

# Robotics and related Digitalization for high human intensive A/C assembly activities

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## **Abstract.**

This doctoral dissertation investigates how digitalisation and collaborative robotics can converge to support human-centred manufacturing through the design and evaluation of Cognitive Assistance Systems (CASs). Within the paradigm of Industry 5.0, which promotes the integration of human intelligence and technological capabilities to achieve sustainable, resilient, and human-oriented production, CASs represent a new generation of assistive technologies aimed at enhancing operators' cognitive performance rather than replacing it.

CASs are technological systems that monitor, guide, and complement human cognitive processes during task execution. They support perception by filtering and presenting relevant information, assist comprehension through adaptive and context-aware instruction delivery, and facilitate decision-making and action planning by providing feedback, recommendations, or shared control in collaborative tasks. In doing so, CASs help operators manage information complexity, reduce mental workload, and maintain high levels of attention and accuracy, thereby improving both productivity and well-being in industrial environments.

This dissertation investigates how these forms of assistance can be effectively designed and implemented, integrating digital instruction design, interface delivery, and collaborative robotic interaction into coherent frameworks. Mental workload and human-robot symbiosis are adopted as transversal constructs that inform both the design rationale and the evaluation methodology. The research is organised into four main lines that progressively explore how assistance can be designed through structured instruction methodologies, delivered through sustainable wearable technologies, embodied through collaborative robotics, and conceptualised through a multidimensional reference model.

The first research line focuses on the informational layer of CASs, which concerns how procedural knowledge is structured and conveyed to support human comprehension and execution. Within CASs, assembly instructions represent the fundamental medium through which operators receive cognitive guidance during task performance. However, existing approaches often lack systematic approaches for aligning instructional content with operators' cognitive processes, thereby limiting the cognitive effectiveness of assistance. To address this gap, the *Streamlined Assembly Instruction Design (S-AID)* methodology was developed. It provides a structured process for task decomposition, identification of information requirements, and mapping of these requirements onto suitable digital formats. Preliminary experimental results have demonstrated that S-AID-based instructions enhance the efficiency and quality of assembly processes, whilst concomitantly reducing mental workload.

Building on this foundation, the second research line explores the interactional layer of CASs, examining how instructional information can be effectively delivered to operators. In the literature, Head-Mounted Displays (HMDs) have repeatedly shown superior efficiency and accuracy compared with traditional screen-based systems, as they allow hands-free interaction and maintain the

operator's focus within the task environment. Nevertheless, for these devices to serve as viable components of CASs, their sustainability over extended usage must be demonstrated not only in terms of performance but also in terms of usability, comfort, and mental workload. To this end, Assisted Reality (aR), Augmented Reality (AR), and conventional screen-based displays were compared in a prolonged assembly task using a multidimensional evaluation framework encompassing performance and human factors. Results confirmed that both AR and aR outperform traditional screens in efficiency and error reduction. Nevertheless, while AR enhanced quality and efficiency through immersive visual cues, its usability was constrained. Assisted Reality, offering a lighter and less intrusive setup, achieved the most balanced outcomes, highlighting its potential as a sustainable interaction modality for CASs in industrial environments.

The third research line addresses the physical layer of CASs, centred on the integration of collaborative robotics as an embodied form of cognitive assistance. This part of the research focused on the conceptualization of *Symbiotic Human–Robot Collaboration (SHRC)*, defined as the most advanced expression of collaboration within CASs. The study first established a theoretical framework describing six analytical dimensions: *effort, speed, knowledge, decision-making, ergonomics, and safety*. These dimensions provide a structured basis for analysing and evaluating the symbiotic relationship between human and robot. On this foundation, a methodology for assessing SHRC scenarios was proposed, followed by the definition of a design methodology to support the systematic creation of symbiotic tasks. These conceptual and methodological contributions advance the understanding of the cobot as a cognitive agent within CASs, capable of complementing human abilities through shared autonomy, adaptive coordination, and bidirectional information exchange. The applicability of both methodologies was demonstrated through two case studies.

Finally, the fourth research line integrates the findings from the previous studies into a multidimensional reference model for CASs, linking their informational, interactional, and physical layers into a unified analytical framework. The model encompasses five dimensions: *Cognitive Functions, Autonomy, Adaptivity, Interaction Modality* and *Portability*. Each dimension is supported by dedicated rating scales that enable systematic profiling and benchmarking of CASs. An experimental verification across four CAS configurations preliminarily confirmed the model's ability to discriminate how variations in autonomy and interaction modality influence operator performance and mental workload. The model thus serves both as a conceptual framework for understanding assistance in human-centred manufacturing and as a practical tool for the design and evaluation of next-generation CASs.

Overall, this dissertation tries to advance the conceptual, methodological, and empirical understanding of CASs as integrative frameworks that combine digital guidance, human-centred interfaces, and collaborative robotics.