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Dissertation Title: Versatile AI-powered Machine Vision for Quality Control of Highly Reflective Parts

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Abstract or Public Summary: Automated optical inspection of reflective metallic surfaces remains challenging due to specular glare, low defect contrast, and the limited availability of annotated data for training deep learning models. This thesis proposes an integrated set of methodologies for industrial visual inspection that address these challenges across the entire processing chain, from image acquisition and data generation to real-time inference, with an emphasis on robustness, computational efficiency, and adaptability to different inspection scenarios. First, data-centric strategies are introduced to alleviate annotation scarcity, including defect-free synthetic image generation using diffusion-based models, photorealistic rendering from three-dimensional geometric models with automatic annotation, and active learning schemes that combine uncertainty, diversity, and reduced human annotation effort. Second, an explainability-guided inference strategy is proposed, based on the analysis of class activation maps obtained via principal component decomposition, enabling the identification of visually relevant regions and a reduction in inference-time computational cost while preserving detection sensitivity. Third, augmented reality is explored as an acquisition and interaction component, supporting operator-driven multi-view imaging and distributed integration between acquisition and processing modules. The proposed methodologies are validated through their application in industrial automated optical inspection cells designed as modular and configurable instances, in which different combinations of acquisition, illumination, and processing can be adapted to new components and defect types with minimal hardware changes and, at the software level, primarily through the provision of new image data. Within this context, the approaches are evaluated in representative industrial scenarios, demonstrating consistent performance across multiple inspection tasks. For filing detection, a precision of 97.90% and a recall of 98.10% are achieved, while hole integrity verification reaches an accuracy of 97.30% and a recall of 94.10%, with no false positives observed. In surface porosity detection, based on a region-focused inference regime, an F1-score of 89.80% is obtained on complete parts while maintaining cycle times below one second. In endoscopic inspection, limitations related to contrast and internal surface texture are identified, motivating future improvements based on geometric pre-segmentation and illumination optimisation. In the augmented reality

scenario, real-time detection achieves 86.70% precision and 87.30% recall on previously unseen parts, demonstrating generalisation capability under natural illumination conditions.

Doctoral Programme: Doctoral Program in Electrical and Computer Engineering

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