



HAL
open science

Identifying the Trend of Research on Mechatronic Projects

Ruben Bolaños, Antonio Carlos Valdiero, Luiz Antônio Rasia, João Ferreira

► **To cite this version:**

Ruben Bolaños, Antonio Carlos Valdiero, Luiz Antônio Rasia, João Ferreira. Identifying the Trend of Research on Mechatronic Projects. 18th IFIP International Conference on Product Lifecycle Management (PLM), Jul 2021, Curitiba, Brazil. pp.25-39, 10.1007/978-3-030-94399-8_3 . hal-04195224

HAL Id: hal-04195224

<https://inria.hal.science/hal-04195224v1>

Submitted on 4 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



This document is the original author manuscript of a paper submitted to an IFIP conference proceedings or other IFIP publication by Springer Nature. As such, there may be some differences in the official published version of the paper. Such differences, if any, are usually due to reformatting during preparation for publication or minor corrections made by the author(s) during final proofreading of the publication manuscript.

Identifying the Trend of Research on Mechatronic Projects

Ruben Dario Solarte Bolaños¹[0000-0002-3129-0317], Antonio Carlos Valdiero²[0000-0001-7447-2076], Luiz Antônio Rasia³[0000-0001-8334-0956] and João Carlos Espindola Ferreira²[0000-0001-7746-4354]

¹ Tecnoparque Nodo Pitalito SENA H 417030, Colombia

² Federal University of Santa Catarina, Florianopolis SC 88040900, Brazil

³ Regional University of Northwestern Rio Grande do Sul State RS, Ijuí RS 98781720, Brazil

Abstract. Mechatronics is an interdisciplinary field of engineering sciences characterized by the integration and interconnection between mechanical engineering, electrical engineering, and computer science. Mechatronic products are mostly structurally complex, but they are an optimal solution for many fields of industry such as medicine, agriculture, agribusiness, among others. The main objective of this article is to identify research trends on NPD (New Product Development) mechatronics projects today. For this, a bibliographic review is made, citing important works in the area since 2001, addressing the main objective of each research, in order to group them into approaches and identify current research trends. In the end, it is concluded that the trend is to reduce the total cost of a mechatronic product, as well as to begin to adapt concepts of the new technologies of Industry 4.0 (I4.0) to the NPD mechatronic projects. The goal is to facilitate the collaboration, in a more formal way than social communication and, consequently, simplifies knowledge reuse.

Keywords: Mechatronic product, NPD projects, research trend, timeline.

1 INTRODUCTION

All mechatronic products share mechanics, electronics, and software content in their design structure. In this way, it is important to point out that mechatronic products differ from one another in their design structures, due to the functional requirements defined for each product [1]–[4]. According to [5], most mechatronic products can be represented by mechatronics indicators, which encompasses the elements: flexibility, intelligence and complexity. As stated by Park and Okudan Kremer [6], it is especially important to study the complexity variable of a mechatronic product to mitigate its effects. The complexity of a mechatronic product is treated in [7], which describes the effects of this variable on the development cycle time, production costs and product quality. The development and design of mechatronic systems is challenging because of their interdisciplinary nature [8]. In the development process, several engineering domains with strong interdependences are involved and have to be considered holistically [8], [9]. Used product development methodologies are based on an individual processing of

the domains, and integrate them late in the detailed design phase of the development process [8]. In early design phases numerical methods can facilitate defining an optimal product design based on given requirements [8].

As time passes by, mechatronic products become even more integrated into networks and communicate and use data to fulfill their functionalities [10]. One of the technologies that have allowed this integration in the network is Internet of Things (IoT). IoT is a network of physical objects embedded with hardware, software, frequently with sensors, and network connectivity, enabling data collection and exchange [11].

To identify the trend or direction of NPD mechatronic projects at present, a bibliographic review is made in this document, which allows identifying the main objectives of each article, thus grouping works with similar approaches. Each approach is assigned a numerical value referring to the number of citations per year. With the numerical value, the slope between the years 2001 and 2020 of each approach is calculated, and the slope is taken as an indicator of the current research trend.

This article provides a classification of some publications found in the literature on mechatronic projects, with the purpose of identifying the research trends on that topic.

2 REVIEW OF NPD MECHATRONICS PROJECTS

According to [12], the term "Industry 4.0" was used for the first time during the Hannover Fair, symbolizing the beginning of the fourth industrial revolution. Thus, 2011 was chosen as a turning point in this work, beginning the systematic revision 10 years before [2001-2010]. 2011 is considered a very important year for the analysis of the effects of the arrival of I4.0 technologies used in NPD mechatronics projects.

The scientific bases explored in this work were: ScienceDirect, Scopus and IEEE. Through the systematic review, 78 articles were selected. The keywords for the selection of are: new product development, Mechatronic and I4.0. Finally, the articles that have the purpose of mitigating costs or complexity effects, increase operating performance and quality or reducing times in the development of mechatronic products were chosen. This chapter shows a description of the articles addressed in this review.

The authors in [13] presented a method for mechatronic development process for future "smart" autonomous vehicle systems in order to satisfy special needs within the experimental verification and validation of such systems. The work in [5] presents a table to measure the complexity of a mechatronic product, explaining the concepts are used to evaluate it. [14] proposed a low cost software prototype that was developed to enable numerical control programming based on microcomputers. [15] proposes low cost fuzzy control solutions for controlling servo systems in mechatronic systems. [16] represents a product by implementing the DSM (Design Structure Matrix) matrix to manage the dependencies and relationships of the product components, and the DMM (Domain Mapping Matrix) matrix to compare two different mechatronic projects. [17] presents an approach to analyse and measure the correlation between the structural assembly of mechatronic products and the composition of their development and production costs. In [18] a design of a new low-cost humanoid robot named as CALUMA (CAssino Low-cost hUMANoid robot) was illustrated. [19] presents an integrated and open-architecture motion control (OMC) development environment.

In [20] a prototype model of a resonant valve was developed. The main objective was to reduce costs because pneumatic actuators have several advantages such as light

weight, safety, low cost and high compliance. An approach for using hierarchical models in the design of mechatronic systems was presented in [1]. The works [17] and [45] showed the single phases of Development in Mechatronics according to the V-Model in VDI 2206.

[22] used the MDM (Multiple Domain Matrix) and DSM matrices to obtain the structural model of a complex product: an intelligent gas meter. The main objective of the implementation of these matrices is to reduce the level of complexity to increase the stability of the systems, in response to alterations, also achieving the management of changes in the product with the lowest consumption of time and costs. A generic procedure model was presented in [23] for the integrative development of mechatronic products and production systems plus a convenient specification technique. A computational intelligence method was presented in [24], based on a Locally Linear Neurofuzzy (LLNF) method for estimation and prediction of the time and cost of the NPD projects based on the Earned Value Management (EVM). [25] shows the twelve phases for the development of a new mechatronic product.

[26] presented a design approach that focus on ensuring that mechatronic products are well-designed, since the scope is oriented towards design validation. A practical case was presented in [27], where the change propagation management in the design and development of a smart gas meter was investigated. [28] presented an approach based on product requirements. Assuming that products with similar indicators require similar development efforts, databases are set-up to allow for development cost prediction. The model was validated for a civil aircraft.

A multidisciplinary interface model for design of mechatronic systems was presented in [4], in order to enable the multidisciplinary integration among design team members from different disciplines. The authors of [29] developed a cost overrun predictive model using five known drivers of complex systems development cost (mechatronic products). A software system was developed in [30] for open architecture CNC systems, and the module is able to translate ISO 14649 part 21 and ISO 6983 data interface model code as per internal structure of machine.

[31] presents a modelling and parameter identification methodology of a servopneumatic linear drive unit with complex internal design that takes into account the influence of dead volume in terms of system dynamics. A study on various developments in the positioning control of the pneumatic cylinders is presented in [32]. The pneumatic actuators provide many advantages, such as cleanliness, low-cost, high power to weight ratio, easy maintenance, safety, anti-explosive, long working life.

[33] proposed a new open CNC system based on the low power embedded platform, named open and high-performance CNC (OHP-CNC). In [34] an open architecture soft-CNC system based on RTX (real-time extension) and an IPC (Industrial personal computer) is developed. In [35] a low-cost mechatronics system is presented as a proof-of-concept that can be used by students and professionals in physical therapy training, and by engineers to design and produce orthopaedic and orthotic devices for upper and lower limbs. The work in [36] contains a description of the work done in developing a simple low-cost system for tracking upper human limb motion system with satisfactory accuracy and repeatability. The research in [37] describes the context of the extension of mechatronic systems to cyber-physical ones, firstly by highlighting their similarities and differences, and then by underlining the current needs for Cyber-Physical Systems (CPSs) in the manufacturing sector. A scalable service-oriented architecture and virtualization technique are presented in [38], and describes communication methods of a cyber-physical manufacturing cloud.

The development of an open-loop controller implemented in the Arduino platform was presented in [39], seeking to reuse an existing CNC machine for performing simple manufacturing operations. A method to improve the accuracy of mechatronic systems used for measurements of complex geometry was presented in [40].

The authors of [41] proposed an approach to create clients in the CNC system to allow solving the task of multi-interface control of the CNC machine. In [42] a new mechatronic index is proposed for evaluating mechatronic alternatives in the conceptual design phase. An approach for design and development of a CNC machining process knowledge base using cloud technology is presented in [43]. [44] attempts to enhance accuracy of a pneumatic actuator without reduction significantly its speed by interconnecting two pneumatic cylinders to form a linear manipulator series. The authors of [45] proposed a method based on Knowledge Based Engineering (KBE). The method has the following features: (a) to support the designers in the different steps of the design cycle; (b) to reuse the design results and adapt them to requirement changes. The contribution lies in adapting KBE application roles to mechatronic design.

The authors of [46] reduced manufacturing cost of lower limb prosthesis. The authors of [47] proposed a model to determine how early to participate on creating some strategies about treating of e-scrap. The work in [48] presented an approach for developing low cost CNC systems by controlling CAN drives. In [49] an approach is proposed with the use of canned cycles, which allow unifying the process of dialog programming for machines with CNC systems from different manufacturers. The authors of [50] proposed a CPPS conjoint design process based on mechatronic systems and CPS. The authors of [51] show how artificial neural networks (ANN) can be used to improve mounting accuracy in automated assembly systems. [52] describes the structural and modular architectures for the design of smart mechatronic and cyber-mix mechatronics systems used in laboratories and in industry.

[53] proposes a configuration design method for mechatronic systems in the context of industrial manufacturing. The work in [54] proposes a methodology for identification and design (ID) of smart operations in manufacturing. The research in [55] described a procedure for the evaluation of variability in the complex chain between the point where measurements are taken and algorithms executed in the evolving I4.0 scenario. A solution to farm irrigation using IoT and machine learning techniques is presented in [56]. The work in [57] investigated the relationship between mechatronic product complexity and team seniority as planning parameters for the new product development project, exploring the effect on project performance. The work in [10] presents a systematic product development methodology for developing customizable IoT devices, which involves more processes than a mass-produced mechatronic product. In [58], a pick and place robot was integrated with Global System for Mobiles (GSM) technology, Radio Frequency Identification (RFID) equipment, and sensor technology to enhance robot functionality.

A product-related dependency index is proposed in [59] that can be used during the conceptual design of mechatronic systems. [85] and [86] presented the design and construction of two smart mechatronics prototypes: (a) smart mechatronic base isolation system that uses an Earthquake Early Warning (EEW) system for activation; and (b) a mechatronic smart skin (MSS). [62] presents a design methodology that provides an integrated, concurrent, and system-based viewpoint to mechatronic design, which differs from the non-optimal sequential design methodologies.

A methodology to harmonize the design cycle of mechatronic systems is described in [63]. [64] proposes a new type of CNC system called invisible numerical control (INC) system, to simplify CNC architecture and improve CNC architecture re-

configurability and function reusability. A CNC engraving machine using Arduino One was presented in [65]. The purpose of this mini-CNC is to engrave on acrylic materials with high accuracy and low cost. The design and implementation of a mechatronic system is presented in [66], where by some treatments can be performed automatically. The mechatronic system and its auxiliary equipment were mounted on a three-wheeled mobile platform.

In order to make optimized control design for mechatronic system, a simplified model was presented in [67], which used a model order reduction technique, enabling preserving the dominant physical parameters and reveal the performance limiting factors. An intelligent CNC controller with a hierarchical structure was presented in [68], whose upper layer contains the machining process planning system using cloud technology. The authors of [69] suggested an universal approach to the integration of the third-party and in-house solutions into a CNC system, including their interaction in the system.

The authors of [70] proposed an architecture of a configurable CNC system in order to allow configuring and reconfiguring the CNC system in different ways, from “classical” to “cloud”, as well as providing maximum computing power. This does not require any changes in the hardware and software of the CNC system. [71] presents the design and development of a VR (Virtual Reality) bicycle system under a VDI 2206 approach. Successful integration was achieved of a physical system, a VR system, and a control behavior system to compose a virtual bicycle simulator.

The challenge of implementing IIoT (industrial IoT) and CPS in small and medium enterprises (SMEs) was addressed in [72], focusing on the integration of information technology, which supports data storage, collection and analysis, with the operation technology supporting the creation of physical value.

Recommendations for future research topics to overcome the obstacle of introducing smart automation in SMEs are provided in [73]. A case study of human-robot collaborative assembly applied to the production of a pneumatic cylinder in a learning factory laboratory was shown in [74]. An explorative set of hypotheses of requirements for the implementation of I4.0 concepts in logistics processes for SMEs was presented in [75]. The research in [76] discussed features of intelligent products, machines, and facilities in manufacturing and logistics systems, as objects that are able to provide data for their own virtual image. “Digital twins” can be established of products and process flows, in order to be used for planning and control of the plant. The digital connection between the products and the actual plant enables smart automation of the processing steps. This requires permanent and real-time traceability of objects and their states.

The authors of [77] analysed the importance and potential of effective and efficient logistics operations, and outline enabling technologies for automation in logistics systems. A structured approach was provided in [78] to carry out self-assessment for I4.0 implementation. A systematic literature review was carried out in [79], as well as a focus group study to identify organizational issues that might hinder I4.0 implementation. The authors of [80] built a low-cost semi-automatic robot prototype that carries out a couple of farming processes. Finally, the work in [7] presented a model for cycle time estimation in NPD mechatronics projects.

3 APPROACHES IDENTIFICATION

In this section, the papers were grouped into subsets by similarities in their objectives and research results. After analyzing each subset, the name and general description were defined according to the contents of the grouped articles. Tab. 1 contains research papers focused on developing mechatronic projects. It can be observed how the approaches of this research topic have changed over time. Eight approaches are identified in this research. Seventy-eight documents were studied in total. Tab. 1 shows the grouped reviewed papers, according to the focus of each publication.

TABLE 1. REVIEW OF APPROACHES FOR DEVELOPING MECHATRONIC PROJECTS

Approaches	Description	Publications
A1	Reducing costs in mechatronic product development or manufacturing by means of low-cost technology implementation.	[14], [15], [38]–[41], [44], [46]–[49], [56], [20], [64]–[66], [71], [80], [30]–[36]
A2	Cost and time prediction in mechatronic product development projects.	[7], [24], [28], [29], [57]
A3	Optimization and visualization of the mechatronic system design (management complexity design) to mitigate development and manufacturing costs and increase functional performance (Accuracy). Managing change propagation (mechatronic product design) with the least cost.	[5], [10], [45], [51], [55], [59], [62], [67], [69], [81]–[83], [15], [84], [16]–[18], [22], [27], [32], [42]
A4	Approach to design conjointly a mechatronic product and its production	[23], [50].
A5	Mechatronic Systems Project (Mechatronics Product Development models to decrease product development costs and time).	[1], [3], [53], [59], [62], [63], [69], [4], [8], [9], [19], [21], [23], [25], [45]
A6	Mechatronic product validation methods.	[26] [13]
A7	Mechatronic Systems Project with Industry 4.0 technologies.	[10], [37], [66], [70], [74], [85], [43], [50], [52], [54], [55], [58], [60], [61]
A8	Implementation of Industry 4.0 concepts in mechatronics processes for SMEs (Small and Medium Enterprises).	[12], [72], [86]–[88], [73]–[79], [85]

In order to maintain an optimal relation between cycle time, cost and quality in the development of mechatronic products, the approach with the largest amount of publications (A1 approach) focused on proposing low-cost technological solutions for cost reduction but maintaining a good functional performance.

It can be observed in Fig. 1 that there is a total of twenty-nine projects that propose development methodologies for mechatronic products, which are divided into two groups: A5: development of mechatronic products (15); and A7: development of mechatronic products integrating concepts of Industry 4.0 (14).

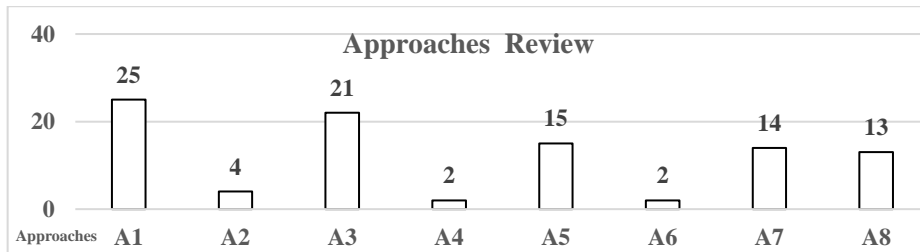


Fig. 1. Amount of papers grouped by approach.

It can also be noticed that, as time progresses, the methodologies in the development of mechatronic products begin to include concepts derived from Industry 4.0 such as IoTs, CPS (Cyber-Physical Systems), Cloud Computing, IIoTs (Industrial Internet of Things), Big Data, among others (Fig. 2). The methodologies for mechatronic product development are represented by the A5 and A6 approaches.

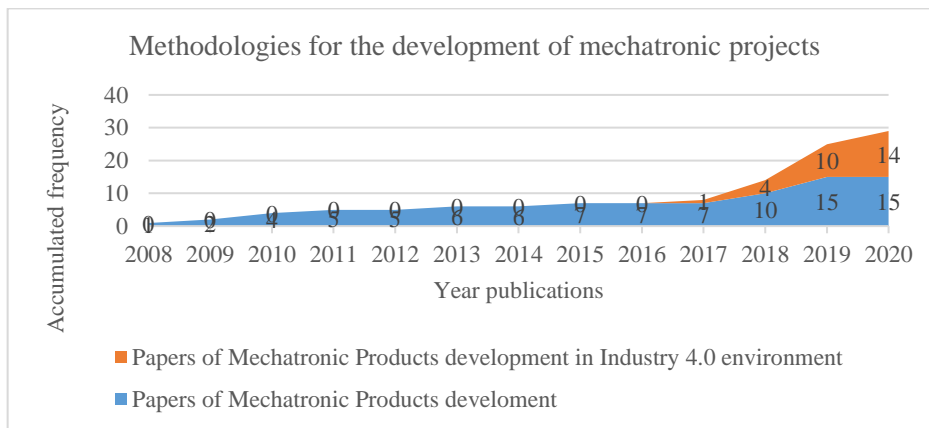


Fig. 2. Methodologies for the development of mechatronic products.

Twenty-two papers addressed the issue of reducing costs of design management (optimizing product structure/increasing functional performance) and change propagation management (approach A3). Thirteen publications focused on how SMEs can implement technologies such as CPS, IIoTs, collaborative robots, and other tools involved in Industry 4.0 (smart manufacturing) (approach A8). Four papers focused on proposing time and cost prediction models in the mechatronic product development process (A2). Two approaches proposed methods for conjoint mechatronic product and process development (A4), whereas two publications proposed a model for mechatronic product validation (A6). Fig. 3 shows the cumulative frequency per year of the publications grouped in each approach.

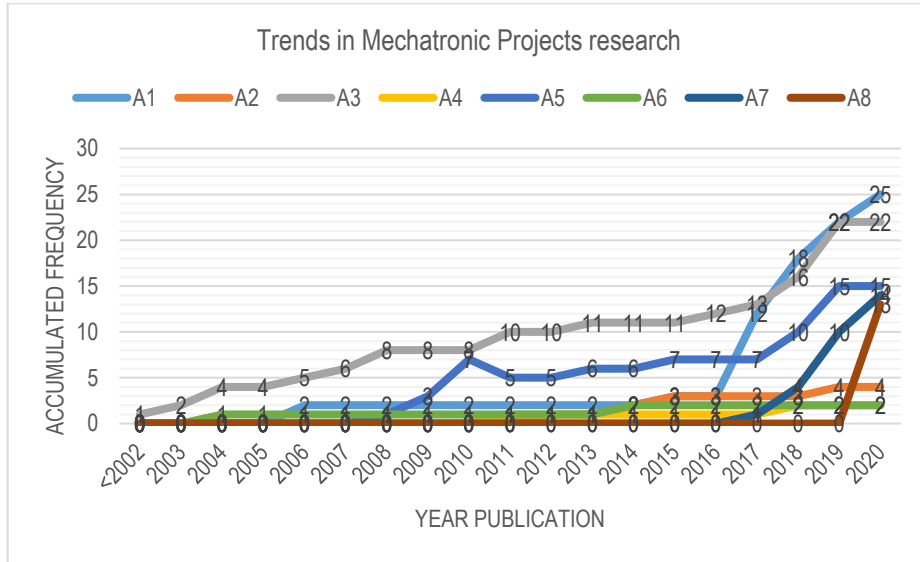


Fig. 3. Methodologies for the mechatronic products development.

According to Fig. 3, the approach with the largest increase from 2016 onwards is A1. The values presented in Tab. 2 are obtained by calculating the slopes from 2016 to 2020 for each approach. The slope is calculated by Equation (1).

$$s = \frac{n_2 - n_1}{y} \quad (1)$$

Where: s = slope

n_1 = amount of publications in 2016

n_2 = amount of publications in 2020

y = number of years (equal to 4 in this case)

If the slopes are taken as the trend indicator, the approaches from largest to lowest current research tendency would: A1, A7, A8, A3, A5, A2 and A4 (tied), and A6. In this way, it is concluded that the research trend for mechatronic NPD projects contemplated the A1 approach in the first place, followed by the A7 and A8 approaches.

TABLE 2. SLOPE OF THE APPROACHES APPLIED IN PUBLICATIONS FROM 2016 TO 2020

Approach	2016	2020	Slope
A1	3	25	5.5
A7	0	14	3.5
A8	0	13	3.25
A3	11	21	2.5
A5	7	15	2
A2	3	4	0.25
A4	1	2	0.25
A6	2	2	0

In this paper, the slope represented the trend research today for the NPD mechatronics projects.

4 ANALISYS AND DISCUSSION

From the steepest approaches (A1, A3, A7 and A8) presented in table 2, it can be concluded that the research trend for mechatronic NPD projects aims to create methodologies that allow: 1. Reduce development costs of mechatronics products for Industry 4.0, and 2. Management of the complexity of the design of mechatronic products for Industry 4.0. Despite the fact that the concept of industry 4.0 appeared in 2011, through the analysis of fig. 2 and fig. 3, it can be observed that only until 2017 joint works began to appear in the design of mechatronic products integrated to I4.0 technologies.

In the same way, it can be said that the conception of a mechatronic product as a mechanism associated with a control system and an actuation system or another, must be updated to add connectivity components that allow a mechatronic system to be coupled to I4.0 systems. Therefore, it has become a mechatronic product with more components and of a more complex nature.

5 CONCLUSION

In this research, several publications on mechatronics projects were surveyed, from which eight different approaches were identified on the new mechatronic products development. By taking into account the number of publications per year of each approach, the slope of publications between the year 2016 and 2020 was calculated as an indicator of the research trend. The largest slope was A1 approach (reducing costs in mechatronic products development or manufacturing by means of low-cost technology implementation), which corresponds to the current research trend in the NPD projects for mechatronic products development today.

The present work becomes the beginning of a future work that aims to build a knowledge base for the development of mechatronic products in Industry 4.0 environments. This article presents an overview of mechatronic projects development and the research horizons in this area, which becomes a contribution of literature for researchers who are starting their scientific work on mechatronic projects.

Acknowledgment

The authors would like to express their gratitude to SENA Colombia and UFSC (Federal University of Santa Catarina) for the support to this project (SIGPEX Numbers: 202002173 and 202002437) with scientific initiation, master and doctoral research. This research was partially supported by the CAPES (Coordination for the Improvement of Higher Education Personnel) and FAPESC (Research Foundation of the State of Santa Catarina).

References

- [1] P. Hehenberger, F. Poltschak, K. Zeman, and W. Amrhein, "Hierarchical design models in the mechatronic product development process of synchronous machines," *Mechatronics*, vol. 20, no. 8, pp. 864–875, 2010.
- [2] P. Hehenberger, "Perspectives on hierarchical modeling in mechatronic design," *Adv. Eng. Informatics*, vol. 28, no. 3, pp. 188–197, 2014.
- [3] D. Hofmann, M. Kopp, and B. Bertsche, "Development in Mechatronics - Enhancing reliability by means of a sustainable use of information," *2010 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, pp. 1263–1268, 2010.
- [4] C. Zheng, J. L. Duigou, M. Bricogne, and B. Eynard, "Multidisciplinary interface model for design of mechatronic systems," *Comput. Ind.*, vol. 76, no. 6, pp. 24–37, 2015.
- [5] V. C. Moulianitis, N. A. Aspragathos, and A. J. Dentsoras, "A model for concept evaluation in design - An application to mechatronics design of robot grippers," *Mechatronics*, vol. 14, no. 6, pp. 599–622, 2004.
- [6] K. Park and G. E. Okudan Kremer, "Assessment of static complexity in design and manufacturing of a product family and its impact on manufacturing performance," *Int. J. Prod. Econ.*, vol. 169, pp. 215–232, 2015.
- [7] R. D. S. Bolaños and S. C. M. Barbalho, "Exploring product complexity and prototype lead-times to predict new product development cycle-times," *Int. J. Prod. Econ.*, vol. 235, p. 108077, 2021.
- [8] C. Tamm, S. Perfetto, C. Tamm, S. Perfetto, C. Tamm, and S. Perfetto, "Design and Optimization of Mechatronic Systems Using a Holistic and Parametric Simulation Approach," *IFAC Pap.*, vol. 52, no. 15, pp. 271–276, 2019.
- [9] J. Lenz, T. Wuest, and E. Westkämper, "Holistic approach to machine tool data analytics," *J. Manuf. Syst.*, vol. 48, pp. 180–191, 2018.
- [10] S. K. Gogineni, T. Riedelsheimer, and R. Stark, "Systematic development methodology for customizable IoT devices," *Procedia CIRP*, vol. 84, pp. 393–399, 2019.
- [11] S. Stankovski, G. Ostoji, X. Zhang, I. Baranovski, and S. Horvat, "Mechatronics , Identification Tehnology , Industry 4 . 0 and Education," no. March, pp. 20–22, 2019.
- [12] D. T. Matt and E. Rauch, "SME 4.0: The Role of Small- and Medium-Sized Enterprises in the Digital Transformation," in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 3–36.
- [13] J. Hilgert, T. Bertram, and M. Hiller, "Development of smart vehicles using a scaled mechatronic environment," *IFAC Proc. Vol.*, vol. 37, no. 14, pp. 85–90, 2004.
- [14] D. D. da Costa and A. G. Pereira, "Desenvolvimento e avaliação de uma tecnologia de baixo custo para programação CNC em pequenas empresas," *Production*, vol. 16, no. 1, pp. 48–63, 2006.
- [15] R. E. Precup and S. Preitl, *Low cost fuzzy controlled servo systems in mechatronic systems*, vol. 4, no. PART 1. IFAC, 2006.
- [16] M. Danilovic and T. R. Browning, "Managing complex product development projects with design structure matrices and domain mapping matrices," *Int. J. Proj. Manag.*, vol. 25, no. 3, pp. 300–314, 2007.
- [17] S. C. Braun and U. Lindemann, "The influence of structural complexity on product costs,"

2008 *IEEE Int. Conf. Ind. Eng. Eng. Manag. IEEM 2008*, pp. 273–277, 2008.

- [18] N. E. Nava Rodriguez, G. Carbone, and M. Ceccarelli, “Simulation results for design and operation of CALUMA, a new low-cost humanoid robot,” *Robotica*, vol. 26, no. 5, pp. 601–618, 2008.
- [19] G. Botto, S. Carabelli, L. Suarez, M. Visconti, and P. Truccone, “Open motion control: A model based development platform for rapid prototyping,” pp. 1445–1450, 2009.
- [20] Y. Nishioka, K. Suzumori, T. Kanda, and S. Wakimoto, “A new control method utilizing multiplex air vibration for multi-DOF pneumatic mechatronics systems,” *IEEE/RSJ 2010 Int. Conf. Intell. Robot. Syst. IROS 2010 - Conf. Proc.*, pp. 3037–3042, 2010.
- [21] V. S. Vasić and M. P. Lazarević, “Standard Industrial Guideline for Mechatronic Product Design,” *FME Trans.*, vol. 36, pp. 103–108, 2008.
- [22] A. Ahmadinejad and A. Afshar, “Complexity management in mechatronic product development based on structural criteria,” *Mechatronics (ICM), 2011 IEEE ...*, pp. 7–12, 2011, [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5971266.
- [23] J. Gausemeier, R. Dumitrescu, S. Kahl, and D. Nordsiek, “Integrative development of product and production system for mechatronic products,” *Robot. Comput. Integr. Manuf.*, vol. 27, no. 4, pp. 772–778, 2011.
- [24] M. Fasanghari, S. H. Iranmanesh, and M. A. Karam, “Proposing an advanced computational method for completion time estimation of the New Product Development (NPD) projects,” *2012 11th Int. Conf. Inf. Sci. Signal Process. their Appl.*, no. 7 82, pp. 961–967, 2012.
- [25] S. C. M. . Barbalho and H. . Rozenfeld, “Mechatronic reference model (MRM) for new product development: Validation and results [Modelo de referência para o processo de desenvolvimento de produtos mecâtrônicos (MRM): Validação e resultados de uso],” *Gest. e Prod.*, vol. 20, no. 1, pp. 162–179, 2013.
- [26] P. Couturier, M. L??, A. Imoussaten, V. Chapurlat, and J. Montmain, “Tracking the consequences of design decisions in mechatronic Systems Engineering,” *Mechatronics*, vol. 24, no. 7, pp. 763–774, 2014.
- [27] S. A. Ahmadinejad and A. Afshar, “Management of Change propagation in Mechatronic Product Design Based on Minimum Cost of Changes,” pp. 666–671, 2014.
- [28] J. E. Heller, M. Löwer, and J. Feldhusen, “Future Product Development Cost Prediction Model for Integrated Lifecycle Assessment,” in *IFIP Advances in Information and Communication Technology*, 2014, vol. 442, pp. 377–386.
- [29] M. Adoko, T. Mazzuchi, and S. Sarkani, “Developing a Cost Overrun Predictive Model for Complex Systems Development Projects,” *Proj. Manag. J.*, vol. 46, p. n/a-n/a, 2015.
- [30] Y. Yusof and K. Latif, “New interpretation module for open architecture control based CNC systems,” *Procedia CIRP*, vol. 26, pp. 729–734, 2015.
- [31] C. R. Rad and O. Hancu, “An improved nonlinear modelling and identification methodology of a servo-pneumatic actuating system with complex internal design for high-accuracy motion control applications,” *Simul. Model. Pract. Theory*, vol. 75, pp. 29–47, 2017.
- [32] D. Saravanakumar, B. Mohan, and T. Muthuramalingam, “A review on recent research trends in servo pneumatic positioning systems,” *Precis. Eng.*, vol. 49, pp. 481–492, 2017.
- [33] C. yi Deng, R. feng Guo, X. Xu, R. Y. Zhong, and Z. Yin, “A new high-performance open CNC system and its energy-aware scheduling algorithm,” *Int. J. Adv. Manuf. Technol.*, vol. 93, no. 5–8, pp. 1513–1525, 2017.
- [34] J. Wu, D. Li, and S. Wang, “The design and experimental research of an open architecture

- soft-CNC system based on RTX and an IPC,” *Int. J. Adv. Manuf. Technol.*, vol. 89, no. 5–8, pp. 1387–1399, 2017.
- [35] H. Lara-Padilla, X. S. Sánchez, and T. A. Paucar, “Design and evaluation of a low-cost mechatronic system to study upper and lower limbs biomechanics,” *GHTC 2017 - IEEE Glob. Humanit. Technol. Conf. Proc.*, vol. 2017-Janua, pp. 1–5, 2017.
- [36] A. Anuar, K. S. M. Sahari, and E. C. Yue, “Development of a low cost upper limb motion tracking system with real-time visual output,” *IRIS 2016 - 2016 IEEE 4th Int. Symp. Robot. Intell. Sensors Empower. Robot. with Smart Sensors*, no. December, pp. 146–150, 2017.
- [37] O. Penas, R. Plateaux, S. Patalano, and M. Hammadi, “Multi-scale approach from mechatronics to Cyber-Physical Systems for the design of manufacturing systems,” *Comput. Ind.*, vol. 86, pp. 52–69, 2017.
- [38] X. F. Liu, M. R. Shahriar, S. M. N. Al Sunny, M. C. Leu, and L. Hu, “Cyber-physical manufacturing cloud: Architecture, virtualization, communication, and testbed,” *J. Manuf. Syst.*, vol. 43, pp. 352–364, 2017.
- [39] A. Quatrano, M. C. De Simone, Z. B. Rivera, and D. Guida, “Development and implementation of a control system for a retrofitted CNC machine by using Arduino,” *FME Trans.*, vol. 45, no. 4, pp. 565–571, 2017.
- [40] N. V. Ruzanov, M. A. Bolotov, V. A. Pechenin, N. D. Pronichev, and E. R. Stepanova, “The Method of Improving the Accuracy of Mechatronic Systems for Complex Geometry Measurements,” *Procedia Eng.*, vol. 176, pp. 529–539, 2017.
- [41] S. N. Grigoriev and G. M. Martinov, “An approach to creation of terminal clients in CNC system,” *RPC 2018 - Proc. 3rd Russ. Conf. Comput. Technol. Appl.*, pp. 1–4, 2018.
- [42] V. C. Moulianitis, G. A. D. Zachiotis, and N. A. Aspragathos, “A new index based on mechatronics abilities for the conceptual design evaluation,” *Mechatronics*, vol. 49, no. November 2017, pp. 67–76, 2018.
- [43] Y. Ye, T. Hu, C. Zhang, and W. Luo, “Design and development of a CNC machining process knowledge base using cloud technology,” *Int. J. Adv. Manuf. Technol.*, vol. 94, no. 9–12, pp. 3413–3425, 2018.
- [44] D. Saravanakumar, B. Mohan, T. Muthuramalingam, and G. Sakthivel, “Performance evaluation of interconnected pneumatic cylinders positioning system,” *Sensors Actuators, A Phys.*, vol. 274, pp. 155–164, 2018.
- [45] M. Mcharek, T. Azib, M. Hammadi, J. Y. Choley, and C. Larouci, “Knowledge sharing for mechatronic systems design and optimization,” *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1365–1370, 2018.
- [46] F. Valencia, D. Ortiz, and D. Ojeda, “Design and testing of low-cost knee prosthesis,” *2017 IEEE 2nd Ecuador Tech. Chapters Meet. ETCM 2017*, vol. 2017-Janua, pp. 1–6, 2018.
- [47] I. Bula, V. Hoxha, and E. Hajrizi, “Robot from Mechatronics Scrap -Begggar Robot,” *IFAC-PapersOnLine*, vol. 51, no. 30, pp. 216–219, 2018.
- [48] G. M. Martinov, A. Al Khoury, and A. Issa, “An approach of developing low cost ARM based CNC systems by controlling CAN drives,” *MATEC Web Conf.*, vol. 224, 2018.
- [49] L. I. Martinova and N. N. Fokin, “An approach to creation of a unified system of programming CNC machines in the dialog mode,” *MATEC Web Conf.*, vol. 224, 2018.
- [50] F. Mhenni, P. Hehenberger, O. Penas, M. Hammadi, and J.-Y. Choley, “Systems Engineering Approach for the Conjoint Design of Mechatronic Products and Their Manufacturing Systems,” *IEEE Comput. Soc.*, no. 978-1-5386-3664-0/18/\$31.00 ©2018 IEEE,

2018.

- [51] P. Bobka *et al.*, “DEVELOPMENT OF AN AUTOMATED ASSEMBLY PROCESS SUPPORTED WITH AN ARTIFICIAL NEURAL NETWORK,” *J. Mach. Eng.*, vol. 18, no. 3, pp. 28–41, 2018.
- [52] G. Gheorghe, “Original Concepts and Achievements for Designing of Concepts and and Achievements for Designing Designing of of Smart Smart Mechatronics Cyber-MixMechatronics Laboratories in the Industry Designing Smart Cyber-MixMechatronics Laboratories,” *IFAC-PapersOnLine*, vol. 51, no. 30, pp. 598–603, 2018.
- [53] C. Zheng *et al.*, “Interface model-based configuration design of mechatronic systems for industrial manufacturing applications,” *Robot. Comput. Integr. Manuf.*, vol. 59, no. May, pp. 373–384, 2019.
- [54] B. C. Menezes *et al.*, “ScienceDirect and Design of Industry Opportunities in Manufacturing: Identification and Design of Industry Opportunities in Manufacturing: Identification and Design of Industry Opportunities in Manufacturing: Examples from Mature Industries to Level Sy,” *IFAC Pap.*, vol. 52, no. 13, pp. 2494–2500, 2019.
- [55] G. D. Emilia, A. Gaspari, and E. Natale, “Mechatronics Applications of Measurements for Smart Manufacturing in an Industry,” *IEEE Instrum. Meas. Mag.*, vol. 22, no. April, pp. 35–43, 2019.
- [56] A. Vij *et al.*, “IoT and Machine Learning Approaches for Automation of Farm IoT and Machine Approaches Automation of Farm on Computational Intelligence for IoT and Machine Learning Approaches for Automation of Farm Irrigation System,” *Procedia Comput. Sci.*, vol. 167, pp. 1250–1257, 2019.
- [57] S. C. M. Barbalho, M. Monteiro de Carvalho, P. M. Tavares, C. H. Llanos, and G. A. Leite, “Exploring the Relation Among Product Complexity, Team Seniority, and Project Performance as a Path for Planning New Product Development Projects: A Predictive Model Applying the System Dynamics Theory,” *IEEE Trans. Eng. Manag.*, pp. 1–14, 2019.
- [58] S. M. Fati, S. Al-Nabhani, and A. Muneer, “Automated library system using SMS based pick and place robot,” *Int. J. Comput. Digit. Syst.*, vol. 8, no. 6, pp. 535–544, 2019.
- [59] U. Chouinard, S. Achiche, and L. Baron, “Integrating negative dependencies assessment during mechatronics conceptual design using fuzzy logic and quantitative graph theory,” *Mechatronics*, vol. 59, no. March, pp. 140–153, 2019.
- [60] L. Qiu, X. Lin, Y. Wang, S. Yuan, and W. Shi, “A mechatronic smart skin of flight vehicle structures for impact monitoring of light weight and low-power consumption,” *Mech. Syst. Signal Process.*, vol. 144, p. 106829, 2020.
- [61] R. W. K. Chan, Y. S. Lin, and H. Tagawa, “A smart mechatronic base isolation system using earthquake early warning,” *Soil Dyn. Earthq. Eng.*, vol. 119, no. December 2018, pp. 299–307, 2019.
- [62] A. Mohebbi, S. Achiche, and L. Baron, “Integrated and concurrent detailed design of a mechatronic quadrotor system using a fuzzy-based particle swarm optimization,” *Eng. Appl. Artif. Intell.*, vol. 82, no. December 2018, pp. 192–206, 2019.
- [63] M. Mcharek, M. Hammadi, T. Azib, C. Larouci, and J. Y. Choley, “Collaborative design process and product knowledge methodology for mechatronic systems,” *Comput. Ind.*, vol. 105, pp. 213–228, 2019.
- [64] Y. Yao, M. Liu, J. Du, and L. Zhou, “Design of a machine tool control system for function reconfiguration and reuse in network environment,” *Robot. Comput. Integr. Manuf.*, vol. 56, no.

May 2018, pp. 117–126, 2019.

[65] M. Wasif, Q. M. Siddique, S. Sakib, and T. M. Rameez, “Design of Mini CNC using Arduino uno,” pp. 3882–3884, 2019.

[66] I. Gravalos, N. Ziakas, S. Loutridis, and T. Gialamas, “A mechatronic system for automated topping and suckering of tobacco plants,” *Comput. Electron. Agric.*, vol. 166, no. August, p. 104986, 2019.

[67] Q. Li and H. H. Zhang, “Model reduction of a real time multidisciplinary mechatronic system,” *Proc. 2019 20th Int. Conf. Res. Educ. Mechatronics, REM 2019*, vol. 5, pp. 1–5, 2019.

[68] W. Gao, C. Zhang, T. Hu, and Y. Ye, “An intelligent CNC controller using cloud knowledge base,” pp. 213–223, 2019.

[69] G. M. Martinov, P. A. Nikishechkin, A. S. Grigoriev, and N. Y. Chervonnova, “Organizing Interaction of Basic Components in the CNC System AxiOMA Control for Integrating New Technologies and Solutions,” *Autom. Remote Control*, vol. 80, no. 3, pp. 584–591, 2019.

[70] G. M. Martinov, A. B. Ljubimov, and L. I. Martinova, “From classic CNC systems to cloud-based technology and back,” *Robot. Comput. Integr. Manuf.*, vol. 63, no. November 2019, p. 101927, 2020.

[71] G. Hernández–Melgarejo, D. A. Flores–Hernández, A. Luviano–Juárez, L. A. Castañeda, I. Chairez, and S. Di Gennaro, “Mechatronic design and implementation of a bicycle virtual reality system,” *ISA Trans.*, vol. 97, no. xxxx, pp. 336–351, 2020.

[72] R. A. Rojas and M. A. Ruiz Garcia, “Implementation of Industrial Internet of Things and Cyber-Physical Systems in SMEs for Distributed and Service-Oriented Control,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 73–103.

[73] L. Gualtieri, I. Palomba, E. J. Wehrle, and R. Vidoni, “The Opportunities and Challenges of SME Manufacturing Automation: Safety and Ergonomics in Human–Robot Collaboration,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 105–144.

[74] L. Gualtieri, R. A. Rojas, M. A. Ruiz Garcia, E. Rauch, and R. Vidoni, “Implementation of a Laboratory Case Study for Intuitive Collaboration Between Man and Machine in SME Assembly,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 335–382.

[75] P. Dallasega, M. Woschank, H. Zsifkovits, K. Tipayawong, and C. A. Brown, “Requirement Analysis for the Design of Smart Logistics in SMEs,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 147–162.

[76] H. Zsifkovits, J. Kapeller, H. Reiter, C. Weichbold, and M. Woschank, “Consistent Identification and Traceability of Objects as an Enabler for Automation in the Steel Processing Industry,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 163–192.

[77] H. Zsifkovits, M. Woschank, S. Ramingwong, and W. Wisittipanich, “State-of-the-Art Analysis of the Usage and Potential of Automation in Logistics,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 193–212.

[78] V. Modrák and Z. Šoltysová, “Development of an Organizational Maturity Model in Terms of Mass Customization,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*,

- D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 215–250.
- [79] G. Orzes, R. Poklemba, and W. T. Towner, “Implementing Industry 4.0 in SMEs: A Focus Group Study on Organizational Requirements,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 251–277.
- [80] K. Ramesh, K. T. Prajwal, C. Roopini, M. H. M. Gowda, and V. V. S. N. S. Gupta, “Design and Development of an Agri-bot for Automatic Seeding and Watering Applications,” *2nd Int. Conf. Innov. Mech. Ind. Appl. ICIMIA 2020 - Conf. Proc.*, no. Icimia, pp. 686–691, 2020.
- [81] D. M. Sharman and A. A. Yassine, “Characterizing complex product architectures,” *Syst. Eng.*, vol. 7, no. 1, pp. 35–60, 2004.
- [82] S. Diagne, A. Coulibaly, and F. D. B. De Beuvron, “Complex product modeling based on a Multi-solution eXtended Conceptual Design Semantic Matrix for behavioral performance assessment,” *Comput. Ind.*, vol. 75, pp. 101–115, 2016.
- [83] C.-H. Chen, S. F. Ling, and W. Chen, “Project scheduling for collaborative product development using DSM,” *Int. J. Proj. Manag.*, vol. 21, pp. 291–299, 2003.
- [84] Y. Y. Tai, J. Y. Lin, M. S. Chen, and M. C. Lin, “A grey decision and prediction model for investment in the core competitiveness of product development,” *Technol. Forecast. Soc. Change*, vol. 78, no. 7, pp. 1254–1267, 2011.
- [85] K. Židek, V. Modrák, J. Pitel, and Z. Šoltysová, “The Digitization of Quality Control Operations with Cloud Platform Computing Technologies,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 305–334.
- [86] A. Sopadang, N. Chonsawat, and S. Ramingwong, “Smart SME 4.0 Implementation Toolkit,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 279–302.
- [87] E. Rauch, A. R. Vickery, C. A. Brown, and D. T. Matt, “SME Requirements and Guidelines for the Design of Smart and Highly Adaptable Manufacturing Systems,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 39–72.
- [88] C. A. Brown, “Axiomatic Design for Products, Processes, and Systems,” in *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements*, D. T. Matt, V. Modrák, and H. Zsifkovits, Eds. Cham: Springer International Publishing, 2020, pp. 383–401.