UNIVERSITATEA LUCIAN BLAGA DIN SIBIU

Doctoral School of Engineering and Mathematics

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DOCTORAL THESIS

ADVANCING DIGITAL TWIN TECHNOLOGY FOR INTELLIGENT INDUSTRIAL SYSTEMS

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SUMMARY

This thesis addresses multiple challenges in the rapidly evolving field of Digital Twin (DT) technology within intelligent industrial systems, particularly focusing on Industry 4.0 (I4.0) and the human-centric Industry 5.0 (I5.0) paradigms. Despite the growing importance of DTs, the field suffers from fragmented conceptual understanding, diverse architectural proposals, and a lack of standardization.

There are two primary objectives of this research: first, to develop a unified DT architecture that bridges existing models and accommodates varying maturity levels; and second, to demonstrate the practical applicability of this architecture through intelligent industrial applications. The research challenges key questions regarding the current state of DT architectures, the integration of Artificial Intelligence (AI), the inclusion of human operators within the DT context, the potential synergy between Multi-Agent Systems (MAS) and DTs, and the feasibility of developing DTs concurrently with or even before the physical system. The research presented in this thesis addresses these multifaceted challenges by setting the following two general objectives and five research questions:

- **O1**: Develop a unified DT architecture for intelligent industrial systems that bridges existing models.
- **O2**: Demonstrate practical intelligent industrial applications of the proposed DT architecture.

- **RQ1. What is the current state of the art of DT architecture?** Given the novelty of the DT domain, multiple DT models and architectures have emerged. Also, several frameworks and DT taxonomies have been proposed in the literature, providing a confusing understanding of the concept.
- **RQ2. How is AI integrated with DTs of industrial systems?** Manufacturing plants often have a diverse range of equipment and software systems, many of which were not designed to interoperate with modern AI platforms. Having access to both physical system and simulation environments, one related question would be on what data source to use to train the AI algorithms.
- **RQ3. How can humans be a part of the DT context?** In the setting of I5.0, where the operator is collaborating with the manufacturing system, its input and state should be included in the DT for a more comprehensive virtual representation.
- **RQ4. Can MAS and DTs technologies be combined?** While both have applications in industrial systems and similarities can be found between the two concepts – each physical *thing* has a corresponding agent or twin – the roles of each are different. This question explores how MAS and DTs can be integrated into a single system architecture.
- **RQ5. Can there be a DT before having a tangible physical system?** Being a relatively new research domain, most the DTs described in the literature are created

for existing physical objects, with some authors arguing that DT implementation and instantiation can be started only after having a physical system.

The original contributions of the thesis are distributed across four chapters, besides the thesis introduction in Chapter 1 that provides the research goals, research questions, and thesis structure, and the thesis conclusions in Chapter 6.

The first research question, RQ1, is pursued in Chapter 2. This chapter presents the concept of DT and how it evolved in literature in the last years. While the term was introduced more than two decades ago, only the last decade saw a big advance in this field due to the increasing technological capabilities and available computational power. Being a relatively new field from an industrial adoption and scientific popularity point of view, there is still a debate regarding a unified definition or architectural structure. After describing the concept as it was first envisioned in Section 2.1, the thesis explores the main misconceptions regarding different integration levels, definition, lifecycle integration and maturity levels in Section 2.2. Then, the current challenges of the DT domain are presented, followed by an analysis of several DT architectures found in the literature. It is identified that the current state-of-the-art DT architectures do not cover all the maturity levels, while being either too abstract or too concrete, specific to a single application or domain. Given the lack of standardization, Section 2.3 proposes a unified classification of DT integration levels, fulfilling O1. To cover the identified architectural gap, this section also presents a novel modular DT architecture that according to Section 2.4 is flexible enough to allow instantiation at several integration or maturity levels.

Aligning with the second thesis objective, O2, the proposed architecture is instantiated in three different intelligent industrial application domains in the next thesis chapters, covering the areas of interactive training for human-centric manufacturing, intelligent fleet management for a RMS, and renewable energy systems.

In Chapter 3, the proposed DT architecture is instantiated for a training station for manual assembling operations, developing towards O2 completion and providing answers to RQ2 and RQ3. This chapter details the challenge of how humans can be included in the DT context with a use case on a training station for manual assembly operations. Section 3.1 continues with an introduction in the I4.0 domain, highlighting the necessity of the DT in manual assembly systems. Section 3.2 provides a state-of-the-art of similar operator assistant systems and their DT application use case. The physical training station for manual assembling operations is also described. Next, Section 3.3 introduces the proposed architecture of the DT for manual assembly operations. Section 3.4 provides details about the software implementation and instantiation of the DT system, the proposed method of multimodal emotion fusion, and two approaches based on dynamic Bayesian networks and hybrid hidden Markov models for context-based predictors of the next assembly step. Section 3.5 summarizes the contributions and raises concerns regarding ethical AI usage.

Chapter 4 further progresses O2 by presenting a modular reconfigurable production system with multiple autonomous transporter units and the challenges of instantiating the proposed DT architecture, providing answers to RQ2 and RQ4. The chapter continues with Section 4.1 that provides an overview of the manufacturing challenges raised by the "lot size one" requirements, focusing on Reconfigurable Manufacturing System (RMS) and Autonomous Mobile Robots (AMR). Section 4.2 describes the reference architecture of such RMS and the physical characteristics of the RMS prototype. It provides a state-of-the-art on DT used as fleet management software, travel time estimation and missing sensor data imputation. Next, Section 4.3 describes the proposed DT architecture for the RMS and ARM fleet. This section also provides the software implementation details for the instantiated DT but also for the MAS used in controlling the RMS and AMR fleet. Section 4.4 explores the two DT application uses-cases, travel time estimation and sensor data imputation. A long short-term memory network is used for AMR travel time estimation, while algorithms like XGBoost and KNN are evaluated for missing LiDAR data imputation. Section 4.5 summarizes the main findings and contribution of this chapter.

Chapter 5 provides another instantiation of the proposed DT architecture for an industrial high-temperature heat upgrade system, fulfilling O2 and providing answers to RQ5. The focus of this chapter is on developing DTs as the physical system is built. The chapter continues with an introduction of the challenges raised by using renewable energy and waste heat capture systems in Section 5.1. Section 5.2 describes similar state-of-the-art approaches and results of applying the DT paradigm in industrial energy systems. It also provides a description of the twinned physical system. Further, the proposed DT architecture for the industrial high temperature heat upgrade system is detailed in Section 5.3. Instantiation and implementation details of the mathematical model of the system used in simulation, the data flow and process modelling of the system, together with a 3D simulator are provided in Section 5.4. While the current results are obtained on a small-scale laboratory test rig, the section also provides information on the two industrial use cases that are taken into consideration for further testing and validation. Section 5.5 concludes the chapter providing directions for future work on this use case as it is still under development.

Chapter 6 concludes the thesis, providing a discussion of the main contribution in Section 6.1 An explicit list of the original contributions linked with the thesis chapters and publications is provided in Section 6.2. Also, the thesis impact in terms of publications and citations is detailed in Section 6.3. The thesis ends with a discussion on identified limitations and possible future work.

Keywords: Digital Twin, Industry 4.0, Industry 5.0, Artificial Intelligence, Multi-Agent Systems, Reconfigurable Manufacturing System, Autonomous Mobile Robots

CONTENTS

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