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On the Integration of Complex Systems Engineering and Industry 4.0 Technologies for the Conceptual Design of Robotic Systems

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Abstract: This paper presents a novel integration of Systems Engineering (SE) methodologies and Industry 4.0 (I4.0) technologies in the design of robotic systems, focusing on enhancing underwater robotic missions. Using the conceptual design of an underwater exploration vehicle as a case study, we demonstrate how SE can systematically incorporate I4.0 tools to improve mission performance and meet stakeholder expectations. The study begins with an overview of the SE approach, emphasizing the conceptual design stage and aligning it with the application and case study of design theories. We then explore various I4.0 technologies, highlighting their functional benefits rather than technical specifics and addressing design methods for I4.0. Remotely Operated Vehicles (ROVs) are examined in terms of classification, components, and tasks, showcasing their evolution driven by technological advancements, thus tackling the complexity and design of complex systems. The core of our study involves defining stakeholder expectations, using quality function deployment for requirements definition, and performing a functional and logical decomposition of the ROV system. To deal with design fixation within the design team, we developed a tool to help integrate new technologies by also empathizing with their functional capabilities rather than the technology itself. Our approach underscores the importance of understanding and incorporating new technologies functionally, aligning with the transition towards Industry/Society 5.0. This work not only illustrates the synergy between SE and I4.0, but also offers a structured methodology for advancing the design and functionality of complex systems, setting a blueprint for future developments in this field.

Keywords: systems engineering; Industry 4.0 technologies; design innovation; remotely operated vehicles (ROVs); conceptual design methodologies; functional decomposition; complex system integration; human-centric engineering; underwater robotic systems; Industry/Society 5.0

Citation: Restrepo-Carmona, J.A.; Taborda, E.A.; Paniagua-García, E.; Escobar, C.A.; Sierra-Pérez, J.; Vásquez, R.E. On the Integration of Complex Systems Engineering and Industry 4.0 Technologies for the Conceptual Design of Robotic Systems. *Machines* **2024**, *12*, 625. https://doi.org/10.3390/machines12090625

Academic Editors: Alessandro Giorgetti, Gabriele Arcidiacono, Chris Brown, Erik Puik, Nakao Masayuki and Erwin Rauch

Received: 28 June 2024
Revised: 23 August 2024
Accepted: 2 September 2024
Published: 6 September 2024

1. Introduction

Engineering design is challenging because it is far from static in the transition period from Industry 4.0 (I4.0) to Industry/Society 5.0, which focuses on the complete integration of technology to address social challenges and improve quality of life, along with a phenomenon known as human-centricity [1,2]. Technological advances are permanently providing new alternatives and solutions, creating new problems or even full fields of study. The availability of technological alternatives also makes new products more complex than their previous generations. In this ever-evolving landscape of engineering, Systems Engineering (SE) stands as a critical discipline that coordinates the development of complex, multidisciplinary systems across diverse industries, in the time of Society 5.0 (a futuristic concept that advocates integrating technology into every aspect of daily life to improve quality of life) to benefit society [3]. SE has proposed a methodology that allows a systematic approach to developing systems that could involve multiple components from multiple domain expert teams [4].

Among I4.0 technologies, robotic systems have been used in the last decade for risky duties such as ocean exploration [5]. Within unmanned vehicles, one can find that Remotely Operated Vehicles (ROVs) represent an example of systems that have evolved from simple to complex, according to the tasks that are expected to be executed. Initially developed for simple underwater tasks, ROVs have changed from maneuverable underwater camera systems [6] to sophisticated platforms capable of performing intricate operations in deep water environments. Applications range from bomb recovery, searching for lost submarines, and heavy-duty uses for the oil and gas industry [6], to habitat monitoring and conservation [7] and in-water hull cleaning [8], among others.

The evolution of such underwater robotic systems has been driven by technological advances that extend their capabilities in harsh, unstructured environments [6]. The integration of advanced sensory and autonomous navigation technologies has transformed ROVs from manually operated machines to intelligent systems capable of complex decision-making and operations [9]. Current research in the field emphasizes the importance of integrating smart technologies to enhance the autonomy, efficiency, and user interface of ROVs [10]. Some examples include simplifying operation [11], visual-haptic feedback [12], novel pilot interfaces for ROV operation [13], or ROVs being launched and recovered from unmanned autonomous surface vessels [14].

By focusing on smart technologies, we get into one pillar of this work: I4.0. The concept of I4.0 is rooted in a history of industrial revolutions, each marked by breakthroughs that reshaped society [15]. From the steam engine to the use of electricity and the advent of computer technology, each phase has set the stage for the next [16]. I4.0 has built on these advances to introduce a new age of automation and data exchange in manufacturing technologies, setting new standards for productivity, and fostering an environment of continuous improvement and connectivity. I4.0 is characterized by a fusion of technologies that blur the lines between physical, digital, and biological spheres, heavily relying on advances such as the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Machine Learning (ML) [17,18].

The synergy between traditional engineering practices and revolutionary digital technologies is currently imperative. This is the key to significantly improving efficiency and innovation in manufacturing, data management, and system operation [19]. However, the challenge remains in effectively integrating these next-generation technologies to enhance operational effectiveness without compromising reliability or increasing complexity undesirably [20]. An additional challenge for engineers and designers is to avoid using the latest technology just for the sake of it and remain focused on solving the actual needs of users [21]. The user requirements and functional-oriented SE framework are ideal for integrating mature and new technologies into robust solutions while supporting a user-centered design approach.

There is literature on the relationship between robotics and I4.0 [22,23], and on SE and robotics [24–26]. Additionally, works detail ROV development and design from components and specific perspectives [27–29]. However, while I4.0 may not seem closely related to ROVs, there are improvement opportunities that can be approached with I4.0 tools. This work presents a novel integration of I4.0 concepts and SE methodologies in the context of designing an underwater robotic system. Through a case study, this research introduces the development of an underwater exploration vehicle using SE tools, starting from stakeholder identification and requirements definition to presenting a logical decomposition of the exploration system. Functional affinity analysis (FAA) is also presented as a simple yet useful tool to overcome design fixation during the conceptual design stage.

The novelty of this approach lies in the emphasis on requirements and functions closely related to I4.0 solutions. By viewing I4.0 from a functional standpoint, this work facilitates its connection with SE methodologies, providing a new perspective on the application of I4.0 tools to advanced robotics. This integration serves as a reference for applying SE to the domain of advanced robotics under I4.0, illustrating its potential to streamline the integration of cutting-edge technologies into complex systems. Additionally, the structured analysis and design approach provided in this study aims to serve as a blueprint for future developments in robotic systems and other complex engineering projects within the scope of migrating from I4.0 to Industry/Society 5.0.

The organization of the paper is as follows. Section 2 provides the concepts of SE and describes the design process for complex systems. Section 3 describes the technologies of I4.0 and emphasizes the present and future requirements of human-centricity for the implementation of such technologies. Section 4 summarizes the main characteristics that allow a remotely operated underwater robot to be considered a complex system. Section 5 shows the used methodology and presents the new tool to help avoid design fixation. Section 6 presents a case study for the conceptual design of an underwater robotic system using the SE approach. Finally, Section 7 contains the discussion, and Section 8 presents the main conclusions.

2. Systems Engineering

A technical system is defined as "a set of components working together as a whole to achieve a common objective" [30]. These systems operate within an environment where they interact and produce mutual effects. However, several characteristics distinguish a complex system from a simpler system [30]. The first one is that it is a product of engineering, and therefore meets specific needs. The second is that it consists of various components that have intricate relationships between them, and is therefore multidisciplinary and relatively complex. And the final one is that it uses advanced technology in ways that are central to the performance and fulfillment of its primary functions, which involves taking risks during development and, often, high costs.

The concept of SE and its applications emerged in the early 1950s, although it has been promoted by the International Council on SE (INCOSE, San Diego, CA) since the 1990s as an engineering discipline of systems design [31]. It aims to work with all engineering disciplines (mechanics, hydraulics, electronics, sensors, control, etc.) to develop comprehensive solutions that meet the functional, physical, and operational performance requirements of customers and stakeholders [4,30].

The roles of SE are to allocate the system's functions in the appropriate engineering domain, to coordinate those functions, to define the interfaces between functions, and to distribute design tasks, among others [32]. NASA (Washington, DC) defines SE as the practice of balancing organizational, cost, and technical interactions within complex systems [33].

SE spans the project life cycle from the initial idea to develop a functional device that meets the user's needs. Important product features that are considered in this discipline are product function, costs, schedule, user support, quality, manufacturing, and phase-out [32,33]. Additionally, a crucial process in SE is to model the system from a functional perspective, which facilitates decision-making in the design process. This involves decomposing the system into manageable subsystems and ensuring continuous integration across domains [32].

SE follows a sequential process, typically starting with the formulation of the objective and strategic planning, followed by requirements development, architectural design, and component development [34,35]. This process is illustrated in Figure 1. SE starts understanding the global problem, and then progressively decomposes the system into subsystems and components. This process is known as the "top-down approach" in the analysis of needs and requirements. It starts with functional thinking (logical decomposition and functional architecture) and gradually transitions to physical thinking (physical architecture). Following this, a bottom-up approach is employed for the implementation of physical solutions and their actual integration. The process concludes with a comprehensive final evaluation of the physical system [33]. SE is also defined as an iterative process where each step relies on the previous one, but that previous one can receive feedback by subsequent steps [32].

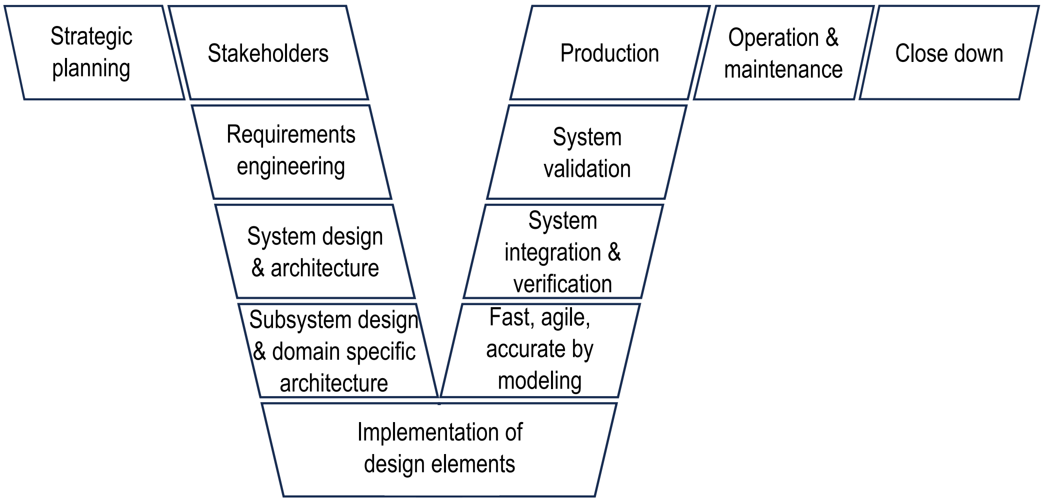

Figure 1. Systems design process V model, adapted from [36] with information from NASA's SE Handbook.

NASA's SE handbook describes SE, including three different groups of technical processes: system design, product realization, and technical management [33]. Focusing on system design (see Figure 2), this process encompasses defining stakeholder expectations, generating technical requirements, translating these into logical models, and designing solutions that meet these expectations [30,33,34].

Figure 2 also illustrates how the three first steps could be related to conceptual design. Conceptual design starts with a needs statement, followed by a context study, requirements engineering, and a review of the state of the art. The system is visualized as a whole, and functions, sub-functions, and functional groups are proposed. The conceptual design stage is critical, as it sets the direction for all subsequent efforts [33].

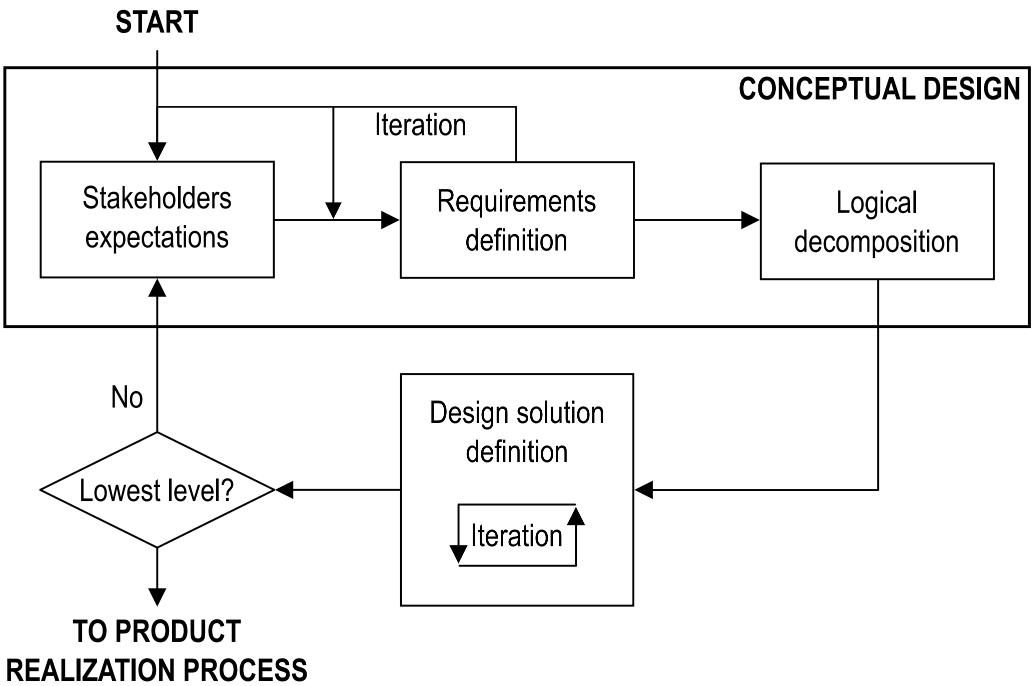

Figure 2. Conceptual design process, inspired in [37] with information from NASA's SE Handbook.

The following design stage aims to transition from the problem domain to the solution domain. This is also known as the design solution definition. In this stage, the functional architecture must be transformed into a physical architecture, and subsystems are established. This could be related to embodiment and detailed design in other representations of the design process. Low-resolution prototypes of individual elements and subsystems are used. Decisions are made based on requirements criteria, with the objective of proposing a physical configuration of the solution with preliminary values. In this system design stage, various disciplines develop the solution for each subsystem. Detailed calculations, tests, and increasingly integrated high-resolution prototypes are prioritized. System specifications are obtained, and a general design review is conducted.

Construction or production (product realization) aims to produce the components according to the obtained specifications. This involves the construction and testing of the system. Once constructed, formal qualification reviews and evaluation and acceptance tests are performed. Like any design process, these stages have iterative and recurring components. It should also be understood that, in practice, the boundaries between stages are blurred, and the exact methods to be used may vary from one project to another.

The system project must be developed under consistent technical planning, technical control, technical assessment, and technical decision analysis processes. It allows project traceability from requirement, configuration, and technical management through technical assessment and risk management [33].

Finally, SE emphasizes a User-Centered Design (UCD) approach, prioritizing end-user needs and feedback throughout the design and development process. By integrating user requirements into system specifications, the goal is to create products, systems, or services that are not only effective and efficient, but also satisfying for the user [38,39]. Integrating user requirements into the overall system requirements ensures that technical specifications align with user expectations.

3. Industry 4.0

To understand the concept of an industrial revolution, it is necessary to define the periods of human history marked by significant economic, social, and industrial changes and transitions in manufacturing processes driven by innovative technologies [40].

3.1. Industrial Revolutions

The First Industrial Revolution (1760–1840) marked the transition from agricultural economies to industrialized societies, primarily in Britain. This era was defined by the introduction of machinery in the textile and iron industries, which spurred economic growth and societal changes. Key innovations such as the steam engine and mechanized spinning and weaving technologies shifted production from manual labor to mechanized processes. These advancements laid the foundation for the modern industrial economy [41].

The Second Industrial Revolution (1860–1914), often referred to as the American Industrial Revolution, was marked by significant technological advancements, including the adoption of electricity, the internal combustion engine, and breakthroughs in the chemical and steel industries. This era witnessed substantial industrial growth fueled by innovations in transportation and communication, such as the development of railroads, automobiles, and the telegraph. These advancements led to rapid urbanization and the expansion of global trade, profoundly transforming industries and societies worldwide [42].

The Third Industrial Revolution, also known as the Digital Revolution, began in the second half of the 20th century and continues to this day. This period is characterized by the transition from analog to digital technologies, driven primarily by the widespread adoption of computers and the internet. These advancements have transformed industries and societal interactions on a global scale, leading to the creation of new sectors and fundamentally reshaping existing ones [16,43].

The Fourth Industrial Revolution is revolutionizing market competitiveness through the adoption of innovative processes that incorporate digital technologies, automation, and data-driven decision-making. These advancements are establishing new paradigms in production, consumption, and interaction with the world [17,18]. The concept of Industry 4.0, often referred to as I4.0, was initially proposed in Germany in the early 2010s, aiming to create smart and interconnected companies [44]. These companies leverage cyber-physical systems to optimize processes by integrating sensing, computation, control, and networking into physical objects and infrastructure, thereby connecting them to the internet and each other [45].

3.2. I4.0 Technologies and Their Functionalities

I4.0 is characterized by the use of the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Machine Learning (ML), as well as other technologies, some of them summarized and related to their functionalities in Table 1. These technologies facilitate the extensive availability of data via an internet connection. They enable a deeper understanding of industrial and consumer behaviors through data analysis. This, in turn, supports learning from experience, modeling, and predicting phenomena [17].

Table 1. I4.0 technologies functional description.

I4.0 Technology	Optimized Summary of Functions
Internet of Things	Collect real-time data, analyze and process, allow the user to remotely monitor and control the IoT device the collected data, and enable automated actions based on predefined conditions [46–48].
Artificial Intelligence/ Machine Learning	Analyze large datasets to identify patterns, trends, objects, and correlations; use historical data to predict future outcomes; and enable machines to interpret and understand visual and audible information [46,49,50].
Robotics	Navigate through environments without human intervention, identify and manipulate objects, facilitate communication and collaboration between robots and humans, and incorporate ML and AI to adapt to changing environments and optimize performance [51–54].
Big Data Analysis	Employs advanced algorithms to process and analyze extensive data sets, deriving insights for strategic decision-making and operational optimization. Enables real-time data analysis for proactive management [55,56].
Augmented/Virtual Reality	Enhances real-world and virtual environments for immersive interactions, training, and visualization. Augmented Reality overlays digital content onto the physical world, while Virtual Reality creates fully immersive digital environments [57–60].
3D Printing	Rapidly prototypes physical models, enable the production of customized and personalized products tailored to individual needs, and facilitate the production of small batches of products economically [47,61,62].
Cloud Computing	Provide virtualized computing infrastructure over the internet, including virtual machines, storage, and networking. Provide scalable and on-demand storage resources over the internet. Provide tools and services for processing, analyzing, and visualizing large sets of data [63].
Cybersecurity	Ensures the protection of digital assets, securing data and systems from cyber threats. Essential for maintaining data privacy, integrity, and secure online transactions in an interconnected ecosystem [64].
Digital Twin Technology	Creates virtual models of physical systems for simulation and analysis. Facilitates optimization and predictive maintenance, enabling better decision-making through virtual testing and monitoring [65,66].
Blockchain	Offers a secure and transparent method for recording transactions and tracking assets through decentralized ledgers. Enhances trust, security, and efficiency in digital exchanges and supply chain management [67,68].

IoT plays a key role in I4.0, connecting physical objects, devices, and systems to the internet, aiming to receive and transmit data through wireless networks, to process them, and subsequently report the object status or perform an activity without any human operation [17]. Functionally describing IoT, it enables the connection of physical devices and objects to the internet, allowing them to collect and exchange data. In the industrial context, this means that machines, sensors, and other equipment can communicate with each other in real time.

This process is strongly related to Big Data, as the large amount of data generated by IoT needs to be analyzed to derive insights and understand the systems' behavior. Big data analytics involves the processing and analysis of large volumes of data to derive meaningful insights [55]. In I4.0, this tool helps in making data-driven decisions, predicting equipment failures, optimizing processes, and improving overall efficiency. Subsequently, AI and ML algorithms are employed to analyze data, recognize patterns, and make autonomous decisions, contributing to the smart side of I4.0 [46].

An important concept that defines a scalable and accessible platform for storing and processing large amounts of data are Cloud Computing. I4.0 facilitates the centralized storage of large datasets, collaborative work, and remote access to resources [69].

Advanced robotic technologies are also important in I4.0, they are systems capable of cognition, navigation, mobility, and complex interactions [70]. Robots equipped with AI and sensors can perform tasks autonomously. In many industrial applications, these robots can handle repetitive or dangerous tasks, improving efficiency and workplace safety. They are meant to perform complex jobs in hostile environments, data extraction, enhance productivity and reliability, automate processes, and carry out inspections and surveillance, among other tasks [23]. In this way, the robotic systems are strongly linked with I4.0 elements, as they employ technological elements such as digitization, automation, and connectivity [22].

Integration of IoT in robotic systems implies using sensors that allow collecting and transmitting data to adapt themselves to changing conditions and work collaboratively with human workers and other machines, as they could generate enough amounts of data to ease data-driven decision making, as well as allow remote monitoring and control [22,49,71]. IoT capabilities in robotic systems can provide valuable data for predictive maintenance, quality control, and process optimization. In terms of surveillance activities, equipping robots with vision, imaging systems, and AI, leads to important inspection tasks that empower the robot to make its own decisions or wait for an operator's instruction. Robots are important in driving the I4.0 pillars of automation, data-driven decision-making, and connectivity.

It is important to recognize I4.0 from the perspective of its contribution to solving people's problems, rather than focusing solely on its technologies. This approach aligns with the concept of the migration to Society 5.0, which aims to balance economic advancement with the resolution of social issues [1,72]. Understanding technologies from the perspective of the functions or tasks they can perform enables a connection with functional and systemic thinking. This helps in developing new user-centered solutions based on the best available technologies or by adapting technologies according to their functionality. This key aspect is illustrated in the exercise shown in Table 1. This exercise is part of the methodology presented in this work, aimed at effectively helping designers embrace new technologies to solve problems they are already familiar with.

4. Remotely Operated Vehicles

A robot is generally defined as a machine or mechanical device engineered to execute tasks autonomously or with minimal human intervention [73]. Robots usually include a physical structure, actuators for movement, sensors for perception, and a control system governed by computer programs [74]. The primary objective of physical robots is to execute specific functions, often in environments where human intervention may be impractical, unsafe, or where high precision and efficiency are required [75,76]. Robots come in various forms, ranging from industrial robotic arms to mobile robots [77,78]. They find applications in logistics, industrial manufacturing, defense and security, space, land, and underwater exploration [51,79].

Within the domain of mobile robotics, we distinguish between remotely operated and fully autonomous devices. This category includes Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles/Systems (UAVs/UAS) for terrestrial and aerial operations, respectively. In aquatic settings, developments include Autonomous Surface Vehicles (ASVs), which are essentially robotic boats, along with Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). ROVs are defined as unmanned remotely controlled submersible vehicles [6] that operate in underwater missions such as ocean exploration, offshore inspections, scientific research, deep-sea archaeology, and underwater maintenance. These vehicles are typically equipped with cameras, sensors and, in some cases, mechanical arms for tasks such as collecting samples or performing maintenance, for multiple hours, in depths up to 6000 m [9,10].

The development of ROVs can be traced back to the first exploration prototype in the 1950s and naval applications in the 1960s [11]; by the 1970s, the oil and gas industries were responsible for developing and taking advantage of this technology. Although traditionally linked to military and oil industries [80], their use has been extended to biological monitoring applications [81], and the renewable energy industry [82].

4.1. Description of ROV Systems

According to the NORSOK U-102 standard [83], ROVs are classified into five different classes. Class I, for observation, is typically equipped with a video camera, lights, and propellers; Class II, for observation with additional load capacity, is equipped with at least two additional sensors; Class III, for working, has sufficient capacity to load additional sensors and actuators to manipulate objects; Class IV, for work on the seabed, has wheels or other means of traction; and Class V, prototypes and other vehicles in the development phase. They dictate how the size and requirements are defined, and determine the capabilities and systems that should be integrated to get to the design objective.

An ROV can be described in terms of a set of components [28]: vehicle, surface station, surface/vehicle interface, control, and software. The vehicle itself is in charge of carrying out underwater tasks. The surface station provides an interface with the operator and contains the mechanical and power infrastructure required on the surface for the vehicle and other subsystems to operate. The surface/vehicle interface, also known as the Tether or Umbilical, allows the connection between the vehicle and the surface station. The control system is transversal to all subsystems and is in charge of the algorithms that give intelligence to the ROV system. The software is also transversal to all subsystems, and provides the computing infrastructure that allows communications, capture, management, processing of information, and vehicle control. This is an example of a components-centered description.

An ROV system is illustrated in Figure 3. The surface side shows the surface control station and the launch and recovery system. There is a surface/vehicle interface or tether cable. The Underwater side of the ROV presents the frame, float block, thrusters, and the tether cable connection. There is also a variety of other components that may change on specific models. Some of the usual components are cameras, lights, sensors, and sonar systems. ROVs in Classes III and IV usually include manipulators and other tools.

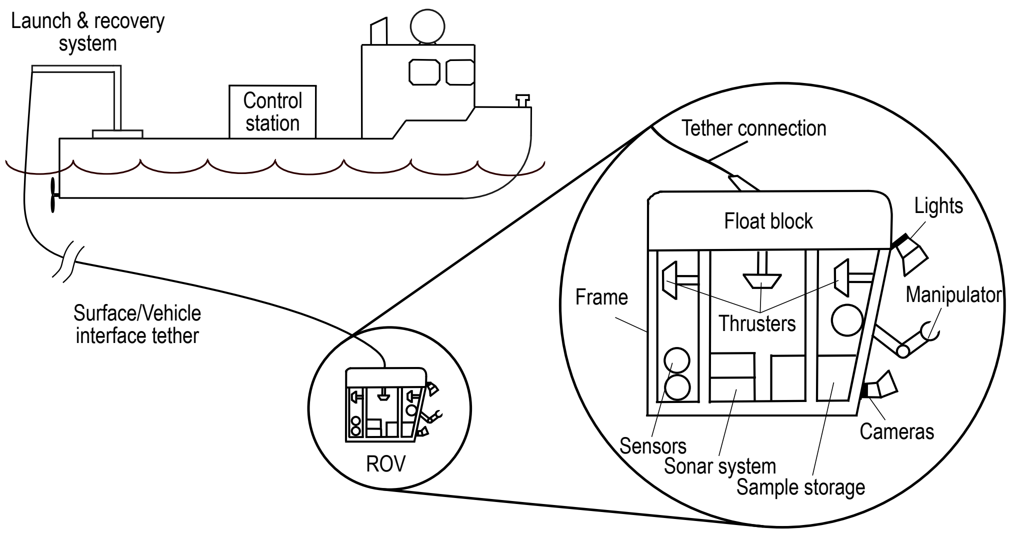

Figure 3. ROV underwater exploration system main components.

An ROV is a complex system given its sub-system interactions. Although there are some components available off the shelf, their integration into a system is a complex task, leading to the need for multiple iterations and an interdisciplinary work team to accomplish its design process, requiring different basic disciplines that make up robotics: mechanics, electronics, control, and computing. Despite being a mature technology, numerous recent efforts can currently be found to improve its navigation capabilities and levels of autonomy [84–89], as well as its monitoring capabilities through the implementation of different measurement equipment [90,91].

The requirements specified for the design of an underwater exploration system typically include: vehicle class, operating environment, operating depth, required degrees of freedom, weight and maximum dimensions, communications technology, navigation instruments, and auxiliary systems, among others [28].

4.2. SE and I4.0 Integration for ROV Development

Integrating SE methodologies with I4.0 concepts in the design and development of ROVs can offer significant advantages in overcoming the challenges associated with complex robotic systems. The functional-centric approach of SE emphasizes a deep understanding of system requirements and functions, encouraging designers to explore innovative solutions rather than relying solely on familiar methods. This approach helps mitigate design fixation, a common issue where experienced designers might default to known solutions, potentially overlooking new technologies and approaches.

SE fosters a structured process that evaluates potential solutions against the system's functional requirements, enabling the seamless integration of cutting-edge technologies, such as those from I4.0 and others. By clearly defining requirements and systematically evaluating potential solutions, SE reduces the likelihood of costly design changes later in the process or the need for unnecessary prototypes. This not only saves time and resources, but also accelerates the development cycle, allowing for more efficient allocation of budgets.

5. Conceptual Design Methodology

As stated before, conceptual design is the most important stage of the process because it establishes the foundation and direction for the subsequent work [33].

5.1. Stakeholder Expectations

For SE, stakeholders are fundamental elements in the system development process. The stakeholders of a system are those individuals who have the right to influence the requirements because they will be affected (positively or negatively) by the system under development. Different activities have to be performed with stakeholders to identify and define their expectations. Such expectations include needs, goals, objectives, constraints, and success criteria.

5.2. Requirements Definition

A requirement is a fundamental concept for SE. It is the result of a formal transformation of one or more needs into an obligation of an entity to perform a certain function or possess a certain quality, given certain constraints. In SE, a set of clear, complete requirements that do not interfere with each other must be obtained. There should also be an understanding of the required functionalities, priorities, and costs, as well as the management of requirement changes that may arise throughout the process [34].

Requirements engineering seek to consolidate needs and requirements that will guide the system's development. Requirements are important because they help establish the scope, allow all stakeholders to have a voice, justify development costs, accurately report progress, and determine when the project has successfully concluded [34].

Requirements can be classified in several ways. One classification includes customer requirements, functional requirements, performance requirements, and design requirements. Two strategies can be used to consolidate requirements: elicitation and elaboration. Elicitation is achieved explicitly and directly from stakeholders through strategies such as interviews and workshops. Elaboration involves obtaining requirements that are not explicitly proposed by stakeholders but are derived from the study of the context, the technology of other requirements, etc. [92]. "Bad requirements cannot be fixed by good design" [34,93], summarizes the importance of requirements engineering and conceptual design. Requirements are also key inputs when conducting a selection process to acquire a commercially available system (or technology) ready for operation.

A useful tool is the Easy Approach to Requirements Syntax (EARS) proposed by Mavin et al. [94]. This methodology is characterized by helping to generate a concrete and sufficiently technical redaction to the requirements. This avoids overly vague or excessively complex writings. Once requirements are properly stated, they are presented to stakeholders so they approve the list. Finally, it is important to have requirements prioritized. Stakeholders establish requirements priority by giving them a punctuation (1 to 5).

5.3. Quality Function Deployment-House of Quality

Requirements are often processed to obtain technical criteria that allow for decision-making later in the design process. Techniques such as the House of Quality (HoQ) can be applied at this stage [93,95–97]. HoQ is just the first of four matrices included in the Quality Function Deployment (QFD) method. These matrices span the whole product development cycle. However, in the conceptual design stage, only the first matrix of the QFD is created, i.e., the HoQ.

The first step in the HoQ process involves defining the requirements. It is also crucial to have users assign priority scores to these requirements to ensure their importance is accurately reflected.

The second step involves translating user requirements into Engineering Characteristics (EC). These are defined in terms of controllable attributes by the design team. While these technical requirements do not dictate specific solutions; they should be articulated as measurable or quantifiable specifications [98].

Thirdly, the HoQ exercise for the ROV system is carried out adhering to established HoQ guidelines [93,99]. In this exercise, the relationship between user requirements and engineering characteristics is evaluated and assigned scores of 0 (no relation), 1 (weak relation), 3 (moderate relation), or 9 (strong relation). These scores, combined with the prioritization of user requirements, facilitate the ranking of engineering characteristics.

This ranking is of great importance, serving as a guide for decision-making since it identifies which characteristics are most critical to address, taking into account potential conflicts or resource limitations.

5.4. Logical Decomposition

The logical or functional decomposition requires us to understand the system to be designed in terms of the tasks or functions the system will perform. It can be explained as a strategy where the system's main complex function is divided into several levels of simpler and more specific functions. In this way, it is easier to understand the system's internal interactions and look for better solutions to fulfill the requirements [34,95]. To create this simplified representation, functional groups are defined, and lower-level support functions are included in each group, as will be illustrated in Section 6.

5.5. Functional Affinity Analysis

Even when using SE principles, design fixation can overshadow new developments. There is a tendency to rely on well-known solutions, which would lead to less innovative designs or slower technology updates. We propose a methodological tool in order to reduce bias towards only the traditional or already-known tools and improve the adoption of new alternatives to solve problems.

The functional affinity analysis (FAA) would be an intermediate step between the conceptual design and basic design, as shown in Figure 4. This tool requires designers to extract a list of functions from the logical decomposition (FtS), and also a list of functions performed by new technologies (FNT) which, in this case, come from Table 1. Once both lists are extracted, the idea is to look for matches between the two lists, without checking any specific technology or component name. With this strategy, we aim for designers to genuine problem (FtS) and solution (FNT) match without prejudice towards the technology or component to be used, as seen in Figure 5. After the matches have been established, the technology name is made explicit and the possible solution will be part of the possible solutions obtained on the divergent stage. This strategy can be used along other known divergence tools as SCAMPER, brainstorming, morphological matrix, etc.

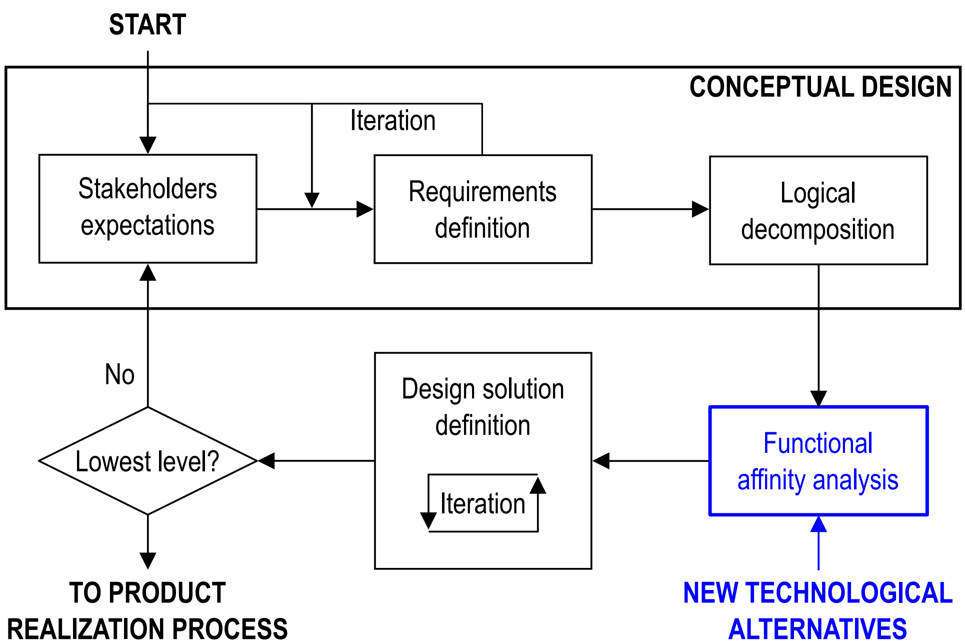

Figure 4. Conceptual design process, including the new functional affinity analysis (FAA). Inspired in [37] with information from NASA's SE Handbook.

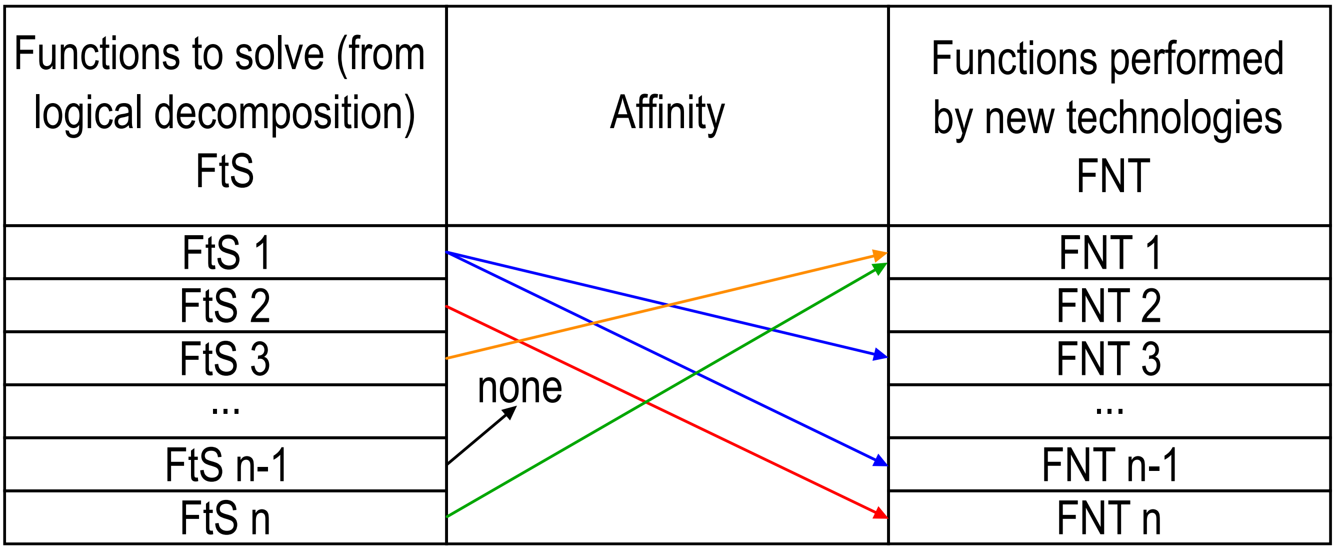

Figure 5. Functional affinity analysis (FAA). Colored arrows come from each FtS and can go to several FNT.

Finally, as part of the design solution definition (basic design), the alternatives will be evaluated, and the best solutions will go to further refinement (convergent stage).

6. Case Study: Conceptual Design of an Underwater Exploration System

This case study begins with a request from an undisclosed company for an experimental robotic system to support oceanic exploration activities. The approach follows the steps depicted in Figure 4.

6.1. Stakeholder Expectations

In this case study, stakeholders were identified in five groups: (i) the company managers who approved the budget and execution of the design project, (ii) professionals (engineers and geologists) who raised the technical requirements, (iii) the operational personnel who are responsible for the operation of equipment, (iv) the personnel in charge of analyzing the information obtained by the system, and (v) the personnel of the platform from which the system will be operated (ship, oil/gas platform, dock, etc.).

For this case study, the summary of stakeholders' expectations are given as follows:

- The Remotely Operated Vehicle (ROV) is an experimental observation system designed for underwater exploration in the ocean, up to 500 m deep. Its main functions include capturing high-quality images and video of the sea floor and collecting solid and liquid samples.
- The ROV is compact and lightweight, with a mass between 100 and 300 km. It features a video system able to capture and display multiple videos simultaneously, instead of having to switch between cameras. It also includes multiple power and data connections, and a lighting system adapted for underwater conditions. The design emphasizes minimal power consumption and high-speed data transmission.
- The ROV is targeted at markets involved in hydrocarbon exploration and marine scientific studies. Its data transmission capabilities are enhanced with the potential for real-time data, depending on the availability and mission-specific requirements. The design ensures easy operability with minimal personnel, and its sample collection capacities are optimized within the vehicle's physical limitations.

Note that this is a summary; behind every statement, there is a lot of information and analysis. For example, an expected weight between 100 and 300 km has implications related to logistics, transportation, operative costs, crew size, safety, and so on.

6.2. Requirements Definition

Several user requirements can be identified within an underwater exploration ROV project. Some of them are strongly related to the utilization of I4.0 technologies, which are used among the whole system. Table 2 shows a summary of user requirements.

Table 2. Stakeholder's requirements definition and prioritization score.

Req. ID	Requirement	Short Name	Priority Score
1	The ROV shall collect underwater liquid and solid samples	To collect physical samples	3
2	The ROV shall record underwater images	To acquire images	5
3	The images shall be clear and readable	Image quality	4
4	The ROV shall preserve data of variables of interest in time	To store data of variables of interest	4
5	The ROV shall be capable of communicate instant variables to the surface station	To transmit information from ROV to surface	5
6	The surface station shall have different communication options	Surface station with connectivity flexibility	1
7	The ROV shall preserve recorded images information	To store image information	4
8	The ROV shall reach the desired position and orientation in the area of interest	ROV positioning	5
9	The ROV shall withstand the environmental conditions while guaranteeing continuous operability	Protection	3
10	The ROV shall be able to navigate underwater from the deployment site to the mission site through underwater obstacles	Maneuverability	5
11	The ROV shall have a command center from where the mission is controlled	Surface station	5
12	The ROV shall have flexibility to connect additional equipment for possible mission variations	Possibility of connecting own equipment	2

6.3. Quality Function Deployment—House of Quality

The HoQ exercise for the ROV system is carried out as detailed in Table 3, following the steps explained on Section 5. The final EC score highlights the most crucial engineering characteristics of the underwater exploration system, with data transmission speed, video resolution, image resolution, and storage autonomy emerging as the top priorities among the 13 evaluated technical requirements.

Table 3. ROV streamlined HoQ focused on potential I4.0 technologies solutions.

USER REQUIREMENTS			**ENGINEERING CHARACTERISTICS (EC)**												
Requirements	**Priority Score**	**Normalized Priority Score**	**Data Transmission Speed**	**Video Resolution**	**Image Resolution**	**Storage Autonomy**	**Additional Ports in Surface Station**	**Sensors' Specification**	**Number of Cameras**	**Quantity of Measured Variables**	**Video Output Frequency**	**Information Storage Specifications**	**Additional Ports for Communic**	**Camera's Degrees of Freedom**	**Additional ports Available Vehicle**
To acquire images	5	0.11	9	9	9	9			9		1	1		1	
To transmit information ROV to surface	5	0.11	9	3	1			1		3					
ROV positioning	5	0.11	3												
Maneuverability	5	0.11	9	1					1	1				1	
Surface station	5	0.11	9	3	3	3	9		3	3	3	3	9		
Image quality	4	0.09	3	9	9	3					3				
To store data of variables of interest	4	0.09	3				3	9		9		9			1
To store image information	4	0.09		9	9	9	3	9			9				
To collect physical samples	3	0.07	3	9					3					3	
Protection	3	0.07	3	3				1	3					1	
Possibility of connecting own equipment	2	0.04	9				9	3		3		3	1		9
Surface station with connectivity flexibility	1	0.02					9						9		
		EC Score	4.9	3.9	3.0	2.3	1.7	1.7	1.6	1.5	1.5	1.2	1.1	0.4	0.1

6.4. Logical Decomposition

The main function of the ROV system in the case study is to collect images and samples in the ocean at depths of up to 500 m. To achieve this function, several support functions must be defined and accomplished. A logical decomposition for the ROV is shown in Figure 6. This simplification presents the following five functional groups.

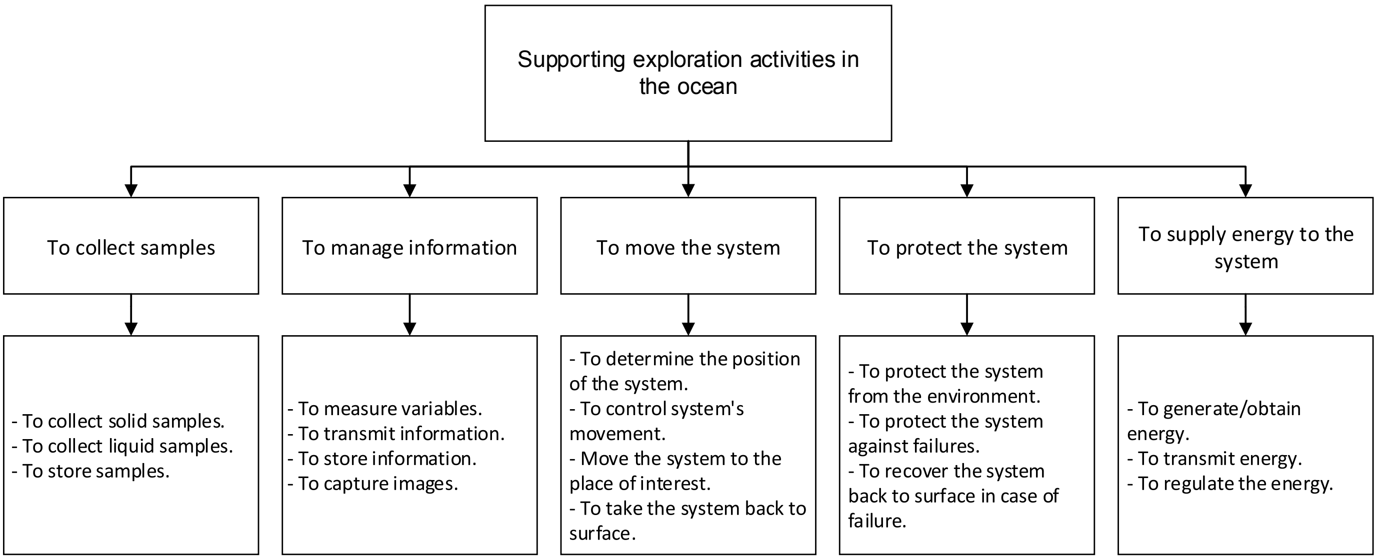

Figure 6. ROV functional decomposition.

1. To collect physical samples. This functional group is responsible for collecting and storing water samples as well as solid samples. As in any other complex system, this function is not isolated, and depends on the fulfillment of other functions to achieve its goals. It highlights the interdependent nature of system functions, relying on precise movement and data management to successfully collect and catalog samples.
2. To manage information. This function deals with all the data sent from the control room to the robot. It also manages the data generated from sensors and components and brings them to the surface. Data needs to be collected, transmitted, classified, stored, and retrieved. From the point of view of I4.0, this functional group would be the heart of the system.
3. To move the system. No meaningful sample or data can be obtained if the ROV is not located in the desired exploration area. This functional group deals with tasks related to bringing the robot into the water, as well as moving the robot through the water until it reaches the place where samples are going to be taken and back to the surface/support vessel. Determining ROV position and orientation is also a task of this functional group.
4. To protect the system. An ROV has interactions with other systems (support vessel, launch and recovery system, etc.) and with the environment (water, waves, currents, reefs, rocks, sand, etc). There are also internal failures that need to be addressed. Active and passive protection must be performed from possible damages. This functional group includes: protecting against failures, protecting from the environment, and recovering procedures if something fails.
5. To supply energy. Powering the ROV's mission, this function deals with the generation, regulation, and distribution of energy to various components. Given the diverse energy needs of the ROV's systems (from propulsion to sensors), this group is tasked with ensuring a reliable energy supply under varying operational conditions, addressing challenges such as energy efficiency and the distribution of power to optimize mission duration and capability.

The functional groups in Figure 6, and their supporting functions are not standalone; they are interconnected, illustrating the ROV's system complexity and the need for an integrated approach to its design and operation. This decomposition not only aids in understanding the system's operational framework, but also sets the stage for identifying technical requirements and addressing design challenges. In this case, guided by the principles of I4.0 for a smarter, interconnected solution.

Example: Logical Decomposition for a Lower Level Functional Group

The functional group in charge of managing data would be the backbone of an ROV. Figure 7 presents the specific functional decomposition of the functional group `to manage information`. By making this decomposition, the support functions that take the system closer to the main objective are properly identified. It means, which tasks or functions are needed for the ROV system to capture images, measure variables, transmit information, and store it.

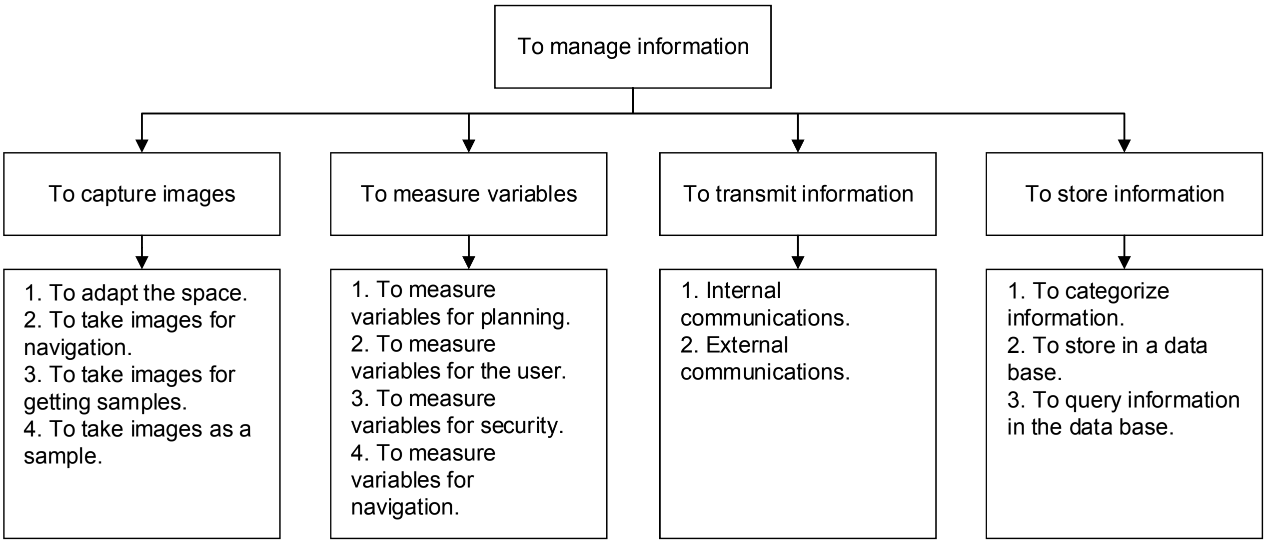

Figure 7. Specific logical decomposition of manage information functional group.

As seen in Figure 7, the `manage information` functional group is decomposed into four lower-level groups. The following brief descriptions are helpful for further conceptual analysis.

- To capture images. For this case study, images refer to both pictures and video. Images are used in several ways in ROVs. They are the main input for pilots to decide how to navigate, hence, human controllers require quality images. Images are also important to decide where to take a physical sample or which sample should be taken, in case the ROV is equipped to do so.
  For exploration missions, pictures and videos themselves are the samples, and after being captured, they will be analyzed by specialists. For instance, if studying biodiversity in some ocean area, biologists will analyze images in order to identify and catalog what was recorded.
  Finally, no image will be recorded if there is not adequate lighting. Beyond a 100-meter depth, sunlight is completely absorbed, so ROV systems need a way to adapt the environment for cameras to work.
- To measure variables. As well as with images, variables are used for several purposes. There are some variables from the vehicle and from external sources required to make decisions regarding whether or not to do an immersion or other mission planning (i.e., current speed, tides, weather, underwater visibility, etc.). Other variables are associated with samples; for instance, water temperature, dissolved oxygen (with the corresponding depth), and coordinates where the values were recorded.

Safety variables are information collected in order to monitor the vehicle itself and its surroundings in order to avoid risks or to take action in case of damage or accidents. For example, not only the ROV's depth is important, but also distance from the bottom, and monitoring if there is humidity inside sealed cases with electronics. The circuit's current and temperature are also monitored, etc. Pilots need to be checking on these values or checking on alarms in order to take proper actions.
Finally, while pilots rely mostly on real-time video to navigate, other variables may be helpful as well. For example, distance from the bottom is important to avoid colliding. ROV coordinates relative to the surface platform are required as feedback when trying to reach a specific location with the underwater vehicle.
- To transmit information. Information is collected both underwater and in the surface station, and such information is required in both sides of the system. There is even information from external sources required for the system to work. For this reason, reliable communication is required inside the vehicle and between the vehicle and the surface station, or even beyond the surface station. Some information needs to be transmitted in real or near real time (for example, navigation video, navigation variables, and safety variables, among others). Depending on the amount of information collected or the system's capabilities, information can be partially transmitted while some other is stored and analyzed after the mission.
- To store information. Given the volume of data that is generated, a strategic approach to data storage is essential. Information storage, whether onboard the ROV, at the surface station, or distributed across both, must prioritize data integrity, organization, and accessibility. This function addresses the need for comprehensive data management strategies to accommodate the extensive data collected during missions of the robotic system.

Notice how these descriptions are not focused on which specific device or strategy is going to be used. All the descriptions are centered on what needs to be done. This is part of the SE approach to functional and systemic thinking. Once this level of detail is obtained, it is easier for the engineering team to think about devices and equipment that might serve as solutions to reach the functional objective. However, before selecting specific physical components, the functions need to be well established and interrelated between them, as well as the interaction with external inputs and variables.

6.5. Integrating Functional Decomposition with I4.0 Enhancements

Functions presented in Figure 7 are a part of the set of tasks that need to be fulfilled for the ROV to perform as required by customers. The next step in the design is to establish solution alternatives for each function and to select the best ones. This section discuses possibilities obtained after performing a functional affinity analysis between functions from Figure 7 and functions from technologies described on Table 1.

At this point, we introduce one more tool to help explain the approach for I4.0 technologies in this conceptual design. The Kano Model [100] is a framework used in product development to categorize customer preferences into five main types, aiming to enhance customer satisfaction. These categories are as follows.

- Must-be Quality Attributes: basic needs that are taken for granted when met but cause dissatisfaction when missing.
- One-dimensional Quality Attributes: features that lead to satisfaction when fulfilled and dissatisfaction when not, with a proportional relationship between the level of fulfillment and customer satisfaction.
- Attractive Quality Attributes: unexpected features that significantly increase customer satisfaction without causing dissatisfaction when absent, serve as differentiators.
- Indifferent Quality Attributes: features that neither enhance nor diminish customer satisfaction.
- Reverse Quality Attributes: features that can cause dissatisfaction when present and satisfaction when absent, varying among different customer segments.

The functions in Figure 7 can be related to solutions into Kano's Must-be and One-dimensional Qualities. These categories are about what is expected by customers and also required by them explicitly. It means that these characteristics can be traced back to user requirements.

The Attractive Quality category refers to characteristics that users are not expecting in the product, probably because they do not know the technology. In the context of ROVs systems, by understanding I4.0 capabilities, the design team may find characteristics that can be implemented on new models. It is possible that customers did not require all of them, but it does not mean they are not useful or important. Attractive Quality does not necessarily include new functions to the system, but it may change the way functions are usually solved.

Section 6.4 describes the functions for functional group "To manage information". From those descriptions, it is clearly expected that ROV pilots or users will be in charge of analyzing all the information generated by the ROV system. What if, by introducing I4.0 capabilities, the ROV system can make some of the decisions, assist the pilots, or find some of the results and save some time and work for pilots and users?

This part of the work aims to discuss some alternative solutions, including I4.0 technologies. These are not traditional solutions to ROV's functions, but may be interesting Attractive Quality Attributes. Table 4 presents functions from Figure 7 with a summarized example of how they are typically solved in terms of devices/components. It also suggests ideas that may be added to those functions by taking advantage of I4.0 tools. The last column shows which user requirements may be beneficially impacted if the new approach is implemented, the numbers correspond to the requirement ID on Table 2. In this way, Table 4 connects the functional thinking from logical decomposition with the functional description of I4.0 technologies presented in Table 1 and user requirements.

As an example, let us consider surveying fish populations and coral species on deep coral reefs (depths greater than 80 m). It is expected that the ROV capture video of the area. ROV pilots are not necessarily biologists; hence, they are not able to identify what they are watching on screen. Biologists might be in the control room, but real-time video is too fast to identify all the specimens recorded. Biologists will have to take a copy of the video and analyze every second in order to obtain the expected survey. This process can take a lot of time, and the survey will be finished only after the expedition has already ended. What if the ROV is equipped with an AI image recognition model which can generate the survey in real or near real time? This would be an improved solution to the requirements of storing data of variables of interest and storing image information (Req. IDs 4 and 7).

Another example can be related to automatic lighting. ROV pilots have the task of regulating the ROV lights in order to allow the cameras to record when ambient light is not enough. However, pilots' perception of lightning may not be the best for the cameras. The ROV could be equipped with a smart lighting system trained to improve lighting for videos and images. This may work based on IoT tools and a photography-trained AI. This would be beneficial for collecting physical samples, acquiring images, image quality, ROV positioning, and even maneuverability (Req. IDs 1, 2, 3, 8, and 10).

From the functions described, it is also viable to see an ROV as a source of data from different origin (video, pictures, sensor values, digital data, weather reports, coordinates, etc.) and in structured, semi-structured, and non-structured formats. Since missions can last hours, and an expedition may include several missions, an ROV may become a source of data with Big Data characteristics: velocity, volume, value, variety, and veracity. From this point of view, it makes sense to take advantage of already existing Big Data tools to manage the information. Requirements 4 and 7 would be impacted by this approach.

Table 4. Conceptual improvements for the ROV system by including I4.0 capabilities

Subfunction	**Standard Solution**	**Ideas from I4.0 to Replace or Improve Standard Solution**	**Impacted Requirement (Req. ID)**
To adapt the space	Underwater lights (led, laser, etc)	Smart lights, IoT, AI	1, 2, 3, 8, 10
To take images for navigation	Waterproof cameras	AI for obstacle alarms to pilot. VR tools for better feedback to pilots	8, 10
To take images for getting samples	Waterproof cameras	AI for image recognition of potential physical samples	1
To take images as samples	Waterproof cameras	AI for image recognition and classification (depending on the mission)	2, 3
To measure variables for planning	Weather radars (rain, winds, surges, ocean currents), probes and sensors	Integration of various sensors with data analysis capabilities. IoT and Big Data	6, 8, 9
To measure variables for the user	Sensors (depth, axial speeds, ROV position)	User-friendly interfaces for real-time data monitoring	4, 5
To measure variables for safety	Sensors for circuit current/overcurrent (breaker, fuse), temperature sensor, humidity sensor in sealed compartments	IoT sensing and controlling internal safety conditions	5, 9
To measure variables for navigation	Sonar system (distance to seabed, depth, coordinates, position with respect to the reference)	AI-based navigation systems for optimized route planning. VR tools for better feedback to pilots.	1, 2, 8, 10
External communications	Tether cable to surface station	Satellite communications for global data transmission from surface station. IoT.	5, 6
To categorize information	Manually classifying information, programmed classifying scripts	Automated data categorization and indexing systems. AI and ML	4, 7
To store in a database	Database on internal hard-drive on ROV	Cloud storage with access from different locations	4, 7
To query information in a database	Database query software	Advanced query processing algorithms for quick retrieval. Big Data tools	4, 5

The objective of this study case, which focuses on one functional group of an ROV system, was to show a path for stating divergent solutions inspired by the possibilities provided by I4.0 tools. This path is well structured by using SE concepts and tools that can be used not only for ROVs, but also for other complex systems under development.

As described, the next step in the design would be to establish solution alternatives for each function and to select the best ones. This would be part of a divergence and convergence process included in the design solution definition stage. Even with I4.0 technologies suggested to improve some of the ROV functions, there will be several alternatives for implementation (hardware and components alternatives and brands, service providers, software platforms, etc). Selecting components and providers is outside of the scope of this study case.

6.6. ROV Development Previous Experience

The underwater robotic system whose development inspired the proposed methodology is an ROV designed to operate at depths of up to 500 m and to advance marine technology development in Colombia. Aristizábal et al. [96] demonstrated the use of SE as a highly effective tool for developing marine vehicles and projects requiring modular hardware architectures. This approach involved the design, construction, and integration of the hardware components for the ROV, based on the vehicle's functional division. Subsequently, Zuluaga et al. [97] addressed the development of a flexible and modular software architecture using SE principles, considering functional division during the design process to facilitate the integration of components and subsystems. Figures 8 and 9 show the result of stages corresponding to system integration and verification and system validation for the ROV, as depicted in the V model (Figure 1).

The proposed conceptual design methodology presented in this work was created after we were challenged to conceptualize a complex system involving I4.0 technologies. For this reason, the methodology was build upon these experiences which were both beneficial and challenging. The main benefits were the experience with SE tools and familiarity with the ROV contexts, and the main challenge was to understand new to the team technologies and avoiding design fixation.

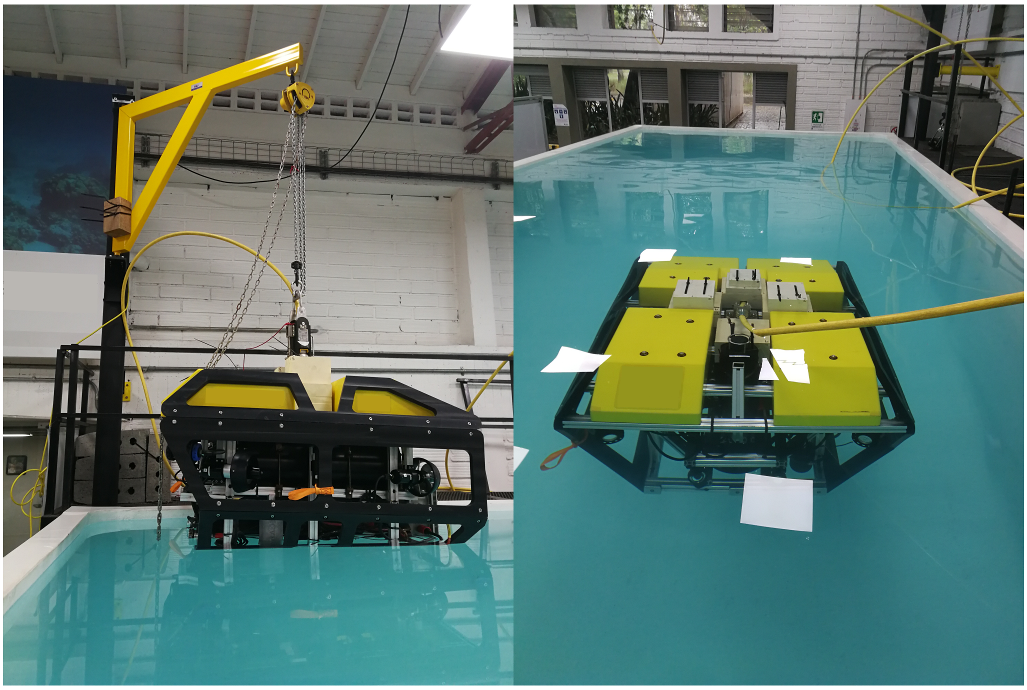

Figure 8. ROV system integration and verification during lab tests.

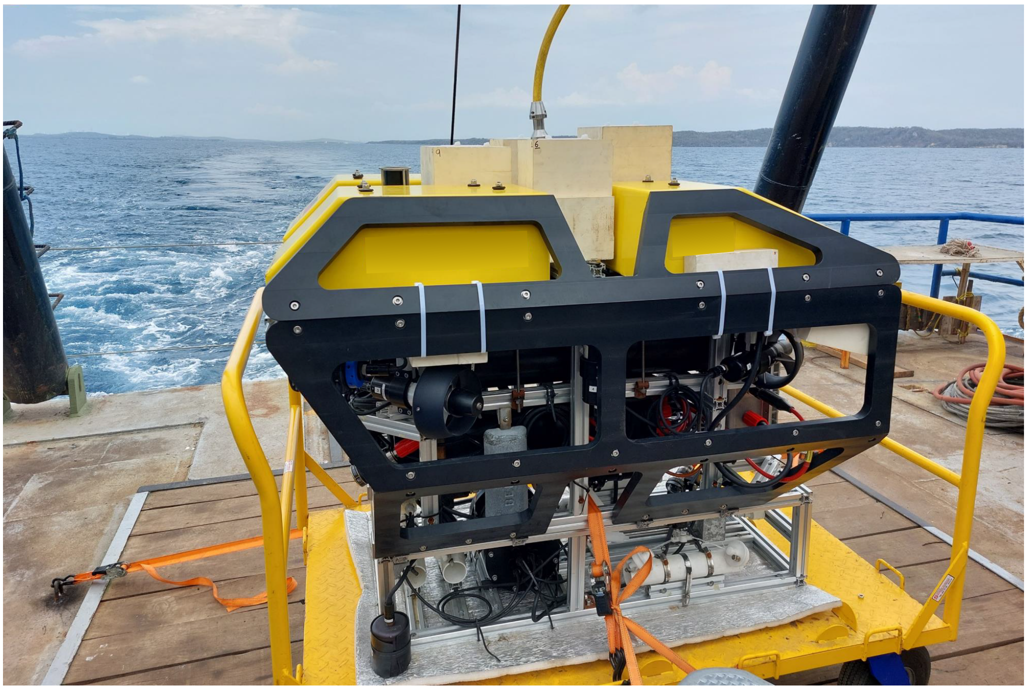

Figure 9. ROV system validation during seatrials.

7. Discussion

The integration of SE with I4.0 technologies is a tool for innovation. In this case, by adopting a functional-oriented view of technology integration, ROVs that are potentially more effective, efficient, and adaptable to the complex demands of underwater missions are conceptualized. However, we only approached one of the functional groups from Figure 6; this means there is still room for more conceptual improvements and ideas to be explored by using the same approach.

Through the study, it has been illustrated how ROVs can be transformed by I4.0 technologies, specifically through the integration of AI for real-time data analysis and autonomous decision-making. This is a departure from traditional ROVs that primarily rely on direct human control. The smart integration of IoT and Big Data analytics into ROVs can lead to improved operational autonomy, enabling these vehicles to perform high-precision tasks with greater reliability and less human intervention. The approach not only aligns with the evolving demands of underwater exploration and monitoring, but also sets lines for future research in marine technology.

A challenge faced by this transformation was design fixation. Even by following SE's framework, some designers were more comfortable proposing solutions they had already worked with (for example, when they designed the ROV system). In order to avoid this, the idea of a tool to connect "anonymous" solutions with functions to solve was proposed. This was the origin of the proposed functional affinity analysis (FAA). This approach also helped to overcome the problem of the I4.0 technology-centric approach, often leading to a disconnection between the tools developed and the actual needs of the user. The tendency to impose or sell technologies without a complete understanding of user requirements must be avoided. This study addresses such challenges by advocating for a user-centered design paradigm, which ensures that technology integration aligns closely with user requirements and enhances system usability.

The integration of SE with I4.0 technologies provides a powerful framework for addressing the complex demands of modern engineering projects. This study demonstrates the practical application of design theories within a real-world case study, showcasing how SE can be adapted to develop advanced robotic systems. By focusing on stakeholder needs and functional requirements, the SE approach ensures that all aspects of the design process are comprehensively addressed, providing a robust methodology for managing complexity.

The incorporation of I4.0 technologies, such as IoT, AI, and Big Data, into the ROV design significantly enhances the system's capabilities. These technologies enable real-time data processing, autonomous decision-making, and improved operational efficiency, illustrating the transformative potential of I4.0 tools. This integration not only aligns with current trends in industrial design but also sets the stage for future advancements in robotic systems and other complex engineering projects.

Managing the complexity of the ROV design required a structured approach that decomposed the system into manageable subsystems. SE methodologies provided the necessary tools to coordinate the development of these subsystems, ensuring seamless integration and functionality. This approach can be applied to other complex engineering projects, demonstrating the versatility and effectiveness of SE in managing complexity.

Future research should explore the integration of additional I4.0 technologies and further refine the methodologies used in this study. Potential areas for investigation include the application of advanced AI algorithms for autonomous navigation and decision-making, the use of blockchain for secure data management, and the development of more sophisticated IoT networks for enhanced connectivity.

The concept of User-Centered Design prioritizes the end user's needs, challenging the notion that technology should dictate user behavior [101]. Rather, technology should seamlessly integrate into users' lives by addressing their specific requirements. The emphasis is not solely on adopting the latest trend but on configuring, personalizing, improving, or creating solutions that align with the users' needs and preferences. Table 4, which connects functions, solutions, suggested functional improvements, and user requirements, makes explicit the User-Centered Design approach in this study case.

Moreover, the emerging concept of Society 5.0 offers a corrective to the shortcomings of I4.0. In this paradigm, the technologies pioneered by I4.0 are harnessed with a clear focus on serving humanity [1,102,103]. Society 5.0 envisions a convergence of these innovations to enhance the quality of life for individuals. It represents a paradigm shift where technology, rather than being an end in itself, becomes a means to execute tasks that directly address and fulfill the diverse needs of people.

This work provides an example of how I4.0 technologies can be integrated into complex systems, like ROVs, while still focusing on user requirements. In this way, this research underscores how SE, a mature and robust platform, can facilitate the transition and support the realization of Industry 5.0 by integrating complex systems more thoughtfully and sustainably.

The conceptual design exercise presented also aligns with the INCOSE SE Vision 2035 [104], with ideas like the emphasis on integrating advanced technologies and adopting a holistic, stakeholder-focused approach to SE. Vision 2035 envisions a future where SE leads in the development and integration of complex systems, enhancing their functionality and adaptability to meet changing requirements and environments.

Additionally, INCOSE highlights the importance of sustainable and human-centric design approaches. United Nations' Sustainable Development Goals and the Society 5.0 concept are actually explicit referents for SE Vision 2035. This reflects a call for systems engineers to be leaders in technological development and integration while remaining aware of the societal and environmental impacts of their designs. In other words, to keep developing technology focused on humanity's challenges and needs.

An important limitation of the presented work is that the case study only addressed one out of five main functional groups presented in Figure 6. A full conceptual design will have to analyze all functional groups and each of their sub-functions. This gives an idea of the amount of work required for just the conceptual design of a complex system and the involvement of new technologies in the development process. After a full conceptual design, the design solution definition and product realization process should be implemented in order to achieve the complete ROV development. Those design stages are necessary to deal with potential challenges, limitations, and mitigation strategies. This includes addressing technological readiness, cost implications, operational risks, and any potential resistance to adopting new technologies.

8. Conclusions

This paper addressed the conceptual design stage of an underwater robotic exploration system using SE. The process, divided into three steps—stakeholder expectations, requirements definition, and logical decomposition—emphasized a system and function-centered methodology that prioritizes user requirements. By applying SE principles, we demonstrated how traditional design methodologies can be adapted to modern engineering challenges present in I4.0 developments. This case study highlights the integration of stakeholder needs into the design process, translating theoretical concepts into practical, actionable strategies and ensuring comprehensive coverage of all functional requirements. This structured approach underscores the value of SE in fostering innovation and efficiency in complex system development, particularly within the context of I4.0.

This approach aligns with current engineering trends and demonstrates the potential of I4.0 technologies to revolutionize traditional systems by fostering continuous improvement and connectivity. The complexity inherent in designing the ROV, as a complex robotic system part of I4.0 technologies, was managed through the application of SE principles, decomposing the system into functional groups and systematically addressing each aspect. This structured approach ensured a coherent and manageable design process, despite the high complexity involved. By connecting the robotic system's conceptual design with I4.0 capabilities, we provided a range of possibilities for improving the ROV's performance, oriented towards enhancing user experience in the final system. This case study serves as a reference for integrating digital innovations with conventional engineering practices, offering insights applicable to similar advanced exploration systems.

The proposed methodology has been generated after development of an ROV designed to operate at depths of up to 500 m, where the effective application of SE for advancing marine technology in Colombia was demonstrated. The challenge of conceptualize a new system taking advantage of I4.0 technologies generated the opportunity to created a simple but effective methodological tool, called FAA, in order to overcome design fixation and improve the opportunities of integrating advanced technologies without loosing focus on system functions and customer requirements.

The presented structured approach for proposing divergent solutions inspired by I4.0 tools, using SE concepts applicable to both ROVs and other complex systems. Consequently, SE remains central to advancing technologies, aligning with Industry 5.0 objectives and supported by the INCOSE SE Vision 2035, which underscores these methodologies as foundational for future societal advancements. By offering a case study that integrates I4.0 technologies and emphasizes the importance of understanding their functions before implementation, the research highlights SE's role in designing sophisticated, user-focused systems. Ultimately, this study aims to enrich the dialogue on SE in the digital era, providing adaptable insights and ideas for various high-tech fields.

Author Contributions: Conceptualization, J.A.R.-C., E.A.T. and R.E.V.; methodology, E.A.T. and R.E.V.; validation, J.A.R.-C., J.S.-P. and R.E.V.; formal analysis, E.A.T. and E.P.-G.; investigation, J.A.R.-C., E.A.T., E.P.-G., C.A.E., J.S.-P. and R.E.V. writing—original draft preparation, E.A.T., E.P.-G., C.A.E., J.S.-P. and R.E.V.; writing—review and editing, J.S.-P. and R.E.V.; supervision, J.A.R.-C., J.S.-P. and R.E.V. All authors have read and agreed to the published version of the manuscript.

Funding: This work was developed with the funding of the Universidad Pontificia Bolivariana (UPB) and with the support of the Universidad Nacional de Colombia in association with Contraloría General de la República in the frame of contracts CGR-373-2023 and CGR-379-2023.

Data Availability Statement: Data are available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
EC	Engineering Characteristics
FAA	Functional Affinity Analysis
FNT	Function of New Technologies
FtS	Functions to Solve
HoQ	House of Quality
INCOSE	International Council on Systems Engineering
I4.0	Industry 4.0
IoT	Internet of things (IoT)
ML	Machine Learning
NASA	National Aeronautics and Space Administration
QFD	Quality Function Deployment
ROV	Remotely Operated Vehicle
SE	Systems Engineering
UCD	User-Centered Design
UGV	Unmanned Ground Vehicles
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial Systems

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