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AOI-OPEN: federated operation and control for DAO-based trustworthy and intelligent AOI ecology

Key words: Automated optical inspection; Decentralized autonomous organizations; Parallel data; Federated intelligence

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Motivation

Traditional defect inspection is carried out by human workers. Due to the **inefficiency and error-prone** shortages of manual inspection, **automated optical inspection (AOI)** equippment is designed and used in manufacturing, largely replacing human labor in defect defection.

Motivation

The motivation behind this paper is to address the persistent challenge of data silos and limited collaboration in the AOI industry. Despite the critical role of AOI systems in various manufacturing sectors, the development of advanced AI-driven visual inspection models is hindered by:

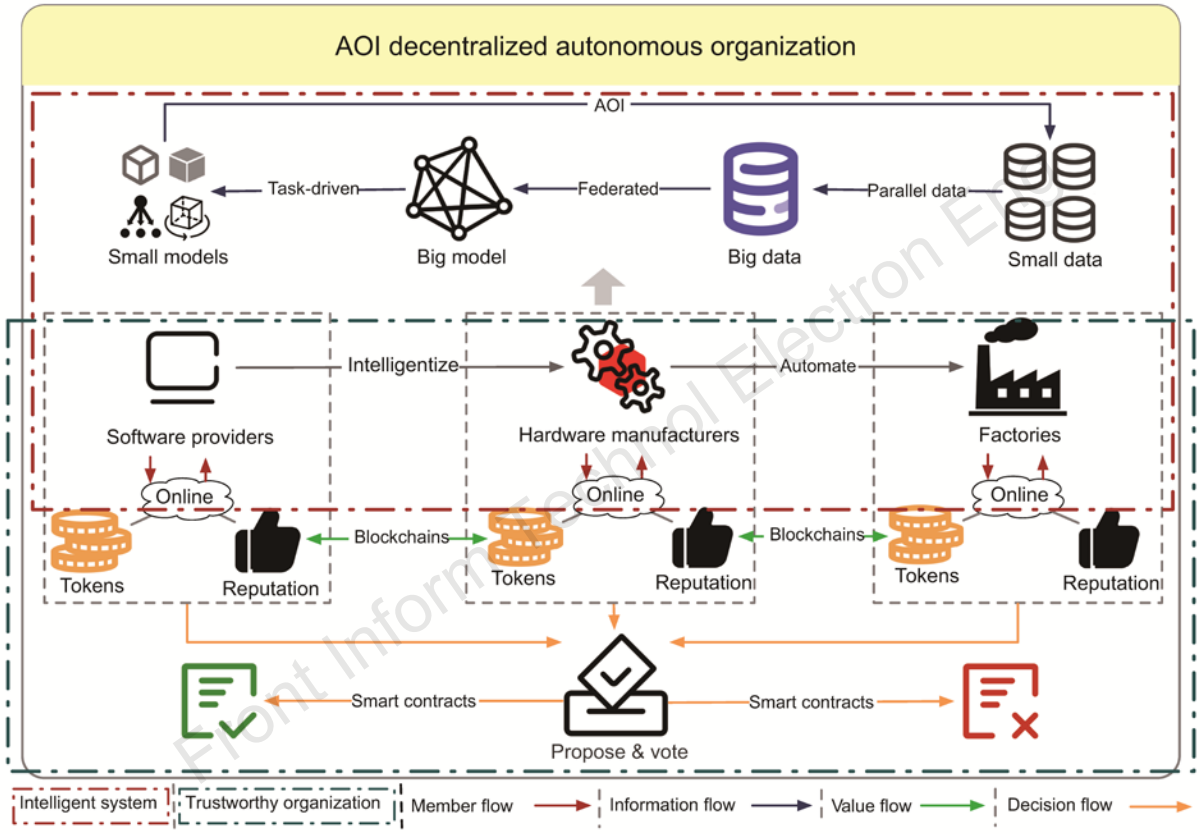
- lack of effective data sharing mechanisms among hardware providers, software developers, and factory users;
- privacy concerns, ownership rights, and competitive risks that discourage stakeholders from contributing valuable production data;
- existing research focus predominantly on imaging and processing techniques, with insufficient attention to cross-organizational data collaboration frameworks.

To overcome these obstacles, we design a trustworthy and intelligent AOI ecology using a decentralized autonomous organization (DAO)-based approach. This novel framework—AOI-OPEN—aims to connect data islands, incentivize participation through decentralized governance, and enable privacy-preserving data utilization via federated intelligence, ultimately fostering a more sustainable and efficient AOI ecosystem.

Main idea

- A novel framework AOI-OPEN is proposed which develops a trustworthy and intelligent AOI ecology and is beneficial to the operations and collaborations of AOI industrial metaverse.
- A DAO is proposed for the AOI community; it effectively organizes the stakeholders and provides democratic decision-making and benefits-guaranteeing mechanisms.
- A data-centric pipeline incorporating virtual–real intelligence and federated intelligence is proposed which strengthens the utilization of distributed data resources and improves the accuracy of defect classification models.

Framework



The overall framework of AOI-OPEN. It includes mainly two parts: the intelligent system (in the red dotted box) which focuses on the construction of high-performance AOI devices, and the trustworthy organization (in the green dotted box) which focuses on the construction of collaborating mechanisms among the AOI ecology

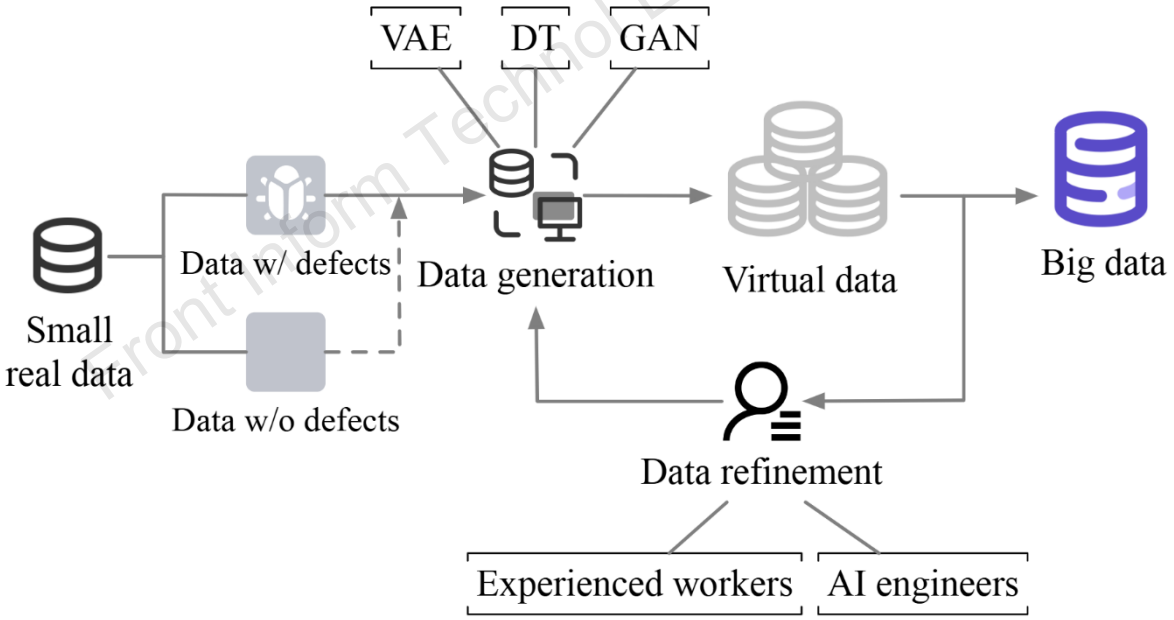
Method

1. AOI-OPEN establishes a decentralized, federated framework that connects software providers, hardware manufacturers, and factories through four key flows—member, information, value, and decision. Enabled by technologies like blockchain, parallel data, and federated learning, these flows support collaborative model building, fair value distribution, and democratic governance via DAO. This ensures trusted, efficient, and intelligent operations across the AOI ecosystem.

- Member flow: integrating diverse entities—software providers, hardware manufacturers, and factories—into the community by enabling seamless offline-to-online identity registration and access.
- Information flow: aggregating distributed data to collaboratively build intelligent inspection models through federated learning and large models.
- Value flow: ensuring fair incentive distribution and benefit sharing to encourage continuous contributions of data and resources.
- Decision flow: enabling democratic governance and transparent rule enforcement via DAOs and smart contracts.

Method

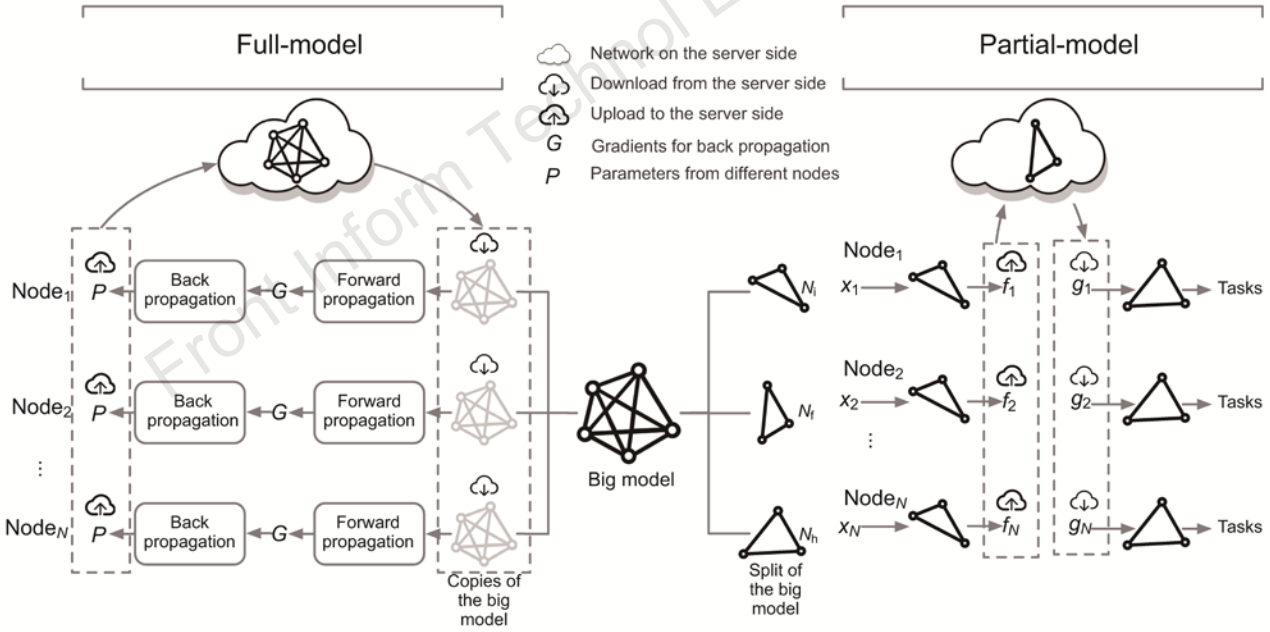
2.1. To address the scarcity of defect samples in AOI, we adopt a parallel data approach that combines digital twins, generative models (e.g., GANs and VAEs), and expert feedback. This method iteratively generates and refines virtual defect data through virtual–real interaction, enhancing both data diversity and model performance in real-world AOI scenarios.



Process of the parallel data approach

Method

2.2. AOI-OPEN combines federated learning, large models, and blockchain to enable secure and collaborative defect detection in AOI systems. It supports full- and split-model training, protects privacy with encryption, and uses smart contracts to incentivize contributions. A DAO-driven voting mechanism ensures fair model evaluation, fostering a trustworthy and sustainable ecosystem.



Privacy-preserving large models in AOI-OPEN

Major results

Table 3 Accuracy of different models

Model	Accuracy (%)
VGG-11	87.44
VGG-16	88.01
VGG-19	87.94
ResNet-18	86.46
ResNet-50	88.50
ViT	78.70
T2T	85.12
DeiT	85.38

Table 4 Classification results of the models trained with different strategies

Method	Accuracy (%)	Precision (%)	Recall (%)
Real	80.5 ($\pm$0.5)	66.3	30.6
Virtual	89.3 ($\pm$0.4)	92.4	90.5
Unsupervised (PaDiM)	80.2 ($\pm$1.1)	91.3	67.6

Major results

Table 5 Classification results with different splitting strategies

Split	Node	Accuracy (%)
Split-H	All	85.6 (±0.3)
	$Node_1$	81.8 (±0.5)
	$Node_2$	77.0 (±0.6)
	$Node_3$	74.8 (±0.4)
	$Node_4$	83.7 (±0.3)
	$Node_5$	84.0 (±0.5)
Split-V	All	88.5 (±0.2)
	$Node_1$	84.7 (±0.2)
	$Node_2$	84.0 (±0.3)
	$Node_3$	86.8 (±0.4)
	$Node_4$	86.1 (±0.3)
	$Node_5$	86.4 (±0.2)

Table 6 Performance comparison between full-model mode and partial-model mode in the FL process

Mode	Number of splits	Cycle-training	Accuracy (%)
Full	1	No	88.5
Partial	2	No	71.2
Partial	2	Yes	79.5
Partial	3	No	69.1
Partial	3	Yes	77.4

Conclusions

- **Parallel data boost model performance**
  Synthetic defect data generated through the parallel data approach significantly improves data diversity and quantity, achieving higher accuracy than models trained on limited real data.

- **Federated learning enhances cross-node collaboration**
  FL consistently outperforms local training, especially under imbalanced data splits, demonstrating its effectiveness in multi-factory settings.

- **Closed-loop refinement is highly effective**
  Human-in-the-loop refinement of synthetic data boosts model accuracy from 89.3% to 97.6%, proving the value of expert feedback.

- **DAO and FL increase participation and trust**
  DAO ensures fairness and transparency, while FL preserves privacy, both leading to higher user engagement.

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