Ph.D. in Information Technology
Thesis Defense

March 19th, 2026
At 11:00 a.m.
Room Seminari Alessandra Alario - Building 21

Alessandro RESTIFO – XXXVIII Cycle

REAL-TIME AND ROBUST VIRTUAL SENSING FOR LASER MANUFACTURING VIA LOW-LATENCY DEEP LEARNING AND CROSS-MACHINE ADAPTATION

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Abstract:

Advancements in high-power laser cutting have positioned this technology as an indispensable component within the contemporary manufacturing landscape. Despite the widespread adoption of this technology, maximizing output quality and cutting efficiency remains challenging due to process variability and constraints arising from static parameters. This research thesis addresses these limitations by pioneering a comprehensive end-to-end methodology designed to generate robust virtual sensors deployable in the industrial context, intended for continuous process supervision in real time. Our virtual sensors continuously monitor the melt pool and kerf region through a coaxial high-speed camera to estimate various quality indicators (including the presence of degraded process states such as plasma formation and loss of cut), thereby enabling diagnostic monitoring and prescriptive actions to optimize both cut quality and factory productivity in real time. The study primarily targets the lack of robustness of traditional machine learning approaches based on handcrafted feature extraction, the trade-off between accuracy and latency in current deep learning models and, most importantly, the industrial challenge of cross-machine generalization and domain shift. The initial stage of the research project involved developing an industrial-grade unified hardware and software platform, which enabled the generation of one of the largest multi-machine laser cutting datasets in the literature to date. Building upon this foundation, the research involved next the improvement and optimization of traditional machine learning baseline pipelines to enable sub-millisecond inference latency and establish a performance benchmark. Finally, an innovative state-of-the-art model architecture based on neural networks and a novel framework enabling zero-shot generalization and weakly supervised fine-tuning have been developed. The first, called CUT-Net, is designed as a hardware-aware model which solves the real-time performance gap of neural architectures in the literature, achieving 153μs inference latency on a single CPU core with a three-state laser cutting classification accuracy of 94.11%. CUT-Net demonstrates marked computational efficiency, achieving up to 450x higher pixel throughput and up to 590x lower memory usage compared to prior high-accuracy approaches in the literature, while introducing for the first time an innovative module for temporal integration and stability improvement, resulting in a 67% reduction in prediction jitter. The second, termed GEN-Cut, presents a completely novel solution to the domain shift problem by attaining 85.5% zero-shot accuracy on unseen cutting machine data (a substantial improvement over the near-random baselines of previous models), complemented by a highly effective framework for efficient data usage and weakly-supervised adaptation, which increases the

system's operational accuracy to 92.7% using only two unlabeled calibration cuts gathered in-situ. In summary, this research thesis provides the state-of-the-art frameworks and technologies needed for building scalable, adaptive, and extremely efficient virtual sensing solutions for laser cutting. The findings provide the foundational infrastructure for the upcoming generation of autonomous and self-optimizing laser manufacturing systems, able to adapt to different working conditions and materials, by targeting optimal cutting quality and maximal industrial throughput in real time.

PhD Committee

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