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

By

Luigi Capogrosso

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Supervisors:
Prof. Marco Cristani, Supervisor
Prof. Franco Fummi, Co-Supervisor

Doctoral Examination Committee:
Prof. Christoph Lüth, *Referee*, University of Bremen
Prof. Nicola Mazzocca, *Referee*, University of Naples Federico II
Prof. Alessandro Beghi, *Member*, University of Padua
Prof. Stefano Di Carlo, *Member*, Polytechnic University of Turin
Prof. Sebastiano Vascon, *Member*, Ca' Foscari University of Venice

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Luigi Capogrosso
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Abstract

Four major evolutions of industrialization have occurred throughout human history, impacting economic growth, population expansion, and significant social transformations. Industry 5.0 is regarded as the next industrial revolution, and its objective is to leverage the creativity of human experts in collaboration with efficient, accurate, and intelligent machines. In this context, the transformation of industrial resources into intelligent and adaptive objects with sensing and acting capabilities leads to intelligent manufacturing. To comprehensively enhance manufacturing systems capabilities, this thesis presents cutting-edge learning-based techniques around the four key pillars of intelligent manufacturing: ***efficient on-edge computing****,* ***accurate anomaly detection****,* ***sustainable new products performance forecasting****, and* ***human-centered systems design****.*

In the efficient on-edge computing domain [1], we explore the application of Split Computing (SC), where a Deep Neural Network (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. Firstly, we developed the ***I-SPLIT*** *[2] and* ***Split-Et-Impera*** *[3] techniques to partition learning models efficiently. However, in many industrial scenarios, the same DNN is used for multiple inference tasks. So, in* ***MTL-Split*** *[4], we studied how to partition such a multi-tasking DNN to be deployed within an SC framework. In* ***Sparsity-SC&EE*** *[5], we present the effect of predefined sparsity within SC to significantly reduce computational, storage, and energy demands during training and inference. We also introduce* ***LO-SC*** *[6], a methodology that leverages the principles of SC to split a DNN for execution entirely on an edge device without sacrificing model accuracy. Finally, we present* ***LE-CPSs*** *[7], examining SC architectures and their impact on controller design.*

Predictive Maintenance (PdM) plays a fundamental role in intelligent manufacturing since it guarantees the ongoing reliability and efficiency of advanced

*technological systems [8]. Central to PdM is anomaly detection, which serves as the initial step in identifying potential issues. This thesis explores both vision-based and time-series-based approaches to tackle this task. In the vision domain, our research focuses on Surface Defect Detection (SDD). Specifically, we develop **In&Out** [9] and **DIAG** [10], two diffusion-based data augmentation methodologies to enhance the performance of learning classifiers. For time-series data, we present **GAIA** [11], in which we highlight the role of Generative Artificial Intelligence (GenAI) in overcoming the limitations of real-world data, and **ChronosAD** [12], the first application of time-series foundation models for fault classification.*

*Another core principle of intelligent manufacturing is sustainability. In particular, the fast fashion industry represents the second most pollutive industry in the world [13]. Accordingly, we focus on addressing sustainability challenges within this sector. In particular, we target the New Fashion Products Performance Forecasting (NFPPF) task and introduce **MDiFF** [14] and **Dif4FF** [15], two novel pipelines based on multimodal diffusion models for forecasting sales of new fashion products.*

*The final aspect centers on fully integrating humans within intelligent manufacturing environments. In **WiFi-Based Detection** [16] and **SITUATE** [17], we develop systems to predict environmental conditions and human movements in indoor settings, ensuring worker safety while maintaining operational efficiency. Finally, in **HC-DT** [18], we introduce the first pipeline for implementing human-centered Digital Twins (DTs).*

*Most of the presented works were examined into the manufacturing infrastructure of the **Industrial Engineering Laboratory (ICE Lab)**. This practical integration allowed for the evaluation of the proposed systems within an operational environment, ensuring their effectiveness and functionality.*

Contents