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Grand challenges in industrial informatics

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Introduction

Industrial Informatics has been a key enabler and even a main inducer of novel developments in industrial engineering along the last decade. This relevant role has become more visible in the context of the ongoing digital transformation processes, triggered by the Industry 4.0 "movement."

The so-called fourth industrial revolution is, in fact, the result of a convergence and integration of multiple information and communication technologies (Camarinha-Matos et al., 2019) (Zheng et al., 2021) (Alexa et al., 2022). Although initially focused on the integration of the cyber and physical worlds, as reflected in the terms "Cyber-Physical Systems" and "Internet of Things", soon the idea was gradually expanded by the addition of "smartness"/"intelligence" facets, as reflected in the terms "smart devices", "smart sensors", "smart machines", "smart systems", and "smart factories". As Industry 4.0 became a kind of buzzword, with strong political support worldwide, several other technologies, often branded as "exponential technologies", and including intelligent robotics, artificial intelligence/machine learning, nanotechnologies, neuro-technologies, sensing and perception, additive manufacturing/3D printing, mobile computing, etc., joined the movement and helped create momentum driving significant industrial transformation and even revitalization.

More recent research agendas, as the European Commission's Industry 5.0 (Breque et al., 2021) (Maddikunta et al., 2022) and Society 5.0 (Broeckaert, 2022) (Deguchi et al., 2020), in addition to a greater emphasis on smartness/artificial intelligence, put the need to consider sustainability and human-centricity aspects more clearly on the table. This is also well aligned with the "UN Agenda 2030 for sustainable development" (Division for Sustainable Development Goals (DSDG), 2015).

The field of Industrial Informatics is thus called upon to move from a purely techno-centric perspective, which mainly characterized Industry 4.0, to a more general perspective in which general societal concerns and human-centric developments are required.

Integration and complexity

A typical characteristic of advanced industrial informatics systems is that they increasingly require the integration of multiple technologies that are at different stages of maturity and have different life cycles. This heterogeneity, as well as the need to keep systems running while they are renewed due to continuous technological innovation, raises the level of interoperability challenges.

Moreover, as we move to higher levels of interconnected systems with increasing degrees of autonomy, often originating from different vendors, it leads to increasing complexity. Understanding the behavior of such systems and properly monitoring their health, or even determining who is responsible when something goes wrong, are of paramount importance (Osorio et al., 2020).

In parallel, and as part of the effort to free oneself from vendor lock-in situations, there is a growing concern to achieve greater technological sovereignty.

Collaborative networks

In the last years, collaborative networks have been identified as a key pillar in digitalization/digital transformation and a fundamental basis for addressing the holistic vision of Industry 4.0 (Camarinha-Matos et al., 2019). This role is not confined to the obvious case of the supply networks or horizontal integration dimension of Industry 4.0, but it is present in all its dimensions. For instance, in terms of "vertical integration", as sub-systems become smarter and capable of increased autonomy, more than integration we need to see an industrial company as a network of smart and partially autonomous elements that need to collaborate to effectively achieve company's goals. The "horizontal integration" dimension naturally involves networking through the entire value chain of suppliers, partners, and customers, for which collaborative networks models have been extensively explored. In terms of "end-to-end engineering", which focuses on integrating all engineering activities related to the whole life cycle of products, we need collaboration internal to the company (among different departments, i.e., revisiting the old notion of concurrent engineering), but also collaboration with external stakeholders and customers (e.g., co-design/co-creation), regulators, etc. The dimension of "acceleration of manufacturing", typically related to the optimization of the entire value chain through the integration of "exponential technologies", also requires new collaboration models not only to integrate such technologies but also to accommodate new stakeholders that were not partners in traditional industrial sectors. The dimension of "digitalization of products and services" not only focuses on the creation of digital product models but also covers the notions of "smart products" and "service-enhanced products"/"product-service systems", which again require collaboration among multiple stakeholders, namely for the provision of integrated business services along the whole product life cycle. Finally, the innovation induced by digitalization also triggers the development of "new business models" that take advantage of or are enabled by the networking and exploitation of data-rich contexts.

The new facets emphasized by Industry 5.0 related to sustainability, resilience, and human-centric systems, also demand for collaboration among multiple entities. All of these requires advances in collaboration models, including "long-term strategic networks" and a growing variety of "dynamic goal-oriented networks", collaboration platforms and tools, new governance models, new cognitive models, new engineering methods, and new business models. One of the side effects of the COVID-19 pandemic was in fact the growing awareness for the possibilities of virtual collaboration through ICT platforms and the fast-evolving market of new collaboration platforms.

Cyber security

As industrial systems become more and more cyber-physical systems with increasing levels of interconnectivity, namely through the Internet, cybersecurity concerns become of paramount importance. Security issues are not new and have been on the IT agenda for a few decades now. But when we focus on the convergence between the cyber and physical worlds, new challenges arise.

Many physical processes are performed using small devices (sensors, actuators) with only limited computational capabilities, often based on commercial off-the-shelf components with very limited protection against attacks. In fact, cyber-attacks can occur at various levels, for example, physical (sensors, actuators) and edge layer, communication layer, and application layer. In addition to unauthorized access to data from sensors and other physical systems, the possibility of having unauthorized access to actuators/machines can lead to significant damage in the physical world. On the other hand, protection measures, if not properly designed, can affect the real-time responsiveness of systems.

Beyond the usual security objectives in traditional IT—confidentiality, integrity, availability—which are often too "data-driven", we need to extend access control policies to physical devices and permitted action/command patterns, which also requires more attention to the authenticity of the involved parties (Ashibani, Mahmoud, 2017).

Furthermore, since systems can be made up of different components, even from different vendors, and can be replaced by other components, we also need to consider potential "insider attacks."

Sustainability, resilience and multi-disciplinarity

Industrial informatics needs to be aligned with and support major societal challenges such as sustainability. Current developments in the areas of "sustainable production" (Machado et al., 2020), "industrial symbiosis" (Baldassarre et al., 2019), and "circular economy" (Pomponi, Moncaster, 2017) require new integration processes and supporting tools. As these processes involve multiple stakeholders, in addition to appropriate collaboration and business models, it is necessary to determine how to distribute responsibility for the various dimensions of sustainability among these stakeholders. This also requires the development of sustainability-focused performance indicators and the implementation of data collection methods for the metrics involved (Camarinha-Matos et al., 2021) (Zhang et al., 2021) (Camarinha-Matos et al., 2022).

Additionally, industrial systems are increasingly exposed to a variety of disruptive events that can severely affect their functioning and that appear to be increasing in frequency and harmful effects. Such events may result from factors such as natural disasters, terrorism, wars and political instability, climate change, pandemic situations, demographic changes, etc., (Ramezani & Camarinha-Matos 2019). This requires new models and tools to support resilience, transformative resilience (Dahlberg 2015), and antifragility (Taleb 2012).

All these aspects clearly require a multi-disciplinary approach.

Moreover, effective solutions to the faced challenges cannot be exclusively techno-centric, requiring consideration of socio-organizational aspects as well. This is evident in the notions of business ecosystem, emerging behaviors in communities of autonomous systems, governance aspects, human-machine/human-systems collaboration, or the human-centric vision introduced by Industry 5.0 and Society 5.0. As such, old concepts like anthropocentric manufacturing systems and balanced automation systems need to be revisited.

Main topics

In order to address the next generation of Industrial Informatics systems and effectively address the mentioned challenges, the following non-exclusive list of topics are suggested:

- *Cyber-Physical Systems.* Including Cognitive and Collaborative CPS, Industrial Internet of Things, Real-time Systems, and their architectures and support platforms.
- *Industrial Collaborative Networks.* Including Collaborative Manufacturing, Collaborative Supply Chains, Collaborative Logistics, Collaborative Digital Ecosystems, Collaborative Robotics, Digitalization and Virtualization.
- *Smart Systems and AI.* Including Smart Manufacturing, Smart Robotics, Smart Products, Smart Energy Systems, Applied AI and Machine Learning, Intelligent and Distributed Automation, Uncertainty and Decision Support in Industrial Systems, Process Modeling, Supervision, Scheduling, and Optimization.
- *Human-Machine Collaboration.* Including Novel HMI, Anthropocentric Systems, Balanced Automation Systems.
- *Sensing and Data-rich Environments.* Including Advanced Sensorial Systems and Intelligent Perception, Big Data and Data Analytics in Industry.
- *Cyber Security in Industry.* Including Analysis and Assessment, Architectures and Techniques.
- *Interoperability and Systems Integration.* Including Semantic Models, Architectures, and Standards.
- *Agility, Resilience and Antifragility.* Including Intelligent Supervision, Risk Management, and Handling uncertainty and disruptive events.

Preventing the hype effects

As new technologies emerge and climb the ramp of inflated expectations (as in Gartner's hype cycle), they tend to exert a tremendous attraction factor. Many researchers try to "join the movement", which is natural, but in some cases, we notice a misuse of concepts and techniques just to ride the "fashion wave". One example happens with blockchain where many researchers try to use this technology, without assessing its full implications, to solve security issues that could often be addressed with simpler techniques.

We can also often notice that some subfields superimpose themselves on the main scientific area to which they belong. This is the case, for example, with Machine Learning or even Deep Learning which is sometimes taken as the complete AI. Another problematic example comes from the application of cloud computing to manufacturing systems, which some researchers have shortened to "cloud manufacturing". Despite the merit of being a simple term, it could be misinterpreted as "fabrication of clouds" and perhaps a better name might be "cloud-based manufacturing."

Although Industrial Informatics has a strong "applied research" flavor, and often the effort is in applying existing computer science models, tools, and methods to industrial problems, it is important to reflect a clear understanding of the semantics and ontological characteristics of these concepts, tools, and methods.

Conclusion

Relevant research contributions to Industrial Informatics need to be positioned in the context of the mentioned grand challenges, should reflect a sound research method, and present novel contributions preferably of a multi-disciplinary nature. The proposed contributions should also have a clear focus on industrial application, while reflecting a rigorous conceptual framework and an effort to discuss the results in terms of their limits and potential generalizability Zhang et al., 2019.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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