Learning-Based Methods for Enabling On-Edge, Accurate, Sustainable, and Human-Centered Intelligent Manufacturing

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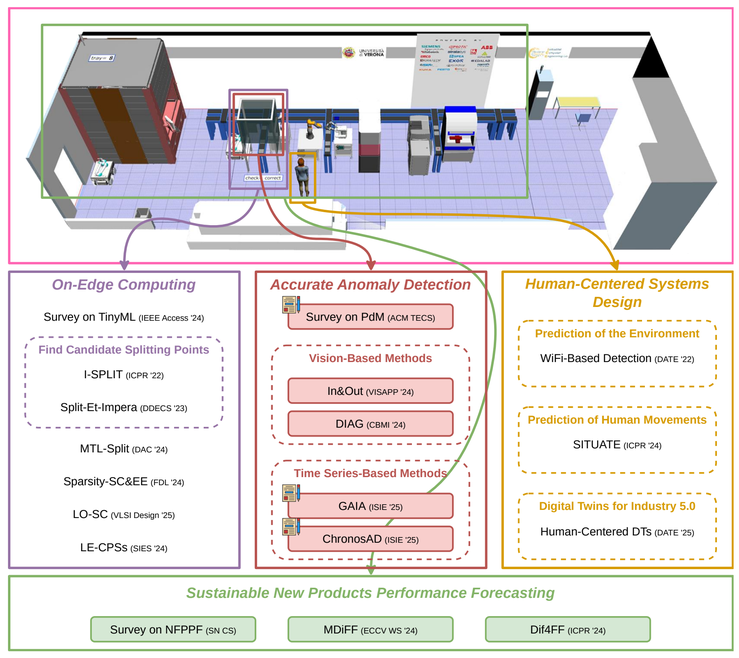
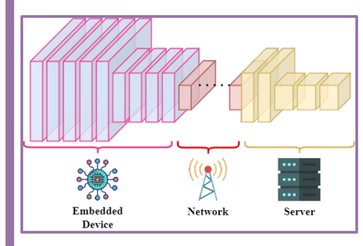
ABSTRACT

Four major industrialization evolutions have occurred throughout human history, affecting economic growth, population expansion, and significant social transformations. Industry 5.0 is considered the next industrial revolution, and its objective is to harness the creativity of human experts in collaboration with efficient, accurate, and intelligent machines. In this context, the transformation of industrial resources into intelligent objects capable of sensing, acting, and adapting leads to intelligent manufacturing. To comprehensively improve manufacturing system capabilities, this thesis presents cutting edge learning-based techniques around four key pillars of *intelligent manufacturing*: **efficient on-edge computing**, **accurate anomaly detection**, **sustainability**, and **human-centered systems design**. The results obtained are shown in the Figure on the right, which presents the real-world setting of the *Industrial Computer Engineering (ICE) Laboratory* of the University of Verona, where the presented contributions were tested and evaluated.

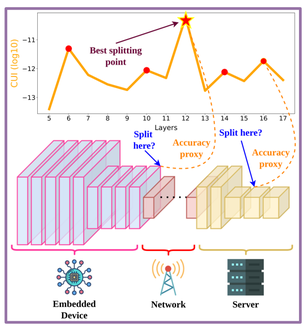


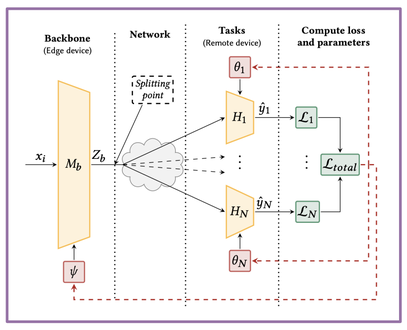
CONTRIBUTIONS

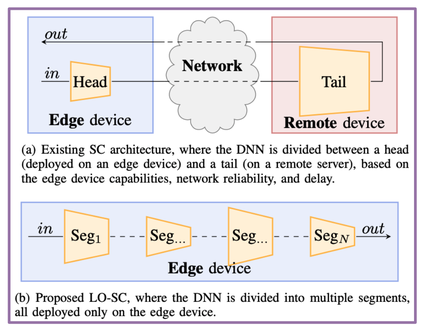
On-Edge Computing



Motivations: We explore the application of **Split Computing**, where a DNN is intelligently split with a part of it deployed on an **edge device** and the rest on a **remote server**, enabling **real-time processing** on large-scale industrial data.





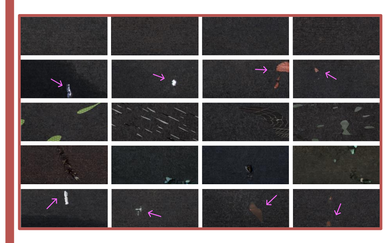


(a) Existing SC architecture, where the DNN is divided between a head (deployed on an edge device) and a tail (on a remote server), based on the edge device capabilities, network reliability, and delay.

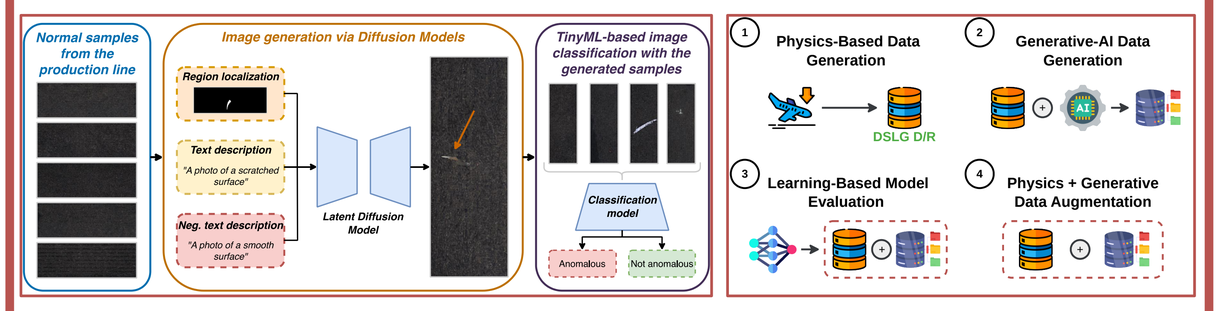
(b) Proposed LO-SC, where the DNN is divided into multiple segments, all deployed only on the edge device.

Innovations: [2, 3] to partition learning models efficiently. [4] to partition multi-tasking DNNs within an SC framework. [5] to significantly reduce computational, storage, and energy demands during training and inference. [6] a novel methodology that leverages the principles of SC to split a DNN for execution entirely on an edge device without sacrificing model accuracy. [7] examines various SC architectures and their impact on controller design.

Accurate Anomaly Detection

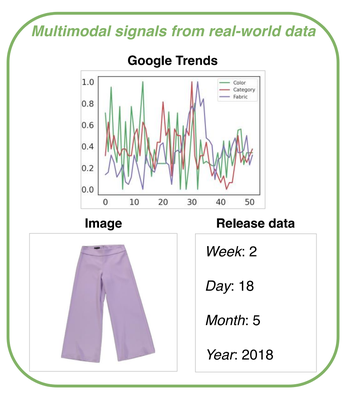


Motivations: **PdM** plays a crucial role in intelligent manufacturing since it **guarantees** the ongoing **reliability** and **efficiency** of advanced technological systems. Central to PdM is **anomaly detection**, which serves as the initial step in **identifying potential issues**.

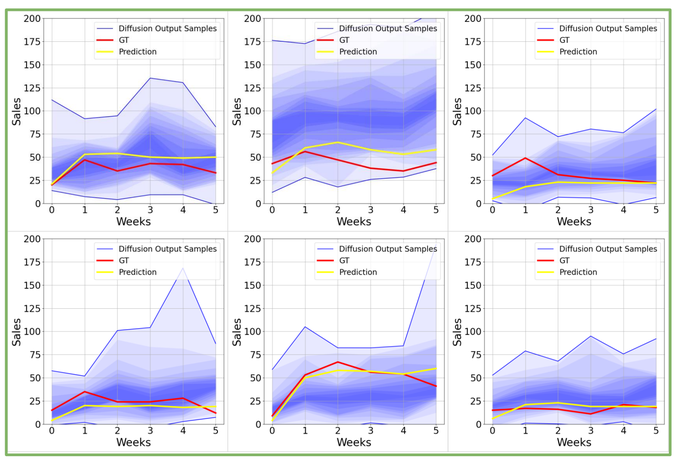


Innovations: [8, 9] two diffusion-based data augmentation methodologies, which, by blending in-distribution and out-of-distribution samples, improve classifier robustness in Surface Defect Detection.
GAIA, in which we highlight the role of Generative AI in overcoming the limitations of real-world data, and ChronosAD, the first-ever proposed architecture able to leverage time series foundation models for fault classification. Both of them are under submission.

Sustainable New Products Performance Forecasting



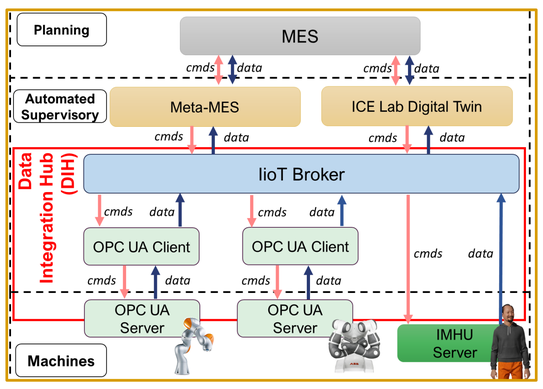
Motivations: Another core principle of intelligent manufacturing is **sustainability**. In particular, the **fast fashion** industry represents the **second most pollutive industry in the world,** responsible for 79 trillion liters of water consumed and 92 million tonnes of waste produced per year, contributing 8% to all carbon emissions and 20% of all global wastewater [13]. Accordingly, we focus on sustainability challenges within this sector.

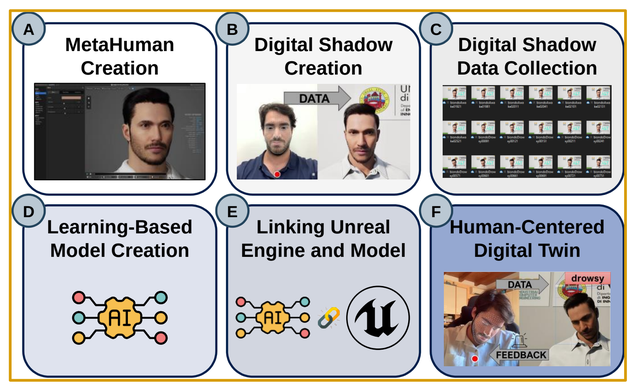


Innovations: [14, 15] are two novel pipelines based on multimodal diffusion models for predicting the performance of a brand-new clothing probe with no available past observations. By improving the accuracy of demand forecasts, these models help mitigate overproduction and reduce waste.

Human-Centered Systems Design

Motivations: We develop systems to predict environmental conditions and human movements in indoor settings. Furthermore, we also introduce the first comprehensive framework for implementing Human-Centered Digital Twins.





Innovations: [10, 11] are systems that are able to predict environmental conditions and human movements in indoor settings, ensuring worker safety while maintaining operational efficiency. [12] is the first pipeline for the creation of a human-centered DT, leveraging Unreal Engine's MetaHuman technology to track worker alertness in real-time.

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