Digital Thread in Smart Manufacturing

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Abstract. The concept of digital twins has emerged from the smart manufacturing space and is now gaining adoption in many other industries beyond manufacturing. A digital twin is a virtual replica of a cyber-physical system that is used to capture the state of the system and to allow reason and decision-making on that state. While there has been much research on this topic, there is less work on the overall lifecycle ecosystem that supports the smooth interoperation of a physical facility (like a machine, a factory or even a supply chain) and its digital components (like data, processes and digital twins), which is called the Digital Thread. The aim of the Digital Thread is the creation of a digital lifecycle ecosystem that links together the data generated throughout a product's lifecycle and represents the data, processes and communication platform that supports a product and its production at any instance of time.

1 Motivation and Goals

In order to realise the concept of a Digital Thread, a range of functions need to work together to allow for the integration and interoperability of physical and virtual representations of a product or process through the Digital Thread [7]. This takes the form of a "digital mesh" and/or open data spaces, that need to be managed, connected, protected, and shared. The research and innovation aspects around and within the digital thread span interdisciplinary topics including Internet of Things and Cyber-Physical System technologies, decentralised and edge computing architectures, Distributed Ledger Technologies (DLT), model driven development, low-code/no-code approaches, cybersecurity, trust and data management strategies.

Important in realising a Digital Thread in any organisation are testbeds and practical experience in collecting, processing and managing data, the integration of models and systems across heterogeneous technologies and paradigms [2,3,9], as well as the associated application development throughout a product lifecycle. In addition, novel mechanisms are required to enable the dynamic creation and adaptation of digital workflows [11] that leverage techniques such as containerisation and modular architectures that facilitate a secure and trustworthy Digital Thread for manufacturing applications [5,8].

T. Margaria and B. Steffen (Eds.): ISoLA 2022, LNCS 13704, pp. 179–183, 2022.
https://doi.org/10.1007/978-3-031-19762-8_12

The **Digital Thread in Smart Manufacturing** track originates from the collaboration of the organizers within the Confirm SFI Centre for Smart manufacturing[1]. It focuses on tools and methodologies that can drive the creation of a digital ecosystem that can form an integrated, open test and demonstration environment for industry and the broader research community.

The large scale adoption of Industry 4.0 has made modern manufacturing sites a rich source of data that can be leveraged to inform and improve decision-making at all levels in a complex manufacturing process. This data needs to be collected, processed and analysed to generate real-time insight that can be utilised to optimise operations, ensure efficiency, minimise costs and improve resilience of a manufacturing site. Despite the advantages of leveraging this data, often attempts to maximise the potential value can fall short due to additional constraints, such as complexity of integration, interoperability, privacy, security concerns and distributed data silos that are difficult to access and share. A recent white paper produced by PTC[2] conducted a survey with industry to analyse the current state of digital thread in industrial sectors. A number of pain points were highlighted, mainly oriented around the challenge with silo'd enterprise systems. These include (but not limited too) the inability of employees across different roles to leverage product data that can deliver value for customers; a disconnect between work streams and roles (e.g. planning, operations) that hinders collaboration and difficulty in getting access to data that can influence more effective decision-making to trigger improvements.

While Digital Thread aims to offer a solution to address these pain points, there remains some open research questions that demand further attention from the community:

1. **Application and infrastructure heterogeneity**: new methods that facilitate interoperability, portability, and integration across heterogeneous platforms and systems are required [4,6]. No code, low code development tools that combine formal model driven approaches are needed.
2. **Scalability**: the boundary between the physical and digital worlds is becoming increasingly blurred, solutions must be able to scale from low-end sensors to large data centres forming systems of systems with limited impact on performance.
3. **Orchestration and adaptation**: systems and services, particularly across heterogeneous compute infrastructure, are essential. Applications and platforms need to be easily re-configurable and have the capability to reside at the different tiers of IT infrastructures (edge-cloud continuum) [1].
4. **Testing and maintenance**: complex distributed systems require novel methods of testing, assurance and maintenance.
5. **Cyber-security and Privacy**: the convergence of IT and OT operations in manufacturing has raised many concerns surrounding the impact on the security of systems. The application and evaluation of emerging concepts

[1] See the Confirm website at https://confirm.ie.

[2] https://www.cimdata.com/images/PLMRoadMap/The-State-of-Digital-Thread-0721.pdf.

such as Zero Trust to address this is required. Scalable privacy preserving techniques are also required.

6. **Organizational Boundaries**: collaboration across industry sectors is viewed as a key component of smart and resilient manufacturing. As such, new mechanisms are required that provides incentives and trust assurance across independently operating entities and ecosystems [10] (e.g. embedding of governance policies in automated interactions and digital workflows).

The track presents a selection of papers that addresses aspects of the open research topics as discussed above. They include new architectures, models, techniques, and tools for the implementation of the Digital Thread. Particular emphasis is placed on the constraints, challenges and impact of achieving a digital thread in the smart manufacturing domain.

The included contributions provide a broad perspective on the current state-of-the-art in both Digital Thread and its role in the manufacturing domain. The research works propose solutions to address difficult problems relating to integration, interoperability, cyber-security, trust management, data-driven application development and systems modelling. The track offers an opportunity to discuss new ways in which we can leverage digital thread to tackle challenges of scalability, heterogeneity and interoperability in order to accelerate the development of adaptive, flexible and robust digital applications that are to become the digital fabric that binds the physical and virtual in factories of the future.

2 Overview of Contributions

In *Integrating Wearable and Camera based Monitoring in the Digital Twin for Safety Assessment in the Industry 4.0 Era* [2], the authors Michele Boldo, Nicola Bombieri, Stefano Centomo, Mirco De Marchi, Florenc Demrozi, Graziano Pravadelli, Davide Quaglia and Cristian Turetta propose an automatic system for monitoring individuals operating in an industrial environment. This information is utilised for mapping human actions to both the safety procedures and the behaviours of robotic systems that operate autonomously in the same environment. The authors leveraged federated Kafka instances as digital thread to integrate an edge based monitoring system with tools that create digital twins for risk assessment and prevention deployed on the cloud.

In *Model-driven Engineering in Digital Thread Platforms: A practical use case and future challenges* [3], the authors Hafiz Ahmad Awais Chaudhary, Ivan Guevara, Jobish John, Amandeep Singh, Amrita Ghosal, Dirk Pesch and Tiziana Margaria present a model-driven approach to the engineering of integrated Industrial Internet of Things (IIoT) applications covering a middleware for data acquisition from heterogeneous sensors, low-code platforms for analytics, process modelling and application development. The approach provides an abstraction layer for rapid prototyping and enable non-expert programmers to responsibly (through appropriate security measures) and directly participate in the software development cycle. The paper provides a practical use case in the context of Smart Manufacturing to demonstrate how a more efficient system construction and interoperability can be achieved using the proposed model-driven engineering approach.

In *Trust and Security Analyzer for Collaborative Digital Manufacturing Ecosystems* [5], the authors Pasindu Kuruppuarachchi, Susan Rea and Alan McGibney propose the development of a trust and security analyzer that can be utilised to provide assessment and assurance for integrating multiple digital twins that form a collaborative digital ecosystem in a smart manufacturing context. The focus is on providing a reference architecture to enable a holistic representation of trustworthiness across independently operated digital twins. By bootstrapping the digital thread with such an analyser aids in evaluating the security, resilience, reliability, uncertainty, dependability, and goal analysis of a collaborative ecosystem. A description of the initial implementation addressing security analysis of application programming interfaces (API) as data exchange end-points for digital twin integration is provided.

In *DISTiL: DIStributed Industrial Computing Environment for Trustworthy digiTaL workflows: A Design Perspective* [8], the authors Alan McGibney and Sourabh Bharti presents an initial analysis of the system requirements, architectural considerations, and challenges that need to be overcome to realise distributed and trusted digital workflows with a focus on use cases in the domain of smart manufacturing. The architecture outlines three tiers that constitute intelligent software agents that operate as Decentralised Autonomous Organisations (DOA) providing i) a distributed data layer, ii) trust overlay and ii) resource orchestration and provisioning.

In *Using Model Selection and Reduction to develop an empirical model to predict energy consumption of a CNC machine* [9], the authors Liam Morris, Andriy Hryshchenko, Rose Clancy, Dominic O'Sullivan and Ken Bruton provide an approach that leverages digital thread to feed a model development lifecyle to build an empirical energy consumption model of a CNC machine to predict energy consumption based on only product throughput in the absence of other features. An initial exploratory use case is provided which demonstrates a high accuracy of predictability that can be applied across other CNC machines or machining assets.

In *Crazy Nodes: Towards Ultimate Flexibility in Ubiquitous Big Data Stream Engineering, Visualisation, and Analytics, in Smart Factories* [11], the authors Mirco Soderi and John Breslin present a software framework, which allows users to remotely deploy, (re)configure, run, and monitor the most diverse software across all the three layers of the Smart Factory (edge, fog, Cloud) via API calls. This involves the integration of various software technologies, frameworks, and programming languages, including Node-RED, MQTT, Scala, Apache Spark, and Kafka. A proof-of-concept is provided where user interfaces and distributed systems are created from scratch via API calls to implement AI-based alerting systems and Big Data services (e.g. stream filtering and transformation, AI model training, visualization).

Acknowledgement. This project received funding from Science Foundation Ireland (SFI) under Grant Number 16/RC/3918 (CONFIRM Centre).

Finally, we would like to express our deep gratitude to the ISoLA organizers for their tenacious work to provide the infrastructure for our and other tracks, which allows engaging and creative discussions among researchers and practitioners across different communities, leading to new insights and perspectives of the techniques and foundations of design, analysis, implementation and testing for innovative and emerging applications.

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