Review

Mechatronics Coevolution with Its Enabling Technologies for Design and Fabrication Advancements

Nikos Aspragathos *

Posted Date: 12 June 2026

doi: 10.20944/preprints202606.1021.v1

Keywords: mechatronics; enabling technologies; coevolution; reciprocal interaction; transformative innovations; design of advanced components and systems; challenges and trends

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 June 2026 doi:10.20944/preprints202606.1021.v1

Review

Mechatronics Coevolution with Its Enabling Technologies for Design and Fabrication Advancements

Nikos Aspragathos

Mechanical and Aeronautics Department, University of Patras, Greece; aspragat@upatras.gr or asprag@mech.upatras.gr

Abstract

In this study, coevolution approach rather than evolution is considered to analyse how enabling technologies influence mechatronics progress, advancements and innovations. Attention of this work is given to reveal the mutual interaction between mechatronics technology and its enabling technologies, since mechatronics methodologies, engineering tools and applications support their advancements, along their coevolution with mechatronics. With their coevolution mechatronics technology reach new maturity levels to fulfil the demand of many industrial domains for advanced systems design and of other economic sectors for designing new innovative equipment. For systematic reasons, the impact of each enabling technology on the evolution of mechatronics is investigated and the support of mechatronics to the advancement of the considered enabling technology is examined. The coevolution of mechatronics is considered through the progress and synergy of its enabling technologies in a reciprocal mode. The investigated and demonstrated coevolution of mechatronics with its enabling technologies is expected to contribute to identifying the future challenges of mechatronics that are briefly presented in the section of discussion. The paper concludes with hints for future research, development and methodologies and organization of mechatronics components and systems design, under the proposed coevolution conceptualization and investigation.

Keywords: mechatronics; enabling technologies; coevolution; reciprocal interaction; transformative innovations; design of advanced components and systems; challenges and trends

---

1. Introduction

The concept of coevolution originated from biology to define reciprocal evolution of different features of the same species or the interaction and joint evolution of two or more species (genomes). The coevolution term was adopted by researchers working on social sciences [1], investigating the mutual influences between technology and societal aspects such as industry, markets, culture and institution [2–4]. The coevolution term was rarely used within the technology literature to represent the reciprocal interaction of various technological sectors. The theory of parasitism was introduced to illustrate the mutual interaction between technological domains, where the parasite-host relationships have been investigated to encourage coevolution of technologies dealing with advanced complex systems [5]. It has been argued that the more parasite (enabling) technologies, the faster advancements of the host or master technology interacting with the parasites.

Technologies are defined as "enabling", when they bear high transformative potential for a productive system in which they are deployed. Enabling technologies attracted the attention of researchers to investigate their contribution to industry advancements and transformative transitions. An in-depth examination of the enabling technologies supporting Industry 4.0 paradigm such as Internet of Things (IoT), big data, cloud, robotics, artificial intelligence and additive manufacturing has been provided in [6]. Another survey [7] revealed emerging insights into advanced manufacturing of Industry 5.0, by investigating the latest progress of enabling technologies, such as artificial intelligence of things (AIoT), beyond 5G communications, and collaborative robotics.

The enabling technologies for industry and manufacturing are supported by other enabling technologies showing the structure of the technological knowledge. As an example of this interrelation, the enabling technologies for Internet of Thinks and Digital Twins have been presented [8,9]. The IoT enabling technologies were summarized into the following classes: sensing, identification and recognition, hardware, software and cloud platforms, communication technologies and networks, algorithms, positioning technologies, data processing, power and energy storage, and security mechanisms [8]. While for the Digital Twins (DT), a large range of enabling technologies are required to support different modules of Digital Twins, such as physical entity, virtual model, DT data, smart service, and connection. Two or more enabling technologies reaching a maturity level with collaboration and synergy foster and create transformative changes and innovations to the master technology.

Coevolution occurs when two or more technologies and/or sciences reciprocally affect each other's development through the process of their mutual interaction. However, each technology is supported by several other technologies and other relevant scientific and research fields. The subordinate or supporting technologies for further progress, are enabling technologies, which are merged concurrently in a synergetic way for the advancements of the supported technology. An enabling technology provides the engineering framework for design and manufacture components and/or modules as well as methodologies, fundamental capabilities and engineering tools that could be used for other, integrated technologies of higher complexity to design, develop and function new products and systems that could be incorporated in various application domains.

Intensive basic and applied scientific research and engineering are required for the development of enabling technologies to reach new maturity levels fuelling the transformative changes and innovation in the investigated core technology [10]. In the relevant literature the main conception of influence is unidirectional, only the support of the enabling technologies is considered for the advancement of the supported or master technology and not vice versa. For the first time in the present article, it is investigated and shown that coevolution of enabling technologies with mechatronics is the dominant process of technology progress and advancements which help researchers to identify mechatronics research challenges and trends. The progress and advancements of enabling technologies are investigated in conjunction with mechatronics technology applications used in its enabling technologies.

The term mechatronics appeared in late 60’s to define the synergy of mechanical and electronics engineering disciplines and their corresponding technologies that enabled mechatronics technology [11]. The abstract model of a typical mechatronic system was represented by a simple scheme including sensors and actuators interconnected with a computer for control and interaction with the user. The critical role of interdisciplinarity and synergy of engineering disciplines and enabling technologies, namely mechanics, electronics, computers and control have been highlighted by a variety of representative schemes. The most used scheme has been the overlapping circles of the enabling technologies of that time mechanics, electronics, control and computing [12].

Habib presented the evolution of mechatronics from the beginning till the first decade of the 21st century [13]. Initially, engineers of the involved disciplines and technologies worked separately and independently, where the electrical and electronics engineers were called to equipe with electronics and control, the designed mechanical part of the considered mechatronic system. Later with their synergy, some functionalities performed by complex mechanisms were replaced by electronic control and information processing, thus the mechanical structure was simplified and resulted in reducing complexity, weight and cost, and increasing reliability and flexibility. In the same paper, the enabling technologies of mechatronics were presented along with their maturity, with emphasis on digital electronics, embedded microprocessors, informatics and communication, optics, control and Artificial Intelligence (AI).

Sensors and actuators with embedded processors for built-in controllers are important enabling technologies that contribute to the evolution of mechatronics [14]. New soft and smart materials have been discovered [15], and new soft and\or self-contained sensors [16] and actuators or sensor-actuator hybrid systems [17] have been developed to change the design and building of mechatronic systems towards modular mechatronics [18]. Another important enabling engineering and technology is mechanical and materials [19], which did not attract much attention considering the contribution to the evolution of mechatronics.

On the other hand, mechatronic design and development methodologies [20–22] that were enhanced and matured over time based on research and engineering practice were used for the design of self-contained components and modules developed in the framework of mechatronics enabling technologies such as actuators and sensors [23–25]. Currently, mechatronics researchers and engineers put efforts to build a new generation of mechatronic systems with advanced intelligent behavior, autonomy, high adaptability and reconfigurability with self-monitoring and self-repair capabilities.

Mechatronics technology is the enabler for the technological development of the basic economic sectors, mainly in the primary and secondary production sectors and contributes to their development and transformative innovations [26–28]. In a technology roadmap [29], mechatronics was considered as enabling technology for the development of manufacturing. This roadmap presents the vision of strategic challenges identified in several high-impact industrial sectors: Aeronautics, Automotive, Consumer Goods including Pharma and Medical Devices, Capital Goods and Railways, and many others such as agricultural machinery and systems, ship construction. The Eumecha Roadmap [30] dealt with the contribution of mechatronics to a new generation of production systems by investigating the interdependence between drivers and enablers in achieving the targets-abilities of the new generation's production systems. In this roadmap, the growing intelligence/automation of the mechatronic systems as well as the growing complexity were identified, however these changes drive to completely new characteristics and capabilities of mechatronic systems supporting the new generation of production systems, for example Manufacturing and Industry 4.0 and 5.0 [6,31].

In recent years, mechatronics has enhanced the application domains of manufacturing, automotive, aerospace, food processing, medicine, precision agriculture, and biomechatronics [32]. In this context, mechatronic systems can be extended to Cyber-Physical Systems (CPSs) to integrate other aspects of the above application domains such as physical, administrative and social [33]. This role of mechatronics as enabler to technological sectors mentioned above is very important to the evolution of mechatronics, however it is out of scope of this work, which is devoted to investigating the coevolution of mechatronics with its enabling technologies.

The role of enabling technologies in the development and maturity cycles of technology was investigated and a qualitative model was presented for understanding the process of transformative changes and innovations [10]. In their publication, they show that the combination of mature enabling technologies allows the creation of the next transformative level of the considered enabled technology, however they did not consider the inverse action and the coevolution of these technologies. To our knowledge, the concept of technology coevolution was used by Coccia and Watts considering the model of parasite-host relationships, which has similarities to the relationship between enabling and enabled technologies [5]. It is critical to investigate the mechanism of evolution along with their enabling technologies, of the most important and significant technologies for the general technological development, since we could identify the trends and challenges considering the coevolution approach, however there is a lack on the investigation of mechatronics progress and advancement under the concept of coevolution.

For the first time, the present paper investigates the mutual interaction between mechatronics and its enabling technologies, and the consideration of coevolution rather than the evolution of mechatronics is proposed. In the proposed approach for this investigation, the contribution of each enabling technology to mechatronics is shown and the enabling role of mechatronics to this

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 June 2026 doi:10.20944/preprints202606.1021.v1

technology is completed with remarks on the reciprocal support to their progress and advancement, based on the maturity of general and relevant scientific and technological research. This interactivity and future trends and challenges in mechatronics coevolution are discussed which could be useful for mechatronics engineers in design and implementation of new mechatronic systems by considering the suggested mechanism of coevolution.

The present work has the aim to highlight the mechatronics coevolution rather than to present a review on mechatronics technology following the well-known patterns of organizing and writing a review. The rest of the paper is suitably organized in a way to systematically investigate the mutual interaction of each enabling technology with mechatronics. In section 2, the main enabling technologies are identified, and in each of sections 3-7 the coevolution of the enabling technology with mechatronics is presented. In section 8, a summarizing discussion on the integrated interactive influence of enabling technologies to mechatronics, challenges and coevolution trends are presented.

2. Mechatronics and Interactivity with Its Enabling Technologies

In mechatronics literature, the enabling technologies and the synergy of the engineering disciplines (IT, Electronics, Mechanics) were considered to show the evolution of mechatronics as well as the support of mechatronics to various industrial and economic sectors, such as automotive, aerospace, precision agriculture, and manufacturing. In general, the conceptualization of enabling technologies for the evolution of mechatronics was unidirectional [10,28,34].

In the present paper, the mechatronics coevolution is presented by investigating the interdependence between enabling technologies and the considered enabled domain, to show that mechatronics is enabler to its enabling technologies, thus forming a virtuous helix of mechatronics coevolution to higher levels of maturity, which is the predominant mode of technological and scientific progress [1–5]. Figure 1 schematically shows the interdependence between enabling technologies and disciplines with mechatronics, where the roles of driver and enabler are simultaneously shared by the involved technology domains and mechatronics, as it is demonstrated with systematic and strong evidence presented in the following sections. In the future, other interdependent technologies can be identified, and other types of effects can be considered, however the main mechanism of coevolution is demonstrated. The interaction between the presented enabling technologies is mostly done with their reciprocation via mechatronics, as shown in Fig. 1. For example, control technology influences the sensors and actuators technology via mechatronics, since mechatronic methodologies and tools are used to design and implement self-contained, modular sensor-actuators systems.

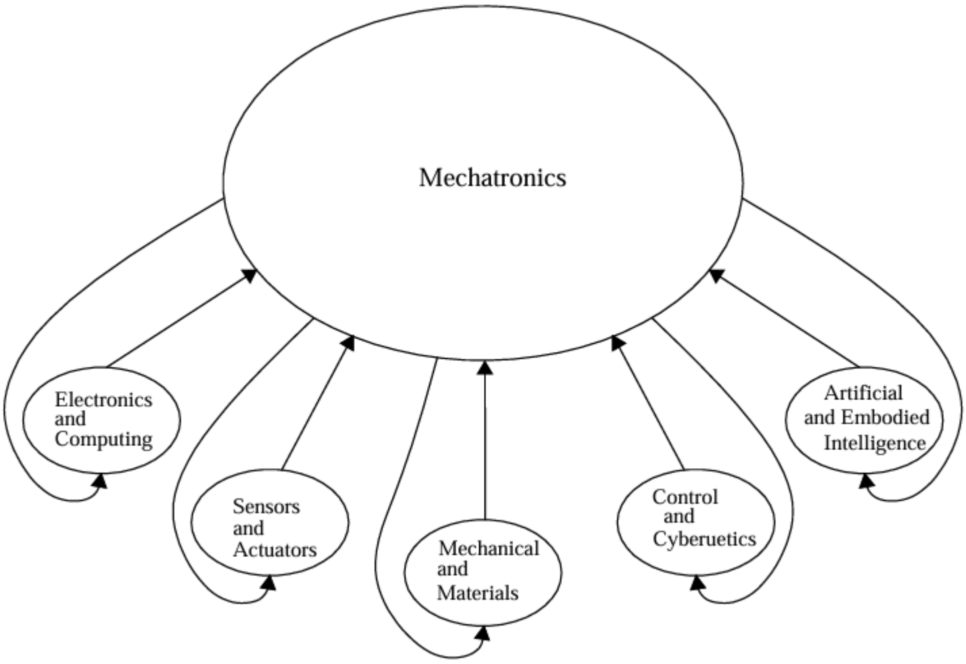

Figure 1. Interdependencies between enabling technologies and mechatronics.

In abstract conceptualization, a mechatronic system transforms and transfers energy and information simultaneously, therefore the accumulated knowledge and technology in these large areas could be used in mechatronics evolution [35]. In this study, the main technologies enabling mechatronics evolution that are identified are the following: Electronics and Computing, Sensors and Actuators, Mechanical and Materials technologies, Control and Cybernetics, and Artificial and Embodied intelligence. Bioengineering could be added to form biomechatronics, but this would be considered in future work. Other research and development domains that could be considered as enablers to mechatronics are computer aided design, modelling and simulation tools and methodologies such as digital twins and hybrid modelling; however, their investigation is beyond the scope of this paper. Of course, we have not to forget the richness of the scientific background created by the basic research in mathematics, physics, chemistry and biology that supports the considered enabling technologies based on the precious work of the scientists and researchers of the current and previous generations.

In this paper, the concept of coevolution is adopted, since it is a powerful logic for the development of inter-technology approach in the study of technological advancements and progress as it has been argued by Norgaard [36]. Two technologies coevolve when they have a creative impact on each other's evolution. Biologists distinguished between "direct" and "diffuse" coevolution, where the first describes the species-to-species coevolution and the second shows a widespread influence considering many species interaction [37]. In our approach, the "direct" type of influence is adopted to study the coevolution of mechatronics with its enabling technologies. Of course, enabling technologies interact each other but mostly via mechatronics so the "direct" type is more suitable and facilitates the systematic investigation of mechatronics coevolution, which is the master technology.

The theory and model based on the idea of parasite-host relationships that have been used to explain the long-run coevolution of technological complex systems, it has been tested on the investigation of evolution of specific systems namely aircraft, tractor and bicycle in response to natural selection in the field of markets, which is close to biological systems evolution [5]. In biology coevolution, models have been proposed for the study of phylogenetic reconciliation for specific species based on genetic evolution [38].

doi:10.20944/preprints202606.1021.v1

The above-mentioned models are not suitable for mutually interacting technologies like the coevolution of enabling technologies with mechatronics, since this investigation is not confined to specific equipment or systems but to the entire domain including research, methodologies and the framework of engineering tools. On the other hand, in biology the generation variations are based on randomness and probability, while in technology the progress depends on human or institutional decisions and directives to be followed in research and development. In this paper, a qualitative approach is proposed to study the coevolution of mechatronics with its enabling technologies based on systematic investigation and selection of the most relevant from the rich literature. The coevolution in mechatronics with its enabling technologies, that is shown in this work, could be used as basis for the development of quantitative computational models for studying this coevolution or the coevolution of specific systems.

3. Electronics and Computing Technology with Mechatronics Coevolution

In this section, the interactivity and coevolution of electronics and computing technology with mechatronics is investigated and proved using a careful selection of publications. In the first part, the influence of electronics and computing technology on mechatronics, while in the second part the vice-versa interaction is investigated to show their coevolution, as it is summarized at the end of this section.

3.1. Electronics and Computing Enabling Mechatronics

Electronics and computing form a key-enabling technology for mechatronics progress and advancements. The rapid progress of electronics and computing technology has boosted the evolution of mechatronics; using them for high-precision processing of large amounts of data with progressively higher speeds, and lower costs and sizes. Electronics and digital computing evolved very fast and apart from the powerful computers used in the design and simulation of mechatronic systems, the embedded computing processors in mechatronic devices and systems are very significant, basic components for mechatronic systems [39]. The growth of mechatronics started when electronics reached the first level of maturity with the introduction of microprocessors [15]. Embedded processors are the "brain" of any simple or complex mechatronic system and are included in production systems, vehicles, machines and everyday home or hand devices [39]. In this section, the coevolution of electronics and computing with mechatronics is demonstrated through the integration of electronics and computing in mechatronic systems.

According to the TATA [40] report, the major building blocks of an embedded system are microcontrollers / DSP, integrated chips, Real-Time Operating System (RTOS), industry-specific protocols and interfaces and printed circuit board assembly. Semiconductor devices include integrated chips, microcontrollers, Field-Programmable Gate Arrays (FPGAs) and System-on-Chip (SoC). Today the trend is to build embedded systems with high precision processing of large amounts of data that run at lower frequencies and voltages, which include parallel cores on a single chip, thereby increasing the overall performance. FPGAs have been integrated successfully into mechatronic systems, such as in servo drives used within the control systems of industrial numerical machine tools [41]. Brain-like chips have been introduced in mechatronics systems, apart from FPGAs and Application-Specific Integrated Circuits (ASICs) [42]. ASICs microchips, which include a large part of the electronic elements in a single integrated circuit, are used in specific applications. Brain-like processors are micro-electronic architectures specifically designed to simulate the operation of human neurons and synapses. The building of brain-like chips is a very promising technology; however, it is still in its initial phase and particular issues and challenges should be resolved to be used massively in mechatronic systems [43].

To overcome limitations of classical silicon electronics, quantum, neuromorphic and organic electronics were developed based on research achievements in physics and biology [44,45]. Quantum electronics provide faster, energy efficient, smaller and scalable computing systems. Using quantum, neuromorphic and edge AI computing, we obtain better machine learning, faster response, shorter

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 June 2026 doi:10.20944/preprints202606.1021.v1

latency, and further miniaturization, which open new directions and high potential for AI applications. Organic transistors present great potential for design and implementation of biocompatible synaptic devices for in-vivo medical applications. Attributes like flexibility, biocompatibility, cost-effectiveness, lightweight, lower energy consumption and the integration of organic electronics with living systems have been explored in [45]. Significant progress has been made in the design and structure of flexible, stretchable and wearable inorganic and organic electronics that can be bent, stretched, or folded without losing functionality [46]. Stretchable electronics could be used in mechatronic devices and systems with flexible parts like robot soft hands, prosthetics, wearable sensing and monitoring and other similar applications. These directions in electronics and computing research and development are very promising for the design of new advanced mechatronic devices and systems and open new transformative changes in mechatronics technology evolution.

Embedded systems have been designed with specific functionality and have been integrated into larger mechatronic systems such as robots, manufacturing automation machines and lines, and medical devices. Since an embedded system controls the physical process within a mechatronic system it has real-time computing constraints. Methodologies, software platforms for building virtual prototypes and engineering tools have been developed for modelling, simulation, and design of embedded electronics integration in mechatronic systems applied in industrial sectors such as aerospace and automotive [47,48]. Since mechatronics technology and engineering practice are enablers for the industrial sectors, the latest advances in embedded systems have enhanced the intelligence of mechatronic systems, which play a pivotal role in industrial sectors and in Industry 4.0 and 5.0 evolution [49–51]. The relevant literature focuses on the role of electronics as an enabling technology for the evolution of mechatronics, however the inverse direction of interactivity has not been emphasized or completely ignored. The production of computers, embedded electronics and microprocessors integrated on high-tech and automation equipment is based on the evolution of mechatronics as revealed by the study of electronics fabrication, that is investigated and demonstrated in the following subsection.

3.2. *Mechatronics as Enabler to Electronics and Computing*

In this subsection, the influence of mechatronics on electronics and computing is presented emphasizing fabrication technology for electronics, which is the platform for computing. Basic research work on mathematics, physics and materials, which are the main scientific areas enabling amazing advances in computing and electronics; however, very sophisticated mechatronic methodologies and systems are required for manufacturing chips, microprocessors and computers. Mechatronics technology evolved very fast in parallel with electronics and computing, for the development of modern and advanced laboratories and manufacturing systems, like lithography machines, Additive Manufacturing (AM) and 3D printing, robots, assembly automation and packaging lines, that are used for integrated circuits and computers production.

Key equipment and processes for chip manufacturing include lithography, etching, ion implantation, chemical vapor deposition, testing, and packaging, which were developed and evolved using mechatronics design and implementation methodologies [52]. Thus, the machining precision, automation, stability and reliability were improved considerably, and the chip size and overall production cost were reduced.

The most advanced precision mechatronic components and the overall system design and implementation are used for building lithography machines with extraordinary nanometer accuracy. In [53], motion control issues were identified in wafer scanners considering the required accuracy and mechatronic dynamics to investigate the performance and select the most suitable control system. Among them are the setpoint generator for smooth motion profiles, single-DOF and multi-degree-of -freedom (DOF) decoupling controllers. Semiconductor manufacturing is a highly competitive research and development topic, where the latest advances in intelligent monitoring, control, and automation are considered for the design of this mechatronic equipment [54].

Lithography machines are some of the most complex and extremely precise mechatronic systems ever built, assembled by tens of thousands of components, coming from highly specialized suppliers across the globe. In [55], the limitations of the state-of-the-art lithography machines and the prospects have been outlined. To overcome the technology limitations, it was recommended to consider techniques applying shorter wavelength light source and reduce loss of light with short wavelength in transit.

In Figure 2, lithography, which is one of the most advanced mechatronics systems, is selected to show the mutual interaction of mechatronics with electronics and computing using the double helix, where the term performance is used in a generic meaning including various aspects of improvement. This figure shows the coevolution, which increases the performance of both, since continuously higher performance electronics and computing are available to mechatronics engineers for the design and implementation of higher performance lithography equipment, and vice versa. Advanced mechatronics design of lithography equipment achieved very high acceleration with low jerk for smooth motion and ultra-high-speed using fine mechanisms and cutting-edge controllers, high rate of measurements, perfect synchronization of wafer and reticle motions and many other high precision mechatronic parts and components, which became possible with the fabricated advanced electronics.

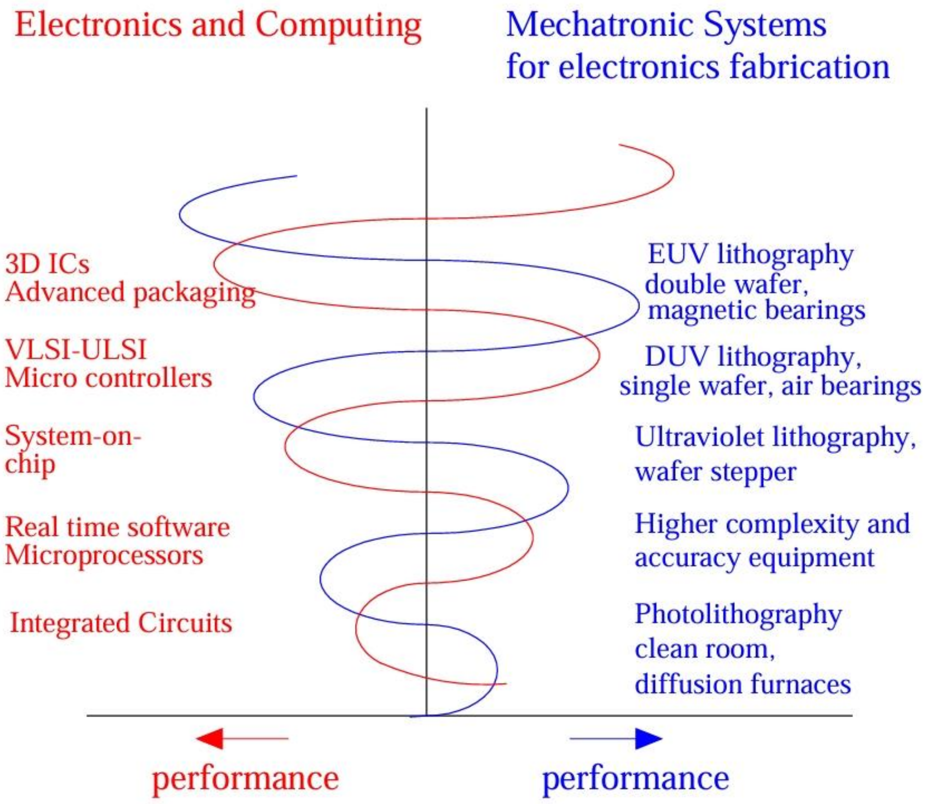

Figure 2. Double Helix represents electronics and computing with mechatronics coevolution via lithography.

The standard photolithography processes are not compatible with the fabrication of stretchable electronics, therefore alternative processes have been proposed by the research community working in the relevant fields of physics, chemistry and engineering. Laser-based fabrication techniques possessing suitable features were proposed for the fabrication of soft and stretchable electronics using a variety of materials such as inorganic materials, elastomers, ceramics, and composites [56]. An alternative for the fabrication of electronic circuits, and systems on flexible or bendable substrates is printing technology with advancements in precision and reliability based on recent mechatronics methodologies for building suitable printing systems [57]. However, in future, innovative methods should be developed to increase stability and reliability in every stage of the design and fabrication process to increase yield numbers and quality.

With mechatronics methodologies and components, the machining accuracy and stability have been significantly improved, while the need for human intervention and production costs is reduced [52,58]. It is estimated that chip fabrication technology will obtain smaller feature sizes, including nodes of 7 nm, 5 nm or even smaller. In a publication presenting an analysis of mechatronics and chip manufacturing, has been proposed to pay significant attention to 3D integration techniques and sophisticated packaging like selective laser melting, to bypass certain issues linked to traditional scaling methods, which has the potential to transform the industry fundamentally [59]. AI utilization is expected to leverage vast amounts of data and advanced algorithms in the design and operation of mechatronic systems for semiconductor production, optimized processes, reduced waste, and enhanced product quality, which can be exploited in a new stage of mechatronics evolution.

In this subsection, the critical role of mechatronics technology is demonstrated for the development of modern and advanced laboratories and manufacturing systems for integrated circuits and computers production. It is revealed that mechatronics is the key technology for the exponential advancements of electronics and computing, since mechatronic methods and engineering tools are continuously improving and have made transformative changes to the equipment for fabrication of electronics and computing hardware. In conjunction with the investigation of the influence of electronics and computing on mechatronics performed in the previous section, their reciprocal interaction was revealed, which fosters their coevolution.

The above analysis reveals that there are continuous interaction and coevolution of electronics and computing with mechatronics technology. The schematic diagram shown in Figure 3 presents the interactivity between mechatronics and electronics and computing towards their coevolution. In this figure, the main science and basic research for electronics hardware and software are presented, however the investigation and presentation of this contribution is out of scope of this work. With the presented approach for coevolution, it can be concluded that new and future trends in electronics technology should be considered in conjunction with electronic fabrication methods based on the evolution of mechatronics technology and systems. Some aspects of current and future state of coevolution are suggested in the following.

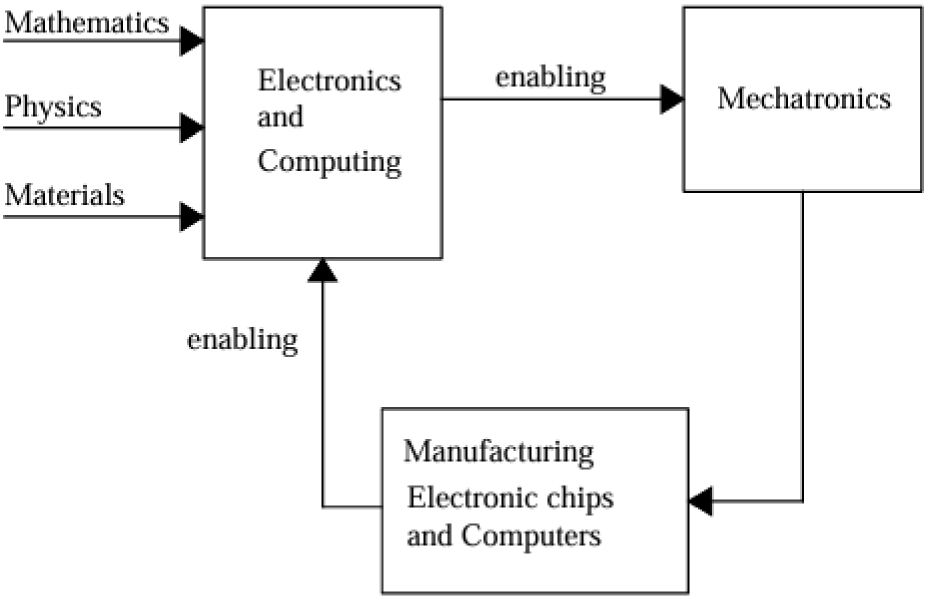

Figure 3. A schematic showing the interactivity between mechatronics and Computing-Electronics.

doi:10.20944/preprints202606.1021.v1

- Fabrication of flexible and stretchable electronics requires the development of advanced mechatronic systems, while these electronics are necessary for new mechatronic systems like flexible robots.
- Organic, quantum and brain-like electronics present a lot of advantages over traditional inorganic electronics, concurrently embedded systems and edge computing are indispensable for the advancements of mechatronic systems
- AI effect on the growth of semiconductor manufacturing is twofold, requiring innovative AI-capable electronics such as neuromorphic, and by enhancing the mechatronics technology to provide new advanced chip fabrication systems. Laser-based and printing mechatronic systems are promising technologies for further development of electronics fabrication.
- Methods for advanced packaging and assembly of electronics should be developed to reduce the chip volume with enhanced functionality and in parallel, autonomous robots with high dexterity and precision will be used for manufacturing.

4. Sensors and Actuators Technologies Coevolve with Mechatronics

This section presents the investigation of mutual interaction between sensors-actuators and mechatronics to demonstrate their coevolution. In the first subsection, the contribution of sensors and actuators technologies to mechatronics advancements is presented and the second part shows how mechatronics enables sensors and actuators technologies, which are presented together, since advanced mechatronic components modules and entire systems include both. However, in some cases it is imperative to present separately sensor and/or actuator types with the mechatronics approach for their development.

4.1. Sensors and Actuators Enabling Mechatronics

Sensing and actuation technologies are included in mechatronics enabling technologies, since they continuously enhance the capabilities and performance of mechatronic systems. Sensors and actuators are the two basic components of any controller included in a mechatronics system making it smart and functional [60,61].

Sensors are indispensable components of any mechatronic system and progress in sensor technology has leveraged mechatronics evolution. Sensors have a long history starting from simple thermostat and mechanically activated switches to detect contact with passing objects that were replaced in the 50's by motion detectors based on ultrasonic waves. Since then, sensors have reached advanced levels of integration (e.g. coupling sensors-actuators), and capabilities such as automated fault detection, diagnosis, and correction as mentioned in AMA [62].

For systematic reasons, the great variety of sensors that are integrated in mechatronic systems could be classified in different categories according to transducer types or application classes. There are electromechanical sensors such as force sensors, accelerometers, tactile, and IMU. Another class of sensors include ultrasound, vision and optical such as cameras, infrared, Lidar, laser point and beam sensors. Electrochemical and biosensors are used for measuring a broad spectrum of chemical substances and body signals such as glucose meter, gas detection, electrocardiogram, encephalogram, soft and wearable sensors [63]. Sensors are used in mechatronics for mobility, autonomous systems, safety, construction, manufacturing, healthcare, environmental protection and many other applications even in systems for sensors fabrication.

In recent years, sensor technology has undergone incremental and transformative changes [16]. Interdisciplinary research has matured various technologies and revealed operation principles that have been adopted to develop new sensing paradigms in micro and nanoscale systems as well as using new polymeric materials. A recent literature review showed that the growing scientific interactions between different research fields generate coevolutionary trajectories towards general-purpose and/or specialized technologies, such as wireless sensors, biosensors, fiber-optic, and optical sensors, with manifold applications in mechatronic systems [64]. To overcome the limitations of individual sensors and obtain a more comprehensive identification, perception and recognition of the monitored system, data are fused from different sensors, such as accelerometers, gyroscopes, and magnetometers for mobility.

Current sensor technology produces intelligent self-contained sensors including amplifiers, embedded microcontrollers, noise control, signal conditioning, standard interfaces achieving high-performance, high-power density, and integration/miniaturization, with standard interfaces. Senor systems have lower costs, and smaller sizes, while they are decentralized/networked, self-diagnosed, self-calibrated, and sometimes self-repaired using their reconfigurability based on redundancy. The trends in sensor technology include easy connectivity (modularity), packaging compactness with embedded computing power and intelligence by coupling mechanical, physical, chemical, optical, and biological sensing functionalities with control, electronics and software, using mechatronics methodologies.

Research attention is and will be devoted to wireless communication, energy harvesting, biomedical, soft wearable, intelligent and quantum sensors [65]. Self-powered and self-contained modular sensors to be easily integrated in mechatronic systems were applied in manufacturing systems, machines and devices for various applications such as automotive, precision agriculture, home appliances, robots etc. [66,67]. These characteristics were developed using mechatronics design approaches which were, and it is one of the drivers for the design and production of self-contained sensor modules that are integrated into modular mechatronic systems. The major components of autonomous modular sensor systems are sensor element(s), signal amplifiers or transducers, microcontrollers, data memory, RF transceivers, antennas, energy supplies, and application-specific multifunctional housing, which resembles an entire mechatronic system, particularly if they can have self-calibration and self-repair capabilities.

Like sensors and actuators are indispensable components of mechatronic motion control systems, while they resemble true mechatronic systems if accompanied by sensors and controllers. Actuators convert an input signal (usually electric) to an output of mechanical energy and force, and they are distinguished into the following main categories according to the type of transduced energy domains: thermomechanical transduction, magneto-mechanical transduction, electromechanical transduction and fluid-mechanical transduction [68].

Apart from the improvement in traditional actuators, recent years research efforts have been devoted to the development of high precision, smart, soft, biomimicking, and micro actuators by exploiting various transduction phenomena [69–74]. New materials, mechatronic designs and manufacturing processes have been explored to improve the precision and performance of actuators. A mechatronics methodology is presented for the optimal design and control of a long-stroke high precision micro-positioner along with possible applications such as low-cost desktop micro-milling machine [69]. Smart and soft actuators have been introduced by biomimicking and using new materials with special characteristics that integrate controllers, communication, and possibly sensing and fault detection capabilities [70,71]. Another type of soft actuator has been developed using Shape Memory Alloys (SMA), since they present high work density, low weight and size actuators that enable complex motions to be performed. SMA actuators have been used in mechatronic and MEMS devices, robotics and biomedical and space applications. In [72], state–of–the–art thermal and magnetic SMA actuators and their motion performance were analysed. Magnetorheological materials change their properties with the variation of the applied magnetic field; therefore, this type of material has been used to design adaptive compliant actuators that have mechatronic applications such as in robotics, wearable devices and prosthetics [73,74]. Smart electrohydraulic actuators with adaptive intelligent controllers to adjust the velocity and impedance behavior have been developed for the actuation of large-scale high power mechatronic devices [75].

For new types of micro-actuators, the most considered actuation techniques are thermo-responsive, magnetic, piezoelectric, and soft actuation as well as their high precision MEMS and biomedical applications [76]. Piezoelectric actuators were integrated into mechatronic systems based on their excellent characteristics such as precision, broad working stroke, high resolution, short latency, high stiffness and actuation force [77]. Research direction for the improvement of the piezoelectric actuators to fulfil the advanced requirements of mechatronic systems are miniaturization, use of higher quality and purer materials, backlash suppression, smooth motion, and use sophisticated controllers for improved trajectory tracking and accurate positioning [78]. A large variety of electrostatic actuators have been designed and fabricated such as micromotors, micro-valves, micro-pumps, micro-relays, micro-mirrors, radiofrequency switches, wave propagating environment control and micro-resonators having various shapes and operating modes [79]. Development of electrostatic actuators is a promising topic for micro positioning in mechatronic systems and micro-object manipulation and assembly in electronic industry [80]. Future trends in electrostatic actuation include the use of better materials, designing advanced shapes, and applying advanced control methods to be used in innovative mechatronic systems.

Sensors and actuators technology evolved in conjunction with mechatronics, since these are pivotal technologies enabling mechatronics to reach high levels of maturity, providing high precision, rapid response, and interaction with the environment of mechatronic systems. Modular units integrating sensors and actuator with controller have been developed following a co-design mechatronic approach, that could be used to facilitate the design and development of high performance complex modular mechatronic systems [81]. Sensors and actuators, with power supply, and microcontrollers have been integrated for the advancements of manufacturing tools to improve robustness, accuracy, reliability and productivity of machining [82]. Hybrid soft sensor-actuator systems have been proposed to integrate intelligent detection and motion, where actuator-assisted sensors detect the environment changes and sensor- assisted actuators act to the environment [17]. Design approaches have been introduced for the integration of sensor-actuator in intelligent mechatronic devices [83]. Modes of functional synergy have been presented such as adaptive actuation, sensor fusion and feedback architecture enabling flexibility and autonomy in complex mechatronic systems.

Considering the enabling influence of sensors and actuators technologies to mechatronics, it is important to investigate both technologies in their synergy and integration rather than separately, since functional materials have enabled tight coupling between sensory input and mechanical output, as well as there is a tendency for modular design of mechatronic systems, like robots, including self-contained sensor-actuator units.

In this section, strong evidence and arguments are presented demonstrating the high importance of sensors and actuators technologies to mechatronics evolution. The inverse action is examined in the next section to complete the investigation and demonstrate their coevolution.

4.2. Mechatronics Supporting Sensors and Actuators Technologies

In this subsection the influence of mechatronics on sensors and actuators technologies is presented to support the concept and the reality of their coevolution, which is critical for advancements and innovations. For the development of advanced sensors and actuators, a framework for design methodologies, engineering tools and fabrication techniques as well as sophisticated mechatronic systems are used for their manufacturing with reliability and reduced costs in high volumes. This is critical for the performance and widespread applications of sensors and actuators.

At the beginning the design and fabrication of conventional sensors and actuators, like electromechanical, well established interdisciplinary methods and manufacturing process have been used. For example, the manufacturing process included manual work and simple electromechanical tooling for moulding, milling, assembly, packaging etc. With the advancement of mechatronics, new more sophisticated, automatic, and later intelligent machines have been used for sensor and actuator fabrication. Synergy and interaction between mechatronics and precision technologies are required for the development of advanced sensors and actuators with embedded intelligence [84].

Since the present paper is devoted to investigating and showing the coevolution of enabling technologies with mechatronics, the rest of this subsection is focused on the latest advances in the mechatronic contribution to the fabrication of smart, soft and micro sensors and actuators. A mechatronics approach and methodologies have been followed to design and fabricate smart, compliant, and self-contained actuators from large scale powerful systems to soft and micro/nano-actuators [23,85]. Mechatronic methodologies have been used for design, optimization and control of actuators like a long stroke linear nano-positioner, where an innovative air-bearing/bushing has been assembled instead of double shaft arrangement thus a significant simplification has been achieved [86].

Design and fabrication of soft actuators and soft micro-actuators present several challenges and require innovative mechatronic approaches and complex high accuracy fabrication systems. For simple soft actuators, molding and silicon casting have been used, however these processes are not suitable for advanced soft actuators with complex structures, so 3D printing and other novel processes have been proposed to be performed by mechatronic fabrication devices [87]. Soft lithography has been employed to pattern and fabricate elements for soft micro-actuator construction integrated with morphological computation [88]. Soft lithography uses only one design template instead of multiple steps with several photomasks required in conventional photolithography.

Mechatronic methods for integration and advanced fabrication processes are critical for the development of novel sensor systems. Additive manufacturing has been used for fabrication of sensors, however building an integrated sensor system with additive manufacturing presents several issues that specified in [89]. Fabrication of flexible sensors for strain measurement has been implemented using mechatronic systems and techniques like fused filament fabrication (FFF), direct ink writing (DIW), and vat photopolymerization (VPP) to address the weaknesses of conventional 3D printing and AM processes [90,91]. For fabrication of biosensors and biodevices, advanced printing and deposition techniques transformed considerably the process of deposition of biological molecules based on the progress of used mechatronic systems [92].

Recent advances of sensors for MEMS and their fabrication processes have been presented [93]. Examples of the considered sensors include micro cantilever based piezo resistive sensors for bioMEMS applications, novel thermocouple-based gas flow sensors, triboelectric energy harvesters and sensors, DRIE-based MEMS differential capacitive accelerometers, and others with the corresponding fabrication procedures. The equipment used for the fabrication of such sensors is complicated, advanced mechatronic systems for electron beam lithography, bulk, high aspect ratio and other micromachining technologies. This is another piece of strong evidence showing the interaction and coevolution of sensors and mechatronics technologies

The tendency is towards size minimization of sensors and actuators and use of smart and soft materials, therefore rapid and adaptable fabrication processes are used such as 3D or 4D printing, shape deposition manufacturing, lithography, fused deposition modelling, continuous direct light processing, rapid liquid printing and laser sintering [94]. Lithography process is performed in high complexity, ultraprecision and high output mechatronic systems integrating sensors and actuators. Mechatronics technology achievements in dynamics, control and design have been exploited for the development of lithography machines for accurate pattern transfer and very high-speed motion of the wafer scanner that achieves nanometer level tracking error [53]. Engineering methods and tools from different disciplines and technologies enabling mechatronics are integrated to design a flexure-based roll-to-roll (R2R) printing system with precision and repeatability in the range of nanometres including mutli-DoF mechanisms that control the position/force of the print roller, capacitance probes, eddy current sensors and load cells to monitor the displacements of the flexure stage and contact force in real time as well as control strategies to decouple the cross-axis and cross-stage motion [95]. The methodology for design and implementation of mechatronic fabrication systems is critical to achieve cutting edge micro sensors and actuators that are used in current sophisticated mechatronic components, modules, devices or large complex systems [96]. For example, advanced high precision control is required for process like thin film etching to guarantee the reliability and improved performance of fabricated sensors and actuators.

In Table 1, the coevolution of the sensors and actuators technologies with mechatronics through their interaction is summarized. Along with their coevolution sensor and actuator technologies contributed to the development of mechatronic systems of higher precision, reliability, controllability, safety and lower size and cost that have been used for the fabrication of advanced, high performance miniaturized sensors and actuators.

Table 1. Coevolution of sensors and actuators with mechatronics. The arrow at the left of table shows the coevolution towards higher performance and miniaturization.

Sensors enabling Mechatronics	**Actuators enabling Mechatronics**	**Mechatronics for design and fabrication of sensors and actuators**
Modular self-contained micro sensor-actuator systems (MEMS)		Complex Intelligent ultra-high precision fabrication
Self-contained sensors Smart and Soft sensors Micro-sensors Multi-sensors Tactile sensors Electrochemical and biosensors. Vision and Optical Electromechanical Simple switching	Self-contained actuators Smart and Soft actuators Micro-actuators Electrostatic Piezoelectric Magnetoreological Thermomechanical Magnetomechanical Electrohydraulic Electromechanical	3D printing devices Lithography systems Additive manufacturing Intelligent manufacturing systems Advanced Mechatronics design methodology Manufacturing automation High precision manufacturing Conventional design and manufacturing

From the presented investigation, it became obvious that many of the abilities and the characteristics of sensor and actuator systems have the characteristics of the mechatronic systems mentioned above. The synergy of corresponding disciplines is necessary to design and manufacture sensors and actuators alike mechatronic systems by considering the differences in scope. In [68], it is stressed that "The combination of functions by means of mechatronic integration of disciplines in the design of actuators has clear functional benefits."

In Figure 4, a schematic block diagram shows this interaction contributing to the coevolution of the sensors and actuator technologies along with mechatronics as well as the basic research domains that contribute to the theory and basic principles for sensing and actuation. With the rest of the enabling technologies considered, sensors and actuators technologies enable the evolution of mechatronics and simultaneously the synergetic mechatronics methodologies for design and fabrication contribute to the advancement of sensors and actuators technologies. These interdependencies between sensors and actuators technologies as well as other mechatronics enabling technologies and mechatronics are the driving force for the technology evolution towards qualitative and innovative transitions to new levels of coevolution.

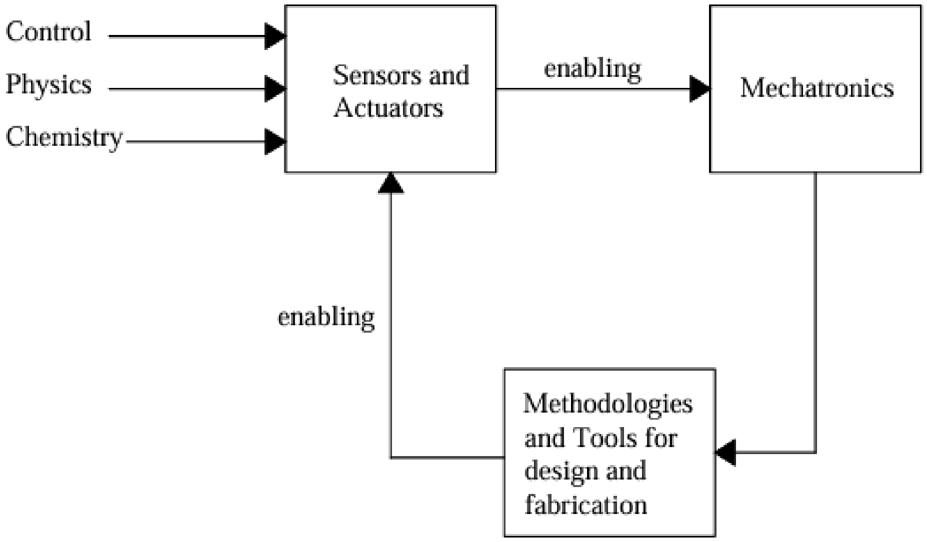

Figure 4. A block diagram showing the interaction of sensor-actuator technologies with mechatronics one.

5. Coevolution of Mechanical and Materials Technologies with Mechatronics

In this section, the contribution of mechanical and materials engineering advancements to mechatronics evolution and vice versa are presented. For systematic reasons, the first subsection presents the influence of mechanical and materials technologies to the progress of mechatronics, while in the second subsection the inverse influence is presented, showing the coevolution of the investigated technologies. This division is not very strict, since in each side of influence the inclusion of interactivity is unavoidable and it is stressed.

5.1. Mechanical and Materials Technologies Enabling Mechatronics

Mechanical engineering is pivotal enabling technology for the progress of mechatronics contributing to kinematic, dynamic, fluid dynamic and thermodynamic analysis and design of any mechatronic system. Mechanical engineering is involved synergistically in mechatronic advancements considering precision, control, efficiency and cost, size and weight reduction. Mechanical design and dynamics of high precision mechatronic systems are critical, for example in photolithography, where the accuracy and precision at nanoscale strongly depend on the mechanical part of the system, which is very difficult to be designed, manufactured and controlled compared to the included optical system. The mechanical engineering contribution to photolithography and the most crucial components evolution of the mechanical part have been presented in a critical review [58]. The contribution of mechanical engineering is significant in new materials such as metamaterials, thermal effects and thermal energy transfer and cooling as well as in the interconnections and packaging of small size mechatronic systems such as MEMS and embedded systems. On the other hand, mechanical engineering has benefited significantly from the mechatronics methodologies and advancements. “Nanotechnology and biotechnology will dominate technological development and will be incorporated into all aspects of technology” was stressed in a report by ASME [97] devoted to the Future of Mechanical Engineering. A publication review on the main issues and research trends in mechanical engineering argued that the main topics are optimal design, material engineering and mechanics, which enable mechatronics advancements [98].

In chemical engineering, research has been conducted on advanced materials, metamaterials, biomaterials and nanotechnology, which have been involved in a fast-evolving field of technology enabling mechatronics evolution, as they found applications in micro-electronics, sensors, actuators and MEMS [99].

Metals, steels, and plastics are well-known conventional mechanical materials utilized for the design and fabrication of machine elements of mechatronics systems. Materials could be classified in metallic, polymeric, ceramics, composites and smart and soft materials. Metallic includes stainless steel, aluminum, titanium and others that are critical for mechatronics due to high strength, durability and low cost. Polymeric are lightweight materials that have flexibility and high impact resistance. Ceramics present remarkable durability and rigidity but are fragile, however they are resistive to corrosion and have low electric connectivity and thermal conductivity. Composites of two or more materials have been used in building mechatronic devices due to flexibility, excellent strength-to-weight ratio, high durability, lightweight, and corrosion tolerance.

In the last few decades, mechanical and chemical technologies have introduced smart and soft metamaterials that have been used for design and development of mechatronic systems. Metamaterials are materials with synthetic structure that have been artificially developed to obtain mechanical, electromagnetic, optical, acoustic and thermal properties other than those characterizing conventional materials [100,101]. Examples of mechanical metamaterials include auxetic, anisotropic mass density, ultra-lightweight, negative mass density and modulus, dilatational, nonlinear, bistable, reprogrammable, and seismic shielding. With the evolution of mechatronics advanced manufacturing processes have been developed such as lithography machines, and AM systems that have been used for the fabrication of mechanical metamaterials with negative Poisson’s ratio, negative elasticity and bulk modulus [102].

Smart or intelligent materials have been designed with varying properties that can be controlled by applying external stimuli, such as electric or magnetic fields, stress, chemical compounds, moisture, light, and temperature. Smart materials are used in many mechatronic devices and self-contained modules, including sensors and actuators, or artificial muscles, particularly electroactive polymers [103,104]. In [103], various types of bioinspired smart and soft materials based on multi-scale architecture and surface engineering have been introduced. These materials consist of a 2D or 3D multilayered structure with certain mismatched mechanical, optical, photothermal, or other physicochemical properties that can be exploited to fabricate multi-stimuli-responsive elements such as wearable strain sensors, 3D stretchable electronics and dynamic displays, that have been integrated into mechatronic devices. Another category of smart materials includes Shape Memory Alloys (SMA); piezoelectric, magneto-strictive, electro-rheological and magneto-rheological fluids, and self-healing materials. The operation of semi-active mechatronic devices such as dampers, brakes or clutches, are based on the property of magnetorheological fluids to change their apparent viscosity by applying a varying magnetic field so that the damper behaviour can be intelligently controlled [105]. Hybrid biomaterials have advanced electrical, magnetic, mechanical, and chemical properties compared to standard biomaterials, enabling the development of biosensors and other implantable devices [99].

In mechatronics technology, methods and tools have been developed for design and microfabrication of sensors and moving mechanical parts at the microscopic scale. Material technology is critical to the development of MEMS, because new materials that are feasible in MEMS should be micro-fabricated to achieve micro-size lightweight and low-cost mechatronic devices [25,106,107]. New paths for future research are opened in multifunctional, intelligent materials with sensing, energy harvesting, actuation, adaptation, and information processing capabilities that could be used for MEMS and mechatronics advances even though this research is in its infancy [108]. In the last paper, a “mechanical metamaterial electronics (meta-mechatronics)” platform have been introduced for designing smart self-powered materials that can sense external stimuli and process the information to form an integrated closed-loop control system. These special functionalities were obtained by the fusion of metamaterials, digital electronics and triboelectric nano energy harvesting technologies. Such materials could find applications in MEMS, flexible electronics and mechatronics with higher integration, and lower weight and cost.

The investigation presented in this subsection shows the strong influence of mechanical and materials technologies to mechatronics progress and advancements that will be completed with the investigation of inverse action, presented in the next subsection to demonstrate and prove their coevolution.

5.2. Mechatronics as Enabler to Mechanical and Materials Technologies

The scope of this subsection is to investigate the role of mechatronics technology as enabler to mechanical and materials technologies. Advanced mechatronic systems such as industrial robots, CNC machines, machining centers, automated production lines, plastic injection moulding machines, stereolithography and other additive manufacturing systems, and measuring devices are used to produce materials and manufacture machine elements, integrated machine parts and synthetic components for implementation of mechatronic systems [109]. To show this interactivity, one of the most representative and advanced mechatronic systems used in manufacturing, the industrial robot is chosen. Intensive research in mechatronics enabling technologies and methodologies has been devoted to upgrading robot capabilities, while robots are used to manufacture mechanical parts, materials and electronic components that are integrated to implement mechatronic systems [110,111].

Figure 5 shows an example of the interaction between mechatronics technology and mechanical and materials technologies via the industrial robot, while similar cases could be shown for other mechatronic systems used in manufacturing of mechanical parts, components and new materials. The industrial robot applications that are shown in upper to middle part of figure 5, namely are the same but present increasing complexity and are more demanding. However, robot capabilities are continuously progressing based on mechatronics evolution so could face the higher requirements. Current industrial robots have greater speed and accuracy, increased payload and reach, higher production efficiency, reduced errors and cost, obtain high product quality, greater flexibility and autonomy. These advances have been enabled by using breakthroughs in electronics, control, sensing and perception, advanced actuation using smart and soft materials, AI, machine learning and embodied intelligence, which enabled mechatronic advancements [112,113].

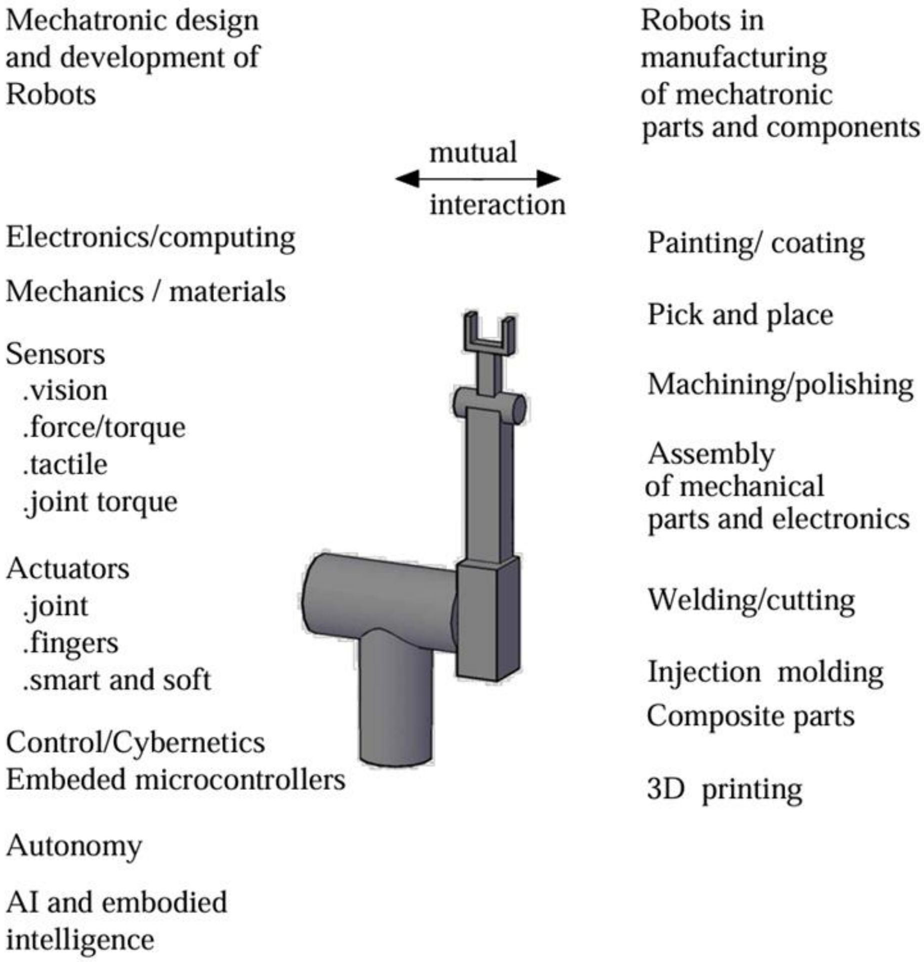

Figure 5. Mechatronics and manufacturing interaction via robotics. .

New industrial applications have been designed and implemented to automate manufacturing processes, that are based on the new advanced capabilities of robots, such as composite parts manufacturing with robotic fiber placement, automated tape laying and automated plies layup. The robots are equipped with suitable dexterous grippers to drape the prepreg in single or multi-robot manufacturing cells [114]. An approach has been proposed for design and implementation of mechatronic complexes that could be used for hybrid manufacturing of mechanical elements and components [115]. The proposed mechatronic complexes could integrate conventional subtractive machine tools with additive technologies. AI, machine learning, IoT with mechatronics enabled smart manufacturing of high-performance materials that are used in critical industries such as aerospace, automotive manufacturing, medical applications and renewable energy [116]. Metallic or synthetic high-performance materials include optimized alloys of stainless steel, nickel and magnesium and nanostructured composites such as Teflon and Chemraz.

For the fabrication of metamaterials and other materials integrated into simple mechatronic components or complex mechatronic systems, particular processes have been developed, using AM systems. Mechatronics methodologies and engineering tools have been used in the instrumentation, modelling, and control of AM systems, while future research efforts are required to make true advancements in AM platforms [117]. With the progress of AM technology, mechatronic components and/or integrated mechatronic devices can be produced incorporating mechanical and electronic functionalities in a sequential process [118,119]. In [118], the authors introduced a process chain for the direct application of conductive structures to the surface of a component made from standard materials using AM techniques. The method was tested and verified using Digital Light Processing as a model AM technique and a glass-filled photopolymer as a material model. In addition, the transferability of the process was demonstrated for other AM processes and materials, such as stereolithography and selective laser sintering. An overview of the seven groups of AM fabricators has been presented in conjunction with the feedstock of the amenable materials to be processed within each group [117]. The materials investigated were polymers, metals, ceramics and composites followed by a survey of their properties suitable for the fabrication of machine elements in mechatronic applications.

With advancements in mechatronics, instead of cartesian AM powder beds, alternative configurations have been investigated and proposed for reducing the processing time to enhance the productivity of AM systems that can be used in the mass production of mechatronic components. Rotary powder beds have been developed for simultaneous laser melting and powder recoating; thus, laser utilization has been improved, as well as other forms of AM, where continuous spiral or helical toolpaths have been demonstrated to improve productivity. In [120], a comparative study between Cartesian and Polar AM architecture was presented, focusing on a mock reluctance motor design that could be used in the electric vehicle industry considering the advancements in magnetic material development for laser powder bed fusion (LPBF). In addition, the limits of productivity are elucidated by exploring the toroidal volume and the number of powder dispensers and lasers. This AM rotary architecture introduces increased complexity, which can be solved by exploring advancements in mechatronics technology.

Subtractive and additive manufacturing (AM), 3D printing, and robotics are rapidly evolving, integrating advanced mechatronic capabilities such as higher automation, real-time self-monitoring diagnostics and observation of the printing process, intelligent control for a wider range of applications, multi-material large scale printing, enhanced precision, material waste reduction, increased productivity and reliability and reduced downtime [121].

In conclusion, fabrication processes have undergone transformative changes in the rapid and customized manufacturing of mechatronic components based on the maturity of materials and mechatronics technologies. This interactivity shows that mechanical and materials technologies are enablers of mechatronics and simultaneously mechatronics is enabling their evolution, which is strong evidence and proof of their coevolution. This interactivity is presented by a diagram in Figure 6, where enabling basic and applied research is required for the development of new smart and soft materials that are produced by manufacturing mechatronic systems.

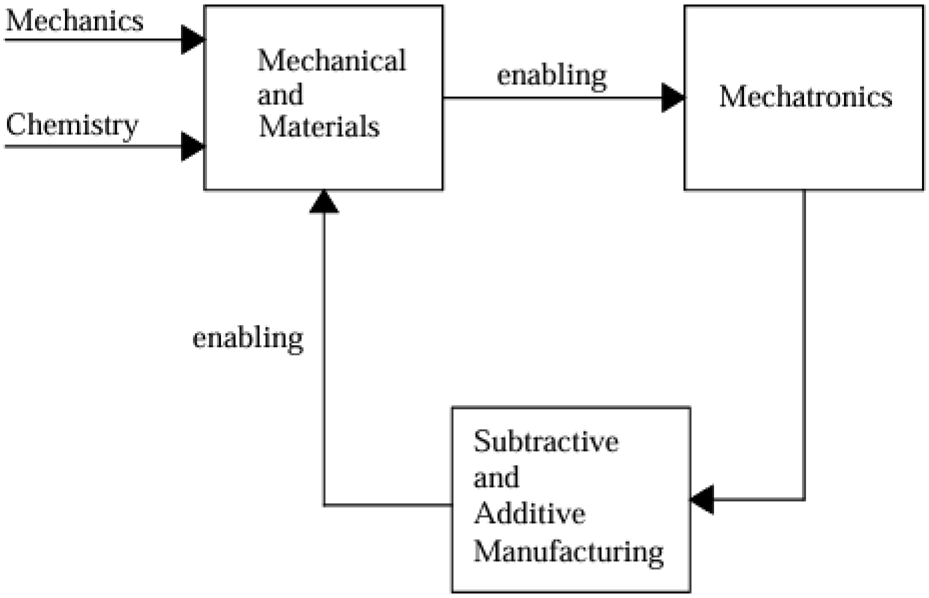

Figure 6. A schematic of the interactivity between mechanical and materials technologies with mechatronics.

doi:10.20944/preprints202606.1021.v1

6. Coevolution of Control and Cybernetics Technology with Mechatronics

In this section, the influence of control and cybernetics technology on mechatronics technology is investigated, as well as the reverse impact of mechatronics to control and cybernetics, under the concept and scope of showing their coevolution.

6.1. Control and Cybernetics as Enabler to Mechatronics

Controllers have been integrated in any mechatronic system from an open loop to more sophisticated current control schemes that should be considered from the conceptual design phase of mechatronic devices and systems [122]. Mechatronic systems have inherent model uncertainties or dynamic behavior changes along their working life and might operate in unstructured environments that can be confronted with proper controller design.

Automatic control and cybernetics technology have emerged as key enablers for engineered systems and among them for mechatronic systems have emerged from the beginning of the appearance of this technology. Control and cybernetics form a scientific and technological field involving research from mathematicians, engineers, physicists, economists, and biologists, which was established in 1960, with the theoretical foundation of servomechanism. The International Federation of Automatic Control (IFAC) was created, and its first World Congress was held in Moscow in 1960 [123].

Usually, simple PID controllers have been applied because they perform considerably well with relatively low tuning and design effort. However, with the increasing complexity of mechatronic systems and working environments uncertainty, a challenge in control engineering is to introduce innovative and advanced control methods. In addition to PID, more sophisticated methods have been developed by researchers such as robust, adaptive, impedance, model predictive control (MPC), optimal, and stochastic. Robust control methods including H-infinity, sliding mode control (SMC), deal with systems uncertainty and working conditions with disturbances. When an accurate model of the system to be controlled cannot be obtained, then adaptive control has been used to adjust its parameters.

Intelligent control methods based on expert systems, fuzzy logic, and neural networks, have been applied in mechatronic systems ranged from micro- and nanoscale to large-scale devices and systems [124]. Emerging intelligent control and automation methods and algorithms are integrated in complex, non-linear, high performance, large scale mechatronic systems enabling them to interact successfully with dynamic environments with high uncertainty [125]. The current high-performance mechatronic systems in terms of efficiency, accuracy, readiness, and operative ability in a variety of environments require advanced control systems as presented in a special issue devoted to new trends in control [126].

Mechatronic systems will continue to grow towards higher complexity and model uncertainty, interconnected, and more influential, in ways that we can’t yet imagine. Integration of machine learning with control theory could be the research direction to resolve the uncertainty and complexity in dynamic modelling of mechatronic systems to be controlled [127]. The growing synergy of cybernetics and control theory and practice with machine learning enabled more intelligent, adaptive and resilient robotics and other advanced complex mechatronic systems. Design and implementation of laboratory prototypes are required for data collection to be used in machine learning, which belongs to mechatronics technology, showing their biliteral influence.

Table 2 presents the interactive influence and coevolution of mechatronics technology with Control and Cybernetics technology, where mechatronics is the driving technology, since it responds to the demand for higher complexity and performance of manufacturing systems and mechatronic devices and systems such as home appliances, aircraft, cars, robots and many other systems used in technological domains and production sectors. On the other hand, Control and Cybernetics technology responded to this demand for high performance advanced systems with the role of enabling technology to mechatronics.

Control and systems theory is closely related to cybernetics, an interdisciplinary theory and technology for studying the structure of regulatory systems. Cybernetics unifies control with communications theory, in a new scientific discipline as defined by Wiener in his famous seminal book [128]. His approach was based on the ability to build devices according to models of living organisms that are capable of effectively reacting in response to environmental stimuli. Cybernetics was characterized by a tendency to universalize the notions of feedback communication, as the underlying principle of the technological and living world, which extended to economy and sociology. Kolmogorov [129] abridged cybernetics as a science devoted to the study of systems of any nature, which can receive, store and process information to use for control of modern mechatronic systems.

Cybernetics is strongly interdisciplinary and multidisciplinary, offering a comprehensive systems approach to analyze complex, nonlinear, multi-agent decentralized, self-organized, and reconfigurable systems, so it is worth noting that such characteristics are present and are expected to represent mechatronic systems [130,131].

Table 2. The interaction of Mechatronics as driver with Control and Cybernetics as enabler.

Mechatronic Systems evolution	Control and Cybernetics evolution
Cyber-Physical (CPS) systems	Cybernetics 2.0: control, communication and organizational aspects.
Systems of Systems structure	
Large scale and higher complexity	Cybernetics: control and communication
Modular structure	Intelligent control: decision making and autonomy
Self-contained modules	Distributed control
Non-linear and model uncertainty	Optimal, stochastic and adaptive control
	Robust control
Embedded electronics integrated	Servomechanisms and feedback control
Simple elecromechanical	

Later the name cybernetics has shown a decline, particularly in USA, even though the interaction between control and communication evolving rapidly around the world in connection with advances in biology and bionics based on AI and computer advancements [132]. In 90s, the notion of cybernetics was revived again to notify the space of communication over computer networks taken the name cyberspace. Considering the modern trends of cybernetics research, the latest development on cybernetics has been presented and analysed as a theory of systems organization and control, called cybernetics 2.0 [133]. Subsequently Cyber Physical Systems appeared to represent the merging of the virtual world of cyberspace with the physical world [134,135]. However, that was the original meaning of cybernetics given by its founders showing the strength of the notion of cybernetics combined with the amazing advances in AI and the Internet, which reached the status of the Internet of Things. CPSs share common methodologies and application domains with the new generation of mechatronics that have undergone transformative transitions considering the balanced synergy of all the enabling disciplines and technologies rather than emphasizing mostly cyberspace and the Internet of Things (IoT).

doi:10.20944/preprints202606.1021.v1

6.2. Mechatronics as Enabler to Control and Cybernetics

Mechatronics gave the floor to control and cybernetics technology to be further developed, since complex and advanced mechatronic systems working in uncertain environments require new, innovative control methods and algorithms. Mechatronic laboratory equipment has been implemented to experimentally test and compare new controllers before being applied to commercial systems [136]. Recently Rapid Control Prototyping (RCP) and Hardware-in-the-Loop (HIL) methodologies have been used in the development, testing and experimental validation of control systems, without the need to realize a full test setup [137]. Hardware-in-the-Loop is a methodology used to test control algorithms in mechatronic laboratory equipment that closely resembles the actual physical system [138,139]. Design and implementation of an experimental HIL testbed has been presented [138], which can be used for rapid prototyping of actuator control techniques, with the ability to test their performance under load and power system transients. A case was presented for control testing and performance evaluation of the designed controller for landing gear under realistic operation conditions, that could be used for testing controllers of other mechatronic systems.

In [139], a HIL setup has been implemented for physical simulation of complex mechatronic systems, which can be used to design and test control techniques and algorithms. This experimental system includes two brushless motors connected by a shaft. The first motor is under test and actuates the system, while the second represents the physical simulator of the dynamic model of the mechatronic system. For the simulation of complex systems, a library of components modelling mechanical and hydraulic systems has been implemented and integrated in the experimental physical setup, which is one example of the influence of mechatronics to control, supporting their coevolution considered and shown in the present work.

Summarizing this section, we could conclude that control and cybernetics technology are critical enablers of mechatronic technology, while mechatronics technology is used to develop experimental laboratories for testing control methods for new mechatronic systems, which demonstrates the mutual interaction and coevolution of the two technologies.

7. Artificial and Embodied Intelligence Coevolution with Mechatronics

In this section, the enabling action of artificial and embodied intelligence on mechatronics evolution as well as the reverse influence of mechatronics on artificial and embodied intelligence are considered demonstrating their coevolution. Of course, artificial and embodied intelligence interact with mechatronics in conjunction with other enabling technologies like electronics and computing, and control and cybernetics, which is considered in some parts of this section.

7.1. Artificial and Embodied Intelligence Enabling Mechatronics

This subsection presents the investigation of the influence of artificial and embodied intelligence to the evolution of mechatronics contributing to transformative changes on the intelligence, autonomy, innovation and performance advances of mechatronic systems.

At the beginning Artificial intelligence (AI) was considered as a pure computer-software discipline developing algorithms for expert systems, learning and cognition trying to emulate the human way of thinking and decision making. Fuzzy logic, neural networks and genetic algorithms are considered as the core theories for AI, but currently deep learning is a challenge particularly as Convolutional Neural Networks (CNNs) could be paired with significant computation resources of ever-growing supercomputers. AI progress has enabled intelligence in various technologies and among them mechatronics [140]. This special issue have presented several papers with control applications of AI in mechatronics, such as electrohydraulic control, and optimal control of dual clutch transmission. Of course, many more intelligent approaches can be found and will be developed in the future with higher learning abilities, imitating human behaviours, for the design, optimization and control of mechatronic systems.

Expert systems and Fuzzy logic have been based on human expertise and rule base developed after expert knowledge extraction and experimentation using linguistic variables instead of numerical ones [141]. These early AI methodologies have been used for mechatronic systems control and decision-making offering improved performance, stability, handling uncertainty and better adaptation to changing conditions compared to well-known control methods requiring models of the system to be controlled [142–144]. However, the design and implementation of Fuzzy logic present parameter tuning difficulties, wide range of experimentation and limitations in generalization that could be mitigated using later advances in artificial intelligence.

In [145], a review has been presented considering AI support from the conceptual to the final phase of the design and implementation of advanced and innovative mechatronic systems. AI facilitates the linking of increasingly diverse disciplines and knowledge domains to support engineers in improving system performance and efficiency and speeding up the development of advanced innovative mechatronic products. AI offers methods and tools for decision support, multi-criteria optimization, prediction quality, modelling, self-monitoring and intelligent control. Thus, AI can bring transformative changes in mechatronic systems behavior, such as adaptability, efficiency, precision, reliability, and autonomy.

Latest advances and rapidly evolving artificial intelligence including neural networks and machine learning methods unlocked advanced capabilities of mechatronic systems and enforced transformative and innovative changes in mechatronics technology [146,147]. Artificial intelligence and deep learning approaches brought new advancements in mechatronic technology enabling mechatronic systems to enhance cognition and perception, self-monitoring, self-optimizing intelligent control, autonomy and decision-making, efficiency, performance, precision and intelligent interaction and adaptation to e environment, in real-time [148,149]. The integration of deep learning techniques into mechatronic systems present several issues to be resolved like data scarcity, model interpretability, real-time processing and power requirements in resource constrained devices.

Embedded AI systems integrate hardware and software engineering and significantly support the development of intelligent resource limited mechatronic devices and systems [150]. Real-time data analysis is performed with embedded AI, while reduced data transmission and latency in time-critical applications, increased bandwidth and energy efficiency have been achieved. An active area of research has been focused on deep neural network optimization techniques and specialized AI hardware accelerators that are critical enablers of the success of embedded AI in mechatronics. Recently [151], aspects of methods and applications have been investigated for deploying artificial intelligence on embedded devices, such as AI algorithms and models on resource-constrained hardware, computation speed up for embedded devices, neural network compression, and application models of embedded AI. To overcome the resource limitations in memory, data processing and power requirements, artificial intelligence was deployed on edge computing components of mechatronic systems and methods for optimizing neural networks have been applied [152]. The potential of analogue memories has been considered to improve computational speed and power efficiency compared to digital processing.

By increasing the utilization of edge AI for embedded systems, a new era is opened in mechatronic applications. Various techniques have been used such as developing lightweight neural networks, model pruning, and neural architecture search to develop more energy-efficient and faster with reduced latency AI applications in mechatronic systems. It is also considered to use Tensor Processing Units for real-time execution of neural network workloads close to sensors and actuators [153].

In Table 3, the enabling influence of AI to mechatronics is presented by selecting transformative changes of both technologies, to higher levels of maturity along their coevolution. The arrow shows the direction of their advancements and improvements. The integration of AI technology in mechatronics increases the intelligence, precision, and autonomy towards innovative transformation in various conventional manufacturing applications as well as in the context of Industry 4.0 and 5.0 [6,7]. However, this investigation is beyond the scope of the present study. In widespread and well-known approaches and applications, the disciplines involved in AI are computer science, linguistics, perception, and psychology. In 80's, embodied intelligence attracted the attention of researchers and in addition to the previous disciplines new ones have been involved such as mechatronics engineering, robotics, biology and neuroscience [154]. Under this consideration, artificial and embodied intelligence contribute synergistically to the evolution of mechatronics, which is an enabling technology for AI advancement showing their mutual effects and interdependence. The progress of embodied intelligence is expected to play a vital role in the evolution of mechatronics technology, because intelligence shifts from a computational to embodiment perspective, which is compatible with mechatronics technology as investigated and revealed in the next subsection. Mechatronics technology could get through a qualitatively new innovative era, since embodied intelligence technology would enable mechatronic devices and systems to step up from programmed autonomy to learning by experiencing successful interaction with the physical and technical environment.

Table 3. Artificial and embodied intelligence enabling Mechatronics.

	Artificial Intelligence	Mechatronics
↑	Quantum AI	Embodied intelligence
	Edge AI	Intelligent systems
	Deep learning	Embedded processing
	Neural learning	Autonomous systems
	Fuzzy logic	Decision making
	Expert Systems	Automation

7.2. Mechatronics as Enabler to Artificial and Embodied Intelligence

Mechatronics technology has a considerable contribution to artificial and embodied intelligence advances and innovations, since mechatronic methodologies have been used for design and fabrication of electronics and computing systems for running artificial intelligence and machine learning algorithms and building systems with embodied intelligence. The contribution of mechatronics to electronics and computing is presented in subsection 3.2, while this subsection deals with the influence of mechatronics on the evolution of embodied intelligence, in conjunction with other enabling technologies.

The intelligence of biological organisms emerges through "brain" and "body" interacting with the environment via sensory feedback, the nervous system, low-level sensory-motor processes, self-monitoring, self-control and autonomy; therefore, they could cope with uncertainty, changing conditions, or unknown environments and recover from failures. In analogy, artificial embodied intelligence is not confined to the computing "brain" and algorithms, but it involves the entire bodily structure and interaction with the physical, technical and virtual environment. Embodied intelligence refers to technical systems that possess the ability to perceive the environment and its state through multiple sensors and adapt and interact with the environment via their sensory-motor controls.

doi:10.20944/preprints202606.1021.v1

However, these systems are far inferior compared to biological organisms, considering their structure and entire status, and their ability to complete unknown or previously unseen tasks, or to exploit their interactions with the environment [155]. The authors of the last paper presented the current trends and future challenges of embodied intelligence in technical systems, such as neuroscience and cognition, bioinspired soft robots, development of smart and/or soft materials, and a unified methodology to integrate embodied intelligence into technical systems, in other words, into mechatronics technology.

Mechatronics has a pivotal role in design and development, fabrication and operation of systems involving embodied intelligence, since it reached a maturity level with the coevolution of the presented enabling technologies in the previous sections. Soft robots and dextrous artificial hands with embodied intelligence attracted the attention of mechatronics research and engineering community. Despite the impressive advances and innovations in robotics research and development, a key mechatronic challenge is the development of robot hands with high dexterity to perform complex manipulation of objects with various shapes, rigid, flexible, fragile or sensitive like fruits. The integration of embodied intelligence could overcome some limitations in design, fabrication, control, and performance to implement effective dexterous robotic manipulators and hands. An approach based on the idea of iterative co-design has been presented including simultaneous design iteration of the hardware and controller for multi-fingered hands [156]. This approach exploits embodied intelligence to achieve the requested performance by designing the brain (controller) and body (mechatronic design) simultaneously, which extends sensing and perception at physical and computational level simultaneously. Mechatronic methods have been used to design and implement dextrous robot hands with a combination of tactile sensors for handling fragile objects [157] and with soft fingers for strawberry harvesting [158], using learning fuzzy control.

In [159], the latest and current research advancements of embodied intelligence integrated in soft robotics have been presented along with detailed reviews of advanced research on embodied morphological computation, embodied artificial evolution, perception, control, and decision making, as well as the potential trends and opportunities for future research on embodied intelligence. Embodied intelligence should be deeply integrated in mechatronics design, since it is highly relevant to mechanisms and materials. For example, by integrating embodied intelligence into mechatronics designing of the robot body, we could achieve flexible and stable locomotion and/or dextrous manipulation, whereas it would be very difficult or impossible to achieve such behavior by relying only on advanced control algorithms and powerful computers.

An algorithmic framework called Multi-Level Evolution (MLE) has been introduced for the three-level evolutionary development of robots with embodied intelligence [160]. At the lowest level, materials have been selected, then components have been created by selecting one or more materials into a geometry. Finally, the authors created robots by integrating components into template “body plans” and evaluated them for a task in selected environments. New candidate materials and components have been investigated during the evolutionary process, by continually increasing the range of robot designs.

Using a simplified block diagram, Figure 7 presents the mechatronics technology contribution to the development of systems with integrated embodied intelligence capable of interacting with their environment. Embodied intelligence integrates computation and hardware such as perception, morphology, learning and action modules in appropriate synergy [161], that could be designed and implemented using mechatronic approaches and methodologies. Wearable devices, and metamorphic robots are some examples of mechatronic components or systems integrating embodied intelligence. Robot hands for high dexterity should mimic the embodied intelligence structure incorporated in human hand, with multiple proprioceptive tactile sensors and fusion for the perception, local signal processing and sensory-motor response with short latency, high degrees of freedom, compliance, high force and energy density compared to size and mass in human muscles. This is a real mechatronic challenge requiring intensive research, development and experimental work showing the need for the coevolution of mechatronics with its enabling technologies for transformative changes.

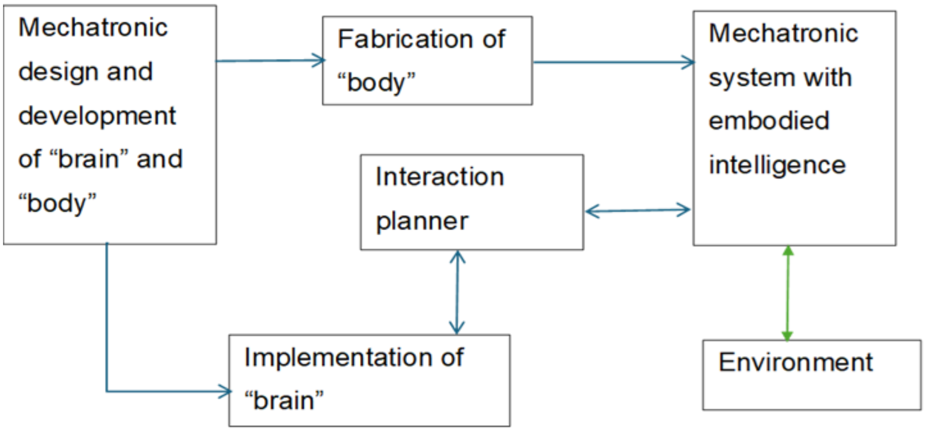

Figure 7. Contribution of mechatronics technology and engineering to embodied intelligence.

Using embodied intelligent technology, morphological computing can offload the computation from a controller onto the body of mechatronic systems reducing the controller complexity. Despite the progress in perception and Large Language Models (LLM), the main challenges for embodied intelligence are related to real-time intelligent interaction with the physical environment. Development of flexible reconfigurable mechanisms, and soft smart materials provide new opportunities for morphological computation. A method has been proposed for the co-design of embodied intelligence in a synergetic and structured way from sensors and mechanical hardware components such as propulsion systems to software modules like control and perception elements [162]. This approach is based on the synergy of heterogeneous engineering disciplines, allowing analytical and simulation-based modeling techniques and requiring mechatronics interdisciplinarity.

Embodied intelligence faces significant challenges for implementation in current smart manufacturing systems, since most of the automatic, intelligent components and sub-systems should have the capability for physical interaction with objects, mechanisms, and humans. Therefore, the manufacturing entities like robots, machine tools, and production equipment should have "bodily" intelligence to be integrated and interact within higher levels, such as combinations of multiple embodied intelligent entities forming new advanced with higher autonomy production lines, which are complex mechatronic systems [163].

The complexity of mechatronic systems is increasing, and their dynamic modelling and working environment are not well structured, present time changes and model uncertainties, which are great challenges that could be faced using embodied intelligence progress as a critical enabling technology for the evolution of mechatronics. In parallel, mechatronic advances enable embodied intelligence evolution by providing experimental platforms and manufacturing systems, such as bioinspired robots and AM to produce smart and soft materials necessary for building embodied intelligent systems. In summary, the coevolution of mechatronics with artificial and particularly embodied intelligence is imperative for the technological progress in intelligent manufacturing systems and intelligent machines and systems that could be used in any technological domain and our daily lives.

8. Discussion on Mechatronic Challenges and Future Coevolution Trends

Mechatronics is a wide range technological domain supporting the design, development and manufacturing of almost any technological system, starting from sophisticated complex manufacturing lines to most advanced intelligent machines like robots, cars, airplanes, medical and home devices. In the relevant literature mechatronics is considered as an interdisciplinary and transdisciplinary engineering field that benefited from its enabling technologies in a unidirectional manner. However, this paper shows that mechatronics has reached a high maturity level after transformative changes and reached the status of comprehensive science and technology with related research topics, methodologies and tools in mutual interaction and coevolution with the presented enabling technologies. In this investigation, apart from the bidirectional interaction between enabling technologies and mechatronics, the concurrent interaction between enabling technologies is considered either directly or via mechatronics, which is considered as the master technology playing a central role in their coevolution.

The future trends and challenges in mechatronics coevolution should be considered in conjunction with the expected research and advancements and the incremental knowledge accumulation in enabling technologies to reach maturity levels for transformative changes. Some of the main challenges and trends closely connected to the coevolution of mechatronics are briefly presented below.

In electronics and computing, advanced miniaturized electronics with low power consumption; materials for quantum, neuromorphic and embedded system-on-chip (SoC) processing, and advanced mechatronic systems for IC production and packaging are required. In terms of hardware implementation, a major change is required to address the computational needs of the embodied intelligence integrated into mechatronic systems.

The coevolution of enabling technologies with mechatronics has reached a level that permits the development of self-contained hardware and software modules that could be used in the modular design and structure of complex mechatronic systems. Examples of self-contained actuator modules have been reported in research publications as well as in commercial applications [164,165]. Highly integrated sensor-actuator-controller units, and soft actuators with sensing capability and programmable actuation performance or self-sensing antagonistic SMA actuators with controllers have been used or proposed in robotics development. In the automotive industry, self-contained actuators include electric motors, pumps and hydraulic cylinders with controllers and sensing abilities used for power steering. A platform was developed for building modular Wireless Sensor and Actuator Network (WSAN) nodes with the desired functionality by integrating plug-and-play hardware modules, including a variety of sensors, actuators, communication interfaces, power sources and other peripherals [166]. More research and development efforts are needed to build new mechatronic modules with self-monitoring, self-contained capabilities and standard interfaces, which will dramatically improve the design and manufacturing of higher level large mechatronic systems.

Another trend in mechatronic systems is the integration of research advancements in biology and medical science, to formulate biomechatronics [167]. The development of biomimetics, and biomedical engineering, will enable biomechatronics advancement in an interactive mode between the life sciences and mechatronics engineering for their coevolution.

Higher levels of perception and cognition are achieved via sensing fusion and embedded AI, considering all the known sensing abilities of the human body-brain integrity. Sensors and actuators are integrated with embedded high-speed processing to achieve low latency, minimal energy consumption and configuration design by transferring concepts from biological systems research. Using soft and smart materials, sensors and actuators have been integrated into a mechatronic intelligent sensor-actuator module with advanced applications in pliable prosthetic elements such as hands and fingers.

Edge computing requires purpose built or customized high speed and power efficiency chips for specific applications like embodied intelligence. Their fabrication presents several technical challenges related to complex architectures for the integration of a variety of chips and their connectivity as well as miniaturization, modular assembly of components and flexible manufacturing systems to face the demand for customized chips [168]. We have seen that quantum computing is a highly promising technology for accelerating computing power with high power efficiency. A challenge for mechatronics technology is the design and development of systems for fabrication of computing in quantum dots, since systems relaying on electron-beam lithography suffer from poor uniformity and low yield. An alternative fabrication facility was proposed using all-optical lithography to overcome these limitations [169]. The current fabrication systems do not have the capability to optimize the production of high-coherent devices, because they are not compatible with the processes used for production of supercomputing qubits. An approach was proposed for fabrication of superconducting transmon qubits in a 300 mm complementary metal–oxide–semiconductor (CMOS) pilot line with resulting relaxation and coherence times exceeding 100 μs [170]. The presented industry-scale process has satisfactory performance and yield using just optical lithography and reactive-ion etching, metal lift-off, angled evaporation and electron-beam writing. These examples of the required advances in mechatronics systems for manufacturing quantum computing chips show the worth of understanding the coevolution of electronics and computing with mechatronics, since the next generation of fabrication systems will use the supercomputing power of quantum chips in virtuous cycle of innovations.

Nanotechnology is an emerging scientific and technological area that could enable mechatronics to advance in a new direction of evolution to develop Nanomechatronic Systems for medical and other applications. As an example, a structural-parametric model, with a parametric structural schematic diagram, and transfer functions of the electro-elastic actuator have been obtained, that can be used for the control of mechatronics systems in nanoscience [171]. With the synergy of nanotechnology and research in supramolecular chemistry advances in molecular mechatronics are expected to be the basis for the development of structural elements such as nanoparticles, nanotubes, nanowires, molecular rotors, molecular receptors and molecular machines, as well as quantum computing for embedded mechatronics [172,173].

Self-powered sensing and computation are other future challenges that will enable a new transformative level of artificial cognitive capabilities in miniaturized meta-mechatronic systems. This challenge should be accompanied by basic research to build a foundation for mechanical metamaterial development and mechatronic systems for their production. The control complexity could be simplified by the development of advanced smart and soft materials in the sense of embodied intelligence.

The implementation of embodied intelligence in mechatronic devices and complex mechatronic systems faces serious challenges such as fusing data from diverse sources, real-time low latency local processing, AI inference and autonomous neural network training, successful sensory-motor interaction with other mechatronic components and the environment. To resolve these challenges mechatronic methodologies for designing and fabrication should be proposed. A representative recent work deals with the implementation of embodied intelligence for empowering customized manufacturing, with emphasis on architecture challenges [174]. To address the identified challenges, they proposed architecture, including four interconnected information loops to integrate multi-source data, intelligent equipment, and manufacturing resources to establish an evolvable embodied factory model showing the need for consideration of the interaction and coevolution of embodied intelligence and mechatronics. Another case showing the required collaborative work and interaction between the considered enabling technologies and mechatronics, deals with the miniaturization of 3D mechatronic integrated device components fabricated by using stereolithography (SLA) 3D-printing technology [175].

Despite the current progress in embodied intelligence, namely morphological computation, sensory-motor coordination and embodied cognition, there are still open issues in each research topic. For example, the achievement of advanced sensory-motor coordination capabilities requires the use of other learning techniques that rely on short-term feedback, which should be revealed by relevant research. Other significant research is related to the theoretical elaboration of various morphological computation and sensory-motor coordination's roles and the need to illuminate the relationship between processes occurring due to mechatronic systems interactions with the environment and processes inside its body.

The study and investigation of technologies coevolution could be used to identify the main challenges and future trends of both enabling and enabled technologies like the ones considered in this study. The mutual interaction of these technologies under the conceptualization of coevolution empowers the rate of progress and advances towards new maturity levels, transformative changes and innovations.

9. Conclusions and Future Work

In this study, the interdependence and bidirectional reciprocal interaction be-tween enabling technologies, namely electronics and computing, sensors and motors, control and cybernetics, mechanics and materials and embodied artificial intelligence and mechatronics are investigated showing their coevolution. The presented analysis revealed that the coevolution of mechatronics is based on the progress and synergy of all enabling technologies with mechatronics technology. It is shown that the trans-formative changes to higher levels of maturity are based on the incremental knowledge accumulation with mutual interaction and coevolution between enabling technologies and mechatronics technology.

The coevolution of mechatronics technology with its enabling technologies is expected to provide a framework for new methods and tools for design and fabrication of advanced intelligent devices and systems with higher levels of flexibility, autonomy, adaptability, resilience, agility, reconfigurability, self-awareness, and self-learning abilities.

In future work, for the progress of mechatronics systems, it is worth investigating the transformative changes in mechatronics technology, considering the structure, characteristics, abilities and design methodologies and tools of mechatronic systems relative to the maturity levels of the presented enabling technologies. For example, the coevolution of Computer Aided Design (CAD) systems, simulators, digital twins and other digital tools that are used for design of mechatronic systems. New enabling technologies and drivers that coevolve with mechatronics technology should be investigated. In addition, much attention should be given to the coevolution of mechatronics with technological production domains such as manufacturing, automotive, aerospace, agriculture, medical and home equipment to fulfil human needs.

Funding: I have no sponsorship or funding in this work.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to thank all the authors of the refenced papers for their valuable work. .

Conflicts of Interest: The author declares no potential conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
IT	Information Technology
RTOS	Real-Time Operating System
FPGA	Field-Programmable Gate Array
ASIC	Application-Specific Integrated Circuit
AM	Additive Manufacturing
SMA	Shape Memory Alloys
MPC	Model Predictive Control
SMC	Sliding Mode Control
IoT	Internet of Things
SoC	System-on-Chip

VLSI	Very Large-Scale Integration
ULSI	Ultra Large-Scale Integration
EUV	Extra Ultraviolet
DUV	Deep Ultraviolet
IMU	Inertial Measurement Unit
DRIE	Deep Reactive Ion Etching

References

1. Mitleton-Kelly, E., Davy, L.K.. The Concept of 'Co-evolution' and Its Application in the Social Sciences: A Review of Literature. In: Mitleton-Kelly, E. (eds) Co-evolution of Intelligent Socio-technical Systems. Understanding Complex Systems. Springer, Berlin, Heidelberg, 2013. https://doi.org/10.1007/978-3-642-36614-7_3
2. Zhang Y., The map is not the territory: coevolution of technology and institution for a sustainable future, Current Opinion in Environmental Sustainability 2020, 45:56–68
3. Muñoz F., The coevolution of technology, markets, and culture: the challenging case of AI , Review of Evolutionary Political Economy, 2024, https://doi.org/10.1007/s43253-024-00126-0
4. Shaoan H., Kainan H., The Co-Evolution of Technology and Institution. In: Yinxing, H. (eds) Dictionary of Contemporary Chinese Economics. Springer, Singapore,2025. https://doi.org/10.1007/978-981-97-4036-9_182
5. Coccia M., Watts J., A theory of the evolution of technology: Technological parasitism and the implications for innovation management, Journal of Engineering and Technology Management, Volume 55, 2020.
6. Bigliardia B., Bottania E., Casella G., Enabling technologies, application areas and impact of Industry 4.0: a bibliographic analysis, International Conference on Industry 4.0 and Smart Manufacturing (ISM 2019), Procedia Manufacturing 42 (2020) 322–326.
7. Bécue A., Gama J., Brito P. Q., AI's effect on innovation capacity in the context of industry 5.0: A scoping review, Artificial Intelligence Review (2024) 57:215
8. Qi Q., Tao F., Hu T., Anwer N., Liu A., Nee Y., Enabling technologies and tools for digital twin, Journal of Manufacturing Systems, Volume 58, Part B, January 2021, Pages 3-21
9. Colakovi A., Hadžialic M., Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues. Computer Networks, Volume 144, 24 October 2018, Pages 17-39
10. Marion, T., Friar, J., 'The Role of Enabling Technologies in Transformative Innovation', in Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft, The Netherlands, 5-8 August 2019. DOI:10.1017/dsi.2019.135
11. Hewit J., Mechatronics design - The key to performance enhancement, Robotics and Autonomous Systems 19 (1996) 135-142
12. Nnodim C. T., Arowolo M. O., Agboola B. D., Ogundokun R. O., Abiodun M. K., Future Trends in Mechatronics, IAES International Journal of Robotics and Automation (IJRA), Vol. 10, No. 1, March 2021, pp. 24~31
13. Habib M., Mechatronics A Unifying Interdisciplinary and Intelligent Engineering Science Paradigm, IEEE Industrial Electronics Magazine · February 2007, DOI: 10.1109/MIE.2007.901480 · Source: IEEE Xplore.
14. Saiful Islam N. H., Al Mahmud Z., Tasnim R., Hossain A., Mobarak H., Advances of materials science in MEMS applications: A review, Results in Engineering, 22 (2024) 102115.
15. Bahl S., Nagar H., Singh I., Sehgal S., Smart material types, properties and applications: A review, Materials Today: Proceedings 28 (2020) 1302–1306
16. Trigona C., Graziani S., and Baglio S., Changes in sensor technologies during the last ten years: Evolution or revolution? IEEE Instrumentation & Measurement Magazine, September 2020
17. Han C., Jeong Y., Ahn J., Kim T., Choi J., Ha J., Kim H., Hwang S., Jeon S., Ahn J., Hong J., Kim J., Jeong J., and Park I., Recent advances in sensor–actuator hybrid soft systems: core advantages, intelligent applications, and future perspectives, Adv. Sci. 2023, 10, 2302775, DOI: 10.1002/advs.202302775

18. Zheng C., Qin X., Eynard B., Li J., Baia J., Zhang Y., and Gomes S., Interface Model-Based Configuration Design of Mechatronic Systems for Industrial Manufacturing Applications, Robotics and Computer-Integrated Manufacturing, Volume 59, October 2019, Pages 373-384
19. Spaggiari A, Castagnetti D, Golinelli N, Dragoni E, Scirè Mammano G., Smart materials: Properties, design and mechatronic applications., Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 233 (2019): 734 - 762.
20. Mlambo P., Simango D., Chiweshe E., Dera H., Jonathan E., Methodologies for Mechatronic Systems Design: Attributes and Popularity, Zimbabwe Journal of Science and Technology pp123-133 Vol.12, 2017.
21. Moulianitis, V.C., Aspragathos, N.A., Introduction to the special issue on Theories and Methodologies for Mechatronics design, Mechatronics 20 (8), pp. 825-826, 2010
22. Moulianitis V.C., Zachiotis G.-A.D., and Aspragathos N.A., A new index based on mechatronics abilities for the conceptual design evaluation, Mechatronics, Volume 49, February 2018, Pages 67–76.
23. Wang W., Yang R. and Liu M., Design and Fabrication of Micro/Nano Sensors and Actuators, Micromachines 2024, 15, 674.
24. Berri, P.C.; Dalla Vedova, M.D.L.; Maggiore, P.; Riva, G., Design and Development of a Planetary Gearbox for Electromechanical Actuator Test Bench Trough Additive Manufacturing, Actuators 2020, 9, 35
25. Esashi M., MEMS development focusing on collaboration using common facilities: a retrospective view and future directions, Microsystems & Nanoengineering, (2021) 7:60
26. Kuru T. K., and Yetgin H., Transformation to Advanced Mechatronics Systems Within New Industrial Revolution: A Novel Framework in Automation of Everything (AoE) IEEE Access · March 2019, DOI: 10.1109/ACCESS.2019.2907809
27. Cintra Faria A.C.; Barbalho S.C.M., Mechatronics: A Study on Its Scientific Constitution and Association with Innovative Products. Appl. Syst. Innov. 2023, 6, 72. https://doi.org/10.3390/ asi6040072
28. Bigliardia B., Bottania E., Casella G., Enabling technologies, application areas and impact of Industry 4.0: a bibliographic analysis, International Conference on Industry 4.0 and Smart Manufacturing (ISM 2019), Procedia Manufacturing 42 (2020) 322–326.
29. SMART, Technology Roadmap Sep 8, 2019, www.smarteureka.com
30. Eumecha pro, European Mechatronics for a new Generation of Production Systems —The Roadmap, The FP6 Coordination Action (April 2005 - June 2007), www.eumecha.org
31. Xiang W., Le Fang K., Han F., He D., and Han Q., Advanced Manufacturing in Industry 5.0: A Survey of Key Enabling Technologies and Future Trends, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, VOL. 20, NO. 2, FEBRUARY 2024
32. Md. Mizanur Rahman, Farhan Mahbub, Rumana Tasnim, Rezwan Us Saleheen, Editors, Mechatronics, Fundamentals and Applications, Book, Springer, 2024
33. Penasa O., Plateaux R., Patalano S., Hammadi M., Multi-scale approach from mechatronic to Cyber-Physical Systems for the design of manufacturing systems, Computers in Industry 86 (2017) 52–69.
34. Mekid S., Schlegel T., Aspragathos N., Teti R., Foresight Formulation in Innovative Production, Automation and Control Systems, Foresight Journal, Vol 9 No 5, 2007, pp. 35-47
35. Krupczak Jr., Systems Transforming Materials, Energy, and Information. In: Understanding Technological Systems. Synthesis Lectures on Engineering, Science, and Technology. Springer, Cham. (2024). https://doi.org/10.1007/978-3-031-45441-7_2
36. Norgaard, R.B., 1984. Coevolutionary agricultural development. Economic Development and Cultural Change 32 (3), 525–546.
37. Kallis G., Norgaard R. B., Coevolutionary ecological economics, Ecological Economics 69 (2010) 690–699
38. Libeskind-Hadas, R. Tree Reconciliation Methods for Host-Symbiont Cophylogenetic Analyses. Life 2022, 12, 443
39. Nikolić G., Dimitrijević B., Nikolić T., Stojčev M., Fifty Years of Microprocessor Evolution: From single CPU to Multicore and Manycore Systems, FACTA UNIVERSITATIS Series: Electronics and Energetics Vol. 35, No 2, June 2022, pp. 155-186, https://doi.org/10.2298/FUEE2202155N

40. TATA, Trends and Implications in Embedded Systems Development, 2009 Tata Consultancy Services Limited, http://www.tcs.com/sitecollectiondocuments/white%20papers/tcs_hitech_whitepaper_Trends-Implications-Embedded-Systems-Development.pdf
41. Przybył, A., FPGA-Based Optimization of Industrial Numerical Machine Tool Servo Drives, Electronics 2023, 12, https://doi.org/10.3390/electronics12173585
42. Luo S., Analysis of the current situation of mechatronics and electronic chips, Academic Journal of Engineering and Technology Science, ISSN 2616-5767 Vol.5, Issue 11: 1-8, DOI: 10.25236/AJETS.2022.051101
43. Ou W., Xiao S., Zhu C., Han Wand Zhang Q., An overview of brain-like computing: Architecture, applications, and future trends. Front. Neurorobot. Volume 16 - 2022 | https://doi.org/10.3389/fnbot.2022.1041108
44. Gao P., Adnan M., Overview of emerging electronics technologies for artificial intelligence: A review, Materials Today Electronics 11 (2025) 100136
45. Jang H., Biswas S., Lang P., Bae J. , Kim H., Organic synaptic transistors: Biocompatible neuromorphic devices for in-vivo applications, OrganicElectronics127(2024)107014
46. Xie Z., Zhao Z., and Avila R., Structural Design of Flexible and Stretchable Electronics, Mechanics of Flexible and Stretchable Electronics, First Edition. Edited by Yong Zhu and Nanshu Lu. ©2025WILEY-VCHGmbH.Published2025 by WILEY-VCHGmbH.
47. Cirstea, M.; Benkrid, K.; Dinu, A.; Ghiriti, R.; Petreus, D. Digital Electronic System-on-Chip Design: Methodologies, Tools, Evolution, and Trends. Micromachines 2024, 15, 247. https://doi.org/ 10.3390/mi15020247
48. Beghi A., Marcuzzi F., Martin P., Tinazzi F., Zigliotto M., Virtual prototyping of embedded control software in mechatronic systems: A case study, Mechatronics 43 (2017) 99–111
49. Morales I. H., Brief overview of embedded systems for Industry 4.0 Applications and Networks, 2023 IEEE Integrated STEM Education Conference (ISEC).
50. Sonko S., Daudu C. D., Osasona F., Monebi A. M., Etukudoh E. A., and Atadoga A., The evolution of embedded systems in automotive industry: A global review, World Journal of Advanced Research and Reviews, 2024, 21(02), 096–104.
51. Ajani T. S., Imoize A. L., and Atayero A. A., An Overview of Machine Learning within Embedded and Mobile Devices Optimizations and Applications, Sensors, June 2021 DOI: 10.3390/s21134412
52. Li J., Overview of the development of chip manufacturing technology, Proceedings of the 6th International Conference on Computing and Data Science. 2024.
53. Song F.; Liu Y.; Dong Y.; Chen X.; Tan J., Motion Control of Wafer Scanners in Lithography Systems: From Setpoint Generation to Multistage Coordination, IEEE Transactions on Instrumentation and Measurement (Volume: 73), 17 June 2024
54. Chowdhury H., Semiconductor Manufacturing Process Improvement Using Data-Driven Methodologies, October 2023, DOI: 10.20944/202310.0056.v2
55. Wu Y., Xiao Z., The Recent Progress of Lithography Machine and the State-of art Facilities, Highlights in Science, Engineering and Technology, Volume 5 (2022)
56. Park J. J., Kim M., and Ko S. H., Laser-Based Process Development for Flexible and Stretchable Electronics, Mechanics of Flexible and Stretchable Electronics, First Edition. Edited by Yong Zhu and Nanshu Lu. ©2025WILEY-VCHGmbH.Published2025 by WILEY-VCHGmbH.
57. Gengenbach U., Ungerer M., Koker L., Reichert K., Stiller P., Allgeier S., Köhler B., Zhu X., Huang C., Hagenmeyer V., Automated fabrication of hybrid printed electronic circuits, Mechatronics 70 (2020) 102403
58. Song Y., Gui C., Huo Z., Lee S. W., Liu S., Mechanical system and dynamic control in photolithography for nanoscale fabrication: A critical review, Int J Mech Syst Dyn. 2021; 1:35–51.5.
59. Kim M., IN-DEPTH ANALYSIS OF MECHATRONICS AND ELECTRONIC CHIP INNOVATIONS Ayden International Journal of Basic and Applied Sciences, Volume 11(4), 2023 | ISSN: 2997-4372
60. Pawlak A.M., Sensors and actuators in mechatronics: Design and applications, January 2017, DOI: 10.1201/9781315221632

61. Channi H. K., Role of Data Acquisition, Sensors, and Actuators in Mechatronics Industry, in book, Computational Intelligent Techniques in Mechatronics, Kolla Bhanu Prakash, Satish Kumar Peddapelli, Ivan C. K. Tam, Wai Lok Woo and Vishal Jain (eds.) (83–108) © 2024 Scrivener Publishing LLC
62. AMA Association for Sensor Technology, Trends in Future-Oriented Sensor Technologies, 2014, www.ama-sensorik.de
63. Singh R., Gupta R., Bansal D., Bhateria R., and Sharma M., A Review on Recent Trends and Future Developments in Electrochemical Sensing, ACS Omega 2024 9 (7), 7336-7356, DOI: 10.1021/acsomega.3c08060
64. Coccia M., Roshani S. and Mosleh M., Evolution of Sensor Research for Clarifying the Dynamics and Properties of Future Directions, Sensors 2022, 22, 9419. https:// doi.org/10.3390/s22239419
65. Pirzada M., and Altintas Z., Sensor technology: past, present, and future, Advanced Sensor Technology, 2023 Elsevier Inc. DOI: https://doi.org/10.1016/B978-0-323-90222-9.00006-6
66. Aldawood G., Bardaweel H., Self-Powered Self-Contained Wireless Vibration Synchronous Sensor for Fault Detection, Sensors (Basel), 2022 Mar 18;22(6):2352. doi: 10.3390/s22062352
67. Dera P., Talaśka T., Długosz R., A new, cost-efficient modular sensor platform for IoT and predictive maintenance in industrial applications, Journal of Computational and Applied Mathematics Volume 473, February 2026, 116777
68. Pons J. L., Actuators in motion control systems: mechatronics, chapter in Emerging Actuator Technologies: A Micromechatronic Approach, 2005 John Wiley & Sons, Ltd
69. Okyay A., Erkorkmaz K., Khamese M. B., Mechatronic design, actuator optimization, and control of a long stroke linear nano-positioner, Precision Engineering, 52 (2018) 308-322.
70. Shankar NVS, Kamma T. K., Krishna M., Ch H., Kumar, Shalem B., Smart Actuators: A Review, Proceedings of the International Conference on Industrial Engineering and Operations Management Rome, Italy, August 2-5, 2021.
71. Tang X., Li H., Ma T., Yang Y., Luo J., Wang H., Jiang P., A Review of Soft Actuator Motion: Actuation, Design, Manufacturing and Applications, Actuators 2022, 11, 331. https://doi.org/10.3390/act11110331
72. Kim M.-S, Heo J.-K., Rodrigue H., Lee H.-T., Pané S., Han M.-W., Ahn S.-H., Shape Memory Alloy (SMA) Actuators: The Role of Material, Form, and Scaling Effects, Advanced Materials, Volume35, Issue33, August 17, 2023
73. Li C.; Feng Y.; Yoong H.-P.; Liang M.; Chen J., Working Properties of Compliant Actuators Based on Magnetorheological Elastomer, 2021 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM)
74. St-Jean A., Dorval F., Plante J.-S., and Lussier-Desbiens A., Magnetorheological-Actuators: An Enabling Technology for Fast, Safe, and Practical Collaborative Robots, IEEE TRANSACTIONS ON ROBOTICS, VOL. micro40, 2024
75. Li M. and Zhang Q., Adaptive Robust Fuzzy Impedance Control of an Electro-Hydraulic Actuator, Appl. Sci. 2022, 12, 9575. https://doi.org/10.3390/app12199575
76. Ahmad Fuaad M.R., Hasan M., Ahmad Asri M.I., Mohamed Ali M. S., Microactuators technologies for biomedical applications. Microsyst Technol 29, 953–984 (2023). https://doi.org/10.1007/s00542-023-05489-8
77. Mohith S., Upadhya A., Navin K., Kulkarni S. and Rao M., Recent trends in piezoelectric actuators for precision motion and their applications: a review, December 2020Smart Materials and Structures 30(1):013002 (36pp), DOI: 10.1088/1361-665X/abc6b9
78. Zhou X., Wu S., Wang X., Wang Z., Zhu Q. , Sun J., Huang P., Wang X., Huang W., Lu Q., Review on piezoelectric actuators: materials, classifications, applications, and recent trends, Front. Mech. Eng. 2024, 19(1): 6 https://doi.org/10.1007/s11465-023-0772-0
79. Morkvenaite-Vilkonciene I., Bucinskas, V.; Subaciute-Zemaitiene, J.; Sutinys, E.; Virzonis, D.; Dzedzickis, A., Development of Electrostatic Microactuators: 5-Year Progress in Modeling, Design, and Applications. Micromachines 2022, 13, 1256. https://doi.org/10.3390/ mi13081256
80. Kritikou G., Aspragathos N. "Micro-Manipulation Methods and Assembly of Hexagonal Microparts on a Programmable Platform with Electrostatic Forces", International Journal of Mechanics and Control, l. 20, No. 01, pp. 71-80 (2019)

81. Rader S., Kaul L., Weiner P. and Asfour T., Highly Integrated Sensor-Actuator-Controller Units for Modular Robot Design 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM) Munich, Germany, July 3-7, 2017
82. Bleicher F., Biermann D., Drossel W.-G., Moehring H.-C., Altintas Y., Sensor and actuator integrated tooling systems, CIRP Annals, Volume 72, Issue 2, 2023,
83. Wan Z., Fu Y., Wang S., Wei R., Wang Y., Sensor-actuator integration in intelligent devices: from functional synergy to emerging application, Composites Part B: Engineering, Volume 312, 2026,
84. Adeleke A. K., Olu-lawal K. A., Portillo Montero D. J., Olajiga O. K. and Ani E. C., The intersection of mechatronics and precision engineering: Synergies and future directions, International Journal of Science and Research Archive, 2024, 11(01), 2356–2364.
85. Dezaki M. L., Bodaghi M., A Review of Recent Manufacturing Technologies for Sustainable Soft Actuators, International Journal of Precision Engineering and Manufacturing-Green Technology https://doi.org/10.1007/s40684-023-00533-4
86. Okyay A., Erkorkmaz K., Khamesee M. B., Mechatronic design, actuator optimization, and control of a long stroke linear nano-positioner, Precision Engineering, Volume 52, 2018, Pages 308-322
87. Liu J., Cheng Q., Sun T., Liu Z., Xu J., Wang Y., Design, fabrication, and measurement of pneumatic soft actuators: A review, Sensors and Actuators A: Physical, Volume 398, 2026,
88. Tyagi M., Pan J. and Jager E. W. H., Novel fabrication of soft microactuators with morphological computing using soft lithography, Microsystems & Nanoengineering, (2019) 5:44
89. Hossain M. J., Tabatabaei B. T., Kiki M., Choi J. W., Additive Manufacturing of Sensors: A Comprehensive Review, International Journal of Precision Engineering and Manufacturing-Green Technology (2025) 12:277–300
90. De, S., Xu, S., Tang, Y., Jackson, A., Wang, P. L., Rukmani, S. J., MacDonald, E., Zhao, X., Duty, C., Roschli, A., Stano, G., Percoco, G., Stevens, A., & Li, Y. (2026). Printing the future of strain measurement: Flexible sensors via additive manufacturing for wearables, robotics, and smart infrastructure. Sensors International, 7, Article 100375. https://doi.org/10.1016/j.sintl.2026.100375
91. Singh K., Sharma S., Shriwastava S., Singla P., Gupta M., Tripathi C.C., Significance of nano-materials, designs consideration and fabrication techniques on performances of strain sensors - A review, Materials Science in Semiconductor Processing, Volume 123, 2021,
92. Gonzalez-Macia L., Morrin A., Smyth M. R. and Killard A. J., Advanced printing and deposition methodologies for the fabrication of biosensors and biodevices , Analyst, 2010, 135, 845–867 | 845
93. Hajare R., Reddya V., Srikanth R., MEMS based sensors– A comprehensive review of commonly used fabrication techniques, Materials Today: Proceedings 49 (2022) 720–730.
94. Tawk C., Alici G., 5 - 4D-printed pneumatic soft actuators modeling, fabrication, and control,Editor(s): Mahdi Bodaghi, Ali Zolfagharian, In Additive Manufacturing Materials and Technologies, Smart Materials in Additive Manufacturing, Elsevier, 2022, Pages 103-140, ISBN 9780323954303, https://doi.org/10.1016/B978-0-323-95430-3.00005-1.
95. Zhou X., Wang D., Wang J., Chen S., Precision design and control of a flexure-based roll-to-roll printing system, Precision Engineering, Volume 45, 2016, Pages 332-341, ISSN 0141-6359, https://doi.org/10.1016/j.precisioneng.2016.03.010.
96. Wang, W.; Yang, R.; Liu, M. Design and Fabrication of Micro/Nano Sensors and Actuators. Micromachines 2024, 15, 674. https:// doi.org/10.3390/mi15060674
97. ASME, 2028 Vision for Mechanical Engineering, A report of the Global Summit on the Future of Mechanical Engineering, 2008, (www.asme.org)
98. Knapczyk A. and Francik S., Analysis of Research Trends in the Field of Mechanical Engineering, Proceedings of the 12th International Scientific and Practical Conference. Volume II, 74-78.
99. Hossain N., Islam M. S., Al Mahmud M. Z., Tasnim R., Hossain A., Mobarak M. H., Rahman M. K., Advances of materials science in MEMS applications: A review, Results in Engineering, Volume 22, June 2024, 102115

100. Askari M., Hutchins D. A., Thomas P. J., Astolfi L., Watson R. L., Abdi M., Ricci M., Laureti S., Nie L., Freear S., Wildman R., Tuck C., Clarke M., Woods E., Clare A. T., Additive manufacturing of metamaterials: A review, Additive Manufacturing 36 (2020) 101562
101. Chen J., Hu S., Zhu S., Li T., Metamaterials: From fundamental physics to intelligent design, Interdisciplinary Materials. 2023; 2:5–29.
102. Schurger B., Frankovsky P., Janigova S., Bocko J., Kolodziej A., Mechanical metamaterials: properties and classification, Acta Mechatronica - International Scientific Journal about Mechatronics Volume: 8 2023 Issue: 3 Pages: 29-35 ISSN 2453-7306
103. Zeng S., Smith A. T., Shen K., and Sun L., Smart Soft Mate-rials with Multi-scale Architecture and Dynamic Surface Topographies, Accounts of Materials Research · October 2022.
104. Yildirim M., Candan Z., Smart materials: The next generation in science and engineering, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2023.10.116
105. Spaggiari A, Castagnetti D, Golinelli N, Dragoni E, Scirè Mammano G., Smart materials: Properties, design and mechatronic applications. Proceedings of the Institution of Mechanical Engineers, Part L. 2016;233(4):734-762. doi:10.1177/1464420716673671.
106. Pattanaik P., Ojha M., Review on challenges in MEMS technology, Materials Today: Proceedings 81 (2023) 224–226
107. Qu H., CMOS MEMS Fabrication Technologies and Devices, Micromachines 2016, 7, 14; doi:10.3390/mi7010014.
108. Zhang Q., Barri K., Jiao P., Lu W., Luo J., Meng W., Wang J., Hong L., Mueller J., Wang Z. L., Alavi A. H., Meta-mechanotronics for Self-Powered Computation, Version of Record: https://www.sciencedirect.com/science/article/pii/S1369702123000974
Manuscript_689654041922adc7286e348a02155e46
109. Klačková I., Wiecek D. and Dodok T., Mechatronic Systems in Mechanical Engineering, 2022, 20th International Conference on Emerging eLearning Technologies and Applications (ICETA) | 979-8-3503-2033-6/22/$31.00 ©2022 IEEE
110. Moulianitis V.C., Aspragathos N. A. and Dentsoras A. J., “A model for concept evaluation in design- An application to mechatronics design of robot grippers.”, Mechatronics, Vol. 14, No 6, pp 599-622, July 2004.
111. Palli G., Pirozzi S., Natale C., De Maria G. And Melchiorri C., Mechatronic Design of Innovative Robot Hands: Integration and Control Issues, 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
112. Xue1 L., Yang S., Integrated Application and Optimized Design Strategies of Automatic and Servo Control Systems for Industrial Robots, Applied Mathematics and Nonlinear Sciences, 9(1) (2024) 1-26
113. Urrea C., Kern J., Recent Advances and Challenges in Industrial Robotics: A Systematic Review of Technological Trends and Emerging Applications. Processes 2025, 13, 832. https://doi.org/10.3390/pr13030832
114. Khan W., Anjum M., Harris Khan, Hamza A., Jabbar H., Zafar T., Ansari A., Nawaz R., Application of robotic manipulation for carbon fiber reinforced polymers manufacturing- A survey, Composites Part C: Open Access 15 (2024) 100503
115. Chizhik S.A., Kheifetz M.L. & Gretsky N.L. Designing Mechatronic Machine Complexes for Hybrid Manufacturing of Products. J. Mach. Manuf. Reliab. 53, 824–829 (2024). https://doi.org/10.1134/S1052618824700626
116. Jose S., Tonner A., Feliciano, M., Roy T.; Shackleford A.; Menezes P., Smart Manufacturing for High-Performance Materials: Advances, Challenges, and Future Directions. Materials 2025, 18, 2255.
117. Barton K., Bristow D., Hoelzle D., Mechatronics advances for the next generation of AM process control, Editorial, Mechatronics 64 (2019) 102281
118. Vieten T., Weser S., Schilling A., Gläser K., and Zimmermann A., Integration of Mechatronic Functions on Additively Manufactured Components via Laser-Assisted Selective Metal Deposition, Adv. Funct. Mater. 2024, 34, 2312833
119. Bourell D., Kruth J. P., Leu M., Levy G., Rosene D., Beesef A. M., Clareg A., Materials for Additive Manufacturing CIRP Annals, Volume 66, Issue 2, 2017, Pages 659-681

120. Wang P, Robertson G, Gibson BT, Fancher CM, Reynolds J, Borish M, Cruz JR, Chesser P, Stump B, Jackson A, MacDonald E., Improved Productivity with Multilaser Rotary Powder Bed Fusion Additive Manufacturing. 3D Print Addit Manuf. 2024 Feb 1;11(1):231-241. doi: 10.1089/3dp.2022.0288. Epub 2024 Feb 15. PMID: 38389668; PMCID: PMC10880638.
121. Kanishka K., Acherjee B., Revolutionizing manufacturing: A comprehensive overview of additive manufacturing processes, materials, developments, and challenges, Journal of Manufacturing Processes 107 (2023) 574–619.
122. Amerongen J., The Role of Control in Mechatronics, Engineering Science and Education Journal · July 2000
123. Åströma K. J., Kumar P.R., Control: A perspective, Volume 50, Issue 1, January 2014, Pages 3-43
124. Zaitceva I. and Andrievsky B., Methods of Intelligent Control in Mechatronics and Robotic Engineering: A Survey, Electronics 2022, 11, 2443. https://doi.org/ 10.3390/electronics11152443
125. Nguyen A.-T., Dinh T. Q., Chong J., Iwasaki M., Precup R.-E., Ruderman M., Guest editorial introduction to the special issue on “Emerging control and automation technologies for advanced mechatronic systems”, Control Engineering Practice, Volume 136, 2023,
126. Bruzzone, L. New Trends in the Control of Robots and Mechatronic Systems. Appl. Sci. 2023, 13, 3112. https://doi.org/10.3390/ app13053112
127. IFAC President’s Message, Learning the Fundamentals: Some Thoughts on the Present and Future of Controls, JUNE 2025 « IEEE CONTROL SYSTEMS, 10.1109/MCS.2025.3554412
128. Wiener N., “Cybernetics or control and communication in the animal and the machine”, THE M.I.T. PRESS, Cambridge, Massachusetts, 1948
129. Kolmogorov A. N., Automata and Life, in Cybernetics Today, Achievements, Challenges, Prospects, Editor I. M. Makarov, Mir Publishers, Moscow, 1984
130. Mindel D. A., Cybernetics Knowledge domains in Engineering systems (fall, 2000)
131. Schiehlen W., From cybernetics to mechatronics: Seven decades of interdisciplinary engineering, Proceedings in Applied Mathematics & Mechanics , Wiley-VCH GmbH, 2019
132. Alvarez J. T. and Ramırez-Correa P., A Brief Review of Systems, Cybernetics, and Complexity, Complexity Volume 2023, Article ID 8205320, 22 pages https://doi.org/10.1155/2023/8205320
133. Novikov D. A., Cybernetics: from Past to Future, January 2016, Springer, ISBN: 978-3319273969
134. Acatech (Ed.), Cyber-Physical Systems-Driving force for innovation in mobility, health, energy and production, December 2011.
135. Penasa O., Plateaux R., Patalano S., Hammadi M., Multi-scale approach from mechatronic to Cyber-Physical Systems for the design of manufacturing systems, Computers in Industry 86 (2017) 52–69
136. Bello A., Olfe K.S., Rodríguez J., Ezquerro J.M., Lapuerta V., Experimental verification and comparison of fuzzy and PID controllers for attitude control of nanosatellites, Advances in Space Research, Volume 71, Issue 9, 2023, Pages 3613-3630,
137. Hogan D., Albiol-Tendillo L., Kelleher B., Valdivia-Guerrero1 V., Foley R., Rapid-prototyping and hardware-in-the-loop laboratory platform for development and testing of electro-mechanical actuator controls, The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)
138. Seung-Tae C., Park In K., Qiuwei W., Arne Hejde N., Jacob Ø., Real-Time Hardware-in-the-Loop Testing for Digital Controllers, 2012 IEEE PES Asia-Pacific Power and Energy Engineering Conference.
139. Simoni, M. Beschi, D. Colombo, A. Visioli and R. Adamini, "A Hardware-In-the-Loop setup for rapid control prototyping of mechatronic systems," 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), Luxembourg, Luxembourg, 2015, pp. 1-4, doi: 10.1109/ETFA.2015.7301628.
140. Guo K., Special Issue on Application of Artificial Intelligence in Mechatronics, Appl. Sci. 2023, 13, 158. https://doi.org/10.3390/ app13010158
141. Pagounis G., Koustoumpardis P. and Aspragathos N., “Robot motion control using EMG Signals and Expert System for Teleoperation”, In: Zeghloul S., Laribi M., Sandoval Arevalo J. (eds) Advances in Service and Industrial Robotics. (RAAD 2020), Mechanisms and Machine Science, vol 84. Springer, 137-148, June 2020.

142. Sathya, D., Saravanan, G. and Thangamani, R. (2024). Fuzzy Logic and Its Applications in Mechatronic Control Systems. In Computational Intelligent Techniques in Mechatronics (eds K.B. Prakash, S.K. Peddapelli, I.C.K. Tam, W.L. Woo and V. Jain). https://doi.org/10.1002/9781394175437.ch7
143. Dimeas F., Avendaño-Valencia L D and Aspragathos N.. Human - robot collision detection and identification based on fuzzy and time series modelling. Robotica FirstView:1–13, May 2014.
144. Moulianitis V. C., Tsaprounis C. J., Aspragathos N. A., "Online gain adjustment of a robot controller, using fuzzy logic", IFAC, SYROCO'97, Nantes, France, pp. 385-390.
145. Nüßgen A., Degen R., Irmer M., Richter F., Boström C., Ruschitzka M., Leveraging Robust Artificial Intelligence for Mechatronic Product Development—A Literature Review, International Journal of Intelligence Science, 2024, 14, 1-21
146. Xiaoyu L., Application and research of artificial intelligence in mechatronic engineering, 5th International Conference on Mechanical, Control and Computer Engineering (ICMCCE), 2020
147. Gehlot V., Rana P. S., AI in Mechatronics, In book: Computational Intelligent Techniques in Mechatronics, September 2024, 10.1002/9781394175437.ch1
148. Sharkawy A.-N., Koustoumpardis P. N., Aspragathos N., “A Neural Network based Approach for Variable Admittance Control in Human-Robot Cooperation: Online Adjustment of the Virtual Inertia”, Intelligent Service Robotics, Springer, pp. 1-25, 2020., DOI 10.1007/s11370-020-00337-4.
149. Adebisi O., Afolayan A., Ayoade I., Adejumobi P. and Adejumobi I., "Integration of Deep Learning Techniques in Mechatronic Devices and Systems: Advancement, Challenges, and Opportunities," International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG), Omu-Aran, Nigeria, 2024, pp. 1-6, doi: 10.1109/SEB4SDG60871.2024.10630414.
150. Lin H.-Y., Embedded Artificial Intelligence: Intelligence on Devices, COMPUTER PUBLISHED by the IEEE COMPUTER SOCIETY, 0018-9162/23©2023IEEE
151. Zhang Z., and Li J., A Review of Artificial Intelligence in Embedded Systems, Micromachines 2023, 14, 897. https://doi.org/10.3390/mi14050897
152. Żyliński M., Nassibi A., Rakhmatulin I., Malik A., Papavassiliou C. M. and Mandic D. P., "Deployment of Artificial Intelligence Models on Edge Devices: A Tutorial Brief," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 71, no. 3, pp. 1738-1743, March 2024, doi: 10.1109/TCSII.2023.3336831
153. Rabiu Y., Abdulaziz A., Messager N. D., Musa M. I., Bayero N. S., Surajo A., Artificial Intelligence in Smart Sensors and Actuators for Mechatronic Applications, ICON Journal of Engineering Applications of Artificial Intelligence Volume 01 | Issue 01 | 2025
154. Pfeifer R. and Lida F., Embodied Artificial Intelligence: Trends and Challenges, Conference: Ad-Hoc, Mobile, and Wireless Networks, Second International Conference, ADHOC-NOW 2003 Montreal, Canada, October 8-10, 2003.
155. Hughes J., Abdulali A., Hashem R. and Iida F., Embodied Artificial Intelligence: Enabling the Next Intelligence Revolution, 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1261 012001
156. Junge K. and Hughe J., Leveraging Embodied Intelligence for Dexterous Robotic Manipulators Through Iterative Co-design, International Workshop on Embodied Intelligence 2021.
157. Glossas N. I. and Aspragathos N. A., "A cluster based fuzzy controller for grasp and lift fragile objects," 18th Mediterranean Conference on Control and Automation, MED'10, Marrakech, Morocco, 2010, pp. 1139-1144, doi: 10.1109/MED.2010.5547640.
158. Dimeas F., Sako D. V, Moulianitis V. C and Aspragathos N. A. Design and fuzzy control of a robotic gripper for efficient strawberry harvesting. Robotica FirstView:1–14, May 2014.
159. Zhao, Z.; Wu, Q.; Wang, J.; Zhang, B.; Zhong, C.; Zhilenkov, A.A. Exploring Embodied Intelligence in Soft Robotics: A Review. Biomimetics 2024, 9, 248. https://doi.org/ 10.3390/biomimetics9040248
160. Howard, D., Eiben, A.E., Kennedy, D.F., Mouret, J.-B., Valencia, P., Winkler, D., Evolving embodied intelligence from materials to machines. Nat Mach Intell 1, 12–19 (2019). https://doi.org/10.1038/s42256-018-0009-9.
161. Liu H., Guo D. and Cangelosi A., Embodied Intelligence: A Synergy of Morphology, Action, Perception and Learning, ACM Comput. Surv., volume 57, number 7, 2025

162. Zardini G., Milojevic D., Censi A., and Frazzoli E., Co-design of Embodied Intelligence: A Structured Approach, 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems.
163. L. Ren, J. Dong, S. Liu, L. Zhang and L. Wang, "Embodied Intelligence Toward Future Smart Manufacturing in the Era of AI Foundation Model," in IEEE/ASME Transactions on Mechatronics, vol. 30, no. 4, pp. 2632-2642, Aug. 2025, doi: 10.1109/TMECH.2024.3456250.
164. Rader S., Kaul L., Weiner P. and Asfour T., "Highly integrated sensor-actuator-controller units for modular robot design," 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM), Munich, Germany, 2017, pp. 1160-1166, doi: 10.1109/AIM.2017.8014175.
165. Prechtl J., Seelecke S., Motzki P., Rizzello G., Self-Sensing Control of Antagonistic SMA Actuators Based on Resistance-Displacement Hysteresis Compensation, SMASIS2020-2224, V001T03A001; https://doi.org/10.1115/SMASIS2020-2224
166. Mikhaylov K., Huttonen M., Modular Wireless Sensor and Actuator Network Nodes with Plug-and-Play Module Connection, November 2014, Conference: IEEE SENSORS, Valencia, Spain, DOI:10.1109/ICSENS.2014.6985037
167. Liarokapis M., Lamkin-Kennard K. A., Popovic M. B., Biomechatronics: A New Dawn, Chapter 18, Pages 543-566, Biomechatronics, Popovic, Academic Press, Elsevier, 2019.
168. Luo W., The impact of semiconductor technology on edge computing, Proceedings of the 4th International Conference on Materials Chemistry and Environmental Engineering, 2024, DOI: 10.54254/2755-2721/84/20240894
169. Zwerver, A.M.J., Krähenmann, T., Watson, T.F. et al. Qubits made by advanced semiconductor manufacturing. Nat Electron 5, 184–190 (2022). https://doi.org/10.1038/s41928-022-00727-9
170. Van Damme J., Massar S., Acharya, R. et al. Advanced CMOS manufacturing of superconducting qubits on 300 mm wafers. Nature 634, 74–79 (2024). https://doi.org/10.1038/s41586-024-07941-9
171. Afonin, S. M., Electroelastic Actuator of Nanomechatronics Systems for Nanoscience, (2023), Recent Progress in Chemical Science Research Vol. 6. B P International, pp. 15-27. ISBN 978-81-19054-02-2
172. Balamurugan K S, Sivakami A, Mathankumar M, Yalla Jnan Devi Satya pra-sad, Irfan Ahmad, Quantum computing basics, applications and future perspectives, Journal of Molecular Structure, Volume 1308, 15 July 2024
173. Pal K., Kyzas G. Z, Torres M., Ghosh A., Molecular mechatronics in nanotechnology and supramolecular chemistry, Special issue, Journal of Molecular Structure, Volume 1308, 15 Ju-ly 2024
174. Tan et al., "Embodied Intelligence Empowering Customized Manufacturing: Architecture, Opportunities, and Challenges," in IEEE Access, vol. 13, pp. 92740-92755, 2025, doi: 10.1109/ACCESS.2025.3572778
175. Piechulek, N.; Xu,L.; Fröhlich, J.; Bründl, P.; Franke, J. Miniaturization Potential of Additive-Manufactured 3D Mechatronic Integrated Device Components Produced by Stereolithography. Micromachines 2025, 16, 16. https://doi.org/10.3390/ mi16010016