Journal of Theoretical and Applied Information Technology
31st January 2024. Vol.102. No 2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

HARDWARE/SOFTWARE CO-DESIGN IN MULTIPROCESSORS EMBEDDED SYSTEMS AND IOT

KAMEL SMIRI[1], RADIA BEN DIMERAD[2], FAYCEL EL AYEB[3]

[1]Manouba University, Higher Institute of Multimedia Arts Manouba, Manouba University Campus, 2010, Tunisia.Carthage University, Tunisia Polytechnic School, SERCOM-Lab., Tunis, Tunisia.
[2] University of Tunis El Manar, Faculty of Sciences of Tunis, Department of Computer Science, Tunis 2092, Tunisia.
[3]Unit of Scientific Research, Applied College, Qassim University, Saudi Arabia.
GRIFT research group, CRISTAL laboratory, National School of Computer Sciences, Manouba University, Tunisia.
E-mail: [1]kamel.smiri@isamm.uma.tn, [2]radia.bendimerad@fst.utm.tn [3]F.ElAyeb@qu.edu.sa

ABSTRACT

This article presents a comprehensive literature review of current research focusing on the design of Multiprocessor Embedded Systems (MPSoC) and their integration with the Internet of Things (IoT). Additionally, it investigates the prevalence of software/hardware co-design methodologies aimed at enhancing the overall performance of these systems. IoT and MPSoC stand as significant research paradigms, and the incorporation of hardware/software co-design emerges as a pivotal strategy to expedite the processing and analysis of data flows. The article not only defines hardware/software co-design but also underscores its critical role in optimizing the functionality of IoT and MPSoC. Furthermore, it provides clear definitions of IoT and MPSoC along with a comprehensive exploration of various proposed architectures based on these foundational concepts. In conclusion, the article puts forth future research directions, delving into the potential implications of co-design in the context of IoT and MPSoC. It also considers the integration of emerging technologies such as cloud and fog computing, machine learning, and advanced mobile systems like 5G/6G. This forward-looking approach aims to guide future developments in the dynamic intersection of co-design, IoT, and MPSoC.

Keywords: *Internet of things; Embedding; Hardware/Software Co-design; engineering design problem.*

1. INTRODUCTION

The Internet of Things (IoT) represents a rapidly expanding technology wherein a vast array of interconnected devices collaboratively share information or exert control over a designated entity within their respective applications. The data generated by these interconnected objects is poised to revolutionize IoT applications, offering the potential for groundbreaking services in future industrial applications, ultimately enhancing the quality of human life. Effectively managing IoT services and adequately addressing application demands necessitate a well-crafted infrastructure. However, the current research and development trajectory encounters notable challenges. Of particular concern are issues related to network congestion and the imperative for real-time processing within IoT applications [1]. Addressing these challenges is pivotal for the realization of a comprehensive and seamless IoT environment.

Additionally, certain applications with critical resources necessitate thorough evaluation due to stringent requirements for optimal performance. The evolving nature of applications underscores the increasing demands on communication and processing capabilities within networks. Consequently, maintaining a delicate balance in the system becomes of paramount importance. Moreover, the substantial volume of processing and communication frequently requires heterogeneous architectures, incorporating various computing units such as General-Purpose Processors (GPPs), Digital Signal Processors (DSPs), Graphics Processing Units (GPUs), or Field Programmable Gate Arrays (FPGAs).

In light of these considerations, highly integrated processing platforms, particularly Programmable System-on-Chip (PSoC), emerge as a viable solution. PSoCs offer several advantages, particularly in terms of HW/SW interface, facilitated by the presence of a CPU and hardware acceleration in the form of FPGAs, providing essential flexibility [2,3]. Consequently, all previous research in the realm of HW/SW co-design within the IoT context remains a bottleneck in data processing. A cyber–physical system (CPS) or intelligent system is a computer system in which a mechanism is controlled or monitored by computer-based algorithms. Generally a cyber–physical system (CPS) is produced by a Multiprocessor Embedded Systems (MPSoC).

Figure 1 present a typical architecture of MPSoC which is composed by software and hardware nodes connected by a communication network. Hardware nodes are component which does not have the ability of programming. A communication network connects all the nodes together. Software nodes provide the execution environment for applications tasks.

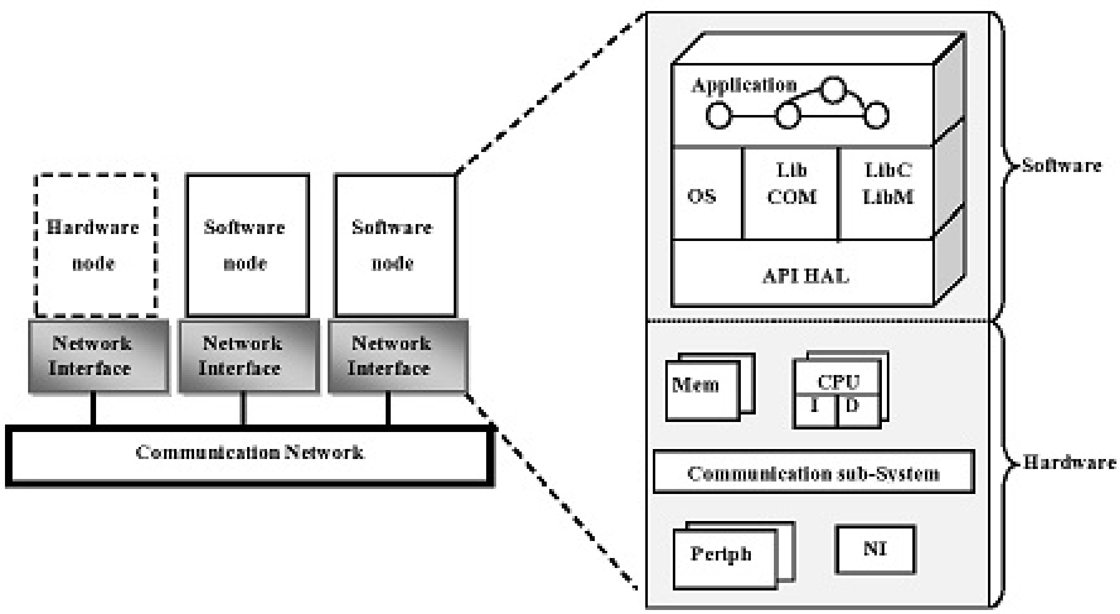

Figure 1: Typical architecture of MPSoC systems

The primary objective is to facilitate the collaboration of processing resources among the presented technologies (IoT/CPS), achieved through the interconnection of various devices and the utilization of their heterogeneous resources (HW/SW). This collaborative approach aims to enhance performance in terms of efficiency and quality of service. Leveraging HW/SW co-design as a computing technology enables the synergistic cooperation between IoT and CPS systems, facilitating informed and robust control decisions. As a valuable resource, it endeavors to mitigate challenges such as latency, computing data costs, reliability, fault tolerance, privacy concerns, and various optimization issues.

Conversely, recent technological advancements, particularly in digital communication tools, have ushered in paradigm shifts that necessitate the integration of novel factors. Within the manufacturing domain, Industry 4.0 stands as a testament to these technological strides, prominently featuring advancements in CPS and IoT [4].

Section 2 outlines the steps undertaken to establish the methodology employed in this review. Moving on to Section 3, the discussion delves into fundamental concepts associated with the two technologies, including embedded systems. Additionally, the section presents an array of diverse performance metrics explored in the realms of both IoT and CPS, followed by a proposed classification of the most pertinent metrics addressed in the last decade. Simultaneously, Section 3 scrutinizes the commonalities and distinctions between IoT and CPS, offering a comparative analysis based on prior studies and exposing various proposed architectures within the IoT/CPS landscape.

In Section 4, the focus shifts to HW/SW co-design, elucidating its application in realizing IoT/CPS-oriented approaches. Section 5 then introduces pertinent works concerning HW/SW co-design in the domains of IoT and CPS. Following this, Section 6 provides insights into potential future directions, outlines open issues, and discusses associated challenges. Finally, Section 7 encapsulates the review with concluding remarks and considerations.

2. METHODOLOGY

This section is dedicated to elucidating the procedure employed to facilitate the rigorous item selection process, as supported by drastic measures. The applied approach ensures a meticulous collection of all articles pertaining to the specific topic, with only the most pertinent ones retained. The initial step involves conducting a comprehensive search using keywords (HW/SW co-design, IoT, CPS) derived from the predefined subject matter. This search is instrumental in assembling a recent array of articles (from 2016 to 2020), encompassing journals, conferences, and book chapters, sourced from reputable platforms including ACM Digital, Elsevier, Springer, Google Scholar, Science Direct, Emerald Insight, and Wiley Online Library.

The second step involves conducting a brief review of the collected articles to initiate the filtering process. This step aims to carefully extract the most relevant articles and identify the sources of data crucial for this study. The filtering process serves to eliminate articles that deviate from the topic or do not serve as relevant references. In the final step, a meticulous reading of the selected articles is undertaken, and the information contained is thoroughly analyzed to gather essential data and present a comprehensive study. Following the initial review, specific words or information may prompt the reader to embark on a second wave of research, facilitating further refinement of the selected articles and a reduction in their number.

3. INTERNET OF THINGS AND MULTIPROCESSORS EMBEDDED SYSTEMS

3.1 Internet of things (IoT)

The Internet of Things (IoT) facilitates the communication among numerous physical objects through dynamic network configurations, low device costs, and the ability to self-organize without human intervention [18]. Its applicability spans various domains, encompassing industries, healthcare, and manufacturing. Notably, Industrial IoT (IIoT) emerges as a significant aspect within the broader context of Industry 4.0 [19]. IIoT distinguishes itself from the conventional IoT environment due to the presence of industrial devices and automation equipment. Broadly speaking, IIoT is characterized by the smart functionality of applications and is frequently deployed in areas such as smart manufacturing, smart factories, and smart cities [20].

The Internet of Things (IoT) is a modern name for Internet connectivity in MPSoC systems or in systems composed of computing objects (Fig 2). The IoT has evolved in line with technological developments. IoT is characterized by the real-time aspect, learning and adaptation to on-board sensors.

Journal of Theoretical and Applied Information Technology
31st January 2024. Vol.102. No 2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

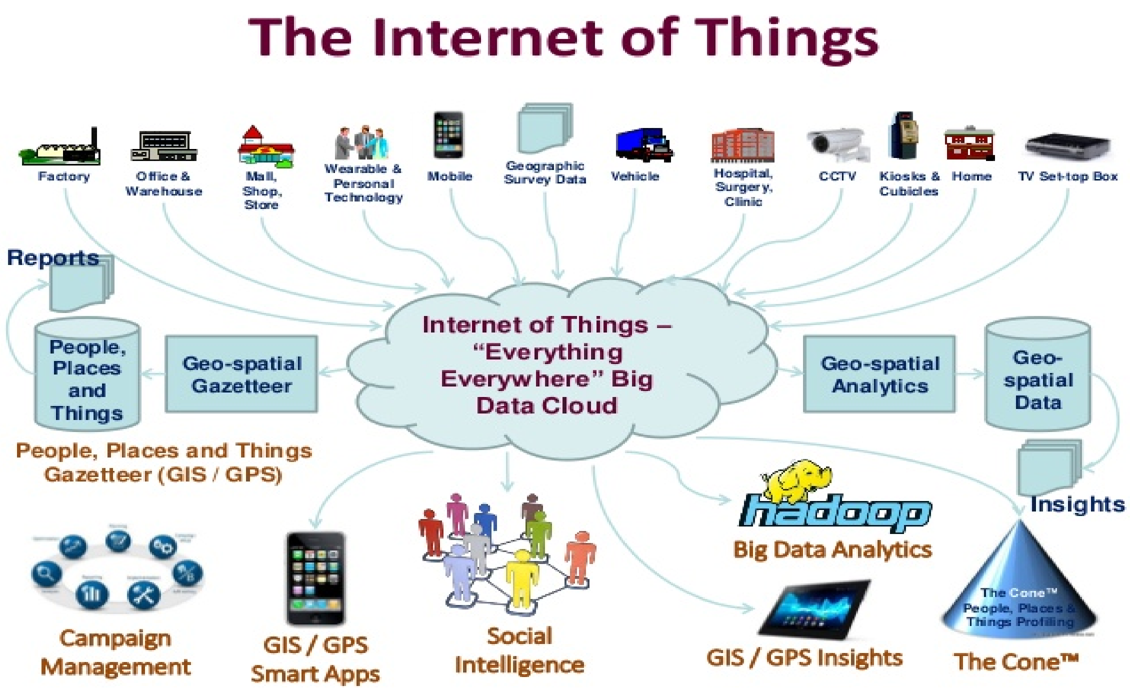

Figure 2: IoT Example [1].

3.2 Cyber Physical System (CPS)

Cyber-Physical Systems (CPS) are autonomous embedded systems comprising collaborative entities formed through instantaneous and continuous interactions between physical and virtual elements [26,27]. Equipped with sensors to perceive their environment, CPS can actively influence physical processes through the use of actuators. The physical sensors offer services for data storage and processing, facilitated via connectivity networks leading to a decision server. This server is manifested through a combination of mechanical and electronic components, along with embedded systems seamlessly integrated into the CPS.

Facilitated by a feedback loop, the decision server oversees, commands, and controls physical processes [28]. Furthermore, CPS incorporates technologies that foster collaboration among increasingly autonomous objects and systems, which are concurrently becoming more reconfigurable. The accessibility of information from any location and at any time is pivotal in this context. Additionally, objects and systems are evolving to become more intelligent, enabling communication with remote services that can provide enhanced intelligence. This transformative evolution allows for profound advancements in the realm of CPS.

3.3 IoT and CPS comparison concepts

Cyber-physical systems are comprised of computational, communication, and control components intricately integrated with physical processes. In contrast, the Internet of Things (IoT) is a technology designed to interconnect diverse devices via the Internet, facilitating data exchange, device monitoring, and process optimization. While these systems have been extensively explored, a notable challenge persists in delineating a clear distinction between them [30]. The differentiation between "Internet of Things" and "Cyber-Physical Systems (CPS)" remains somewhat ambiguous, leading to diverse perspectives on their dissimilarities. Figure 2 represents the relationship between Cyber-Physical Systems (CPS) and Internet of Things (IoT).

Journal of Theoretical and Applied Information Technology
31st January 2024. Vol.102. No 2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

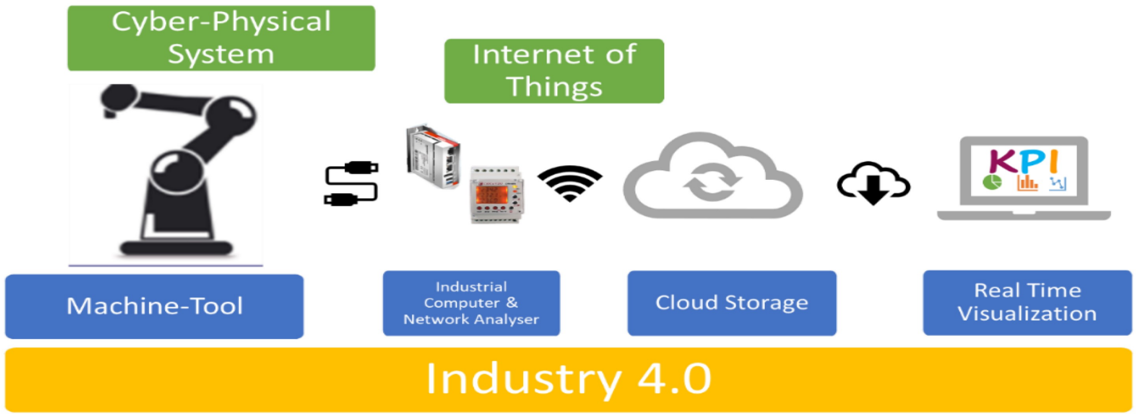

Figure 3: Relationship between Cyber-Physical Systems (CPS) and Internet of Things (IoT).

4. HARDWARE/SOFTWARE CO-DESIGN

In this section, we present a definition of Hardware/Software Co-design (HW/SW Co-design) and subsequently delve into the enhanced value brought about by the implementation of co-design, particularly in meeting the performance requirements mandated by IoT/CPS systems within the domains of Cyber-Physical Systems (CPS) and Internet of Things (IoT).

Embedded systems play a crucial role within larger systems that are built upon IoT and CPS technologies. The intricate interaction among these systems is manifested through control mechanisms or by executing computationally intensive tasks.

The primary role of embedded systems is to ensure rapid processing of the overall system and facilitate the exchange of data with other components, both within the internal and external environment. These systems typically consist of microprocessors or microcontrollers that integrate a suite of hardware-software components to execute and manage operations, often characterized by their fixed nature.

A noteworthy attribute of these systems is their ability to execute a substantial number of operations concurrently, exhibiting a high degree of concurrency. Moreover, embedded systems demonstrate quick reactivity to external triggers in real-time, allowing them to promptly address performance issues [11,12,13,29].

5. RELATED WORKS HW/SW CO-DESIGN IN IOT AND MPSOC

The authors in [25] highlight that Multiprocessors Embedded Systems (MPSoC) and Internet of Things (IoT) represent a category of systems that integrate low-powered sensors/actuators and processing devices/computer controllers into a cohesive and expansive infrastructure. This infrastructure aligns with contemporary trends such as industrial and manufacturing systems, along with concepts associated with Industry 4.0. The evolution of these infrastructures has led to a broadening of IoT and MPSoC definitions, and enhancing their performance has proven to be a complex challenge [24]. Consequently, there is a recognized need for technological advancements at the embedded device level to effectively operate in intricate, compute-intensive scenarios.

On the other hand, embedded components, widely employed in CPS and IoT systems, are progressively gaining the capacity to fulfill diverse requirements. These components offer improvements in time performances and other critical metrics such as cost, bandwidth, latency, power consumption, size, and fault tolerance, as noted in [6,7,8,23].

In [9,10,22], the author's objective is to design an embedded computing interface within the context of Cyber-Physical Systems (CPS), achieved by implementing a set of software tasks that communicate with hardware subsystems interacting with the environment. The Hardware/Software (HW/SW) interface, facilitated by embedded

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

systems, plays a crucial role in the CPS by linking the abstract computing model of application software with the surrounding environment.

Another study discussed in [21] focuses on proposing a controller that utilizes the hardware component, a facet often overlooked, to achieve runtime self-adaptive processing capabilities in CPS. This controller is specifically implemented over an FPGA device and is designed to meet reliability and robustness constraints.

6. ANALYSIS AND DISCUSSION

One of the central challenges in designing an Internet of Things/Cyber-Physical Systems (IoT/CPS) architecture lies in establishing a universally accepted, extensible, and enforced architecture, a predicament that remains unresolved to date. The architecture must, on one hand, accommodate the system's complexity, allowing for interaction with other systems while remaining manageable. On the other hand, it must strike a balance between various performance metrics. One viable solution is the incorporation of Hardware/Software (HW/SW) co-design, a sophisticated technique that can significantly contribute to modeling an IoT/CPS architecture and addressing lingering performance metric challenges.

Moreover, the dynamic nature of system requirements necessitates ongoing adaptations to ensure the system aligns closely with its stipulated requirements. For instance, maintaining self-adaptive behavior to environmental changes requires high-performance processing units, ensuring robustness and tolerance to breakdowns, safeguarding privacy, and preserving energy efficiency. However, these requirements may pose challenges, such as a potential lack of computational power, increased storage costs, limited data storage capacity, and constrained data transfer, thereby intensifying challenges associated with embedded co-design implementation [14,15,16].

7. CONCLUSION

Multiprocessors Embedded Systems (MPSoC) and the Internet of Things (IoT) are pivotal technologies that have become integral to the operations of factories and manufacturing processes. The inherent complexity of these systems, coupled with the extensive use of devices, presents various technical challenges, particularly in shaping the requisite architecture. A driving force behind the advancement of CPS and IoT technologies lies in enhancing system performance, encompassing critical metrics such as real-time capabilities, fault tolerance, power consumption, and security. Successful integration of embedded systems in industrial settings has leveraged co-design methodologies to optimize the time and energy consumption of system devices.

This article provides an in-depth analysis of the integration of hardware/software co-design for an architecture based on CPS and IoT, targeting future industry and manufacturing applications. It introduces a comprehensive list of key performance metrics in IoT and CPS systems over the last decade, showcasing corresponding HW/SW co-design solutions. A comparative analysis between the two concepts of IoT and CPS is presented to elucidate the diverse perspectives found in the literature. The article also investigates relevant IoT/CPS architectures and co-design-based works. In the concluding section, open issues and future research directions in the realm of using HW/SW co-design in the merged field of IoT/CPS are discussed.

REFERENCES:

[1] K. Smiri and F. El Ayeb, "Software/Hardware Task Migration Based on a Checkpoint for Multiprocessors Embedded Systems," Journal of Theoretical and Applied Information Technology, vol. 101, no. 7, pp. 8, April 2023.

[2] Lee, Kwangho, Joonho Kong, and Arslan Munir, "Hw/sw Co-design of Cost-efficient CNN Inference for Cognitive IoT," in 2020 Fourth International Conference On Intelligent Computing in Data Sciences (ICDS), pp. 1–6, 2020.

[3] Rodrí [Author Name not fully provided in the original text]. "Exploring Heterogeneous Scheduling for Edge Computing with CPU and FPGA MPSoCs," Journal of Systems

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Architecture, vol. 98, pp. 27–40, 2019. Elsevier.
[4] Andronie, Mihai. "Sustainable Cyber-Physical Production Systems in Big Data-Driven Smart Urban Economy: A Systematic Literature Review." Sustainability, Vol. 13, No. 2, 751, 2021. Multidisciplinary Digital Publishing Institute.
[5] Zhu, Qi, and Alberto Sangiovanni-Vincentelli. "Codesign methodologies and tools for cyber–physical systems." Proceedings of the IEEE, Vol. 106, No. 9, 1484–1500, 2018. IEEE.
[6] Akeela, Rami, and Mitchell P Krawiec-Thayer. "Efficient HW/SW partitioning of Halo: FPGA-accelerated recursive proof composition in blockchain." Microsystems Technologies, 1–11, 2021. Springer.
[7] Genius, Daniela, Ilias Bournias, Ludovic Apvrille, and Roselyne Chotin. "Model-Based Virtual Prototyping of CPS: Application to Bio-Medical Devices." International Conference on Model-Driven Engineering and Software Development, 74–96, 2020.
[8] Lu, Yang. "Cyber-Physical System (CPS)-based industry 4.0: A survey." Journal of Industrial Integration and Management, Vol. 2, No. 03, 1750014, 2017. World Scientific.
[9] Salman, Ola, Imad Elhajj, Ali Chehab, and Ayman Kayssi. "IoT survey: An SDN and fog computing perspective." Computer Networks, Vol. 143, 221–246, 2018. Elsevier.
[10] Shammar, Elham Ali, and Ammar Thabit Zahary. "The Internet of Things (IoT): a survey of techniques, operating systems, and trends." Library Hi Tech, 2019. Emerald Publishing Limited.
[11] Adana Alparslan Türkeş."Co-Design Approach and Co-Simulation Tools for Networked Cyber-Physical Control Systems." 2020 International Conference on Innovation and Intelligence for Informatics, Computing and Technologies (3ICT), 1–6, 2020.
[12] Wang, Yi, Brandon Saez, Joseph Szczechowicz, Jonathan Ruisi, Tyler Kraft, Stephen Toscano, Zachary Vacco, and Kervins Nicolas. "A smart campus internet of things framework." 2017 IEEE 8th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference (UEMCON), 498–503, 2017.
[13] Salman, Ahmad, William Diehl, and Jens-Peter Kaps. "A light-weight hardware/software co-design for pairing-based cryptography with low power and energy consumption." 2017 International Conference on Field Programmable Technology (ICFPT), 235–238, 2017.
[14] Salman, Ahmad, and Samy El-Tawab. "Efficient Hardware/Software Co-Design of Elliptic Curve Cryptography for the Internet of Things." 2019 International Conference on Smart Applications, Communications and Networking (SmartNets), 1–6, 2019.
[15] Kim, Young Soo. "Teaching Cyber Physical System Co-design: IoT on an FPGA Approach." 2020 IEEE International Conference on Electro Information Technology (EIT), 162–165, 2020.
[16] Wang, Zixiao, Ke Xu, Shuaixiao Wu, Li Liu, Lingzhi Liu, and Dong Wang. "Sparse-YOLO: Hardware/Software co-design of an FPGA accelerator for YOLOv2." IEEE Access, Vol. 8, 116569–116585, 2020. IEEE.
[17] Ruchkin, Vladimir, Grigory Soldatov, Alexei Koryachko, Boris Kostrov, and Ekaterina Ruchkina. "Conceptual model of hardware & software co-design for multicore systems on chip." 2020 9th Mediterranean Conference on Embedded Computing (MECO), 1–4, 2020.
[18] Park, Jong Hyuk, and Neil Yuwen Yen. "Advanced algorithms and applications based on IoT for the smart devices, 2018. Springer.
[19] ElMamy, Sidi Boubacar, Hichem Mrabet, Hassen Gharbi, Abderrazak Jemai, and Damien Trentesaux. "A Survey on the Usage of Blockchain Technology for Cyber-Threats in the Context of Industry 4.0." Sustainability, Vol. 12, No. 21, 9179, 2020. Multidisciplinary Digital Publishing Institute.
[20] Skwarek, Volker. "Blockchains as security-enabler for industrial IoT-applications." Asia Pacific Journal of Innovation and Entrepreneurship, 2017. Emerald Publishing Limited.

[21] Fournaris, Apostolos P, Christos Alexakos, Christos Anagnostopoulos, Christos Koulamas, and Athanasios Kalogeras. "Introducing hardware-based intelligence and reconfigurability on industrial IoT edge nodes." IEEE Design & Test, Vol. 36, No. 4, 15–23, 2019. IEEE.

[22] Krishnan, Janitha, and Shriram K Vasudevan. "An extensive survey on IoT smart gateways, software architecture, related protocols and challenges." 2019 International Conference on Vision Towards Emerging Trends in Communication and Networking (ViTECoN), 1–6, 2019.

[23] Mrabet, Hichem, Sana Belguith, Adeeb Alhomoud, and Abderrazak Jemai. "A survey of IoT security based on a layered architecture of sensing and data analysis." Sensors, Vol. 20, No. 13, 3625, 2020. Multidisciplinary Digital Publishing Institute.

[24] Jozef Mocnej, Winston K.G. Seah, Adrian Pekar, and Iveta Zolotova. "Decentralised IoT Architecture for Efficient Resources Utilisation." IFAC-PapersOnLine, Vol. 51, No. 6, 168-173, 2018.

[25] Atmani, Amine, Ibtissame Kandrouch, Nabil Hmina, and Habiba Chaoui. "Big data for internet of things: A survey on IoT frameworks and platforms." International Conference on Artificial Intelligence and Symbolic Computation, 59–67, 2019.

[26] Giraldo, Jairo, David Urbina, Alvaro Cardenas, Junia Valente, Mustafa Faisal, Justin Ruths, Nils Ole Tippenhauer, Henrik Sandberg, and Richard Candell. "A survey of physics-based attack detection in cyber-physical systems." ACM Computing Surveys (CSUR), Vol. 51, No. 4, 1–36, 2018. ACM New York, NY, USA.

[27] Bonilla, Silvia H, Helton RO Silva, Marcia Terra da Silva, and Franco Gon...

[28] Pagliari, Lorenzo, Raffaela Mirandola, and Catia Trubiani. "A case study to elicit challenges for performance engineering of cyber physical systems." Proceedings of the 8th ACM/SPEC on International Conference on Performance Engineering Companion, 217–222, 2017.

[29] Zhou, Yuchen, F. Richard Yu, Jian Chen, and Yonghong Kuo. "Cyber-physical-social systems: A state-of-the-art survey, challenges and opportunities." IEEE Communications Surveys & Tutorials, Vol. 22, No. 1, 389–425, 2019. IEEE.

[30] Kim, Youngsoo, Alan Chen, Shrikant Jadhav, Clay S Gloster, Thuy Le, and Ping Hsu. "Project based courses in control cyber physical system co-design." Proceedings of the 2016 Workshop on Embedded and Cyber-Physical Systems Education, 1–4, 2016.