Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 119 (2023) 885–890

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

Product Development Process for complex hardware-based solutions: current trends

Pedro A. de A. F. Romeral[a], Eduardo Zancul[a,*], Davi Nakano[a]

[a]University of São Paulo, Polytechnic School, Production Engineering Department, Av. Prof. Luciano Gualberto, 1380, São Paulo (SP), 05508-010, Brazil

* Corresponding author. Tel.: +55 11 2648-6756. *E-mail address:* ezancul@usp.br

Abstract

Innovation processes have evolved significantly. Starting with traditional Product Development Process in the 1990s, novel development approaches have been disseminated, especially approaches originating in the software and service sectors. However, understanding the influence of recent approaches to developing complex hardware-based solutions is still a research issue. This study aims to identify emerging approaches that have already demonstrated adequacy to support hardware design. Therefore, a systematic literature review has been conducted. The research screened 292 papers and analyzed in detail 25 articles published between 2018 and 2022. Our findings indicate increased adoption of creativity-oriented methods and extended prototyping in early phases.

Keywords: Product Development Process (PDP); Design process; hardware; prototyping; Agile.

1. Introduction

The process of bringing innovation to the market has been continuously evolving. The traditional Product Development Process (PDP) fundamentals were established in the 1980s and 1990s, based on stage-gate and simultaneous engineering concepts [1–4], rooted mainly in mechanical engineering knowledge and perspective [5].

Since the beginning of the 2000s, increasingly novel development approaches have risen. Several of these novel approaches, such as Agile, originated from the software and service domains [6]. Development approaches that gained relevance recently – e.g. user-centered Design – are summarized in Table 1.

However, understanding the adequacy, relevance, and impact of recent approaches' in developing complex hardware-based solutions still demands further investigation. Hardware-based products may require development approaches' adaptations and reinterpretations due to the physicality of the products [7]. One example is given by prototyping. During a product development project, prototypes allow testing concepts to explore aspects like design and quality, improving the chances of success [8]. Hardware development also needs tests in tangible ways, bringing attention to physical prototypes, which enable verifying the final product performance considering the real environment and user variability [8]. Kratzer et al. indicate that the design of products might often be impossible to assess without seeing and feeling the actual hardware [9].

Understanding the PDP evolution trends for complex hardware development requires identifying novel approaches that have already been effectively applied to the physical product's domain. Considering all the aspects above, it is important to understand how hardware development has been conducted in the last years, which methods are the most used, and what benefits they can bring.

This study aims to identify emerging approaches that have already demonstrated sufficient adequacy to support complex hardware design processes. Considering improvement aspects, this study seeks to analyze if the selected approaches result in

2212-8271 © 2023 The Authors. Published by Elsevier B.V.

10.1016/j.procir.2023.03.133

shorter lead time, cost reduction, or increased user satisfaction. Therefore, a systematic literature review method is applied, considering PRISMA's method guidelines.

This study is part of a broader research effort aiming to systematize current effective development practices for hardware-based products. As hardware-based, we consider physical products, which may entail embedded software and compose Product-Service Systems (PSS), in which the hardware plays a significant role in value delivery.

The remainder of the paper is structured as follows. Section 2 presents the research methodology. Section 3 discusses the results, summarizing the methods and approaches identified. It also discusses how the papers fit the researched improvement aspects. Finally, section 4 discusses the conclusions, limitations, and suggestions for further research.

2. Methodology

A Systematic Literature Review (SLR) was conducted to understand how hardware development projects have been evolving. The literature review followed the guidelines recommended by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The PRISMA method emerged as a response to improving the quality of Systematic Literature Reviews, offering the reader details about the conduction of the whole study and clarifying possible research biases [10]. Thus, the research followed the PRISMA standard checklist to ensure greater robustness in conducting and presenting the literature review results.

Searches were conducted in the Institute of Scientific Information (ISI) Web of Science database. This database was chosen because of its wide international academic recognition and for presenting studies from different areas of knowledge.

The search string used was: *((hardware development) OR (physical product development) OR (mechatronic* development)) AND (("lead time") OR (cost* reduct*) OR ("customer* satisfaction")).* The string identifies studies on hardware development focusing on process output indicators – reduction of lead time, reduction of costs, or improvement of user satisfaction.

Only peer-reviewed studies, such as articles and reviews, were selected for the study. The publication date was restricted to 2018 to 2022 to identify the hardware development trends in recent years.

Applying the string resulted in 292 unique documents. An initial selection process was conducted by analyzing the title, abstract, and keywords to filter documents that were not in line with the scope of the research.

In the first screening round, the articles that were discarded did not explicitly mention, either in the title or in the abstract, that a hardware-based solution was developed. In the following screening steps, articles were discarded when they did not explore the hardware aspects (13 studies), or present sufficient information on hardware development (6 studies), and when the study was not found for download or was only available in a language other than English (8 studies). Finally, after a full-text review, 25 references were selected for analysis. Figure 1 summarizes the detailed procedure.

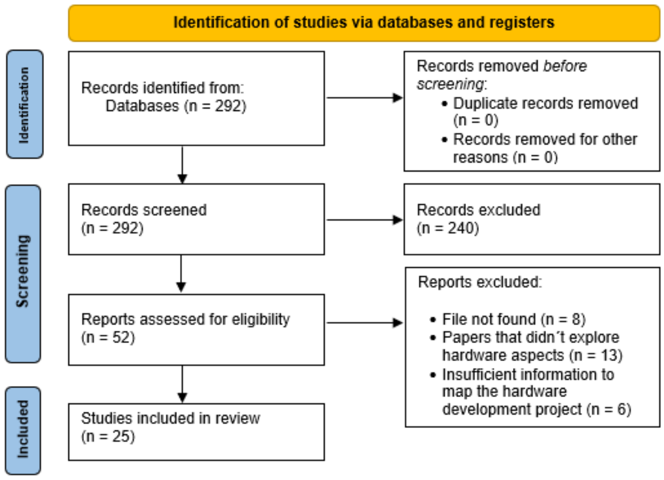

Fig. 1. Study selection flowchart.

The complete analysis procedures and the documentation following PRISMA´s guidelines for this research are available at the Mendeley Data repository [11].

3. Results and discussions

This section presents the approaches, methods, and tools used for hardware development in the selected papers. This study follows the definitions of "approach" and "method" proposed by Andiappan and Wan [12], who investigated the use of these terms in the process systems engineering field. According to the authors, an approach is a way to determine how a problem can be solved. The assumptions originate from concepts, theories, and even working ideas, serving as a practitioner´s outlook to addressing the problem [12]. A method entails how an approach will be practically implemented and encompasses details of how a problem can be solved [12].

The definition of the key identified approaches, methods, and tools is summarized in Table 1. A synthesis of the identified approaches, methods, and tools from the researched studies is presented in Table 2. In this table, studies were classified considering the authors' perceptions and the definition from the literature presented in Table 1. For example, studies that started with prototypes since the beginning of the hardware development were classified as Early Prototyping; studies that emphasized user needs or tests with the final users were classified under the user-centered design approach. One study explicitly characterized the methodology or approach used as a user-centered design [13]. Two studies [14,15] explicitly mentioned what tool was used to conduct the development project – in this case, the Field Programmable Gate Array (FPGA).

Table 1. Methods, approaches, and tools for product development projects.

Method / Approach	Description
Agile	"*Agile is a project management method that brings agility, adaptability, and speed to development projects: It includes micro-planning tools*" [16]
	Agile process requires less planning. It structures the tasks into small increments. It is meant mainly for short-term projects. [17]
	"*Agile–Stage-Gate adds the most value when there is high uncertainty and a great need for experimentation and failing fast. It offers the additional benefits of managing high uncertainty through incremental product versions (protocepts), quick learning cycles, and frequent customer involvement.*" [16]
Design Thinking	*"Design thinking is generally defined as an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign."* [18]
User-centered Design	User-centered design focuses on understanding a user's demands, priorities, and experiences. It can lead to increased product usefulness and usability as it delivers satisfaction to the user. [19]
Systems Engineering	The artifact comprises an assembly of components that can be physical and virtual. The systems engineering role is to produce the design, which, when realized, will result in an assembly of components that exhibits satisfactory behavior. [20]
Product Lifecycle Management	A general plan to manage a product and its lifecycle. It combines processes, instructions, and guidelines and their related applications in practice. Some examples are: analysis results, manufacturing procedures, engineering requirements, and product performance information. [21]
Early Prototyping	*"Rough models built quickly in order to communicate an idea to other team members at a very early stage of the design process."* [22]
	"*Prototypes are most valuable to be used in early ideas and idea development process. Therefore, it is recommended that designers should use prototypes extensively and as early as possible in order to plan the design process more accurately in terms of focal areas, expected user involvement and cost estimations for the final design*" [23]
Hardware / Software Co-Design Flow	A methodology created for associative in-memory processors. The methodology aims to decrease energy consumption and area requirement of the processor architecture to perform a specific task. Its relevance is the improvements aimed at both hardware and software at the same time. [24]
Compensation Circuit Design Flow	*"A systematic and scalable method for approximate circuit design by employing data-driven feature selection techniques rather than using statistical or theoretical analysis, which is extremely suitable for applications at a larger scale."* [25]
	Focused on reduction in energy consumption and hardware costs. [25]
Field Programmable Gate Array (FPGA)	*"A FPGA is a programmable logic device that implements multi-level logic. FPGAs offer low risk, low incremental cost and fast prototyping advantages."* [26]
	"By radically reducing the development costs and the turnaround time for implementing thousands of gates of logic, FPGAs provide a new capability that affects the semiconductor industry." [26]

Table 2. Identified approaches, methods, and tool.

	Approaches				Methods				Tool
	Agile	Design Thinking	User-centered Design	Systems Engineering	Product Lifecycle Management	Early Prototyping	Hardware/Software CoDesign Flow	Compensation Circuit Design Flow	Field Programmable Gate Array
Azocar et al, 2020 [27]			X						
Barrón-Romero and Hernández-Zavala, 2020 [28]				X					
Boye, 2020 [14]									X
Colturato and Chavier, 2019 [29]			X						
Daniyan, 2020 [30]				X					
Falabella, Wallin and Lund, 2018 [31]				X					
Fodor, Silaghi and Veber, 2020 [32]						X			
Heinrich et al., 2019 [33]				X					
Kindt and Binder, 2022 [34]						X			
Lanzotti et al, 2018 [8]		X							
Lopez et al., 2020 [35]						X			
Lu et al., 2021 [36]						X			
Ma et al., 2018 [37]						X			
Mishra et al., 2021 [38]						X			
Montero et al., 2020 [39]	X								
Platt and Liu, 2018 [15]									X
Peiret et al., 2018 [40]				X					
Qiu and Lao, 2018 [25]								X	
Soltes et al., 2018 [13]			X						
Sun et al., 2020 [41]				X					
Vansteenwegen et al., 2019 [42]						X			
Xia et al., 2021 [43]				X					
Yantlr, Eltawil and Salama, 2022 [24]							X		
Zaloga et al., 2020 [44]					X				
Zhou et al., 2021 [45]						X			

One of the prominent methods identified is Early Prototyping. Planning and building a prototype since the initial phases make it easier and faster to understand the idea's feasibility and how it can be developed considering alternatives and restrictions of the project [34–36,38,42]. Early Prototyping can be done using low-cost materials, maintaining the relevance of the tests [32,37,45].

All the studies that applied Early Prototyping developed physical artifacts, testing how the architecture works in each environment. The combination of sensors, boards, and other equipment can be seen as a critical factor during a hardware development project. In this context, the use of physical components from the beginning can accelerate tests to clarify how the proposed solution can solve the identified challenge. The study's main differences relate to the tests' environment, varying from laboratory experiments to real operations.

Systems Engineering was identified as a well-applied approach for hardware development. Some studies aimed to define the requirements and main functions, then started to elaborate the design of these functions, and finally progressed to systems verification and control. Building the hardware and the software involved allows understanding how the physical and virtual components will be integrated and solving compatibility issues [25,30,31].

Some papers adopted a user-centered design approach aiming to understand the user needs and how the final product will solve them. The development of effective hardware needs to consider who will use the proposed solution and if it fits the required purposes [13,27,29]. In all of these studies, a physical prototype was built and tested, reinforcing the relevance of physical contents in hardware projects. One of the studies conducted more than one prototype, starting with critical functions analysis and then evolving robustness and precision [13].

Only one selected study was classified under the Agile approach [39]. The authors discussed the application of agile hardware practices to improve the overall quality of the product. The main aspect noticed about agile for hardware is the influence of architectural decisions to design the physical component. Furthermore, the costs to make changes in a hardware project are higher than in software ones, limiting the number of changing cycles. Despite having just one paper focusing mainly on Agile, another study mentioned Agile and its relevance in improving hardware projects [13].

The Field Programmable Gate Array tool was mentioned in two studies [14,15]. FPGAs can be reprogrammed to desired application or functionality requirements after manufacturing. In these cases, design needs can be addressed more easily than other semiconductor solutions on the market. It elucidates that physical components have been developed considering the possibility of modifications and adaptations to satisfy each product's needs.

Two different studies proposed new methods to conduct hardware development. Yantir et al. [24] presented the Hardware/Software Co-design Flow, inspiring studies that look for better integration between physical and digital platforms. Qiu and Lao [25] developed a specific method for approximate computing focused on circuits. These new methods seem to be influenced by Agile principles, as they perform reduced tasks and there is close user involvement.

All the papers analyzed in this study were classified under three improvement focus: cost reduction, lead time reduction, and user satisfaction improvement. Table 3 shows the studies that perceived a reduction in costs.

Reduction of costs was the most frequent benefit identified in the papers. Cost reduction can be achieved by using simpler materials, conducting tests on a reduced scale, and developing design aspects before prototyping. Cost reduction is aimed when projects have low budgets or develop products with expensive components, so tests with cheaper materials can optimize the hardware development [32,34,37,45]. The use of a structured methodology or approaches like Early Prototyping and Systems Engineering brought advantages during the execution of the projects, setting steps and goals and defining the best way to conduct the activities [41].

All studies classified under Early Prototyping presented cost reduction as the main benefit. This shows that prototyping since the beginning of the project can reduce overall expenses, using simpler materials and performing tests on a reduced scale.

Table 3. Analyzed studies that presented cost reduction in their hardware projects.

Method/ Approach/ Tool	Perceived benefits
Early prototyping	When software and hardware are tightly coupled, defining a method is important to enable flexible solutions and achieve efficiency. [35]
	Early Prototyping allowed analysis of the best combination of materials and its integration with software. [32]
	The Early Prototyping made possible the understanding of available materials and how it influences the final functions, optimizing costs. [45]
	The proposed position detection and status monitoring method brings high-precision detection of the joint position at a low cost. [36]
	The system is user-friendly and cost-effective as no extra wiring is required, and the network environment is independent. [37]
	The developed architecture is highly effective in the gate count and power dissipation reduction in a cost-effective way. [38]
	The system prototype meets the requirements for future deployment in a network for hyperspectral validation of water reflectance data with reduced cost. [42]
	The hardware prototype allowed tests following quality protocols and indicating potential for cost reduction. [34]
Systems Engineering	The use of low-cost ceramic materials showed great conditions for analyzing hotspots. [31]
	The method led to cost reduction in manufacturing by automation of simple and recurring logistic steps. [33]
	Results show that the model can be used to improve the stability of non-iterative co-simulation schemes. [40]
	The system can effectively promote reliability, and the method can address cost reduction in the design stage. [41]
Product Lifecycle Management	The application of the tool reduced resource costs and improved the quality of the implementation of processes. [44]

Hardware projects commonly face constricted time for conclusion [14,39]. Regarding the lead time (Table 4), it is relevant to consider the deadline to deliver the solution and organize tests to guarantee the expected robustness and quality [24,25]. With physical prototypes, tests may require a longer timeframe. We detected that the use of specific methods and approaches like Systems Engineering and Agile can accelerate activities execution.

Table 4. Analyzed studies that presented lead time reduction in their hardware projects.

Method/ Approach/ Tool	Perceived benefits
Hardware/ Software Flow	The method decreases the active area requirement of the processor as well as improves the static energy consumption considerably, which is proven via circuit simulations of nine different benchmarks. [24]
Systems Engineering	The findings can assist manufacturers in their quest for innovativeness in product development as well as reduction in the manufacturing lead time. [30]
	The advantage of the adopted architecture is to process high-quality information in less time. [28]
Compensation Circuit Design Flow	The proposed methodology is suitable for large and complex approximate circuit designs that are not feasible for manual analysis or simplifications. [25]
Agile	The use of Agile to re-design spare parts of a product pointed to a lead time reduction. [39]
Field Programable Gate Array (FPGA)	The proposal significantly reduces design timelines while maximizing the flexibility to adapt to a wide array of mission requirements. [14]
	The amount of time required to deliver the test solution can be reduced from multiple weeks to just a few days. With the FPGA the test and use of the hardware are accelerated. [15]

User satisfaction is the main focus of only four of the selected studies (Table 5). Nevertheless, these studies bring relevant insights. Design errors are quickly detected when the customer needs are included in the hardware development review loop, and technological issues can be rapidly corrected [13,27]. Tests made in real environments with real customers allow for identifying the user perception of the solution [8,43].

Table 5. Analyzed studies that presented user satisfaction improvements in their hardware projects.

Method/ Approach	Perceived benefits
User-centered Design	The integration of the hardware with the other components of the system in a method that seeks to improve the patient's quality of life is promising. [27]
	Based on an electric vehicle project, the authors developed a framework for user-centered design. It shows that it is possible to achieve higher quality delivered and higher customer satisfaction. [13]
Design Thinking	This interactive design approach lets the users (and testers) express their opinion and collect insights that are directed to improve the final solution. [8]
Systems Engineering	The solution has educational purposes, so it considers the users during its development and improvements. [43]

4. Conclusions

This study aimed to understand which approaches are being applied in hardware development projects and which benefits are identified in the practical execution of these projects. Therefore, a systematic literature review was conducted focusing on studies that reported cost reduction, lead time reduction, or user satisfaction improvements. Five approaches, three methods, and one tool were identified.

Hardware development processes are evolving influenced by new approaches, and there are several methods that can be used to improve the creation and robustness of the projects. Almost half of the articles analyzed used Early Prototyping or Systems Engineering. Some studies detailed user involvement. In terms of impacts, most articles reported cost reduction. The use of simpler materials and the conduction of tests since the first phases of the project allow the final product to be launched with greater robustness and satisfy the identified needs.

It is possible to conclude that developing physical prototypes since the beginning of the project contributes to the quality of the solution. This elucidates the necessity of in-person development activities. While working in remote teams has several advantages, it is a limitation when different components and equipment need to be physically assembled in prototyping activities. After the Covid-19 pandemic and the expansion of remote working, it is important to plan the hardware development and tests considering in-person tasks. Even when the hardware is attached to other software, it is important to organize the hardware team to develop the solution considering physical aspects since the first phases.

A combination of approaches or methods can bring an innovative way to explore the user's insights and optimize the project development. One study mentioned two different approaches [13] – user-centered design and agile –, but described the entire process under the user-centered design. No paper showed a clear combination of approaches or methods in this review, indicating an opportunity to be explored further in future studies.

This study has some limitations. The selected timeframe (2018 to 2022) could let some older important papers out of the analysis. Also, the keywords selected for the string are focused mainly on quality aspects, and some applications outside of this scope were not identified. Only one database (Web of Science) was used, and only papers in English were considered for this study.

The findings indicate opportunities for future studies. The scope of the research can be expanded, focusing on benefits in general, without being restricted to the aspects considered in this study. In addition, a bibliometric analysis can be performed to identify the area's main trends, performing searches in databases without adding a time filter. Case studies can be conducted following hardware development projects at universities or companies. Another opportunity is to focus specifically on some approaches or methods, such as Agile, Design Thinking or Early Prototyping, and detail their application for the hardware design.

Acknowledgements

The research leading to the results received funding from FAPESP under Grant Agreement No 2022/03437-0 and CNPq under Grant Agreement 403065/2022-4.

References

[1] Cooper RG. Stage-gate systems: A new tool for managing new products. Bus Horiz 1990;33:44–54.
[2] Cooper RG, Kleinschmidt EJ. New product processes at leading industrial firms. Ind Mark Manag 1991;20:137–147.
[3] Prasad B. Concurrent Engineering Fundamentals: Integrated product and process organization. Prentice Hall PTR, 1996.
[4] Wheelwright SC, Clark KB. Revolutionizing Product Development: quantum leaps in speed, efficiency, and quality. Maxwell Macmillan, Inc., 1992.
[5] Pahl G, Beitz W. Engineering Design: A Systematic Approach. 2nd ed., Springer Science & Business Media, London, 2013.
[6] Atzberger A, Paetzold K. Current challenges of agile hardware development: What are still the pain points nowadays?. Proc Int Conf Eng Des ICED. 2019;August:2209–2218.
[7] Conforto EC, Salum F, Amaral DC, Silva SL, Almeida LFM. Can Agile Project Management Be Adopted by Industries Other than Software Development?. Proj Manag J 2008;39:28–42.
[8] Lanzotti A, Carbone F, Grazioso S, Renno F, Staiano M. A new interactive design approach for concept selection based on expert opinion. Int J Interact Des Manuf 2018;12:1189–1199.
[9] Kratzer MJ, Bauch L, Burkert T, Szost B, Bauernhansl T. Reasons for Engineering Changes Affecting Part-specific Tools: An Investigation in the Automotive Industry. IEEE Int Conf Ind Eng Eng Manag IEEM 2021. 2021:477–481.
[10] Moher D, Liberati A, Tetzlaff J, Altman DG, Altman D, Antes G, Atkins D, Barbour V, Barrowman N, Berlin JA, Clark J, Clarke M, Cook D, D'Amico R, Deeks JJ, Devereaux PJ, Dickersin K, Egger M, Ernst E, Gøtzsche PC, Grimshaw J, Guyatt G, Higgins J, Ioannidis JPA, Kleijnen J, Lang T, Magrini N, McNamee D, Moja L, Mulrow C, Napoli M, Oxman A, Pham B, Rennie D, Sampson M, Schulz KF, Shekelle PG, Tovey D, Tugwell P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med 2009;6.
[11] Romeral P, Zancul E, Nakano D. Review Database for: Product Development Process for complex hardware-based solutions - current trends, Mendeley Data. 2023;V1. https://doi.org/10.17632/dtyh9t765m.1
[12] Andiappan V, Wan YK. Distinguishing approach, methodology, method, procedure and technique in process systems engineering. Clean Technol Environ Policy 2020;22:547–555.
[13] Soltes M, Kappler D, Koberstaedt S, Lienkamp M. A case study of a framework for user-centered hardware development based on the aCar electric vehicle project. 13th Int Conf Ecol Veh Renew Energies, EVER 2018. 2018:1–8.
[14] Boye J. RADSoM - A System on Module Approach for Reusable Spacecraft Processing Elements, IEEE Aerosp Conf Proc 2020:1–8.
[15] Platt TM, Liu C. Reducing test time with FPGA accelerators using OpenCL. 27th North Atl. Test Work. NATW 2018. 2018:1–9.
[16] Cooper RG, Sommer AF. The Agile–Stage-Gate Hybrid Model: A Promising New Approach and a New Research Opportunity. J Prod Innov Manag 2016;33:513–526.
[17] Sharma S, Sarkar D, Gupta D. Agile Processes and Methodologies: A Conceptual Study. Int J Comput Sci Eng 2012;4:892–898.
[18] Razzouk R, Shute V. What Is Design Thinking and Why Is It Important?. Rev. Educ. Res. 2012;82:330–348.
[19] Kling R. The Organizational Context of User-Centered Software Designs. MIS Q 1977;1:41.
[20] Sousa-Poza A, Keating C, Kovacic S. Systems engineering: evolution and challenges. Int J Syst Syst Eng 2015;5:379–399.
[21] Saaksvuori A, Immonen A. Product Lifecycle Management, Third Edit, Springer, 2008.
[22] Innella G, Rodgers P, Rodgers PA, Higuchi T, Muxel A, Paskevicius A. The benefits of prototyping early in design workshops: report and insights from an international collaborative workshop between Chiba Internet-based Design Tools View project. 2017.
[23] Isa SS, Liem A, Steinert M. The Value of Prototypes in the Early Design and Development Process. Proc International Conf Eng Des - ICED 2015. 2015:1–8.
[24] Yantır HE, Eltawil AM, Salama KN. A hardware/software co-design methodology for in-memory processors. J Parallel Distrib Comput 2022;161:63–71.
[25] Qiu L, Lao Y. A Systematic Method for Approximate Circuit Design Using Feature Selection. Proc - IEEE Int Symp Circuits Syst 2018:May.
[26] Trimberger SM. Field-Programmable Gate Array Technology, First Edit, Springer Science & Business Media, New York, 1994.
[27] Azocar AF, Mooney LM, Duval JF, Simon AM, Hargrove LJ, Rouse EJ. Design and clinical implementation of an open-source bionic leg. Nat Biomed Eng 2020;4:941–953.
[28] Barrón-Romero C, Hernández-Zavala A. Hardware implementation of an α - level based binary search and shifting fuzzifier (α - BSSF). J Intell Fuzzy Syst 2020;39:6671–6685.
[29] Colturato AB, Chavier LFC. Decision support system for late blight in tomato and potato. Acta Hortic 2019;1233:19–26.
[30] Daniyan I, Mpofu K, Daniyan L, Fameso F, Oyesola M. Computer aided simulation and performance evaluation of additive manufacturing technology for component parts manufacturing. Int J Adv Manuf Technol 2020;107:4517–4530.
[31] Falabella AD, Wallin DO, Lund JA. Application of a customizable sensor platform to detection of atmospheric gases by UAS. 2018 Int Conf Unmanned Aircr Syst ICUAS. 2018:883–890.
[32] Fodor TG, Silaghi AM, Veber IN. Cost Reduction of Electronics Manufacturing Services Using A Low Cost Hardware Data Exporting Tool. 22nd IEEE Int Conf Autom Qual Testing, Robot - THETA, AQTR 2020 - Proc 2020:2020–2023.
[33] Heinrich H, Deutschlander A, Zoghlami F, Sen OK. The long journey from standardization to fully fab automation and more. IEEE Trans Semicond Manuf 2019;32:408–414.
[34] Kindt RW, Binder BT. Metal Array on a Triangular Lattice. IEEE Trans Antennas Propag 2022;70:1097–1106.
[35] Lopez V, Ishida W, Mayoral A, Tanaka T, Gonzalez De Dios O, Fernandez-Palacios JP. Enabling fully programmable transponder white boxes [Invited]. J Opt Commun Netw 2020;12:A214–A223.
[36] Lu W, Tang B, Wu Y, Lu K, Wang D, Wang X. A New Position Detection and Status Monitoring System for Joint of SCARA, IEEE/ASME Trans Mechatronics 2021;26:1613–1623.
[37] Ma M, Huang B, Wang B, Chen J, Liao L. Development of an energy-efficient smart socket based on STM32F103. Appl Sci 2018:8.
[38] Mishra P, Banerjee A, Ghosh M, Gogoi S, Dutta R. Development of a cost-effective circuit hardware architecture for brushless direct current motor driver. Int J Circuit Theory Appl 2021;49:2183–2198.
[39] Montero J, Weber S, Bleckmann M, Paetzold K. A methodology for the decentralised design and production of additive manufactured spare parts. Prod Manuf Res 2020;8:313–334.
[40] Peiret A, González F, Kövecses J, Teichmann M. Multibody system dynamics interface modelling for stable multirate co-simulation of multiphysics systems. Mech Mach Theory 2018;127:52–72.
[41] Sun B, Li Y, Wang Z, Li Z, Xia Q, Ren Y, Feng Q, Yang D, Qian C. Physics-of-failure and computer-aided simulation fusion approach with a software system for electronics reliability analysis. Eksploat i Niezawodn 2020;22;340–351.
[42] Vansteenwegen D, Ruddick K, Cattrijsse A,Vanhellemont Q, Beck M. The pan-and-tilt hyperspectral radiometer system (PANTHYR) for autonomous satellite validation measurements-Prototype design and testing. Remote Sens 2019;11.
[43] Xia F, Quigley J, Zhang X, Yang C, Wang Y, Youcef-Toumi K. A modular low-cost atomic force microscope for precision mechatronics education, Mechatronics 2021;76:102550.
[44] Zaloga V, Dyadyura K, Rybalka I, Pandova I, Zaborowski T. Enhancing efficiency by implementation of integrated management system in order to align organisational culture and daily practice. Manag Syst Prod Eng 2020;28:304–311.
[45] Zhou S, Wen B, Wang J, Burgos R, Boroyevich D. Design and hardware implementation of the peak current mode switching cycle control for voltage balancing of modular multilevel converters. Conf. Proc. - IEEE Appl Power Electron Conf Expo 2021:1134–1139.