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Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future

Proceedings of SOHOMA 2023

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ISSN 1860-949X ISSN 1860-9503 (electronic)
Studies in Computational Intelligence
ISBN 978-3-031-53444-7 ISBN 978-3-031-53445-4 (eBook)
<https://doi.org/10.1007/978-3-031-53445-4>

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Preface

This volume gathers the peer-reviewed papers presented at the 13th edition of the International Workshop on Service-oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future, SOHOMA'23, organized on 28–29 September 2023 by the SYstèmes et Matériaux pour la Mécatronique (SYMME) and LISTIC (Computer Science, Systems, Information and Knowledge Processing) Laboratories of the University Savoie Mont Blanc of Annecy in collaboration with University Politehnica of Bucharest (the CIMR Research Centre in Computer Integrated Manufacturing and Robotics), Polytechnic University Hauts-de-France (the LAMIH Laboratory of Industrial and Human Automation Control, Mechanical Engineering and Computer Science) and Polytechnic Institute of Bragança (the CeDRI Research Centre in Digitalization and Intelligent Robotics).

The main objective of SOHOMA workshops is to foster innovation in smart and sustainable manufacturing and logistics systems and in this context to promote concepts, methods and solutions for the digital transformation of manufacturing through virtualization, service orientation and agent-based control with distributed intelligence

The theme of the SOHOMA'23 Workshop is “**Sustainability for the digital manufacturing era**”.

In this edition, the workshop focused on how the technological enablers of digital systems can drive the *sustainability* for products, processes, manufacturing and logistics systems in the industry of the future.

Sustainability drivers refer specifically to the technological advances that motivate, encourage and engage the economic (Ec), social (S) and environmental (En) aspects within intelligent manufacturing and logistics systems. The workshop enabled a scientific debate centred on digital control technology and sustainability perspectives. It hosted presentations on innovation delivered by technology to ensure the achievement of the sustainable development goals (technology-centred). Also, it animated discussions about sustainability objectives, challenges and solutions in industry and services that can be solved by technology advances (sustainable-centred).

Two technical sessions grouping 12 scientific papers addressing assessment methods, performance, metrics and key performance indicators, technology, solutions and ethical aspects for sustainability have been organized: *Performance and Sustainability within the Industry 4.0 Context* and *Ethical and Sustainable Perspectives in Industrial Systems*.

In the presented research works, several ideas were approached, starting from the real challenges that manufacturing organizations are facing to reduce their environmental and social impacts while maintaining economic viability. To tackle these challenges, manufacturers are investigating how to minimize their impact on economy, society and environment and thus improve their sustainable performance. To achieve this objective, *sustainability assessment* is the first and most important step; its scope is to provide decision-makers with an evaluation of global to local integrated nature-society systems in short- and long-term perspectives, to assist them in determining which actions

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Collaboration and Self-organization to Enable Self-healing in Industrial Cyber-Physical Systems

Luis Piardi, Paulo Leitão, Pedro Costa and André Schneider de Oliveira

Abstract Fault tolerance (FT) is a critical aspect of industry, where systems are susceptible to disturbance and faults. Traditional FT models, based on the centralization of information to handle fault episodes, no longer meet the current industrial models based on Cyber-physical Systems (CPS). Self-healing is a promising approach for FT in CPS, consisting of the individual competence of each component in detect, diagnose and recover from failures. With this in mind, this paper discusses the engineering of self-healing fault-tolerance in industrial CPS, analyzing the maturation process of this paradigm from the local model through collaboration models and later to self-organization features. The paper also discusses the main research challenges that self-healing FT faces during this process.

1 Introduction

The emergence of new distributed and intelligent structures is being noticed to address the vital requirements of markets to manufacturing companies, namely demanding responsiveness, flexibility, and reconfigurability. Industry 4.0 [8] plays an

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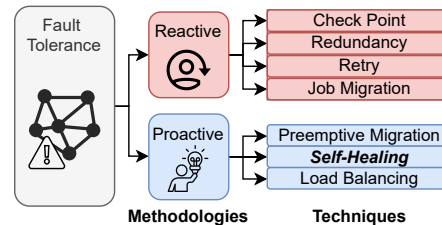
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important role in shaping the manufacturing field by defining design principles, technologies, and standards based on the decentralization of real-time decision-making, connectivity to share data, and advanced data analysis to improve the system's operation.

Industrial Cyber-Physical Systems (CPS) appear as a suitable infrastructure to deploy these Industry 4.0 compliant solutions based on a set of distributed and autonomous entities, combining cyber and physical counterparts, that may cooperate to reach the system's goals [11]. Besides the autonomy and distribution, these systems should exhibit unique characteristics that enhance their responsiveness, flexibility, robustness, and adaptability capabilities, mainly using pluggable and modular features. In this context, fault-tolerance (FT) is highly important since it enables the system to maintain the service quality even in the presence of disturbances [1], and must be considered in the deployment of CPS.

As illustrated in Fig. 1, FT can be conceptualized according to the different methodologies and relating them to resulting techniques. FT systems based on reactive methodologies are designed to mitigate the impact of the failure after the manifestation of a fault. Techniques related to this methodology, e.g., redundancy or job migration, are implemented to reduce the effect of undesired or disturbance events after their occurrence. On the other hand, the proactive methodology is mainly designed to predict the undesired or disturbed event before its occurrence. Techniques related to this methodology, e.g., preemptive migration and load balancing, aim to adapt the system before the fault to minimize the impact of failure [17].

Fig. 1 Overview of fault-tolerance methodologies and techniques.



Self-healing is a proactive FT technique that assumes a crucial role in CPS systems [9], aiming to improve the system reliability and resilience, being designed to self-detect, self-diagnosis and self-recover from failures and faults, and adapting the operation autonomously without the human intervention. For example, a communication network is self-healing if it can automatically reconfigure the routing after one of its nodes fails to continue performing the message delivery.

In this context, sensing techniques, Internet of Things (IoT), and Artificial Intelligence (AI) are crucial technologies to support the detection, diagnosis, and recovery, namely to implement advanced condition monitoring that can detect possible failures or performance degradation in advance. The research work in this field is widespread with the application of these emergent digital technologies to identify and predict failures, mainly aiming to improve such systems' resilience, robustness, and performance. However, industrial CPS are characterized by the distributed

nature of their structures, making collaboration an important characteristic for the overall system operation (that emerges from the interaction among distributed network nodes). This raises a question related to the pertinence of self-healing relying only on local mechanisms for detection, diagnosis, and recover or instead taking advantage of collaboration mechanisms presented in industrial CPS.

Additionally, and taking inspiration from nature, self-organization plays a crucial role in achieving more agile and adaptable systems, which is a process of evolution where the development of novel, complex structures takes place primarily through the system itself, being normally triggered by internal variation processes, which are usually called “fluctuations” or “forces” [10]. Self-organization principles can be found in several domains, such as biology, chemistry, physics, and social organization, and can contribute to enhancing robustness reconfigurability and plugability of complex systems [10, 4].

Having this in mind, this paper aims to discuss the engineering of self-healing fault-tolerance in industrial CPS, and particularly how self-healing systems can be improved with collaboration and self-organization features. For this purpose, after a brief literature review to understand the methodologies and technologies that impact self-healing, a discussion on the design principles that should be considered to enable self-healing in an industrial CPS will be derived. The idea is to build more intelligent, adaptive, and resilient systems considering Multi-agent Systems (MAS) technology as an infrastructure to support collaboration and self-organization and taking advantage of the insights from nature and biology, adapting them to the context and requirements imposed by industrial CPS and not simply copying them. Since the engineering of such systems is complex and challenging, the paper also analyses the research challenges to be considered in their development.

The rest of the paper is organized as follows: Section 2 characterizes self-healing CPS by performing a bibliometrics analysis, and Section 3 presents the design principles to enable the self-healing capabilities in industrial CPS, particularly addressing AI, collaboration and self-organization features. Section 4 analyses the research challenges that emerge when considering collaboration and self-organization to improve the system self-healing. Finally, Section 5 rounds up the paper with the conclusions and points out the future work.

2 Characterization of Self-healing Cyber-Physical Systems

Industrial CPS has received widespread attention from academia and industry due to its potential to address the increasing complexity in manufacturing systems by considering distributed systems that integrate cyber and physical components [11]. The analysis of how collaboration and self-organization extend and can contribute to enhancing self-healing in industrial CPS is essential to understand the level of adoption of these functionalities.

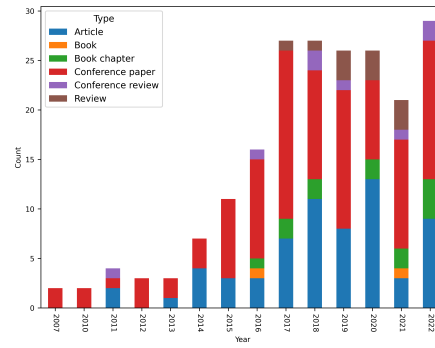
For this purpose, this section surveys the scientific papers, retrieved from the Scopus repository that refer to self-healing in industrial CPS in the title, abstract,

and keywords. The established search query combines self-healing and industrial CPS and their variants as follows:

```
TITLE-ABS-KEY ((selfhealing OR self-healing) AND
("cyber-physical systems" OR "cyber physical systems" OR
"cyber-physical production systems" OR "cyber physical
production systems"))
```

Applying the exclusion criteria, e.g., removing the note, editorial, and retracted articles, the retrieved dataset comprises 83 papers. Fig. 2 illustrates the evolution of scientific papers focusing on self-healing in industrial CPS over the years, having noticed continuous growth from 2007 to 2017 and a kind of stabilization in the last five years. The percentage of published articles in journals has also increased in the last period, indicating a certain level of maturation in adopting the self-healing concept in industrial CPS.

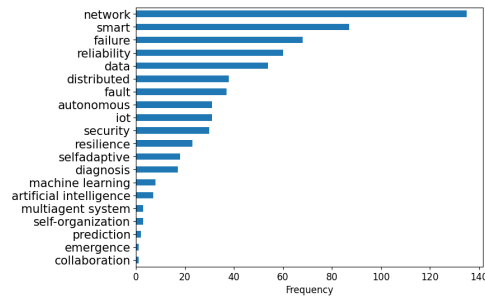
Fig. 2 Evolution of published scientific articles focusing self-healing in CPS over the time.



Analyzing the retrieved dataset, Fig. 3 illustrates the most important methods and technologies associated with the established search, using the n-grams, i.e., a combination of one, two or more words extracted from the papers' analysis using the NLTK python library. From the analysis of the results, it is clear that the main self-healing characteristics appear as significant frequency, namely *reliability*, *resilience*, *fault*, *failure*, *diagnosis* and *prediction*. *Collaboration* and their variants, particularly *network*, *distributed* and *autonomy*, assume a crucial relevance in self-healing CPS, taking advantage of the autonomous and distributed nature established by these systems. In the same manner, *self-organization*, *emergence*, and *self-adaptive* concepts also play a crucial role in developing these systems, but at the moment, with less relevance than the identified for distribution and collaboration concepts.

From a technological perspective, it is interesting to observe that *MAS* assumes a crucial relevance, possibly used as an infrastructure to develop these systems and distribute the intelligence capabilities among the networked nodes. In the same direction, *IoT* is already noticed as the preferable technology to support the collection of *data*, and *AI* and *machine learning* appear as relevant technologies to endow these systems with the capability for detection, diagnosis and recover from the occurrence of faults and failures through the descriptive, predictive and prescriptive

Fig. 3 Methods and technologies and associated to self-organized and self-healing CPS.



analysis of the collected data. Being CPS based on distributed nodes that exchange data, naturally *security* and privacy issues arise and need to be addressed [16].

The conducted analysis made clear the correlation between collaboration and self-organization with self-healing, a promising FT technique when considering distributed CPS with communication and autonomy characteristics, particularly addressing the different types of self-healing. On one side, collaboration and distribution contribute to the extrinsic type of self-healing, where there is a need for an external agent to detect and repair the damage, focusing more on detection and diagnosis phases [14]; on the other side, intelligence and self-organization contribute for the intrinsic type of self-healing, where there is not any need of an external agent to reconfigure the component operation or repair the damage, focusing more in the recover phase [2, 3].

3 Enabling Self-Healing by Collaboration and Self-Organization

This section establishes the main design principles to be considered during the engineering of self-healing industrial CPS, considering the literature review feedback and the insights offered by biology systems, where mechanisms are matured over millions of years. Fig. 4 establishes the self-healing fault-tolerance technological process in the context of CPS. The traditional FT model is built on monolithic and centralized features, where the detection and diagnosis are based on simple logic (e.g., Boolean logic) or statistical analysis (e.g., Nelson Rules). Recently, this paradigm has been improving, firstly through the application of AI-based data analysis algorithms at the individual level, and later through the distribution and collaboration of the data analysis, and through the dynamic self-organization of detection and diagnosis algorithms.

3.1 Individual Detection, Diagnosis and Recover

A self-healing technique comprises four phases: data collection, fault detection, diagnosis, and recovery. This means that each process or device implements these

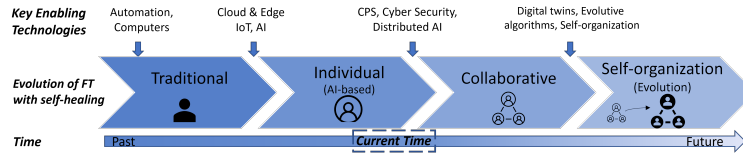


Fig. 4 Self-healing FT system referent phases with enabling technologies in CPS.

phases locally, particularly collecting, aggregating, and storing data related to its operation using IoT technologies, and should implement advanced data analytics, using AI algorithms, for the earlier detection of faults as well as to perform diagnosis and determine efficient actions to recover for the identified faults.

Statement 1 *AI algorithms should be used to support the early detection of failures and faults, as well as to elaborate more efficient diagnosis and determine more reliable recover actions.*

The implementation of these IoT and AI technologies is strongly connected to the condition monitoring and predictive maintenance approaches that are deserving a significant research currently, being the selection of IoT and AI techniques dependent of the application scenario and requirements.

3.2 Distribution and Autonomy to Enhance Collaboration

An industrial CPS is based on a network of cyber-physical components, where each one is capable to implement self-healing techniques (as referred in the previous subsection). The collaboration among distributed individuals can improve the detection and diagnosis of failures and faults, as well as the implementation of recover and mitigation actions. For example, the failures locally detected by individual mobile-robot is propagated to prevent others robots from using a congested route [14], or after detection individually at IoT devices, the data is sent to agents with more processing power to perform the diagnosis, e.g., to analyze and classify the fault [7].

Statement 2 *Collaboration models, e.g., implemented using MAS technology, allows to support a more efficient detection, diagnosis and recover of failures, and consequently improve the system reliability and resilience.*

Due to its inherent characteristics, MAS is a key enabler technology to support the engineering of such collaborative CPS [11], allowing the distribution of intelligence capabilities among networked nodes, each one being autonomous and cooperative, and possessing local knowledge and skills, and a local perspective of their surrounding environment, as illustrated in Fig. 5.

In such systems, the system behavior emerges from the cooperation among individual agents, with the decisions being taken in a decentralized manner, which

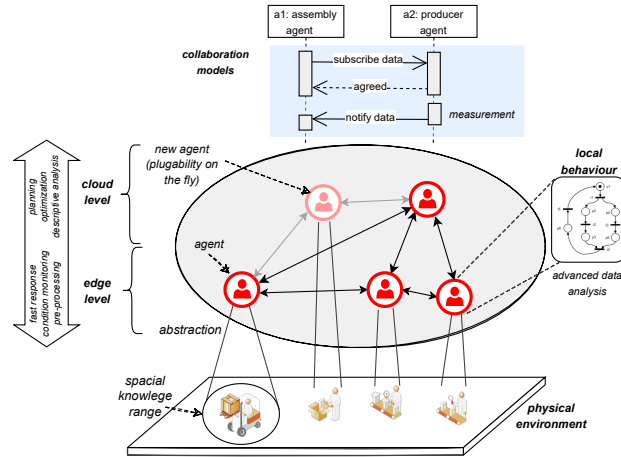


Fig. 5 Distributing intelligence capabilities along edge-cloud layers using MAS technology.

overcomes the typical problems exhibited by the traditional centralized, rigid, and monolithic control structures that are not anymore enough to address the current and robust requirements imposed to manufacturing systems. The decision capability, and particularly the self-healing process, appears at two levels. Firstly, autonomously with self-decision processes that should respond fast and efficiently to condition changes, as analyzed in the previous sub-section, and secondly, collaboratively with decision processes based on the interaction among these individuals through cooperation and negotiation. In this last approach, collaboration models that support the interaction among individual agents can contribute to detect and diagnosis failures faster and more effectively, highlighting the detection of non-observable failures at the individual level, the confirmation of diagnosis procedures, and the collaboration in implementing recovery actions. For example, in a distributed sensor network, if an individual node detects an abnormal situation and can not diagnose this occurrence alone, it can share this information with the neighboring nodes to determine the cause of the failure collaboratively and take corrective actions to mitigate its occurrence. In this approach, the learning models may be trained in a distributed way, where each agent obtains a unique parameterized model from its local dataset instead of centralizing the training and the dataset in a central server [13]. In the case of self-healing, AI models are dedicated to detecting and diagnosing operational failures in machines or processes and the collaboration between the agents supporting the exchange of AI algorithm parameters and operational data, locally and globally, improving the accuracy and efficiency of fault detection and diagnosis. Federated Learning and Swarm Learning deserve to be highlighted among the distributed learning techniques. In Federated Learning, the exchange of information and learning collaboration occurs at the model parameters level, maintaining data privacy [12]. In Swarm Learning, however, collaboration and interaction between

agents are inspired by the behavior of natural beings, such as bees, swarms of fish, and bacterial colonies.

Statement 3 *The intelligence and data analysis capabilities, implemented by using AI algorithms, should be distributed and balanced along the different computational layers from edge to cloud computing.*

At this point, it is important to reflect on the computational layers where agents and intelligence capabilities are deployed since different decision tasks may require, e.g., distinct response time and accuracy, and different intelligence algorithms may require different computational requirements. In fact, on one side, it is required to implement data analysis algorithms that can respond rapidly to condition changes by performing, e.g., condition monitoring, pre-processing and filtering. Traditionally, this type of algorithm should run at the edge computational level, i.e., close to the place where data is being generated, usually using AI models previously trained at the cloud level to address the constrained resource computational platforms at the edge level. Conversely, more powerful algorithms should be used to analyze the historical and real-time data to extract knowledge regarding diagnosis, optimization, and planning. This can be done by cloud computing, taking advantage of its powerful infrastructure in terms of memory and computation power resources. An example is to consider the Digital Twin approach, where the virtual/digital model of the CPS can be deeply analyzed by using simulation and/or AI techniques at the cloud to improve the operation of the real physical system.

3.3 Managing Emergence and Self-organization

Besides collaboration, industrial CPS can exhibit self-organization capabilities to face better condition changes. The inspiration from biology and social organizations can benefit in developing self-organized systems that evolve their structure and behavior facing the condition changes in the environment. ADACOR2 holonic architecture introduces self-organization and chaos principles to achieve a truly evolvable and reconfigurable system, combining two distinct evolutionary theories that offer insights for fast response to unexpected events [2]. The first theory was developed by Charles Darwin [5] and states that overtime species tend to make small internal changes to adapt to their environment. The second one is the punctuated equilibrium theory, which states that species tend to be in a stable state for long periods and suddenly make a drastic change [6]. A similar approach is found in genetics engineering, where genes define the boundaries for adaptation and control, and the metabolism defines/regulates the system behavior. In this case, the evolution can appear with the natural evolution of the genes (DNA mutations) that allow it to adapt to environmental changes over time. Since this evolution is very slow (e.g., the evolution of cells into molecular organisms takes thousands of years), evolution can occur by transmitting information from generation to generation (in the DNA), which speeds up the process.

Statement 4 *Self-organization, combining the continuous and smooth evolution and the disruptive improvement, can contribute to the system re-organization to compensate the lost functionality.*

In opposition to biology, where the evolution is a long and slow process, in industrial CPS, the time to evolve to condition changes is concise and these two components should be considered and properly balanced: the micro/local level responsible for the continuous improvement to face the external changes and the macro level responsible for boosting the disruptive adaptation to condition changes. In this context, individual agents or components interact with each other based on simple rules, leading to emergent behavior that can adapt to changing conditions. When a failure occurs in one individual agent or component, self-organization can contribute to the system re-organization aiming to compensate for the lost functionality or performance degradation without centralized control or intervention. For example, if a node fails in a wireless sensor network, the remaining nodes can re-organize to maintain the network connectivity and coverage.

In such dynamic and self-organized systems, some undesired instability due to nervousness may appear and should be considered since it may affect the system's performance and reliability. In this context, a system that is too calm to respond to perturbations is not precisely the best option, but one that is continuously reacting is also a bad option since it does not allow the stabilization of the newly designed conditions.

Statement 5 *The system balances its nervousness during the self-organization process, e.g., using AI techniques, being not highly nervous neither too calm facing condition changes.*

For this purpose, nervousness mechanisms must be adopted, e.g., AI techniques and stabilization mechanisms embedded in individual entities to avoid instability. An interesting approach is proposed by ADACOR2 that uses stabilizers based on the classical feedback control theory, namely the proportional, integrative, and derivative (PID) controller [3], where the integrative component aims to eliminate the steady state error by limiting the speed of response, and the derivative component aims to predict the future behavior of the error by increasing the speed of response. In such approach, AI can contribute to dynamically adjusting the integral, derivative, and proportional coefficients, allowing the system to adapt to environmental changes.

Using these stabilizers regulates the re-configuration frequency and response and defines the exploration thresholds, allowing the system to push to its limits but restricting its operation under control.

4 Research Challenges

As discussed in the previous sections, the reliability and resilience of a system can be strongly increased with the use of collaboration models and self-organization

capabilities associated with industrial CPS. However, to extract the entire potential from collaboration and self-organization capabilities, several research challenges arise and need to be addressed. Table 1 summarizes the key research challenges as clusters, taking inspiration from the works presented in [11] and [16].

Table 1 Main research challenges to develop self-healing FT in distributed industrial CPS.

Key topics	Research challenges
Engineering individual self-healing nodes	Efficient, reliable and real-time data acquisition, aggregation, and management
	Definition of the proper AI algorithms for predictive, prescriptive, and diagnostic analytics
	Optimization and AI-based data-driven systems; Industry-oriented integration with physical assets (cyber-physical integration)
Engineering self-healing systems based on collaboration and decentralization	Definition of collaborative AI models to support self-healing and consensus policies
	Balancing and managing the distribution of intelligence among edge-cloud layers
	Ensure security and data privacy mechanisms
	Definition of semantic data models for knowledge representation
Engineering self-healing systems based on emergence and self-organization	Support of data uncertainty, reliability, and inconsistency due to time and space myopia
	Industry-oriented communication for data exchanging (cyber-cyber interaction)
	Controlling the system's emergent behavior
	Definition of mechanisms that balances the continuous and disruptive evolution
	Definition of boundaries for autonomic and self-* features (e.g., healing and adaptation)
Infrastructures and methods	Control nervousness in self-organization processes
	Low cost and constrained computational platforms to embed AI algorithms
	Industry communication infrastructures for fast, scalable, robust, and overhead interactions
	Industry frameworks and testbed
	Standards compliance

In the engineering of individual self-healing components, the challenges are related to the development of individual capabilities and behavior of each component, namely the development of cyber and physical counterparts, including reliable and real-time data acquisition, aggregation, and management. Additionally, each node needs to incorporate ML algorithms based on data driven analysis that, in addition to their autonomous control, can execute the detection, diagnosis, prognostics, prediction, and recovery from failures [15].

The introduction of collaboration may positively impact resilience and the ability to detect and diagnose faults collaboratively. In this sense, for complex systems with a large number of components, it is challenging to ensure that the exchange of information takes place in a synchronized way. Individual nodes can suffer myopia, i.e., lack of information, since any decision is based on incomplete and even, at some point, inaccurate information. In addition, AI models face the challenge of being collaborative, that is, each component has its model locally but can request collaboration from other nodes to analyze data when there is uncertainty in the inference or an outdated local model. To improve the achieved collaborative decisions, consensus policies are needed to remove outliers, outdated models, or disconnected results from the application context. Therefore, the collaboration methodology must be generic, serving as a standard to be followed by other systems, which will specify, by the designer or developer, the AI algorithms according to the case study [16]. Furthermore, considering the demand for communication and processing resources for collaboration in self-healing systems, an optimized balance in the deployment of

edge or cloud computational layers should be considered in terms of communication and response time as well as processing power, resulting in improved performance.

The engineering of self-healing systems based on self-organization features requires the development of mechanisms that allow the emergence of properties that improve the system behavior and, simultaneously banish new harmful behaviors that may arise in collaboration between individual nodes. Additionally, it requires the definition of mechanisms that balance the continuous evolution with the disruptive evolution and control the system's nervousness. Another important aspect involves the establishment of boundaries for the autonomic and self-* features, e.g., self-healing and self-adaptation, empowering the system to reach its maximum potential while safeguarding against the violation of behavioral limitations.

To support the development of these innovative self-healing FT systems, Implementing AI algorithms on low-cost devices with constrained resources, e.g., computational power and memory, is currently challenging. These devices are widely deployed at the edge layer and need to support 5G communication technology for fast response, supporting collaboration, and self-organization aiming the fault detection and diagnosis. Additionally, frameworks and testbeds of distributed scenarios are required to validate and accelerate knowledge transfer to the industrial environment. Additionally, it is important to notice the relevance of developing solutions that are compliant with industrial standards, ensuring a wider adoption, e.g., OPC-UA for connectivity and AutomationML for the data models. The maturity in these points will pave the way for interoperability between assets with support for decisions, facing data uncertainty, inconsistency, and incompleteness [11].

5 Conclusions

The paper discussed the engineering of self-healing FT in industrial CPS, particularly the contribution of collaboration and self-organization features, usually presented in these systems, to enhance the systems' resilience and reliability. For this purpose, an analysis and reflection on the current research work in the field was performed, pointing out some design principles that should be considered to increase the system's self-healing. As conclusion, currently, self-healing FT systems are centered on using AI data-driven systems embedded in individual components to perform, e.g., condition monitoring. The following stages of such systems rely on using collaboration models, among these AI-based models, e.g., considering MAS technology and further applying self-organization capabilities to achieve more robust and reliable systems.

Since collaboration and self-organization, besides the identified benefits, also introduce research challenges in the engineering of industrial CPS, the paper also discussed four clusters of challenges that should be considered by practitioners, architects, and system integrators.

Future work will be devoted to developing a collaborative self-healing industrial CPS that considers this paper's design principles, focusing on the distribution of in-

telligence using MAS technology to implement more robust and efficient detection and diagnosis algorithms. This approach will be tested in an industrial case study related to a smart automatic logistics warehouse.

Acknowledgements This work has been supported by the Foundation for Science and Technology (FCT, Portugal) through national funds FCT/MCTES (PIDDAC) to CeDRI (UIDB/05757/2020 and UIDP/05757/2020) and SusTEC (LA/P/0007/2021). The author Luis Piardi thanks the Fundação para a Ciência e Tecnologia (FCT), Portugal for the PhD Grant UI/BD/151286/2021.

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