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Swarm Intelligence-Enhanced Detection of Small Objects Using Key Point-Driven YOLO

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ABSTRACT

Traditional object detection methods, such as anchor-based YOLO variants, face challenges due to the irregular shapes and small sizes of these contaminants. This paper introduces a novel approach that leverages swarm Intelligence to enhance the performance of a keypoint-driven YOLO framework. By integrating keypoint detection with Boundary-Aware Vectors (BBAVectors) and utilizing swarm intelligence algorithms for model optimization, our approach improves the localization and identification of small, irregularly shaped non-metallic objects. By optimizing the feature extraction process through swarm-based techniques and incorporating keypoint-driven object detection, our model significantly boosts precision and recall compared to traditional methods. Evaluated on a custom dataset of fiber like materials, our approach achieves a mean Average Precision (mAP) of 92.9% at IoU 0.5, demonstrating strong performance in real-world applications.

KEYWORDS

Swarm Intelligence, Small Object Detection, Keypoint-Based Detection, YOLO Framework

INTRODUCTION

Ensuring the quality and safety of fiber-like materials is a critical concern in many industries. The presence of foreign objects in these materials poses significant challenges to both the production process and product safety. While metal contaminants are relatively easier to detect using conventional metal detectors, detecting non-metallic foreign objects, such as plastic, paper, and other materials, remains a challenging problem due to their irregular shapes, their varying sizes, and the often complex background of the materials (Chen et al., 2022). This challenge is further exacerbated by the small size of many of these non-metallic objects, which makes their detection particularly difficult due to their scale and the highly textured nature of the fiber-like materials (Zhang et al., 2022). Moreover,

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the high-speed production environments in which these detections occur introduce additional latency and integration challenges, necessitating real-time, scalable solutions.

Traditional object detection techniques, such as anchor based methods like you only look once (YOLO) and faster region-based convolutional neural network (R-CNN), have demonstrated success in general object detection tasks (Agrawal et al., 2022; Bhavana et al., 2024). However, their performance tends to degrade when detecting small objects in cluttered environments. Anchor-based models often suffer from misalignment issues when detecting small objects, resulting in inaccurate bounding boxes or missed detections (Chen et al., 2022; Chen & Guo, 2023). Furthermore, the reliance on predefined anchor boxes reduces their effectiveness when applied to nonmetallic foreign objects, like fiber-like materials, in complex environments where the objects vary significantly in shape and orientation (Cao et al., 2022). Additionally, the inference latency of such models makes them less suitable for real-time applications, particularly in industrial settings where high-speed conveyor belts demand low-latency processing.

Recent advances in deep learning and optimization techniques have introduced more sophisticated approaches to object detection, especially for small and irregularly shaped objects (Cheng et al., 2023; Han et al., 2022). Among these advances, swarm intelligence algorithms have emerged as powerful tools for enhancing deep learning models by improving parameter optimization and decision-making strategies. Swarm intelligence, such as particle swarm optimization (PSO) and ant colony optimization, can optimize model hyperparameters and feature selection processes, leading to more robust detection frameworks. Additionally, keypoint-based detection and box boundary-aware vectors (BBAVectors) have shown promise in improving the accuracy of small object detection by eliminating the dependence on anchor boxes and focusing on keypoints to identify object centers and BBAVectors to delineate object boundaries (Cheng et al., 2023; Cui et al., 2023). Despite these advancements, there remains a gap in comprehensive analyses of their performance in real-world industrial applications, particularly in terms of inference speed, integration challenges, and economic feasibility.

In this work, we propose a novel approach for detecting small non-metallic foreign objects in fiber-like materials using a swarm intelligence-enhanced, keypoint-driven YOLO framework. Our method integrates keypoint detection for precise object localization; BBAVectors to accurately describe the boundaries of small, irregularly shaped contaminants; and swarm intelligence to optimize the model's parameters and improve detection accuracy. Unlike traditional models, our approach explicitly balances the trade-off between detection accuracy and real-time latency, making it suitable for high-speed industrial environments. Furthermore, we present a detailed cost-benefit analysis to demonstrate the economic advantages of adopting our framework, such as reduced downtime and improved product quality. This approach overcomes the limitations of anchor-based methods by providing a more flexible and accurate representation of objects, especially in complex environments with textured backgrounds and small objects (Borde et al., 2023).

We evaluate our method on a custom dataset of fiber-like materials containing various types of non-metallic foreign objects. Experimental results demonstrate that our swarm intelligence-enhanced YOLO framework significantly outperforms traditional anchor-based models in both precision and recall when detecting small objects (Chen et al., 2022; Dahake & Shinde, 2023). A comprehensive error analysis highlights the model's ability to handle occlusions, low-contrast objects, and irregular shapes, while also identifying potential failure modes and mitigation strategies. The model achieves a mean average precision (mAP) of 92.9% at intersection over union (IoU) 0.5, showcasing strong performance in real-world industrial applications (Zhu et al., 2023).

Additionally, we compare our approach with state-of-the-art models, including transformer-based frameworks like detection transformer (DETR), to contextualize its performance within the broader field of object detection. The results emphasize our model's advantage in achieving high accuracy with lower latency, reinforcing its suitability for real-time applications.

The remainder of this paper is organized as follows. The next section provides a review of related work, focusing on existing approaches to object detection and their applications in small object

Solving Graph Coloring Problem Using an Enhanced Binary Dragonfly Algorithm

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