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RESEARCH ARTICLE

Proposal of a Methodology for Mechatronic Design From Ideation to Embodiment Design: Application in a Masonry Robot Case Study Design

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ABSTRACT The growing complexity of industrial automation requires advanced design methodologies that integrate mechanical, electronic, and software systems into cohesive mechatronic products. This paper introduces an innovative engineering design methodology focused on the development of mechatronic products, covering from ideation to embodiment design. For its validation, the methodology was applied in a case study involving the design of a construction robot that automates key tasks such as block transportation, mortar application, and block placement. The robot was designed using a modular approach, allowing for scalability and adaptability to various tasks within the construction environment. To evaluate the methodology's effectiveness, a comparative assessment was conducted using five key criteria: Iterative Process, Multidisciplinary Work, Design Complexity, Usability, and Adaptability. The proposed methodology scored 3, 3, 3, 2, and 2 respectively, on a 0-3 scale, demonstrating strong performance in early-stage iteration, cross-disciplinary integration, and handling of complex designs, with moderate usability and adaptability. These results position the methodology among the most balanced approaches, bridging both classical and modern design methods, such as those proposed by Ulrich or the V-model. Initial validation of this case study, through simulations and conceptual design, highlights the robot's potential to improve efficiency and reduce labor costs. Although the case study targets construction, the methodology is adaptable to various industrial contexts, particularly manufacturing processes requiring automation, modularity, and flexibility. Future work includes the development of a physical prototype and further validation, with the potential to expand the methodology to broader manufacturing environments, fostering human-robot collaboration and adaptive production systems.

INDEX TERMS Bricklaying robot, design methodology, engineering design, mechatronic products.

I. INTRODUCTION

The rapid advancement of robotics and automation technologies has fundamentally transformed modern manufacturing and industrial processes [1]. Robotics, particularly when integrated with smart mechatronic systems, offers unprecedented opportunities for increasing productivity, precision, and flexibility in diverse industries such as manufacturing, construction, and logistics. Mechatronics, which integrates mechanical systems, electronics, and software, has emerged as a critical enabler in developing these advanced automation solutions [2]. However, as the complexity of

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mechatronic systems grows, so do the challenges associated with their design, particularly regarding adaptability, modularity, and interdisciplinary collaboration.

Traditional engineering design methodologies, while effective for certain applications, often fall short in addressing the unique demands of mechatronic systems. These methodologies are frequently too rigid or domain-specific to support the development of flexible, modular systems that can adapt to varying tasks and environments. Furthermore, many existing approaches do not adequately facilitate the iterative, interdisciplinary collaboration needed to ensure the successful integration of mechanical, electronic, and software components in complex systems [4], [5]. This gap in the design process presents a significant barrier to the advancement of industrial robotics and automation technologies.

To address these limitations, this paper proposes a novel engineering design methodology specifically tailored for mechatronic products and industrial robotics. The proposed methodology emphasizes modularity and adaptability, making it particularly suitable for industrial applications that require flexibility and scalability. It also incorporates an iterative, interdisciplinary approach to foster collaboration between mechanical, electronic, and software engineers, ensuring that the complexities of mechatronic systems are effectively managed [6], [7]. By focusing on the specific requirements of industrial robotics and automation, the methodology seeks to enhance the design and development processes for systems that must function in diverse and evolving environments.

The main contribution of this document is an engineering design methodology focused on mechatronic products, covering the process from initial ideation to embodiment design. The approach is grounded in traditional engineering design methodologies, such as those proposed by Ulrich and Dieter, and is enhanced with more advanced tools in the later stages to address the specific demands of mechatronic systems, such as the V-Model methodology, while also considering the architecture and integration of various engineering disciplines. The resulting methodology enables the development of the early stages of the design process, including problem definition, customer needs assessment, product requirements, and specification of product characteristics. It also guides the design through more advanced stages, such as simulations and prototype testing, thereby delivering a solution that is ready for the production phase.

Additionally, the proposal emphasizes the critical role of consumers in the design process. It incorporates users' cultural backgrounds and geographic contexts, particularly during the initial phase of the methodology. From this consideration stems an additional tool referred to as the "Last Minute Change" strategy. This tool is intended to prepare the design team, from the earliest stages, for potential external disruptions such as budgetary changes, new regulations, or last-minute client requests.

The effectiveness of the proposed methodology is demonstrated through its application to the design of an automated masonry robot, developed to address the challenges of confined masonry construction in Mexico. This robot automates key construction tasks, including block transportation, mortar application, and block placement, offering a practical solution for improving efficiency and reducing labor costs in construction environments. The case study validates the methodology and highlights its potential to be adapted for other industrial applications, particularly in robotics and human-robot collaborative systems [8], [9]. This paper is structured as follows: Section II reviews relevant literature on mechatronic design methodologies and industrial robotics, identifying existing gaps in the research. Section III introduces the proposed design methodology, detailing its key phases and components. Section IV presents the case study of the masonry robot, including simulation results and conceptual validation. Section V discusses the results of the methodology being applied in the case study, and Section VI concludes with recommendations for future research and validation through physical prototyping.

II. LITERATURE REVIEW

A. ENGINEERING DESIGN

The field of engineering design encompasses a wide array of branches and methodologies, each with its own challenges, ranging from geographical constraints and resource availability to evolving technologies and individual preferences [4], [11]. While developing universal engineering design methodologies optimized for ideal conditions may seem beneficial, it risks oversimplification [5], [6]. Their real-world application can lead to oversights or unforeseen situations, compromising design integrity. Alternatively, approaches like Design Thinking (DT) offer different perspectives, though they may lack the technical rigor of engineering design. DT emphasizes understanding the customer's needs and characteristics as a foundation for creative and innovative problem-solving. Engineering design, at its core, also centers on solving problems and making decisions [3], [4], [10], through an interdisciplinary, iterative process.

The problem-solving process entails gathering information about the problem, generating multiple potential solutions, evaluating and selecting the optimal one, and testing the chosen solution. In essence, engineering design can be described as a systematic process utilizing various scientific tools to cultivate ideas that can be implemented as solutions for specific problems.

B. MECHATRONICS

Mechatronics has undergone various descriptions and interpretations since its initial conceptualization in Japan in 1969 [12], where it was defined as the integration of electronic systems into mechanical systems. Over the years, this interpretation has evolved, allowing different authors to present their own views on what mechatronics entails.

TABLE 1. Measurement scale to evaluate the characteristics of design methods.

	Value			
Metrics	0	1	2	3
Iterative	The process does not consider the possibility of iterations	This can only be done in specific cases and in a limited way	It is normal within the methodology	Encourages iterations between steps
Multidisciplinary work	Limited to a specific field	Restricted to a small area	Considers work among multiple fields within the same area of knowledge	Interaction between different areas
Design complexity	No technical knowledge is required and it can be completed with basic tools and procedures	The design requires technical advice for certain parts of the process	The design needs to be guided by a professional in the entire process to ensure the success of the design	Specialized equipment, advanced techniques, and expert teams are required to execute the design process.
Usability	No experience or prior knowledge is required	The method can be executed in a straightforward way	The method presents challenges for its application	The method is challenging for its application
Adaptability	The method is restricted to specific uses	The method is restricted to a few projects	The method can be applied to many projects	The method can be used in a wide range of projects

Despite these variations, some commonalities help define the field and its characteristics. Mechatronics represents the integration of various disciplines, such as mechanics, electronics, information technology, and control systems to achieve a synergy that enables innovative solutions to problems that would be difficult or inefficient to address through any single discipline alone [13].

A mechatronic product can be defined as a basic mechanical system onto which sensors can be added to identify the state of the mechanical system itself, obtaining information and sending it to a computerized system. This allows for the processing of that information and the ability to regulate the system's output with the help of actuators that use a signal produced by the information processing [8], [9], [14]. Considering this basic system, mechatronics extends to encompass multiple branches of engineering. Nnodim [2] describes it as an interdisciplinary collaboration that considers the synergy between mechanics, electronics, control, and computing, as well as the relationships between these fields, such as digital control, Computer-Aided Design (CAD) systems, electromechanical systems, and control electronics. Mechatronics covers a wide range of applications, leading to the use of design methods such as the V-model. These methods aim to establish processes that facilitate the proper development of mechatronic systems. They can be applied to design systems focused on tasks like robotic units or generating products and innovative concepts [8], [15], [16], [17], [18].

C. COMPARISON OF METHODOLOGIES

Assessing the effectiveness of a methodology is inherently subjective, as each approach is tailored for distinct objectives. Some methodologies are crafted for industrial settings, while others cater to educational environments; some are suited for managing complex and specialized projects, whereas others are ideal for simpler products.

The vast majority of engineering design methodologies are step-based and aim to provide a systematic process that helps structure requirements, solution proposals, tools, and decision-making. However, these processes are often not followed properly by designers themselves, as they may misinterpret the methodology, overlook, or skip important steps throughout the design process [19].

A notable case arises with the design process presented by Ulrich [5], which outlines a detailed product development journey from conceptualization to patents and economic considerations. However, it mainly focuses on the design of "simple" products. As a result, when the development requires highly specialized systems or solutions for a specific field, Ulrich's model may not effectively address the stages of design, architecture, industrial design, and environmental design. This limitation often compels the design team to turn to an alternative methodology during these stages before returning to Ulrich's model to continue the development process [5].

Therefore, when applying this methodology to the complete design of a mechatronic system, it is essential to supplement it with an approach specifically tailored to the various elements of mechatronics and their integration.

On the other hand, methodologies with more specific approaches, such as the V-model presented in VDI 2206 (2003) [8], [15], offer a highly comprehensive process for the development of mechatronic products, covering everything from requirement definition to design integration and validation. However, this model lacks a human-centered approach, as it primarily focuses on technical aspects. As a result, customer needs are relegated to a secondary role, requiring the use of external tools to obtain this information.

An alternative is the Axiomatic Design [20], which is a function-oriented method. It establishes functional requirements and design parameters, organizing them into a hierarchy and seeking solutions based on two key principles: the Information Axiom and the Independence Axiom. Axiomatic Design thus aims to provide solutions that meet the design requirements. However, it also presents some limitations in practice, such as challenges in dealing with highly complex systems, difficulties in finding suitable solutions for each requirement, and practical constraints when working under tight time frames [19].

Thus, it's important to understand that each methodology can yield the best results when applied correctly and with its intended purpose in mind. With the intention of providing a

TABLE 2. Characteristics of the different design processes.

	Design Approach	Objectives of the methodology	Type of projects	Multidisciplinary approach	Complexity of the systems to be designed	Stage of the process with greater focus	Complexity of applying the methodology
Ulrich [5]	Product Design	Marketing, design, and manufacture	Any commercial product	Multiple disciplines	The process does not consider highly specialized systems	Concept development	The process is detailed and simple
Dieter [6]	Engineering Design	Product-oriented	Any commercial product	Multiple disciplines	Consider design from simple to complex products	Embodiment Design	Detailed process, with medium complexity, depending on the product
Haik [7]	Engineering Design	Product-oriented	Any commercial product	Multiple disciplines	Systems with simple or medium complexity	Requirements	Low complexity
Pahl and Beitz [38]	Engineering Design	Functionality, technical and economic viability of products	Engineering products and projects	Multiple disciplines within engineering	Consider design from simple to complex products	Concept development	It is a moderately complicated process, but extensive
Johnson [39]	Mechanical Design	Technical specifications	Any mechanical system	Mechanical Engineering	Focus on devices with high complexity	Concept generation and technical development	It requires a specialized approach and constant application of multiple concepts
CONDENSE [37]	Product Design	Specifications and economic viability, manufacturing and assembly	Education to engineering projects	Multiple disciplines	Covers a large number of projects, but not highly specialized projects	Information and design selection stage	Requires high communication between all members for proper execution
Teach Engineering [40]	Engineering Design	Education	Any engineering projects	Multiple disciplines within engineering	Engineering systems, excluding highly specialized ones	Balanced	It's a methodology that aims to be as simple as possible
TRIZ [42]	Problem-Solving	Development of innovative solutions	Systems in the industry and technology sector	Multiple disciplines	Simple and complex systems	Identification of patterns and contradictions	It's a complicated methodology; due to its own nature, finding patterns and contradictions can represent a challenge
V-model [8]	Mechatronic design	Mechatronic Systems	Any project focused on mechatronics	Disciplines related to mechatronics	Simple to highly complex systems	Balanced	Depending on the complexity of the system, the methodology will require greater mastery of it and a team with the appropriate knowledge
V-cube [17]	Mechatronic design	Mechatronic Systems	Any project focused on mechatronics	Disciplines related to mechatronics	Simple to highly complex systems	Balanced	The methodology is highly complex, but seeks to be a well-structured process
W\B Box [16]	Mechatronic design	understanding user needs, defining technical specs, and optimizing the design of mechatronic systems	Mainly intended for complex mechatronic systems	Disciplines related to mechatronics	Focus on devices with high complexity	White Box	It requires a specialized approach and constant application of multiple concepts

targeted approach for our proposed methodology, we have established a set of metrics that align with our process objectives. This enables us to evaluate the performance of the methodologies previously reviewed and examine their behavior in relation to these metrics.

Table 2 shows the design methodologies found to be the most used in product development. These methodologies were selected based on their approach to engineering, products, innovative ideas, or mechatronic design, each with a wide range of characteristics, some being oriented towards products, education, or mechatronic systems.

We intended to offer a distinct approach for the proposed methodology, so we defined a set of metrics that align with our process objectives. Our goal is to assess the performance of the methodologies listed in Table 2 and analyze their behavior using these characteristics:

- Iterative: The process allows for iterations between different steps within the design process.
- Multidisciplinary work: Interaction of multiple disciplines related to mechatronics within the process.
- Design complexity: How complex the projects contemplated by the methodology are.
- Usability: Ease of applying the process.
- Adaptability: Ability to adapt to multiple applications.
- Problem-solving process (Handling each stage of this process).

To assess the methodologies, we assigned values ranging from 0 to 3. Depending on the specific criteria, each value corresponds to a particular usage scenario, with 0 indicating the least favorable and 3 representing the most favorable circumstance; the scale is described widely in Table 1. This approach draws inspiration from Barranco [21], which used a similar technique to evaluate various design methodologies.

TABLE 3. Evaluation of the methodologies on each metric.

Methodology	**Iterative**	**Multidisciplinary work**	**Design complexity**	**Usability**	**Adaptability**
Ulrich	2	2	1	3	3
Dieter	3	2	2	2	3
Haik	3	2	1	3	3
Pahl and Beitz	3	3	2	2	3
Johnson	1	0	3	1	1
CONDENSE	2	3	2	1	2
Teach Eng.	2	3	1	3	3
TRIZ	3	3	3	1	3
V-model	3	3	3	2	2
V-cube	3	3	3	1	2
W\B Box	2	3	3	2	1

The results from evaluating the design methodologies are presented in Table 3.

During the analysis of Table 3, it was noticed that there might be a relationship between the different characteristics. This observation is significant because it suggests that when applying a method, it is necessary to consider these relationships.

Considering the possible relationships, two coefficients of correlation were proposed, the first being the Pearson Correlation Coefficient (PCC) [22], This coefficient allows for evaluating the relationship between two variables, producing r values ranging from -1 to 1. If the value is negative, the variables have an inversely proportional relationship; conversely, if the coefficient is positive, the relationship is proportional. The closer the value is to 1 or -1, the stronger the relationship will be. Equation (1) for calculating the coefficient is expressed as follows:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{\left[n \sum x^2 - (\sum x)^2\right]\left[n \sum y^2 - (\sum y)^2\right]}} \tag{1}$$

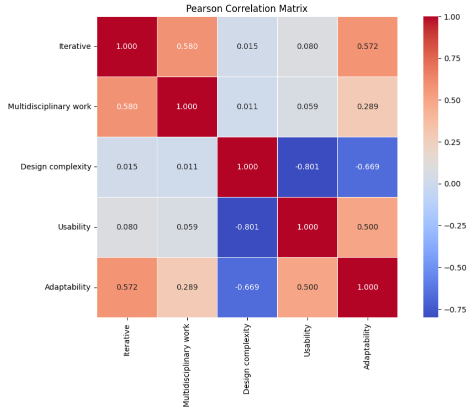

FIGURE 1. **Pearson correlation coefficients *r* of the metrics evaluated for the design methodologies.**

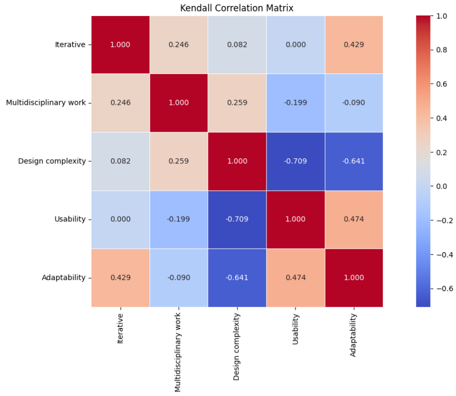

FIGURE 2. **Kendall's (tau-*b*) correlation coefficients of the metrics evaluated for the design methodologies.**

where:

r: PCC
x: Value of the first variable
y: Value of the second variable
n: sample size

The second of the proposed association coefficients is Kendall's τ correlation coefficient, a rank-based correlation coefficient designed to measure the association of ordinal data [23]. Like Pearson's coefficient, it is evaluated on a scale from -1 to 1, where values closer to 1 indicate strong agreement between the variables, while values closer to -1 indicate strong disagreement. Since the data from the different metrics include multiple ties, Kendall's tau-b coefficient [24] will be specifically used, as defined in (2).

$$\tau = \frac{P - Q}{\sqrt{(P + Q + T) \cdot (P + Q + U)}} \tag{2}$$

where:

P: Number of concordant pairs
Q: Number of discordant pairs
T: Number of ties only in the first term
U: Number of ties only in the second term

Both correlations were evaluated based on the following statistical hypothesis:

H0: The evaluated characteristics of the different design methodologies show no correlation between each other.

H1: The evaluated characteristics of the different design methodologies show one or more correlations between them.

The PCC results are summarized in Fig. 1, which identifies five significant correlations: Usability with Complexity in designs, Adaptability with Complexity in designs, Multidisciplinary work with the Iterative process, Adaptability with the Iterative process, and Adaptability with Usability.

In contrast, Fig. 2 presents Kendall's coefficients, which highlight four pertinent correlations: Usability with Complexity in designs, Adaptability with Complexity in designs, Adaptability with the Iterative process, and Adaptability with Usability.

In the first instance, we can confidently reject the null hypothesis (H0) and conclude that significant correlations exist among the characteristics of the engineering design methodologies examined in this study. This conclusion is reinforced by two distinct correlation coefficients, both identifying four key correlations of similar strength. These correlations reveal important interdependencies that could have practical implications for enhancing and optimizing engineering design processes.

The present correlations are:

- Usability and Complexity in designs
  - Very High correlation
  - Disagreement
  - > 0.7
- Adaptability and Complexity in designs
  - High correlation
  - Disagreement
  - $0.5 < 0.7$
- Adaptability and Iterative process
  - Medium correlation
  - Agreement
  - $0.3 < 0.5$
- Adaptability and Usability
  - Medium
  - Agreement
  - $0.3 < 0.5$

Building upon the strengths and limitations of the methodologies analyzed in this review, it is evident that a tailored approach is necessary to address the unique challenges of mechatronic product design. This insight motivates the development of a novel design methodology, one that integrates the iterative flexibility of the V-Model with a strong emphasis on multidisciplinary collaboration and contextual adaptability. Such a methodology not only responds to the technical demands of complex mechatronic systems but also ensures scalability and alignment with real-world constraints. The following section introduces this proposed methodology, detailing its phases, tools, and application framework, with

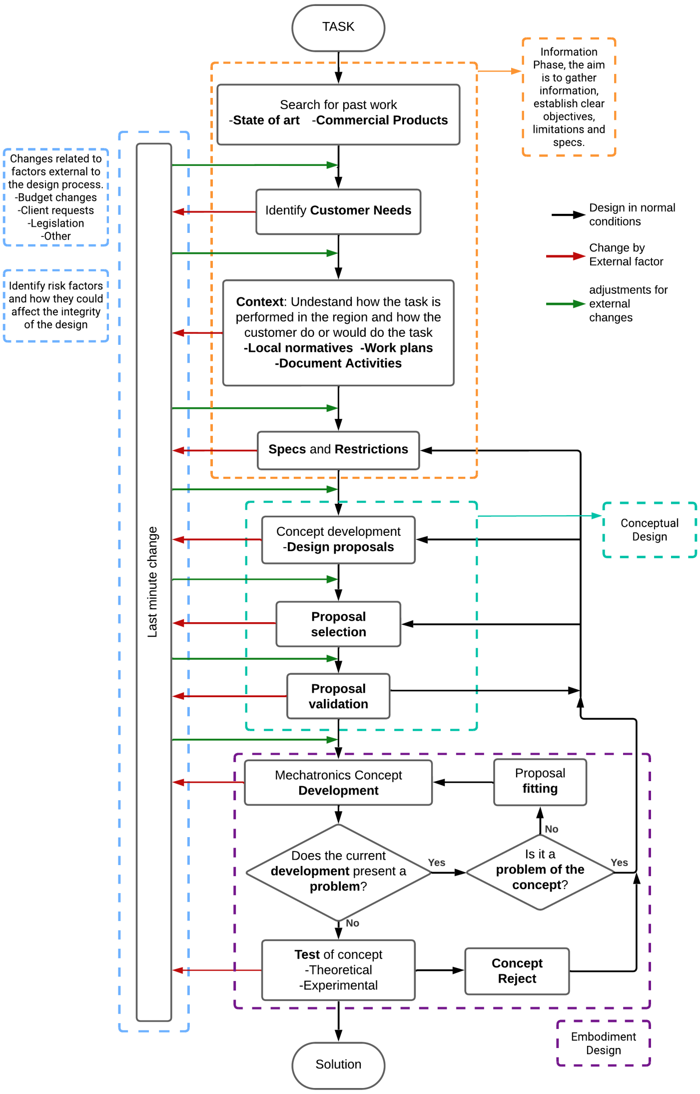

FIGURE 3. Proposal for the engineering design methodology.

the goal of providing a structured yet adaptable pathway for advancing engineering design in the context of industrial robotics.

III. METHODOLOGY

It is important to highlight that the methodology proposed in this document is based on the following concept of a mechatronic product: *A mechanical system integrated with sensors, actuators, electronics, information management, computerization, and control techniques, aimed at creating a product that addresses specific needs.* This description draws on the guidelines in VDI 2206, the work of Riesener, and the definition of a basic mechatronic system from Bolton [8], [9], [14], [15].

Additionally, it is crucial to emphasize that the design process outlined in the methodology encompasses all stages, from the earliest design phases to conceptual design and testing through simulation or prototyping. This approach aims to produce a solution validated through testing, which can be applied in future processes such as manufacturing, economic planning, distribution, and more. This perspective aligns with Barry Hayman's engineering design framework, which views the process as a structured approach involving information gathering, proposal generation, proposal selection, and the development of the selected proposal, all focused on problem-solving [3].

The proposed engineering design methodology for mechatronic products can be seen in Fig. 3. This methodology is based on the problem-solving process, with a structure similar to the design methodologies of Ulrich [5], Dieter [6], and Haik [7]. Its distinguishing factors include a special focus on the acquired information and the formation of the context in which the methodology is to be applied; the incorporation of a tool known as the "Last Minute Change" to prepare the design team to handle unexpected external situations that could risk the integrity of the design; and finally, a special emphasis on the development of the mechatronic part, adapting the concept of mechatronic products and mechatronic design methodologies to our needs [9], [25].

A. INFORMATION PHASE

This stage aims to gather as much information as possible about the problem to be solved, the design, and its idiosyncrasies. This stage aims to establish clear objectives and limitations, justify the design, obtain information from previous work at both commercial and research levels, build a contextual framework, obtain feedback, and identify risk factors.

The stage is divided into four steps:

- Search for Past Work: All information related to the design in previous works is gathered, whether in commercial products or research. There may be solutions or similar work to what is intended. This step will help validate whether to proceed with the design, inspire future stages, and avoid duplications or plagiarism. A research report and an analysis of it are expected.
- Customer Needs: In this step, the goal is to define the design's purpose by identifying the customer's needs. The importance of these needs, as determined by the design team, will guide the entire process, influencing the characteristics of the proposals, specifications, and solution selection. The identification of needs will be carried out as a sub-process following these steps and performing any of the activities that best fit the situation:

  1) Obtain client information.
  2) Interpret client information into needs.
  3) Organize needs under a hierarchy.
  4) Establish relative importance for each need.

  The customer's needs can be interpreted through data and reflected in expected product features, where subjective aspects such as aesthetics or comfort become relevant.
- Context (Local Research): The purpose is to understand the limitations and requirements of a potential solution within a specific geographic area and how the activities are conducted in the region. It is at this step that the context in which the process is being worked on is defined, detailing how activities, regulations, and legislation are carried out at the local level, recognizing parameters, the opinion of potential customers, understanding the idiosyncrasies of the people, and the perception of similar products or services to the project. As research recommendations for generating a research report, the use of Local regulations, published articles, work plans, local products, documenting activities, observing activities in person, patents, or speaking with potential customers.
- Specs and limitations: As the final part of the stage, the definition of specifications and potential limitations or conditions of use must be conducted. This is based on considerations such as client needs, regulations, the current state of the art, and commercial products, all tailored to a specific context in space and time. As an action, it is proposed to establish the client's needs as parameters and complement them with local regulations. These regulations may outline requirements or procedures for some parts of the design, so they should be considered. As a result of this step, a table listing the metrics, which needs are met by them, their impact, and their units are expected. For limitations and usage conditions, they can be developed as a list describing the condition and its limits [5].

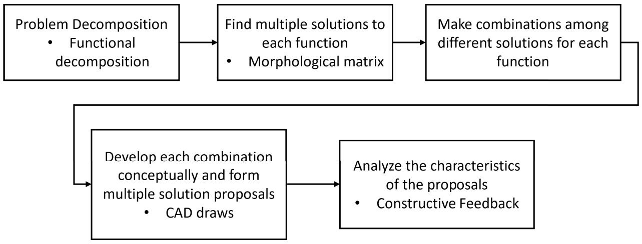

FIGURE 4. Sub-process for concept development.

B. CONCEPTUAL DESIGN PHASE

- Concept Development: The process outlined in Fig. 4 is followed to develop the concepts. Starting with the subprocess, we need functional decomposition; the goal is to break down the problem into smaller actions called functions and find individual solutions for each. For each function, a series of possible solutions must be identified. These can be generated through benchmarking exercises, findings from previous research, brainstorming sessions, and the experience of knowledgeable personnel. These solutions will be combined with the solutions of other functions to form a morphological matrix. Solution proposals will be created by combining the functions' solutions. The solution proposal must be developed at a basic level to develop a basic concept, outlining a basic geometric structure. This development can be done through sketches or a simple CAD design to understand the concept. Additionally, the team is expected to provide feedback on each concept, analyzing it from their perspective and focusing on what they think of each design, which can be reflected in a table of strengths and weaknesses.
- Proposal Selection: Each of the concepts obtained in the previous step must be evaluated regarding the client's needs, parameters, requirements, and any other criteria that may be relevant to the final product. The team should establish criteria to encompass these important

needs and requirements and assess how each concept meets them. The Pugh concept selection method is an effective way to accomplish this task [26].

- Proposal Validation: As the final part of the phase, an additional validation of the previously selected concept is requested. This is intended to prevent potential issues in future stages, such as client rejection, problems with implementing the concept in the region, or failure to meet established needs or requirements. An analysis of the advantages and disadvantages of the chosen proposal, using the elements established during the concept generation, must be conducted to evaluate this potential. This analysis will serve as a tool to supplement any shortcomings in the Pugh table and to either confirm or reject the selected proposal.

C. EMBODIMENT DESIGN PHASE

Once a concept demonstrates the potential to accomplish the task as desired, it is time to develop it into a product or prototype. Considering that this methodology focuses on mechatronic products, the development should be oriented towards mechatronic systems from a technical perspective and complemented by considerations for making it a product.

- Concept Development: The concept development process for this methodology is illustrated in Fig. 5, where the selected concept from the previous stage serves as the starting point. This process involves an iterative cycle among the mechanical, electronic, software, and control subsystems, along with their integration [13], [14]. To achieve this, each subsystem must undergo three key development stages: architecture, configuration, and parameterization.
    1) Architecture: Architecture refers to the foundational structure used to develop the subsystem. It must describe the core functionality of the corresponding part, providing a general layout of the system [11]. The goal is to create a graphical representation that illustrates how the subsystem operates.
    In order to develop an appropriate architecture, the main step is to break down the product into the different actions that must be carried out for the device to function. The goal is to associate each product action with an element that performs it, such as using a motor to "move a conveyor belt." The elements of a product can be organized into blocks known as *chunks* [5].
    Within product architecture, there are two main types. The first is modularity, which means that each chunk of the product is responsible for a single action. As a result, modifying one chunk should not affect the functioning of the rest of the product's actions.
    The second type is integral architecture, which is the opposite of modularity. In this case, a single chunk can perform multiple actions, or a single action may require more than one chunk to be executed.
    This can lead to a wide variety of product models depending on the chosen architecture.
    2) Configuration: Configuration involves connecting the actions defined within the architecture to specific components designed to fulfill those actions. For instance, this may include selecting a motor to drive a gear or choosing a circuit for signal processing. Therefore, in this initial phase, the goal is to define in detail the components and the general structure of the chunks that meet the requirements established during the information stage and address the customer's needs.
    3) parametrization: Parameterization involves defining the values, dimensions, operating conditions, power requirements, and any other functional parameters that may influence product quality or be relevant to a potential prototype.

Throughout the process, integration between the various subsystems—mechanical, electronic, software, and control—must be considered to ensure synergy among these elements. Consequently, the development of architecture, configuration, and parameterization will be interconnected across the different subsystems. This requires an iterative process wherein modifications in one subsystem may impact the others.

Integration can occur at both the component level (hardware) and the information level (software), depicted in Fig. 6. Component integration should result in a mechanical system equipped with actuators, sensors, and electronics that function as a unified system [27].

In contrast, information integration relies on advanced control functions, enabling data analysis and feedback to the mechanical subsystem. This includes signal processing, digital filters, artificial intelligence algorithms, simulations, CAD tools, and more. Lastly, a close connection between the physical and intelligent subsystems is essential, ensuring the physical system is continuously monitored and controlled by the intelligent system to effectively regulate its output.

To achieve an adequate mechatronic design, it is important to emphasize a concurrent approach, in which the different aspects of the field interact with each other. Consequently, any development in one of its branches will affect the rest. Therefore, the mechatronic conceptual development presented in this step should be iterative, allowing for proper development in each part and its integration [14].

By the end of this step, the following outcomes are anticipated: Product architecture diagrams that describe the system's functionality in blocks (Chunks) and illustrate the relationships between its parts. A list of required software and hardware is needed to perform the

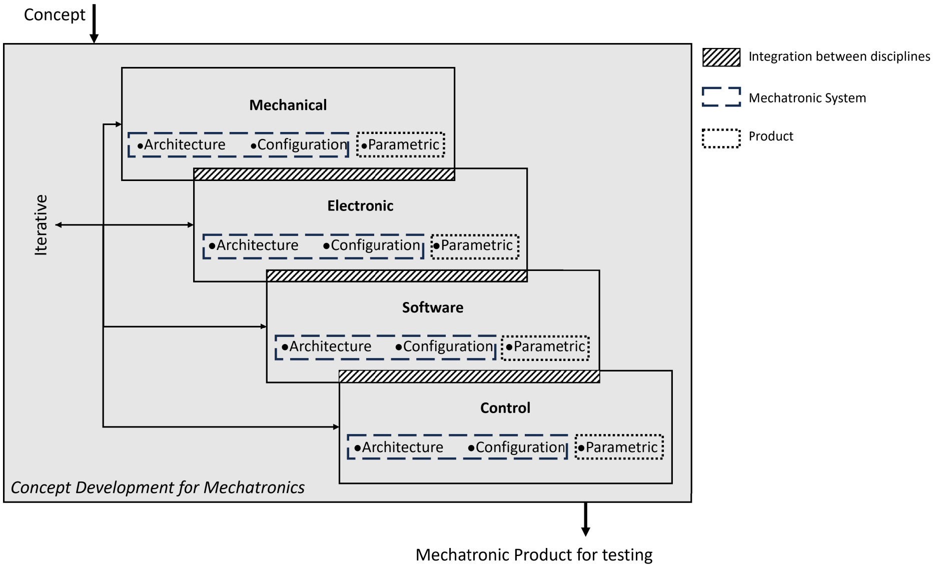

FIGURE 5. **Concept development for mechatronics.**

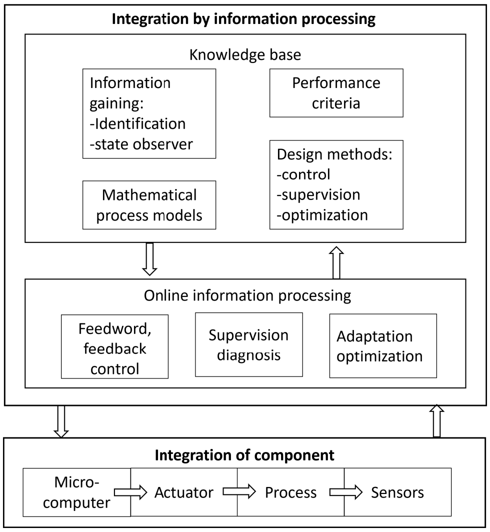

FIGURE 6. **Ways of integration within mechatronic. Extracted [27].**

actions described in the architecture diagram. A list of parameters that the final product or prototype must meet and is expected to operate within.

- Development Evaluation: Problems may arise during the development of the concept. In such a situation, the root cause of the problem should be evaluated. This can lead to two possibilities: the first is that the problem involves technical issues within the conceptual development itself, in which case adjustments should be made, and development should continue. The second possibility is that the problem lies with the concept itself. If this is the case, it is important to identify at which step of the methodology the problem occurs, iterate on that step, and resume the design from that point.
- Test: If the concept development finally includes the elements necessary to consider a model that meets the client's needs, the next step is to proceed with the corresponding tests. The first step would be to conduct software simulations, allowing the solution to be validated logically. This step is mandatory because if physical prototype tests cannot be performed, these simulations will be the only validation of the design.
  For the mechanical component, CAD drawings with appropriate dimensions are expected, ensuring that the mechanical principles enable the system to perform its intended actions correctly. The CAD model should also undergo various tests as required by the design, such as Finite Element Analysis (FEA), aerodynamic simulations, or even ergonomic assessments.
  For the electronic, software, and control components, various tools can be utilized to facilitate communication between the CAD model and these systems. This integration enables the product to be positioned in a simulated real-world environment, where its actions can be programmed as if it were functioning under its actual working conditions. This approach assists in validating whether the selected concept and architecture are suitable.
  The second test would use a physical prototype, allowing us to understand the design's behavior in its real application. The key is to be able to replicate the real-life usage conditions given by the client's needs and parameters described in the information stage. If the tests do not yield favorable results, it is necessary to find the root of the problem and return to work on that point. On the other hand, if the tests meet expectations, the design solution is ready for implementation, and

we can proceed with production, commercialization, or marketing processes.

D. LAST MINUTE CHANGE

So far, the design methodology has been reviewed under normal circumstances. Unfortunately, external factors beyond the design team's control may significantly impact the process. These could include client-requested changes and regulations, changes, budget adjustments, timeline modifications, legal rulings, administrative changes, and staff turnover. Each of these situations is impossible to foresee in advance. Therefore, the proposed methodology incorporates a "Last Minute Change" tool, shown in a blue dotted rectangle in Fig. 3. The purpose of this tool is to maintain constant control over the design process, identify potential risk factors, and, in the event one of these cases arises, pinpoint the step within the methodology where the change has the greatest impact and make adjustments accordingly.

Throughout the process, the methodology requires team members to provide feedback on the progress at each stage, identifying strengths, weaknesses, and potential risk factors for the product design. These reviews will form the foundation for the "Last Minute Change." Throughout the methodology, triggers for these situations may occur, as indicated by red lines in Fig. 3. When a trigger arises, the team must analyze the situation and determine where, in the process, to backtrack and make the necessary adjustments to resume the process from that point. An example of this is when a budget change occurs during the embodiment design stage. Such a change may impact various stages, including constraints, concept design, or the development process itself. If the budget change directly affects the embodiment stage, it will be necessary to revisit a previous step and assess whether the new constraint affects the concept itself or if adjustments can be made to certain aspects of the architecture, configuration, or parameterization to accommodate the change. If neither option is feasible and the budget constraint directly compromises the original concept, it will be necessary to return to the conceptual design stage. In this case, the team should either propose a new concept or select one of the previously developed concepts that meets the new budget constraint.

Table 4 summarizes the steps in each of the three phases of the methodology, as well as the steps that compose them and the corresponding activities.

It is important to highlight that the proposed methodology applies to any mechatronic system that fits the definition of a Mechatronic Product as established at the beginning of this chapter. The methodology aims to cover the entire development process from the earliest design stages, such as problem definition, needs identification, and the establishment of requirements and usage conditions, to the validation of a solution based on a mechatronic system designed to meet customer needs.

TABLE 4. Summary of the methodology and corresponding activities.

	Step	Activities	
Information Phase	Search for past Work	Research report and an analysis	
	Identify Customer Needs	Obtaining and classifying needs Quality Function Deployment (QFD)	
	Local Research	Research report	
	Specifications and limitations	Requirements table List of work limitations	
Conceptual Design Phase	Concept Development	Functional Decomposition Morphological matrix Make combinations Develop each combination on CAD Constructive Feedback	
	Proposal Selection	Pugh concept selection method	
	Proposal Reject	Pros and cons table Justification for the selection or rejection of the concept	
Embodiment Design Phase	Concept Development	Architecture Configuration Design Parametric Design	Mechanical
		Architecture Configuration Design Parametric Design	Electronic
		Architecture Configuration Design Parametric Design	Software
		Architecture Configuration Design Parametric Design	Control
	Test	Simulation Prototype	

IV. CASE STUDY: MASONRY ROBOT

A. INFORMATION PHASE

The proposed methodology was applied for the conceptual development of a robot focused on automating the process of constructing confined masonry walls in Mexico. The process resulted in the overall masonry process concept, which is a modular system for various activities. Additionally, it involved the mechanical and electrical development of two subsystems and their modules: a "Wheelbarrow" for block transportation and an "Elevator" to position the block for placement and lift it to the appropriate height.

The objectives to be met with the robot were the following:

- The design should focus on the premise of possible physical prototyping, so special attention is expected in the operation mode and definition of the components.

TABLE 5. Customer needs - information phase.

No.	Need	Impact
1	Do most of the masonry activities	5
2	Cover the majority area of the wall	3
3	Working with walls of different heights	4
4	Reduce physically demanding work for workers	5
5	Autonomous mobility	4
6	Preference for electrical use	4
7	Safe for workers	4
8	Minimize human error	3
9	Low human interaction	1
10	High repeatability	3
11	Control by an operator	3
12	Place blocks in the correct orientation and position	3
13	Ease of operation	4
14	Manufacturing ease	3
15	Easy to repair	4
16	Secure for Building Integrity	5
17	Movement in irregular ground	3
18	Scalability to other tasks	4
19	Easy to install	2
20	Transportation within the construction	4
21	Increase productivity	3
22	Lower labor cost	2
23	Outdoor work	3
24	The robot must be economical	5

TABLE 6. Projects reviewed in the past work - Information Phase.

Research		
Project	**Focus**	**Concept**
Torpoco L.	All masonry activities	3 Mobile Robots
Kim S.	Paint in construction	Autonomous Mobile Robot (AMR) and robot arm
Klockner M.	Bricklaying	Parallel Kinematic Machine (PKM) robot
Ambrosino M.	Bricklaying	Crane and a robot arm
Shi Q.	Bricklaying	Robot arm in an elevator
Commercial		
Sam 100	All masonry activities	Robot arm in a cart
HadrianX	Bricklaying	Large-scale robotic arm on a truck
ABLR	All masonry activities	Cartesian robot in an elevator

- The robotic platform is expected to work on-site, placing the blocks and mortar directly.
- The system should allow for its transfer to different parts of a multi-level construction.

The client's needs were meticulously identified and assessed, as outlined in Table 5. These needs arose from comprehensive discussions with a local construction company, which clarified specific expectations, requirements, and requests across various parameters. A Quality Function Deployment (QFD) analysis, depicted in a house of quality, was employed to ascertain the anticipated characteristics of the project. This analysis was further refined by examining local construction regulations and the practice of confined masonry in Mexico [28]. Table 6 showcases projects from previous research efforts, including both commercial products [29], [30], [31] and academic studies. Additional references include works by Torpoco-Lopez et al. [32], Kim et al. [33], Klöckner et al. [34], Ambrosino et al. [35], and Shi et al. [36], culminating in Table 7, which delineates the parameters based on both client requests highlighted in green and identified needs.

TABLE 7. Requirements for the masonry robot - Information Phase.

No.	Spec.	Value
1	Block dimensions	20x20x40 cm
2	Thickness of block walls	15 mm min.
3	Block weight	18.25 kg
4	Maximum wall height	4 m
5	Slab resistance	1 to 1.2 Tons per m
6	Minimum aisle width	90 cm
7	Maximum slope angle of the ground	1°
8	Thickness of mortar sores	10 mm approx.
9	Mortar use time once mixed	2.5 hours approx.
10	Mortar drying time	10 hours approx.
11	Mortar Curing time	28 to 30 days
12	Knock out of Plumb	15 mm max.
13	Distance between columns	4 m max.
14	Distance between bond beam	3 m max.
15	Security factor	1.5 min.
16	Electrical power supply	120 to 240 VAC, three-phase 440 V
17	IP protection	IP54 min.
18	Prototype budget	USD 74,700 approx.

The limitations and working conditions expected for the project were also established, including the need for a Human-Machine collaboration. A worker must place the first row of blocks, ensuring they are properly plumbed and level. Operations should occur at times when there is minimal worker presence. Work should be suspended in case of rain. The work area must be free of liquids and objects that could hinder the system's operation.

B. CONCEPTUAL PHASE

Entering the conceptual phase, a functional decomposition was generated considering the main actions the robot must perform to place a block on the wall. From this functional decomposition, the following were taken for the generation of the morphological matrix:

Power supply, installation, movement of the block and mortar, supplying blocks, raising the block to its desired position, applying mortar, properly placing the block, and adjusting the height to adapt to walls of different heights. Through a brainstorming process and based on projects seen in prior research, a morphological matrix was created, and five potential combinations to work with were developed. These can be seen in Table 8.

The concepts were evaluated based on high autonomy, scalability, minimal human interaction, ease of manufacturing, suitability for different wall heights, durability, low cost, safety, ease of transport, and support from other projects. Each criterion was evaluated according to how the concept addressed it. A '+' was assigned if the concept met the

TABLE 8. List of concepts - conceptual design phase.

Concept	Power supply	Robot installation	movement system	Supply Blocks	Raise blocks	Mortar applications	Place the block on the wall	Height adjustment for wall height
1	Batteries	Fixed	Automated Guided Vehicle (AGV)	Manually	Robot arm	Extrusion	Robot arm	Fixed Height
2	Batteries	Foldable	Electric Cart	Manually	Scissor lift	Extrusion	Robot arm	Telescopic system
3	Wiring	Fixed	AMR	Wheelbarrow	Electric Winch	Manually	Robot arm	Scaffolding
4	Battery and wiring	Fixed	AMR	Conveyor	Conveyor	Dispenser	Conveyor	Telescopic system
5	Battery and wiring	Modules	AMR	AMR	Chain/Pulley Lift	Dispenser	Extendable Gripper	Sections

TABLE 9. Concept evaluation for the masonry robot - Conceptual design phase.

	Concepts				
Selection Criteria	1	2	3	4	5
High autonomy	0	-	+	+	+
Scalability	+	+	0	-	+
Low human interaction	+	-	+	-	+
Ease of Manufacturing	0	+	-	-	0
Durability	-	0	-	+	+
Adaptability to Wall Height	-	+	0	0	+
Cost-effectiveness	-	-	-	+	-
Security	+	0	-	0	+
Transportability	+	+	0	0	0
External Endorsement	+	+	+	-	0
Sum of +	5	5	3	3	6
Sum of -	3	3	4	4	1
Sum of 0	2	2	3	3	3
Net Score	2	2	-1	-1	5
Rank	2	2	3	3	1

criterion satisfactorily, a '-' if the concept impeded the fulfillment of the criterion, and a '0' if the concept treated the criterion neutrally.

Reviewing the concept assessment shown in Table 9, we can see that the best candidate was concept 5, a modular system based on Autonomous Mobile Robot (AMR) for moving the robot, positioning it in specific spaces within the work area, and depending on the task to be performed, it can join with another module to accomplish it.

The concept taken for the development is presented in Fig. 7. The masonry system is subdivided into three subsystems: a wheelbarrow for transporting blocks composed of an AMR module and a conveyor for storing and delivering blocks. The next subsystem is an elevator designed to position and lift the block to its designated position on the wall. It requires an AMR module, a block elevator module, and a conveyor to accommodate, hold, and deliver the block. Lastly, we have the mixer module, which is responsible for performing all tasks related to the mortar, such as transportation, maintaining it in suitable conditions and applying it to the wall. These three subsystems will communicate with each other to always be aware of the other's status and give instructions. They should operate only in the designated work area and follow these steps:

Step 0: Prior preparations must be made within the workspace, such as preparing the material, defining which wall will be worked on, ensuring that where the blocks are placed is properly leveled, and designating different areas within the work zone.

Step 1: The three subsystems must be positioned in the safe zone, which will serve as the starting and ending point of the process.

Step 2: The wheelbarrow and the mortar elevator must go to the loading area to await the materials supply.

Step 3: Once materials are available, the mortar and block elevator should be positioned parallel to the wall being worked on.

Step 4: While the wheelbarrow has blocks and they are needed, it should be positioned next to the block elevator to supply it with blocks. It should return to the loading area for more if it lacks supply.

Step 5: The mortar elevator will pour portions of the mix onto the wall and advance to make way for the block elevator. It should return to the loading area if it runs out of mortar and needs more.

Step 6: The block elevator should move to place the block onto the mortar, ensuring it is properly leveled and plumbed.

Step 7: Depending on the state of the wall, if more work is still needed, repeat from step 3. The three subsystems should go to the safe zone if the task is completed. If there is still material on one unit, wait for the material to be removed and consider the activity finished.

C. EMBODIMENT DESIGN PHASE

Conceptual development was carried out for the subsystems and corresponding modules of the Wheelbarrow and the elevator at mechanical and electrical levels. The first of the modules is the AMR, whose architecture can be found in Fig. 8. For the design's configuration and parametric aspects, using a commercial electric stacker with appropriate modifications was considered an alternative to achieve autonomous movement. This is because there are stackers on the market with components capable of moving on unstable terrains, supporting heavy loads, and having dimensions that can be adjusted to the robot's requirements.

Therefore, this alternative only requires technological integration with the rest of the components and avoids the need to redesign the AMR components completely. Additionally, one of these stackers represents a lower cost than commercial AMRs, helping us stay within a limited budget. For the necessary modifications to the AMR module, the incorporation of a mechanism to automate the steering of the AMR must be considered. Given that the AMR would be working with tricycle-based locomotion with the drive wheel at the rear, it only requires adjusting the wheel's steering angle to control its positioning based on the Instantaneous Center of Rotation (ICR), as shown in Fig. 9.

The second of the modules is the brick conveyor, which is responsible for storing the blocks and supplying them to the elevator for placement. Its architecture, seen in Fig. 10,

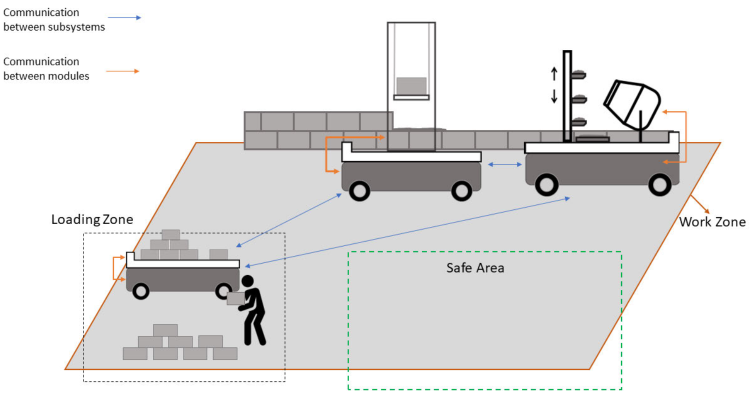

FIGURE 7. Concept operational diagram - Conceptual design phase.

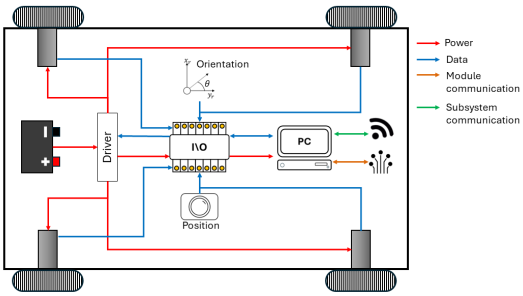

FIGURE 8. Diagram of the AMR's architecture - Embodiment design Phase.

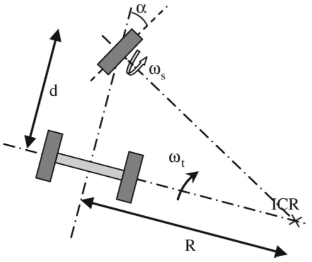

FIGURE 9. Tricycle configuration - Embodiment design Phase. Extracted [43].

features a metal mesh conveyor, allowing debris detached from the blocks, such as dust and stones, to fall to the ground without any issues.

This ensures the mesh has a longer lifespan than other materials that may wear out quickly due to friction with the blocks. The development of this architecture concluded that the module would consist of 4 conveyors, each designed to support a maximum of 3 blocks of approximately 20 kg each. All of these are mounted on a structure that will be attached to the AMR module, thus forming the Wheelbarrow subsystem shown in Fig. 11.

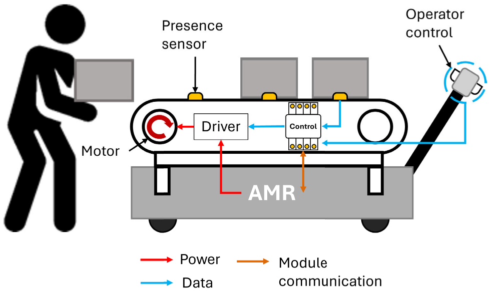

FIGURE 10. Brick conveyor module architecture - Embodiment design phase.

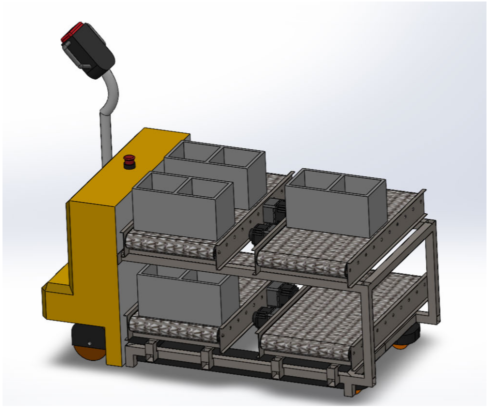

FIGURE 11. Wheelbarrow subsystem CAD - Embodiment design Phase.

Lastly, the conveyor used for the elevator is an adaptation of the wheelbarrow module, adjusting the dimensions and the motor used to handle a single block at a time. The result of the elevator subsystem is shown in Fig. 13.

The elevator subsystem is divided into three modules: the AMR, previously mentioned, the elevator itself, and a conveyor acting as the elevator cabin. The elevator comprises a Rectangular Tubular Profile (RTP) structure divided into sections: a base, a tower, and extensions that allow the

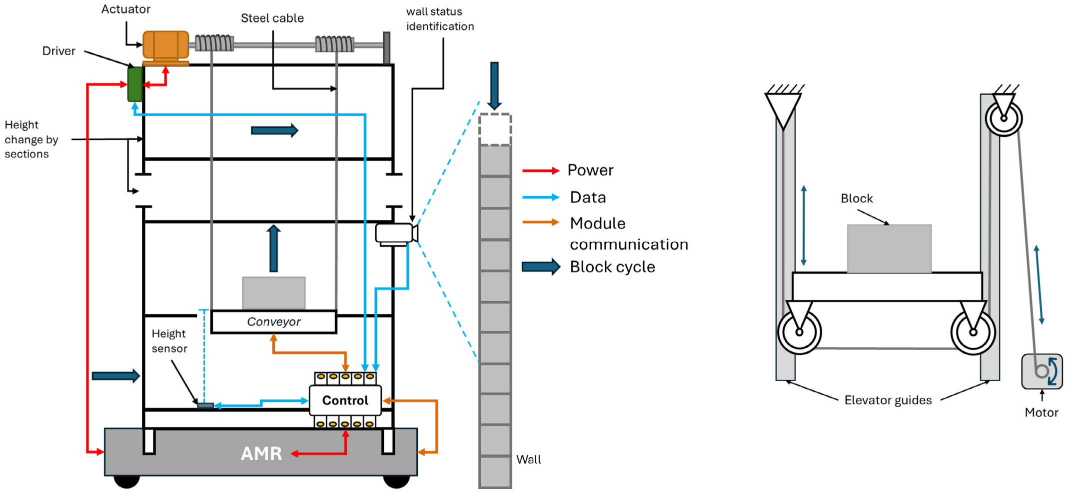

FIGURE 12. Elevator module and pulley mechanism - Embodiment design phase.

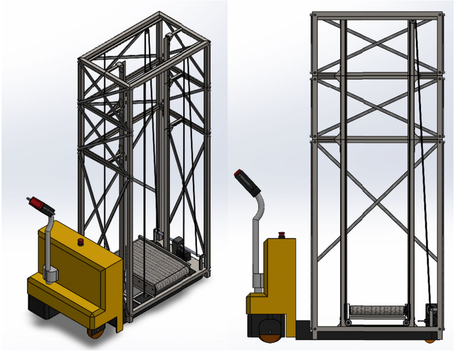

FIGURE 13. Elevator subsystem CAD - Embodiment design Phase.

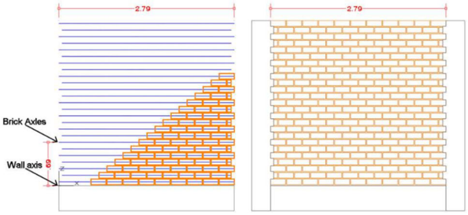

FIGURE 14. Location of coordinates of the blocks by dividing a wall into axes and blocks - Embodiment Design Phase. Extracted [32].

elevator to have a height ranging from 2 meters to 4 meters. The elevator will be equipped with a vision system that allows monitoring the state of the wall in real-time and generating a set of instructions to follow. The architecture and pulley system of the elevator are shown in Fig. 12.

D. TESTING PHASE

As a reminder, for this case study on the design of a masonry robot, the development reached the embodiment design stage, specifically the mechatronic concept design phase. Consequently, the testing plan focuses solely on the proposed approaches for simulation and physical prototyping.

Simulation Plan: For simulation, the proposed tools are SolidWorks 2024 and the Robot Operating System (ROS), in its latest distribution of ROS 1, ''Noetic Ninjemys''.

- SolidWorks will be used to conduct FEA to evaluate the system's structural performance under a load of 315 kg, representing a maximum load of 12 blocks, each weighing 18.5 kg. A safety factor of 1.4 will be applied to ensure robustness in both the wheelbarrow and elevator subsystems.
- In ROS, the objective is to simulate a realistic construction environment based on the workflow diagram shown in Fig. 6. Drawing inspiration from the work of Torpoco-Lopez et al. and Kim et al. [32], [33], the simulation will leverage the Building Information Modeling (BIM) methodology, widely used in construction for model-based design. These models will serve as the foundation for the simulation, giving the workspace for constructing a confined masonry wall.

In this context, a reference frame will be established in which the robot will navigate using x, y, and z coordinates. The masonry wall itself will be divided into two coordinates (x, y) to define the positioning of each block. Each block will be assigned its corresponding coordinates, allowing the robot to determine both its own position in the workspace and the precise location where each block should be placed. This division of the wall is illustrated in Fig. 14.

Prototyping Plan: Based on the simulation results, efforts will be directed toward developing the robot prototype, following the parameters defined during the mechatronic concept development phase. Once the mechanical analysis of the structure is completed, detailed technical drawings, a bill of materials (BOM), and component specifications for each module will be prepared. Prototype Evaluation The prototype evaluation will be conducted in an environment that replicates

TABLE 10. **Assessment of system design concerning the customer needs - Results of the application of the proposed methodology in the case study design.**

Design Considerations	Impact	Design Solution
Do most of the masonry activities	5	Modules should be used to focus on specific activities within the masonry process.
Reduce physically demanding work for worker	5	A subsystem for block transport and another for lifting and placing the block on the wall are used.
Secure for Building Integrity	5	Each subsystem weighs approximately 800 kg, were are considering a Safety Factor of 1.5.
The robot must be economical	5	Commercial products are simple and easy to get, like using RTP to reduce manufacturing costs. Look for commercial products and adapt them to our needs, like the stacker for the AMR.
Working with walls of different heights	4	Structure in sections for walls from 2m to 4m.
Autonomous mobility	4	Shared AMR modules between subsystems.
Preference for electrical use	4	Electrical components are suitable for connecting to traditional 120V AC outlets.
Safe for workers	4	Designate restricted areas for workers and limit their interaction to perform material supply.
Ease of operation	4	Simplicity in each module for simple actions.
Easy to repair	4	Use of commercial products, which are easy to get. The main mechanical systems are designed to be simple in structure and operation.
Scalability to other tasks	4	A modular system that allows for changing tasks according to the module.
Transportation within the construction	4	The system of modules and sections allows disassembly into sections of reduced weight and size.
Cover the majority area of the wall	3	The elevator can reach from the first rows of the wall, although some upper rows are impossible.
Minimize human error	3	Use of multiple sensors and actuators.
High repeatability	3	Use of multiple sensors and actuators.
Control by an operator	3	Integration of controls and HMI.
Place blocks in the correct orientation and position	3	The vision of the state of the wall in real-time to correct errors.
Manufacturing ease	3	Use of commercial products, which are easy to get. The main mechanical systems are designed to be simple in structure and operation.
Movement in irregular ground	3	The stacker is designed to work on irregular terrain like ours.
Increase productivity	3	Designed to work in both day and night shifts.
Outdoor work	3	Minimum IP54 protection for external components.
Easy to install	2	We are coupling between modules designed to accommodate and screw some sections or the use of spring pins for others.
Lower labor cost	2	Designed to work in both day and night shifts.
Low human interaction	1	Designate restricted areas for workers and limit their interaction to perform material supply.

the working conditions of a real construction site, adhering to the client's requirements and the specifications established during the information stage. The robot will be considered successfully validated if it can place blocks in two separate rows of a masonry wall and at three different height levels: bottom, middle, and top sections of the wall.

V. DISCUSSION

The masonry robot was designed following the engineering design methodology proposed in this work, gathering information from previous studies, understanding the confined masonry process carried out in Mexico, defining customer needs, assessing its impact, and establishing a set of characteristics based not only on the needs but also on the context in which the system would be operating, and finalizing the requirements to be met. This approach allowed the generation of several concepts that could meet expectations, which were then evaluated based on specific criteria to select the most promising one. The chosen concept was a modular system composed of three basic subsystems: a wheelbarrow for transporting blocks, a lift for correctly positioning and placing the block on the wall, and a mixer to handle all mortar applications. The proposal was developed according to our conceptual development framework for mechatronic products in Fig. 5, enabling the development of the mechanical and electronic aspects of the wheelbarrow and elevator subsystem.

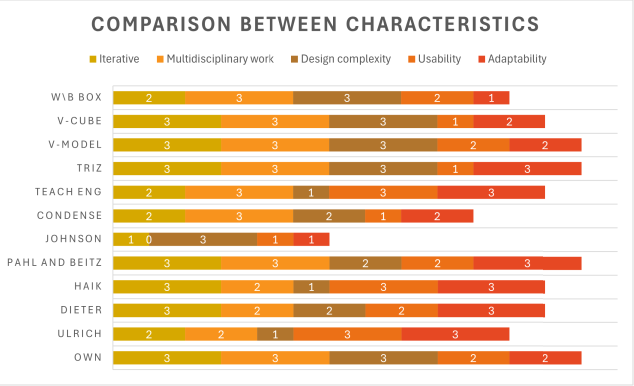

FIGURE 15. **Comparison between the characteristics of the methodologies - Results of methodology.**

Table 10 shows the customers' needs and the solutions provided in the design, considering that specialized solutions were given for high-impact needs. In contrast, some lower-impact needs were addressed within other solutions, ensuring that none of the needs were left unaddressed or unsolved. Evaluating what was done with the proposed design methodology, it was analyzed similarly to the rest of the methods following the metrics in Table 1. Remember that these metrics are based on the characteristics expected to be met with our methodology.

Similar to the approach taken with the design methodologies that served as the foundation for our proposal, this methodology was subjected to the same analysis of the characteristics we aimed to achieve in our design methodology. This was based on the development presented in the case study. The results of the analysis and comparison with the other methods can be found in Fig. 15. Our methodology demonstrated characteristics similar to those of the V-Model, which was expected considering that both models focus specifically on mechatronic systems. By prioritizing an iterative process, multidisciplinary work, and complex design tasks, both usability and adaptability showed some limitations. This is understandable, as certain correlations are inherent in design methodologies. Despite these limitations, our methodology appears to show, at first glance, the capability to develop mechatronic products, from the earliest stages through to the conceptual design development.

Reviewing the proposed engineering design methodology again and the results of applying it to the case study, it is evident that the methodology is focused on generating solutions to a defined problem within a geographic area. It is user-centered, giving the solution characteristics of a product or service. On the other hand, its mechatronic approach endows the methodology with the ability to be used for complex designs.

However, there are still some uncertainties regarding the methodology's adaptability to different industrial contexts beyond mechatronic engineering. While its structure is robust for products that combine mechanics, electronics, and software, it is unclear how this methodology would function in other sectors facing different challenges. In such cases, the methodology might need specific adjustments to manage these environments' complexity and multidisciplinary interactions.

Another point to consider is the inclusion of additional tools that allow for the scalability of the design process and its incorporation into the product production process.

Future research could focus on applying this methodology to more diverse projects, allowing for an evaluation of whether significant modifications are needed in its steps or tools. Additionally, it would be important to explore how the methodology integrates with other aspects related to a product, such as production, marketing, distribution, or user experience.

VI. CONCLUSION AND FUTURE WORK

Based on the results obtained, we can conclude that the methodology meets the desired characteristics, facilitating an iterative design process that supports multidisciplinary collaboration and the creation of highly specialized designs. It enables multiple projects to be executed without excessive complexity. While the usability and adaptability of the methodology do not match its other features, this is to be expected. Fig. 1 illustrates correlations among the characteristics, clarifying that usability and adaptability may be compromised when focusing on a methodology tailored for mechatronic products, which often demand a high level of expertise. Therefore, should it be necessary to prioritize these characteristics, adjustments to the methodology or the exploration of alternative design methods that better align with the needs should be considered.

Furthermore, the case study developed a comprehensive concept within its context, taking into account working conditions, client specifications, budget constraints, and other relevant factors. This justifies proceeding with simulations and the construction of a physical prototype for testing under real-world conditions. The methodology effectively addressed all requirements, prioritizing those with the most significant impact while also considering lesser priorities.

Since the case study progressed to the mechatronic concept development stage, specifically focusing on the mechanical and electronic aspects, it is possible that further development, whether through simulations or prototype construction, may necessitate additional iterations or the integration of new steps into the proposed methodology.

Considering the results, it is important to highlight that the methodology is intended for the development of mechatronic products, as described at the beginning of Chapter III. It covers the process from early conceptualization to embodiment design. Consequently, its adaptation to other fields or applications may be limited and could require the integration of additional tools or the use of alternative supporting methodologies. Furthermore, while the methodology aims to reduce the impact of last-minute changes, it is also important to note that it only considers the scope and capabilities of the design team.

Considering this, it is recommended that the methodology be validated through the development of a physical prototype. This step would serve two purposes: identifying potential shortcomings within the method and thoroughly validating the methodology by demonstrating its capability to guide a mechatronic design from the initial stages, such as problem definition, to final development phases, resulting in a functional prototype that has undergone testing in both simulations and real environments, and is prepared to advance into production, marketing, commercialization, and further stages.

For future research, the development of the control and information aspects of the mechatronic concept design is proposed. This involves detailing the architecture, configuration, and parameterization of these elements, including designing the communication architecture within each module of the platform and between them, as well as developing the corresponding software and control strategies. Following this, the final step involves testing. The case study's testing section outlines the plans established for both simulation tests and prototype testing. The goal is to develop a physical prototype for the wheelbarrow and elevator subsystems, conducting tests in an environment that simulates the conditions of a confined masonry wall construction site in Mexico. The ultimate objective is for the robot to successfully place blocks in different wall rows at three height levels: low, medium, and high.

On the other hand, we propose to further expand this line of research by evaluating different engineering design methodologies. This would enable a more quantitative analysis, including benchmarking of each methodology's characteristics and collecting feedback from individuals with experience in their practical application. Such an investigation could broadly reveal the main strengths and weaknesses of each methodology, as well as help identify key features and relationships among different design approaches.

In particular, incorporating feedback from experienced designers would offer valuable insights into how each methodology performs in real-world scenarios, beyond theoretical or idealized conditions. This comparative approach could also support the development of hybrid frameworks that integrate the most effective elements from multiple methodologies. Furthermore, the results of such an analysis could guide educators, researchers, and industry professionals in selecting or adapting the most appropriate design processes for specific contexts, ultimately contributing to more robust and user-oriented design practices.

AUTHOR CONTRIBUTIONS

Luis A. Salazar-Calderón (Investigation, Methodology, Writing-original draft); Javier Izquierdo-Reyes (Supervision, Validation & project administration, Writing-review & editing); Javier A. de la Tejera (Conceptualization).

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