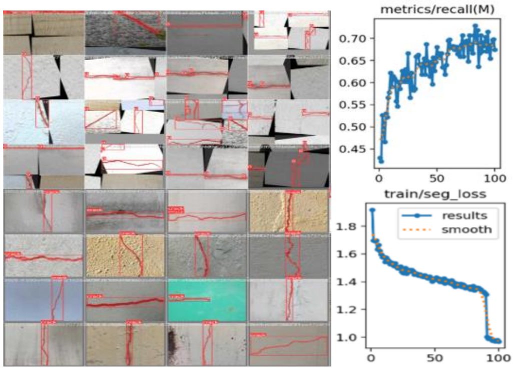

Fig. 2 Deep learning model training results.

The proposed model presented in this study encompasses two critical frameworks: flying robot autonomous navigation and crack detection, as shown in Fig.1. The proposed model presented in this study covers two critical frameworks: flying robot autonomous navigation and crack detection. Autonomous navigation is achieved via an Unmanned Aerial Vehicle (UAV) that follows a predetermined path while employing a high-definition camera to identify and locate cracks within the tunnel. The real-time crack detection method is based on an improved YOLOv8nseg model [4], LCA-YOLOv8n-seg, accurately depicting the crack area in pixel widths. The LCA-YOLOv8n-seg model has the advantages of small size, high detection accuracy, and low detection delay. The crack segmentation is formulated as a binary image labelling problem, where "0" and "1" represent "non-crack" and "crack," respectively.

Specialized training datasets are required to ensure the accuracy of recognition algorithms deployed on UAVs. Therefore, the crack detection model was trained using a color image dataset with manually annotated segmentations. The images were divided into two primary subsets: a training set with 300 images and a testing set with 237 images. Each image was accompanied by a pixel-wise segmentation map covering the cracked regions. The results indicate that the proposed system exhibited a high level of robustness in both panoramic crack image classification and refined crack segmentation. Drones' dual-mode localization capabilities (vision and IMU) and the location information accompanying all captured images enable workers to identify and locate damages rapidly and accurately during repair work. The crack classifier achieved a true positive rate of 96.5%, whereas the crack segmentation model attained an accuracy of over 93.6%, as shown in Fig.2 Overall, this study presents a promising approach to tackle the problem of crack detection in tunnels using UAVs.

IV. Conclusion and Future Work

This study proposed a flying robot-based framework for automated crack inspection in tunnel environments. An image classification algorithm and crack segmentation algorithm were developed to process panoramic images captured by an unmanned aerial vehicle (UAV). The implementation of the proposed system enables safety managers to monitor the distribution of cracks within the tunnel environment effectively, thereby enhancing the reliability of tunnel safety assessments.

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