AI-Driven Adaptive Robot for Micro-Crack Detection and Predictive Structural Health Intelligence

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Effective structural health monitoring (SHM) of carbon steel structures is critical, but is limited by traditional methods in efficiently identifying fine cracks. Thus, this project aims to develop an AI-driven robotic system designed as a low-cost tool for the reliable indication of fine surface cracks (=230μm width) and providing predictive insights. The system uses multimodal sensor (HD visual, IR thermal, ultrasonic) integration in a mobile robotic platform controlled by a Raspberry Pi 5 and ESP32 through edge AI processing. The model comprises a Convolutional Neural Network (CNN) modified with Gabor filters and multi-scale attention layers to perform real-time crack segmentation. To improve detection confidence and reduce false positives, sensor fusion algorithms are implemented in the multimodal sensor data. Furthermore, a physics-based digital twin is developed by utilizing a Finite Element Analysis (FEA)-derived database queried by an external PC to predict potential crack growth based on detected features. A hybrid incremental learning strategy enables adaptation to new data patterns, allowing for progressive intelligence. The system has demonstrated the ability to achieve 91.7% mean Intersection-over-Union (IoU) for fine crack segmentation under baseline environmental conditions, as well as an $R^2 = 0.93$ correlation between predicted and verified crack propagation trends while consistently maintaining ~4.5 FPS and ~220ms latency during real-time inspection trials. This project shows promise of a scalable, cost-effective, and efficient integrated approach to allow for accessible and proactive SHM across industries.

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