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Implications of Technological Progress on UAS Configuration Architectures in the Context of Industry 4.0

Cosmin-Alin MIRCEA
Transilvania University of Brasov, Romania, cosmin.mircea@unitbv.ro

Abstract
It is undeniable how the technology within Industry 4.0 has progressed, especially in recent years, mainly due to the global geopolitical situation. Unmanned Aerial Systems (UAS), as part of the ecosystem of the modern industrial revolution, have experienced accelerated development and increasing use in both the civil and military fields. These developments have integrated very effectively with the low-cost version of these systems, making them very reliable and convenient means for mass production. In the current context, drone systems must be able to support increased autonomy, interoperability and resilience. This paper explores the impact of Industry 4.0 technological advances on UAS configuration architectures. The study highlights how these technologies enable more flexible mission planning and operations involving drone swarms. In addition, it discusses the challenges related to standardization, cybersecurity and energy efficiency that arise when integrating UAS into industry ecosystems. Findings from the Russian-Ukrainian conflict suggest that military technological advances directly influence how UAS are designed and used. This research will highlight the trends and future directions in which Industry 4.0 technology fits.

Keywords
Unmanned Aerial Systems (UAS), Industry 4.0, Architectures, Machine Learning, Artificial Intelligence

1. Introduction

At the beginning of the second decade of the 21st century, the idea of the Fourth Industrial Revolution emerged in Germany, with the idea of creating a world in which virtual and physical systems of manufacturing globally cooperate with each other in a flexible way. This enables the absolute customization of products and the creation of new operating models [1]. The concept of "Industry 4.0" was presented by the German government as a development program in 2011. Similar programs can be identified in other geographical areas in and outside Europe: the "new industrial France" in France, the "Advanced Manufacturing Partnership Project (AMP)" in the USA, "The Revival Strategy" in Japan and "Made in China 2025" in China. Their aim is to make a common front for the adoption of a new industrial paradigm that embraces a set of technological developments both recent and future.

Today's industry focuses on smart factories that integrate cybernetic systems, the concept of the Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), machine learning (ML) and cognitive computing. Furthermore, Industry 4.0 improves operational and strategic decision-making for businesses by introducing real-time data analysis and flexible manufacturing processes. The widespread installation of sensors in physical objects due to their greater afford-ability and the integration of Information and Communication Technologies (ICTs) into industrial settings have made this change possible [2]. Within Industry 4.0, which integrates the technologies mentioned above, there is also an emerging component with a key role: UAS. While the aerial platform can be viewed simply as an autonomous aerial vehicle (UAV), the entire system represents an intelligent node in an interconnected digital ecosystem. A drone can collect and transmit data in real time, can be integrated into distributed sensor networks and interact directly with AI-based analysis platforms. In this way, they contribute to the transformation of industrial, agricultural, logistics or security processes, being a reliable part of the Industry 4.0 paradigm, as autonomous robots (Figure 1).

The contemporary geopolitical landscape, particularly the Russo-Ukrainian conflict, has been a powerful driver of innovation and accelerated deployment of UAS. The diverse application of drones – from cost-effective commercial models to advanced military platforms – has spotlighted not only the disruptive potential, but also the considerable challenges of UAS integration. These developments demonstrate that the rapid technological advancements associated with Industry 4.0 play a pivotal role in the evolution of drone systems configuration architectures, with specific implications for modularity, interoperability and operational resilience in contested settings such as military conflicts.

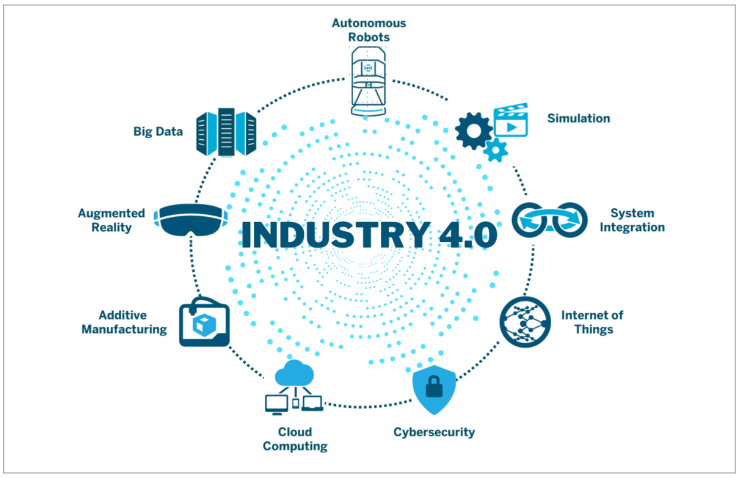

Fig. 1. Industry 4.0 technologies [3]

The objective of this article is to provide a comprehensive review of how technological progress within Industry 4.0 impacts the configuration architectures of UAS.

The paper is structured as it follows: Introduction, Literature Review, Methodology, UAS Configuration Architectures - Current state and trends, Implications of Technological Progress, Challenges and Future Research Directions - and Conclusions.

The research contributes to the understanding of the opportunities and challenges related to autonomy, standardization, cybersecurity and energy efficiency of future UAS designs.

2. Literature Review

Previous industrial revolutions made mass production possible and provided digital conveniences; the fourth industrial revolution or Industry 4.0 came with the transformation of networks, platforms and digital technology, with sometimes dramatic consequences on society, such as digital industrial ecosystems.

According to a qualitative study on a model for architecting Industry 4.0 systems, it is observed that some attributes related to Industry 4.0 are reliability, scalability, interoperability, security and safety, etc. [4, 5]. These aspects will also be analyzed in this paper.

Beyond the general social implications, Industry 4.0 technologies also reshape specific domains such as the military field.

In the military field, Industry 4.0 has an evolutionary character due to the integration of IT equipment with sensors and mobility. The technologies associated with Industry 4.0 also have consequences for the future wars, through the large-scale use of the following components: artificial intelligence (AI), the Internet of Things, new generations of robots, Big Data, synthetic biology, quantum computing, neuromorphic technologies, nanotechnologies, etc. [6].

Within the Sustainable Development Goals (SDGs), autonomous Robots, as part of the Fourth Industrial Revolution, have demonstrated indirect positive effects on the SDGs. They have an average score ranging from -0.1 for reduced inequality (SDG 10) to 2.38 for industry, for its influence on SDG 9 (industry, innovation and infrastructure). Autonomous robots are well known for their ability to develop good quality, reliable and sustainable infrastructure [2]. The technological advancement of UAS is not limited to industry, but also has socio-economic and sustainability implications.

The transformative impact of AI and data analytics is not limited to defence or socio-economic aspects. Similar trends can be observed in other industries, such as pharmaceutical analysis. Recent work in this field demonstrates just how significant the integration of data analytics and artificial intelligence can be [7]. It improves the accuracy, operational efficiency [5] and regulatory compliance.

By analogy, within the realm of UAS and Industry 4.0, these technologies form the backbone for intelligent decision-making, predictive analytics and the development of adaptive system architectures.

Building on these cross-domain insights, UAS architectures in particular are strongly shaped by advanced AI methods such as reinforcement learning (RL) and convolutional neural networks (CNN). Essentially, this branch of machine learning – RL – operates by training systems through a process of virtual rewards and penalties. Notably, Google DeepMind has leveraged reinforcement learning to create AI systems capable of outperforming human experts in both video games and strategic board games like Go, a milestone once considered out of reach for machines [8]. Also, recent developments show that decision-making in multi-UAV systems can be significantly enhanced through hierarchical reinforcement learning [9].

Regarding the swarm concept of the UAVs, a study that addresses the visual challenges specific to the maritime environment (e.g., water reflections) and irregular target movements demonstrates that convolutional neural networks (CNN) can be used by a UAV swarm to successfully track certain targets [10, 11].

Another study emphasizes that integrating drones and the Internet of Drones (IoD) into manufacturing is not merely a sign of technological progress, but also presents a complex set of challenges. Their research identifies twenty distinct obstacles, which they organize into six categories: safety and human resources, communication and technology, financial and operational concerns, legislative and risk issues, social and regulatory factors, as well as payload capacity and battery limitations. To analyse these barriers, they employ Exploratory Factor Analysis (EFA) and further prioritize them using the Analytic Hierarchy Process (AHP) [12]. This work stands out by emphasizing that the adoption of drone technology in Industry 4.0 is not just a matter of technical capability or innovation; it also depends on navigating regulatory, organizational and economic constraints, all of which can significantly impact implementation.

Furthermore, in terms of architectures, according to a recent review on Industry 4.0, the transition from the traditional hierarchical automation pyramid towards decentralized and functional architectures is reshaping the design of both hardware and software in industrial automation and supervision systems. This trend illustrates how Industry 4.0 and IIoT paradigms directly influence system architectures, a perspective highly relevant for understanding the reconfiguration of UAS within smart industrial environments [13].

The paper "*Exploring Contributions of Drones Towards Industry 4.0*" identifies 19 major applications of drones in Industry 4.0, highlighting their role in automating and optimizing industrial processes. An example is the use of thermal sensors mounted on drones, capable of detecting abnormal heat levels and intervening automatically, alerting authorities in critical situations [14].

To sum up, the reviewed literature demonstrates that Industry 4.0 technologies are profoundly reshaping UAS by influencing both their technical architectures and their broader socio-economic impact. From the shift towards decentralized and interoperable system designs, to the integration of AI, Big Data, IoT and advanced robotics, these technologies provide the foundation for adaptive, scalable and intelligent UAS configurations. Moreover, research highlights that the benefits of drones extend beyond industrial automation to sustainability goals and military applications, further underlining their transformative role. Overall, the literature suggests that the future development of UAS architectures in the context of Industry 4.0 will depend on balancing technological innovation with the resolution of regulatory, economic and operational challenges.

3. Methodology

The research paper has a qualitative character due to its focus on the analysis of the recent specialized literature – both scientific papers and books – and architectures in order to discover new perspectives regarding the implications that technological progress has on the configuration architecture of UAS.

The objective of the research is the generation of new theoretical knowledge and the establishment of a framework that also incorporates the influence that, for instance, modern warfare has on technological progress. Therefore, the research question can be formulated as follows: *How do core*

Industry 4.0 technologies (IoT, AI, Big Data, Digital Twins and Cloud/Edge Computing) influence the configuration architectures of unmanned aerial systems?

Furthermore, in order to observe the research trends and directions of various authors in the field, the data collection method was represented by documentary analysis, which involved gathering data and extracting pertinent information from various sources. One method of qualitative analysis that was employed was thematic analysis. Also, it is similar with the research method described in [4], where Google Scholar was used to find evidence about the subject.

By identifying the challenges of standardisation, cybersecurity and energy efficiency, this paper outlines the research gaps and provides future direction for both theoretical and practical approaches regarding the usage of UAS. In this way the paper helps to understand UAS as part of the Industry 4.0 and provides a foundation for more adaptive and intelligent system architectures.

Limitations include the fact that the literature review is based primarily on civilian literature and public sources, rather than classified military sources. Also, focusing on recent sources in the specialized literature may mean missing essential foundations that appear in older works.

Last but not least, the rapid nature of innovation could imply that the conclusions of research in this field may be outdated at any time.

4. UAS Configuration Architectures

The configuration architecture of an UAS involves a set of elements that define the system, which are interconnected with each other (Figure 2). In other words, those architectures define how the parts of an unmanned aerial system are built, connected and work together. This includes hardware and software dimensions, which can have a modular perspective characterized by adaptability.

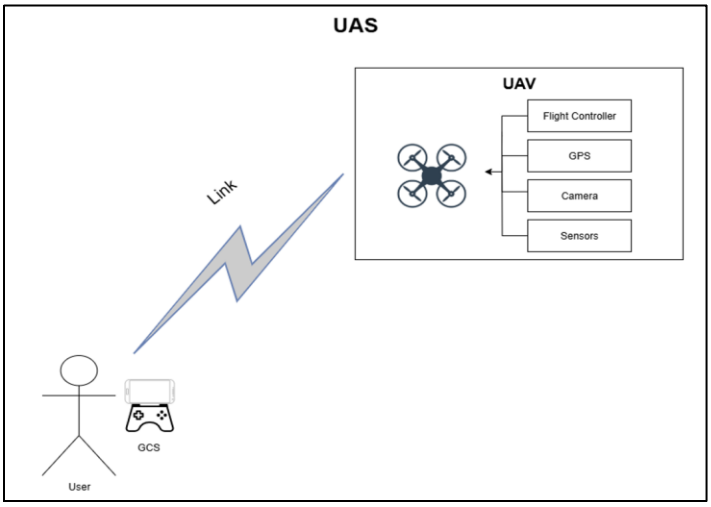

Fig. 2. Basic UAS architecture configuration with low-cost devices [15]

4.1. Current state and trends

A well-defined and modern configuration architecture ensures scalability, interoperability and resilience, enabling UAS to develop into versatile nodes within Industry 4.0 ecosystems, having multiple purposes.

In this context, configuration architectures serve not only as technical blueprints but also as a way to shape the adaptability and effectiveness of UAS in both the civil and military domains.

Current trends in drones include increased autonomy, integration of powerful sensors, possibility of deployment in swarm operations and interoperability in various situations. It can also be observed that most UAVs are low-cost, used even in the military environment, due to their increased efficiency and reliability, as well as their ability to support artificial intelligence.

Due to the integration of AI into their software architecture, an increase in their applications as swarms can be observed, where drones are interconnected with each other and share the same common operational picture (COP) (Figure 3).

Fig. 3. Drone Swarm powered by advanced AI [16]

In support of demonstrating technological progress in UAS, the authors of the article [17] have developed a system, called T-STAR (Time-optimal Swarm TrAjectory planner) that allows drone swarms to move with greater speed and accuracy, with unprecedented precision, even in environments with obstacles.

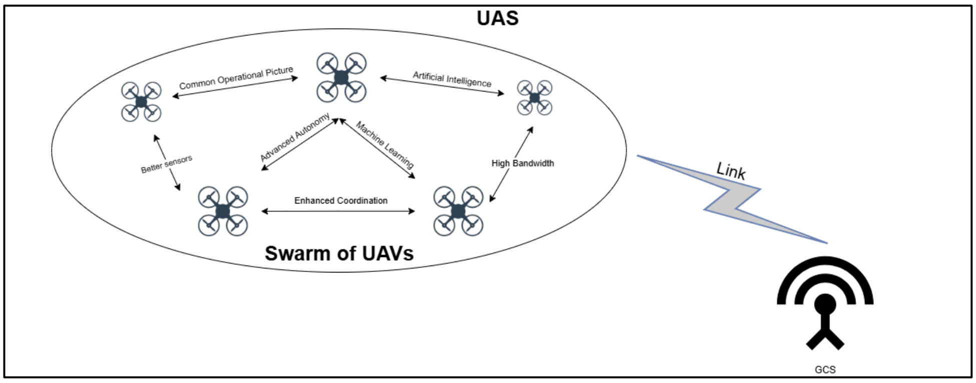

Fig. 4. UAS improvements in the context of swarms [18]

4.2. Implications of Technological Progress

The implications of technological progress on UAS are countless. Table 1 presents some of the aspects that have evolved from the early stages to the current performances.

Table 1. Differences between the early configuration architectures of UAS and the modern stages

Aspects	Early stages	Contemporary stages
Hardware–software integration level	• Poorly integrated • Limited functions • No AI • Basic sensors	• Deeply integrated in a modular and distributed architecture • Incorporation of middleware (e.g. ROS 2, DDS) are used for interoperability • AI/ML is included
Degree of autonomy	• Minimal • Manual piloting	• Advanced autonomy (GPS/IMU navigation, obstacle avoidance, swarm intelligence, object recognition)
Modularity and scalability	• Fixed platforms • Specific payload • Hardware-dependent	• Modular payloads (multispectral cameras, LiDAR, thermal sensors, 4G/5G/satellite communication kits). • Adaptation to different missions • Interoperability
Communication and networks	• Simple radio links • Distance limitations • Bandwidth limitations	• Complex networks (4G/5G, Satcom, mesh networking for swarms) • Encrypted and redundant links

Integration into the Industry 4.0 ecosystem	• Isolated systems, • Used on ad hoc basis (e.g. aerial filming, basic military reconnaissance)	• Intelligent nodes in Industry 4.0 networks • Connected to IoT, cloud, big data and digital twins • Capable of sending data to larger infrastructures
Safety and security	• Minimal • No encryption • No jamming protection • Risk of hacking	• End-to-end encryption • Jamming resilience • Communication redundancy • Standardized protocols

All of these advances have been made possible by the development of artificial intelligence and technologies and have been motivated by economic and industrial factors, along with the realization of the usefulness of these systems. However, a major factor that has contributed to the rapidity with which these technologies have developed is armed conflicts.

The following case illustrates one way in which technology can progress.

Ukraine has begun mass production of the single-use drone (DIU) Batyar developed by the company DeepStrikeTech. Batyar is powered by a gasoline engine, has an own mass of 60 kg, a payload mass of 18 kg and a maximum range of up to 800 km. The system has an inertial navigation system, EO sensors and a CRPA (Controlled Reception Pattern Antenna) antenna [19].

According to representatives of the Ukrainian company, the CRPA antennas mounted on the Batyar models are from the composition of the Kometa navigation modules recovered from captured Russian drones. This fact illustrates how technological advancement can be significantly facilitated through the strategic reuse and integration of sophisticated components sourced from adversary systems. This approach not only highlights adaptability but also underscores a pragmatic form of innovation within the field of drone development.

4.3. Challenges and Future Research Directions

While Unmanned Aerial Systems have made notable strides within the context of Industry 4.0, significant obstacles still persist, hindering their widespread integration and consistent operational reliability.

Firstly, as a consequence of having various platforms and manufacturers which produce different types of unmanned aerial devices, the communication protocols and policies regarding the software architecture might obstruct the interoperability between the UAVs and the GCS.

Furthermore, while the drone swarm is a useful concept and has achieved considerable performance, they are still vulnerable to jamming or GPS spoofing aimed at disrupting the communication links between the airborne devices and the ground control station.

Energy efficiency also remains a pressing issue, as current battery technologies do not yet provide UAVs the best endurance or the ability to lift heavy objects for a long period of time.

Last but not least, managing sensor data from drones presents significant challenges. These systems generate enormous volumes of information – both video and telemetry data – which must be processed, transmitted and stored almost instantaneously. The sheer scale and speed required for real-time handling make this a complex and demanding task in the field. However, in the context of Industry 4.0, massive data generated by UAV sensors can be managed and analyzed through Big Data technologies, enabling real-time processing, scalable storage and automated decision-making, which transforms flows of information into operational advantages [20].

This perspective of the Big Data concept integrated in the field of UAS represents a future direction of research, because in combination with machine learning it allows the UAV to make more efficient autonomous decisions regarding navigation, obstacle avoidance, smart landings and automatic handovers between multiple UAVs. Also, Big Data would allow the integration of data obtained through drone sensors with other IoT systems, optimizing industrial and logistics processes.

Future research will include the field of small, low-cost UAVs (sUAVs), which have dual-use advantages (can be used both civil and military) and can help increase the development of capabilities and technological progress in the context of Industry 4.0, where AI is applied. In the civilian environment, these systems comprising mini-UAVs are accessible and used modularly and as agricultural robots [21], being adopted, for instance, in horticulture [22].

5. Conclusions

Unmanned Aerial Systems have rapidly evolved, now serving as advanced autonomous platforms within the broader framework of Industry 4.0. With key improvements in sensor technology, artificial intelligence and communication networks, these systems are capable of collecting and processing vast quantities of data in real time, significantly enhancing autonomous decision-making and operational efficiency across industrial settings.

This review offers a thorough overview of current UAS configuration architectures and their progress within the Industry 4.0. The industrial technologies enable drones to operate more autonomously, process and analyze massive amounts of data in real time and integrate seamlessly within smart industrial ecosystems. IoT and sensor networks provide continuous situational awareness, AI supports autonomous decision-making and adaptive behaviors, Big Data allows for predictive analytics and performance optimization. The paper not only details notable technological advancements but also critically examines ongoing challenges, such as effective data management and cybersecurity concerns. Moreover, the article identifies research gaps –particularly in areas like scalable system architectures for modern UAVs, coordinated multi-drone operations and efficient data processing algorithms – which are essential for the continued development of robust and resilient UAS solutions.

In conclusion, grasping the impact of these technological advancements, as explored in the review, is fundamental for furthering the deployment of UAS in intelligent industrial systems. This understanding will be pivotal for researchers and specialists aiming to navigate and contribute to the future trajectory of this rapidly developing domain.

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