In this work, the Quality Function Deployment (QFD) and Failure Mode and Effects Analysis (FMEA) methodology based on the "Design for X" concept is studied to define the design criteria of the mechanical characteristics of an EOD robot and validated with a virtual prototype of an Explosive Ordnance Disposal (EOD) robot. The objective is the application of this methodology to obtain a product that meets the quality and reliability specifications, considering the user's needs as input data. To validate this methodology, the technicians of the UDEX (Explosive Ordnance Disposal Unit), the mechanical characteristics of the previous version JVC 0.2 developed by the research team of the National University of San Agustin (UNSA), the minimum specifications of the robots participating in the League of Rescue Robots and the application to work in real environments were taken as a case study. The results indicate that the application of the proposed methodology has significantly improved the quality and reliability of the design. To validate the effectiveness of this methodology, a virtual prototype, called JVC 0.3, was created using SolidWorks modelling software, a significant weight reduction of 27.13 % was achieved and the operating speed was increased to 1 km/h under optimal conditions. Technical analysis of the JVC 0.3 showed significant improvements in several key areas, such as increased modularity for easier assembly and maintenance, decreased overall weight, increased torque and speed, and increased stability during operation. These factors are essential for the practical application of EOD robots in real field operations carried out by specialized units such as UDEX

***Keywords:** quality function deployment, failure mode and effects analysis, explosive, robot*

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APPLICATION OF QFD AND FMEA METHODOLOGIES FOR THE DEVELOPMENT AND IMPROVEMENT OF AN EXPLOSIVE ORDNANCE DISPOSAL ROBOT DESIGN

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1. Introduction

In the twenty-first century, explosive ordnance attacks continue to cause numerous casualties and economic losses; in the United States, there have been more than 400 bombings and the most significant car bomb explosion in 25 years. Moreover, in Latin America, there have been numerous attacks in which many civilians and technicians specialized in deactivating these devices have been affected. There were also numerous explosive device attacks in Peru between 1980 and 2000 by terrorist groups such as the Tupac Amaru Revolutionary Movement (MRTA) and the Shining Path (SL). In response to these events, the authorities created the Explosive Ordnance Disposal Unit (UDEX), which, in cooperation with the Peruvian armed forces, managed to eradicate these terrorist groups and, therefore, also the attacks. However, in the last ten years, attacks have continued to be recorded in different parts of the country [1], so there is still a clear need for support for the Explosive Ordnance Disposal Units.

Considering this situation, robotics has significantly advanced explosive ordnance disposal. Commercial EOD (Explosive Ordnance Disposal) robots have technological capabilities

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that allow them to optimally perform explosive ordnance disposal operations in complex environments. One of the benchmarks in terms of technological development is the Rescue Robot League (RRL) competition. Various mechanical features equip these robots, allowing them to overcome the harsh environments they encounter. Their structure consists of an Unmanned Ground Vehicle (UGV) system, manipulator arm, and gripper, which is very similar to the structure of EOD robots. Several studies support the importance of developing cost-effective EOD robots. For example, the development of a low-cost EOD robot using off-the-shelf parts was described, providing a cost-effective solution for explosive ordnance disposal in resource-constrained environments [2]. In a follow-up study, the results of performance testing of this robot were presented, identifying potential improvements and revisions needed to enhance its operational effectiveness [3]. Meanwhile, the design challenges of the SMR-100 expert robot, a system designed to neutralize explosives, were explored, with particular emphasis on the complexities of the neutralization process in hostile environments [4]. Similarly, the traction characteristics of a track-based EOD robot were evaluated, highlighting the importance of mobility in difficult terrain [5]. Focus was placed on the TEODOR robot, a semi-autonomous system for search, rescue and demining operations, which demonstrated high adaptability in diverse operational scenarios [6]. Finally, the influence of the stiffness of a robotic arm on its accuracy during EOD operations was investigated, highlighting the crucial role of the manipulator mechanics in ensuring safe and effective handling of explosives [7].

To have its own EOD robot, the UDEX requirements for the design of EOD robots were collected in Peru [1], with the first iteration being the JVC 0.1 EOD robot [8]. This version features a rigid locomotion system in the form of a caterpillar of catarinas and chains, a manipulator arm with 4 degrees of freedom (DoF), and a 3-fingered gripper, which in tests showed mechanical problems with the temperature control and handling system when gripping asymmetrical objects, as well as a high weight (155 kg), making transportation and energy consumption difficult. The project continued with a second version, JVC 0.2. This upgrade features a flexible track movement system manufactured using the vulcanization process and a 5 DoF (degrees of freedom) manipulator arm with a 2-finger grip end. In tests, the robot outperformed its predecessor in handling asymmetrical objects and moving on more challenging terrain (stairs and inclines of 30°). However, mechanical problems with moving tracks, slope instability, and the high weight (115 kg) still make handling difficult. The lack of a design methodology leads to user dissatisfaction because designers do not optimally design these robots for local EOD operations.

In the last ten years, the "Design for X" concept has been used for competitive product development in various industries [9], such as industrial robotics [10, 11]. The Quality Function Deployment (QFD) for Design for Quality (DfQ) is one of the tools used to identify customer needs and expectations, both external and internal, prioritizes the satisfaction of these expectations according to their importance [9], and is complemented by Design for Reliability (DfC) using Failure Mode and Effects Analysis (FMEA), which serves to anticipate and identify failures that may arise in the process of creating a product or system [12]. It has been used directly for practical analysis and product design validation in explosive manipulators [13]. In addition to demonstrating reliability in developing mechanical systems [14–17]. Publications [9–17] support the relevance of this study by demonstrating the successful application of QFD and FMEA methodologies in a wide range of fields, including industrial robotics and mechanical systems development. Reference [9] explains the use of QFD to ensure that customer requirements are fully captured and prioritized, while references [12, 13] show how FMEA has been used to preemptively identify and address failure modes in robotic systems, especially in hazardous applications such as explosive ordnance disposal. Furthermore, [14–17] validate the reliability of these methodologies in the production of highly robust mechanical systems operating under extreme conditions, reinforcing the relevance and applicability of this research to the design of EOD robots for UDEX. Taken together, these studies highlight the value of applying the "Design for X" approach in the development of reliable, high-performance systems.

Therefore, research on the development of a virtual prototype through the application of EOD robot methodologies is highly relevant, as it addresses critical operational challenges for context- and environment-specific applications. The integration of methodologies such as QFD and FMEA, within the framework of "Design for X", not only improves the quality and reliability of these systems, but also sets a new standard for innovation in this field. These studies are essential to advance the capabilities of EOD robots, ensuring that future designs are more efficient, reliable and tailored to the specific needs of UDEX operators in high-risk scenarios.

2. Literature review and problem statement

The success of the QFD methodology lies in its ability to closely align product design with customer requirements, which is a critical factor in business-to-business (B2B) environments where product quality and function determine market success [18]. Applied to robotics, QFD has proven effective in industrial contexts, such as in the selection of robots for manufacturing environments, where efficiency and cost-effectiveness are paramount [19]. The methodology has also succeeded in developing specialized robots, such as in-plant nursing robots, where QFD was used to systematically translate user requirements into design parameters that ensure reliability and minimal environmental impact [20]. In the medical field, the integration of QFD with FAHP has led to innovative designs of intelligent delivery robots that not only meet user demands but also improve distribution efficiency [21]. Similarly, in marine research, QFD has been used to systematically incorporate user requirements into the design of autonomous underwater robots, ensuring that they meet critical operational needs [22]. However, the QFD methodology has not yet been directly applied to the design of EOD robots; although it was used for industrial robots, these are poorly suited for explosives or EOD handling [23], suggesting the desirability of conducting a study focused on the customization of these robots, applying such methodology.

On the other hand, the Rescue Robot League (RRL) competitions are a worldwide reference for the development of search and rescue robots, as their prototypes are designed to meet the demanding requirements for maneuverability, dexterity, exploration, and mobility established in the RRL rules developed by the U.S. Department of Homeland Security (DHS S&T) and the National Institute of Standards and Technology (NIST). Although several EOD robots, such as iRAP, Nexis R-5, HURRICAN, and SHINOBI FUHGA3, were designed following the strict rules stipulated in the RoboCup Rescue Rulebook and NIST standards, significant challenges persisted. For example, although the Nexis R-5 managed to excel in mobility in various environments, it did not achieve adequate speed, which was a critical factor for its continuous improvement in subsequent competitions [24]. For its part, the SHINOBI FUHGA3 experienced advances in speed and weight reduction but had deficiencies in its grip system that compromised essential safety aspects for users [25]. These outstanding issues suggest that, despite compliance with international standards, specific optimization needs remain to improve the overall performance of these robots and adapt them to local operational realities. Although these developments provide a solid foundation, optimization tends to be based on general standards rather than considering regional specificity.

Due to its focus on user requirements, the QFD methodology has been successfully applied to a variety of applications, including industrial robots. However, while the Rescue Robotics League (RRL) competition sets high standards, it often overlooks regional features critical to optimizing robot performance. Applying QFD research in diverse contexts could ensure that EOD robots are better adapted to local needs and improve their functionality, efficiency and safety.

3. The aim and objectives of the study

The aim of this study is to develop an optimized design methodology for explosive ordnance disposal (EOD) robots that ensures both high quality performance and reliability under various operating conditions. This will be achieved by integrating Quality Function Deployment (QFD) to systematically capture and prioritize user needs, and Failure Mode and Effects Analysis (FMEA) to mitigate potential risks and improve robot safety and reliability. From a scientific standpoint, this study will identify key technical requirements and failure modes specific to EOD robots, addressing gaps in current designs, which often fail to adapt to regional operational challenges. The practical outcome will be an improved methodology that can be applied on a global scale, improving the overall performance and adaptability of EOD robots to meet local demands and improve operational efficiency.

This methodology will be tested and validated through a case study involving the optimization of the JVC 0.2 model, developed by UNSA and UDEX Arequipa, and compared to internationally recognized rescue robots.

To achieve this aim, the following objectives are accomplished:

– to analyze and collect the UDEX user requirements for the design of EOD robots in Peru and apply the QFD methodology to identify and prioritize these needs and translate them into technical specifications;

– to create a virtual prototype of the JVC 0.3 to validate the methodology and evaluate characteristics such as modularity, weight, torque, speed, and stability;

– to use the FMEA to anticipate and identify potential failures in creating the EOD robot;

– to compare the theoretical performance of the JVC 0.3 with the previous version, JVC 0.2, to verify improvements in quality and reliability.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the optimization of an explosive ordnance disposal (EOD) robot, specifically the JVC 0.2 model, with the objective of improving its adaptability to local operating conditions, reliability and ease of use. The main hypothesis is that the application of Quality Function Deployment (QFD) and Failure Modal Effects Analysis (FMEA) methodologies will significantly improve robot performance by aligning its design more closely with user requirements and identifying potential failure modes early in the development process.

Several assumptions have been made in this study, including that the main operational challenges faced by EOD robots in Peru are consistent with those identified in other regions, particularly in terms of terrain navigation and the need for robust handling systems. In addition, the study assumes that virtual prototyping will provide an accurate representation of the robot's real-world performance.

To simplify the analysis, some design factors, such as extreme environmental conditions (e.g., high humidity, extreme heat), were not considered in detail, focusing instead on the structural and mechanical performance of the robot under typical operating conditions. In addition, some aspects, such as operator training and interface design, were outside the scope of this work.

4. 2. Methodology for explosive ordnance disposal robot design

In this chapter, a methodological framework based on the "Design for X" concept is presented to obtain a high-quality (QFD) and reliable (FMEA) product. Applying a methodology in product development offers several significant advantages, as it allows for understanding user requirements through a structured and organized approach. In addition, it improves the alignment between customer expectations and product features by effectively translating these requirements into design specifications. This methodology is divided into three phases, as shown in Fig. 1: requirements analysis, conceptual design, and validation with a virtual prototype.

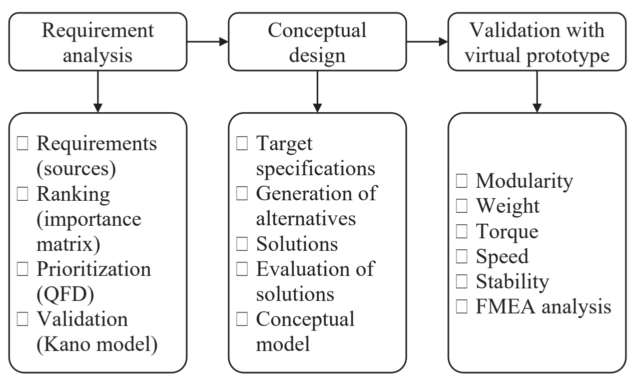

Fig. 1. Comprehensive methodology for explosive ordnance disposal robot design based on design for X

In phase 1 of the requirements analysis, requirements information was collected. Then, this information was categorized using an importance matrix and moved to the double QFD iteration (product and components). Finally, specific features and attributes were identified using the Kano model.

The importance matrix is a critical tool in the quality function deployment (QFD) process, and it is used to prioritize customer requirements based on their relative significance. By assigning weights to each customer need, the matrix ensures that the development efforts focus on the features that will substantially impact customer satisfaction. The requirements are placed in a double-entry table, row, and column and then ranked as follows: If the requirement in the row is less than, equal to, or greater than the one in the column, it is scored (0), (1) and (2) respectively.

Quality Function Deployment (QFD) is a systematic methodology used in the product development process to translate customer requirements into specific, measurable technical specifications. The primary goal of QFD is to ensure that the final product aligns closely with the needs and expectations of the end-users, thereby maximizing customer satisfaction and reducing the risk of product failure. QFD begins by identifying and gathering detailed customer requirements, often referred to as the "voice of the customer". These requirements are then organized and prioritized in a structured format, typically using a tool known as the House of Quality (HoQ). The HoQ is a matrix that links customer needs to the engineering characteristics of the product. This linkage allows the design team to systematically evaluate how well the product will meet the customer's expectations and to identify any trade-offs that might be necessary during the design process.

Kano model, his method allows to validate the characteristics obtained from the two iterations of QFD. This method classifies the characteristics or attributes according to the satisfaction of the user as follows:

– mandatory (O) are the minimum needs that, if absent, cause great dissatisfaction but do not increase satisfaction if they are present;

– one-dimensional (U), they are valued positively, and the more these attributes are found in the products, the better acceptance they will have;

– attractiveness (A) is an unexpected characteristic that positively surprises and increases satisfaction;

– the indifferent (I), irrelevant and expendable, do not influence satisfaction. Inverts (INVs) are perceived as unfavorable and reduce satisfaction by increasing their presence.

A questionnaire is developed with functional and non-functional questions for these characteristics. The answers are categorized in Table 1:

1) I dislike and don't tolerate:
2) I don't like, but I tolerate;
3) I don't mind;
4) It's essential;
5) I like.

The users complete these forms, and the results are averaged to determine if the trait is one-dimensional (U), attractive (A), mandatory (O), indifferent (I), inverse (INV), or doubtful (D).

Table 1

Attribute evaluation with kano model

Attribute	I like	It's essential	I don't mind	I don't like, but I tolerate	I dislike and don't tolerate
I like	D	A	A	A	U
It's essential	INV	I	I	I	O
I don't mind	INV	I	I	I	O
I don't like, but I tolerate	INV	I	I	I	O
I dislike and don't tolerate	INV	INV	INV	INV	D

In phase 2 of the conceptual design, a morphological matrix, as shown in Table 2, was used to generate solutions considering the objective characteristics that emerged from the requirement analysis. These solutions were evaluated using a scoring procedure. A virtual conceptual model of the prototype was then developed using SolidWorks for the Arequipa Region. This advanced design software facilitates the evaluation of results, such as the weight, dimensions, and drawings required for manufacturing. This 3D model also allowed the robot's modular design to be optimized by selecting commercially available components from the local market. In addition, SolidWorks provided tools for the part-stress simulation and motion analysis, which are crucial elements for ensuring the feasibility and efficiency of the final design.

Table 2

Morphological matrix, example

Module	Feature or function	Tools		
UGV System	Locomotion system	Track	Wheels	Legs
+	+	+	+	+

The solutions are evaluated and classified based on the technical criteria. The relative weighting of each criterion was determined as follows: whether the criterion in the row is less (0), equal (1), or more (2) important than the criterion in the column. The solutions are compared between rows and columns using the same procedure as above.

In phase 3, the methodology was validated by verifying the virtual prototype. The model was subjected to a series of evaluations for modularity, weight estimation, required torque, speed, and stability. Finally, potential failures were analyzed using an FMEA matrix to assess its reliability.

A free body diagram (FCD) was used to determine the required torque, representing the forces and torques acting on the robot in a critical situation, such as an inclined surface. This approach allows to analyze the dynamic conditions of the robot under specific constraints using the following equations:

$$V_t = \frac{\pi * n * D}{60}, \tag{1}$$

$$T = \frac{m * g * D * \left(\mu * \cos(\theta) - \operatorname{sen}(\theta)\right)}{2}, \tag{2}$$

$$P = \frac{\pi * n * T}{30}, \tag{3}$$

when:

– V_t is the tangential velocity;
– T is the torque;
– P is the power;
– n is the rotational speed;
– D is the wheel diameter;
– m is the mass of the EOD Robot;
– g is the acceleration due to gravity;
– c is the coefficient of friction;
– θ is the incline angle.

Finally, Failure Mode and Effects Analysis (FMEA) is a systematic methodology used to identify, assess, and mitigate potential failure modes within a product or process. By analyzing each possible failure mode, FMEA helps prioritize risks based on their severity, occurrence, and detectability, allowing teams to implement corrective actions to prevent or reduce the impact of these failures. The use of FMEA is crucial for enhancing the reliability and safety of a product, as it proactively addresses potential issues before they occur.

This methodology is particularly important in complex projects where the consequences of failure can be significant, ensuring that risks are managed effectively and that the product meets high standards of quality and performance.

4. 3. Case study: JVC robot – UDEX

To illustrate this methodology, the Explosive Ordnance Disposal Unit (UDEX) in Arequipa serves as a relevant case study. The UDEX is responsible for the identification, neutralization and disposal of explosive ordnance, a critical task to ensure public safety in urban and rural areas where unexploded ordnance poses a risk. In this case, QFD and FMEA methodologies were applied to design a robot specifically adapted to the geographical and operational conditions of the region.

The first prototype, "JVC 0.1", was evaluated using the FMEA matrix, revealing several critical shortcomings. These included difficulties in moving over sloping terrain, problems with the ability of the three-finger gripper to grasp explosive ordnance, and the high weight of the robot, which required six people to mobilize it [8]. These problems underscored the need to redesign the robot to improve its functionality and efficiency. As a result, a second version, "JVC-02" [26], was developed in 2022, incorporating improvements such as a flexible trapezoidal rail system, a manipulator arm with six degrees of freedom, and a two-finger gripper.

However, new technical challenges arose in this second version. Although the robot's movement on inclined terrain improved, there were mechanical failures in the motor joints on steep slopes. The gripper, with an additional degree of freedom that allowed it to rotate 360°, worked well for most tasks, but failed and stalled at maximum extension. In addition, the robot's tempering system was still robust but complicated maintenance of the tracks, and its weight still required four people to transport. The robot is teleoperated to keep operators at a safe distance, but there were problems with image and video transmission.

This case exemplifies the application of QFD and FMEA methodologies to address the specific challenges faced by the UDEX Arequipa, while demonstrating the broader applicability of these methodologies to similar EOD robots around the world. The iterative design process and attention to local operational needs highlight how these tools can be used to refine and improve robot designs in diverse regions with differing requirements.

5. Results of research on the design and validation of an explosive ordnance disposal robot using quality function deployment and failure mode and effect analysis methodologies

5. 1. Requirements analysis and application of quality function deployment for explosive ordnance disposal robot design

From the specifications of the Rescue Robot League, at least 6 degrees of freedom are required for precise positioning and orientation. The payload ranges from 1 to 15 kg, the average arm length is 1.2 m, and the weight ranges from 35 to 77.5 kg. Chain-based movement ensures stability on rough terrain. Construction materials such as aluminum alloys and carbon for strength and lightness make up the basic criteria. In addition, manufacturing costs range from 23,000 EUR to €60,000 EUR, offering a relevant economic perspective. As a second source there are the results of the FMEA analysis performed in the previous study it follows that the latest version, JVC-0.2, still requires improvements. The most critical points include that the weight of 115 kg should ideally be reduced to less than 77 kg. The second point is the motors, which have enough torque for movement, but the travel speed is deficient (10 to 11 cm/s). And finally, a form was developed for UDEX technicians asking them about the minimum requirements of the new robot. 80 % of technicians had more than 5 years of experience and 50 % of respondents had already used an EOD robot. This gives certainty about the quality of their answers. In an interview, they also gave information about recent cases, the type of explosive, the place of use, the safety distance during use, the deactivation method, etc. This information complements the real needs of the users (UDEX technicians).

Based on the above, it can be summarized that the needs of users can be divided into 7 main features as shown below:

1. Lightweight refers to the total weight of the EOD robot; in the previous version (JVC-0.2), it was 115 kg, but it is proposed to reduce this value to 77.5 kg, as with similar robots in the RRL.
2. Speed: this refers to the robot's speed of travel. In the previous version (JVC-0.2), this depended on the locomotion motors, which had enough torque, but the travel speed was very low (10 to 11 cm/s). It is recommended that it be 27.78 cm/s or 1 km/h, as in similar EOD robots.
3. Ergonomics: this refers to the ease of movement of the EOD robot by UDEX agents without causing them injury. To perform this action, the previous version (JVC-0.2) had handles on the top of the chassis, but this position combined with the robot's weight (115 kg) caused injuries to the UDEX agents.
4. Safety: this refers to the reliability of transporting the explosive device without being unintentionally released and detonated. The previous version (JVC-0.2) had a gripper, but the wrist rotation was not mechanically locked, so the explosive device had unpredictable movements and was susceptible to detachment. This was compounded by the impact of the tracks when ascending and descending slopes or uneven terrain.
5. Ease of maintenance refers to obtaining spare parts and maintaining the EOD robot. In the previous version (JVC-0.2), the robot was built with locally available components and had a skeletal structure that made it easy to maintain.
6. Autonomy: this refers to the operating time of the EOD robot, which was 1 hour for EOD operations in the previous version (JVC-0.2).
7. Maneuverability refers to the robot's ability to move over rough terrain continuously. The previous version (JVC-0.2) could move linearly on flat ground and stairs up to an angle of 30°, but if to turn on this terrain or over a 30° slope, the robot's movement system got jammed.

The UDEX technicians and the research team scored them on the importance matrix. The results were averaged and are shown in Fig. 2, where safety is shown in the foreground, followed by weight and rank. These results were entered into the QFD with their respective relative weighting in the user requirements column.

The seven user requirements, lightweight, fast, ergonomic, safe, easy to maintain, autonomous, and maneuverable, are the input data of the first iteration of the QFD-Product. This method attempts to convert the user's requirements into technical or design features that solve them overall for the product as a whole.

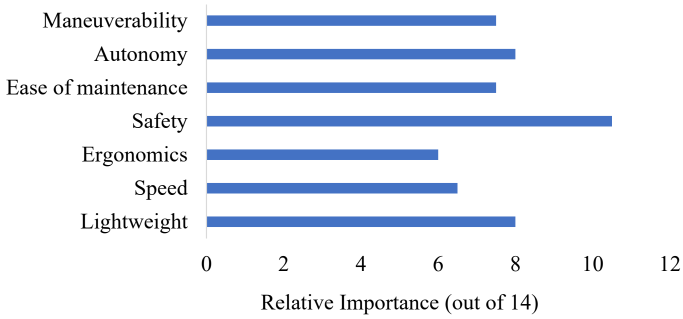

Fig. 2. Features according to their importance

The correlation between specifications is also examined to avoid redundancies between specifications. Finally, each specification's metrics and degree of implementation difficulty are defined. The QFD also compares with the robots analyzed in the background: IRAP, NEXIS R5, SHINOBI FUHGA3, DYNAMICS HURRICAN, JVC 0.1 and JVC 0.2. These are assigned a score from 1 (worst) to 5 (best) for each requirement. The specifications obtained in the first iteration become the input data for the second iteration. The analysis is performed similarly, with the only difference being that the specifications are more detailed for each component of the EOD robot. From the analysis of the two iterations of QFD, the most important for the design of an EOD robot are speed, maneuverability, ergonomics, and weight. As shown in Fig. 3, 4, it became clear that the use of higher power motors, locomotion system mechanisms, volume, and robot geometry is essential in decision-making for prototype design; other considerations such as materials and manufacturing processes, are less critical, but these two have a direct impact on the cost of building the robot, so a solution is sought that is easy to implement and can meet the requirements of the project.

The following are the attributes selected for the application the Kano model: Damping system, low weight, lifting systems for transport, irreversible reducers in the wrist, easy maintenance, lightweight materials, lithium-ion batteries, energy Saving System, higher power motors and geared motors, ease of transport, safe Movement System, compact design, spare parts, available and interchangeable components.

Finally, the results are presented in Table 3.

The results show the following: increased engine power, locally available spare parts, low weight, compactness, and ease of maintenance. These results aid in decision-making for the final design of the EOD robot and provide a detailed understanding of what features are necessary, attractive, or simply mandatory. This insight-driven approach strengthens alignment between product features and customer expectations, increasing the likelihood of successful implementation and adoption in the operating environment.

Finally, after analyzing this phase, in which the QFD method and the Kano model were applied to understand the users' expectations and priorities, Table 4 with the target specifications is presented. These represent the minimum criteria for developing the EOD robot.

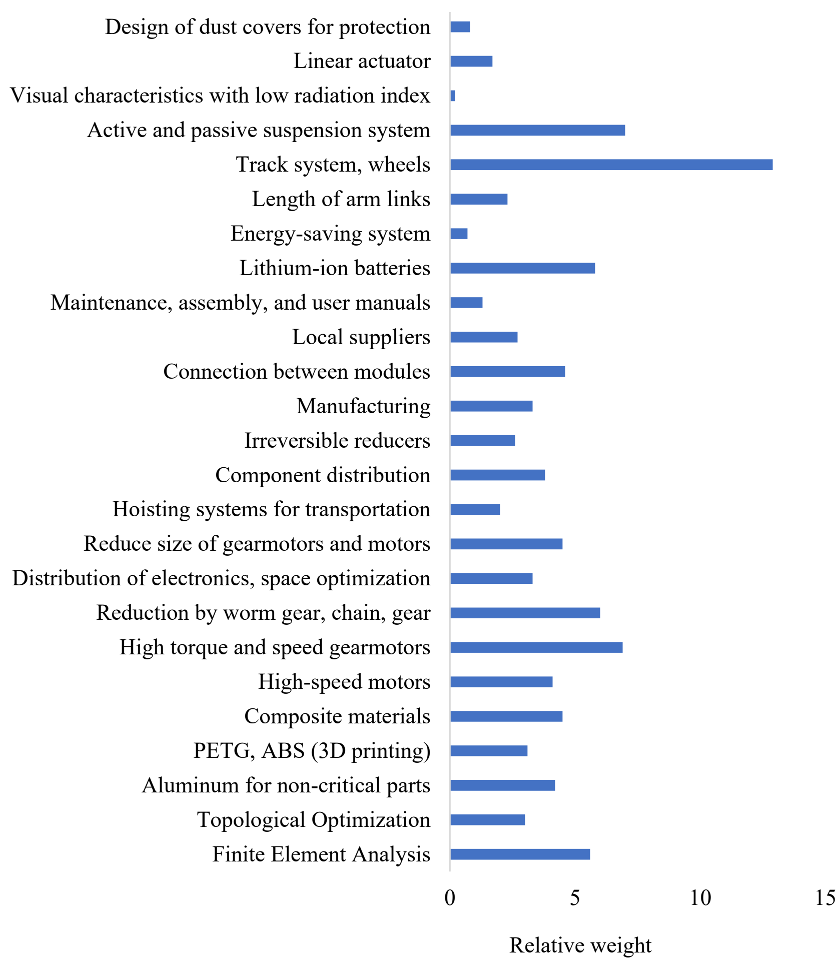

Fig. 3. Quality function deployment — product specifications

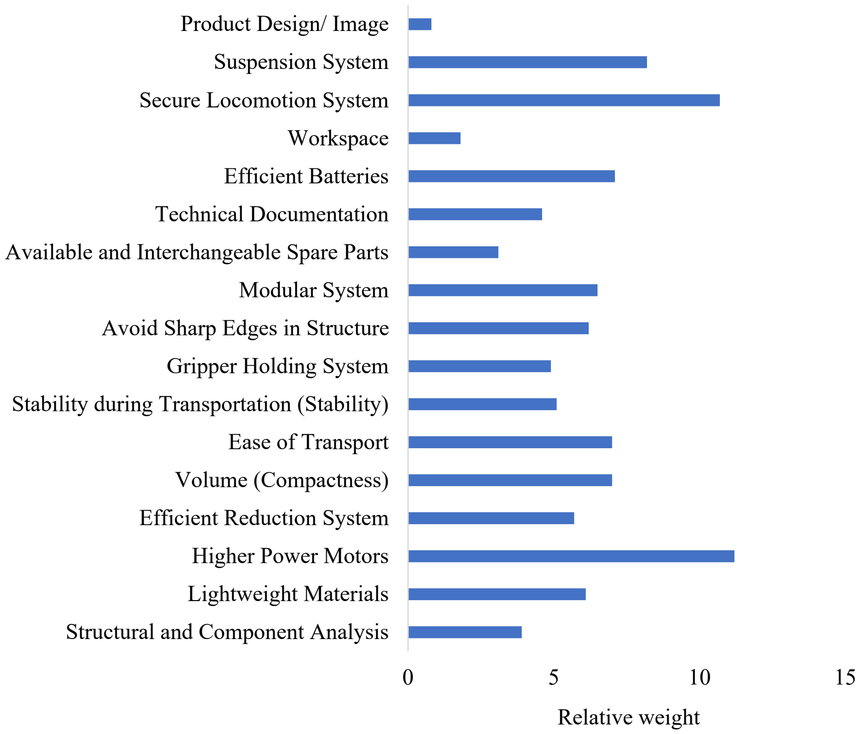

Fig. 4. Quality function deployment – component specifications

Table 3

Kano model results

Attributes	Kano classification
Suspension system	Indifferent
Low weight	One-dimensional
Lifting systems for transportation	Mandatory
Irreversible gearboxes in the gripper	Mandatory
Ease of maintenance	One-dimensional
Lightweight materials	Indifferent
Lithium-ion batteries	One-dimensional
Energy-saving system	Indifferent
More powerful motors and gearmotors	Attractive
Ease of transportation	One-dimensional
Secure locomotion system	Mandatory
Compactness	One-dimensional
Available and interchangeable spare parts/components	Attractive

Table 4

Objective specifications

Requirement	Metric or щbjective ipecification
Low цeight	Less than 77 kg
Speed	1 km/h on flat terrain
Modularity	Disassembly and assembly in 360 min aprox
Maneuverability	Turning radius less than 1 meter

Low-weight requirements ensure the robot can easily transport and maneuver in the field. Achieving a 1 km/h speed on flat ground is a priority to ensure efficient robot movement during operation, reducing response time lag. The modular specification allows for disassembly and assembly in approximately 360 minutes, reflecting the need for easy maintenance and the robot's adaptability in various operational scenarios. Finally, the maneuverability criterion is defined by a turning radius of less than 1 meter, ensuring the robot can move in tight spaces and complex environments. These are parameters necessary to match the robot design to the operational needs determined through user feedback and technical analysis.

5. 2. Development of the Virtual Prototype JVC 0.3

To carry out this process, a morphological matrix was used, which proposes tools or means to achieve the desired features or functions; the prototype is divided into three modules (UGV system, robotic arm and gripper), each directly related to one or more features. This matrix allows proposing alternatives that meet the identified requirements and objectives. For example, for the robot locomotion system, tracked, wheeled or legged systems could be considered. For motor power, options such as permanent magnet DC motors and brushless DC motors are considered. Power reducers may include chain, helical and worm gear reducers. Overall weight is kept below 45 kg through the use of topological designs and lightweight materials such as aluminum and ABS in non-structural parts. The UGV architecture can be modular, rigid or hybrid, facilitating maintenance. In the robotic arm, the gears in the joints could be worm or planetary and the motors in the joints can be permanent magnet DC motors or DC servo motors, all designed to maintain a total weight of less than 20 kg. The arm is designed to have between 5 and 7 degrees of freedom, and its architecture can also be modular.

Finally, the gripper includes rotational locking systems such as worm gearboxes, which facilitate safe and precise handling of objects. Of these combinations of solutions considered, the five most realistic and feasible are proposed.

Five proposed solutions for robot design were evaluated based on technical criteria such as low weight, speed, ergonomics, safety, maintainability, autonomy and maneuverability presented in Table 5.

Table 5

Matrix of possible solutions

Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Wheels	Track	Legs	Wheels	Track
Permanent Magnet DC Motor (WIPER)	Brushless DC Motor (WHEELCHAIR)	Permanent Magnet DC Motor (WIPER)	Brushless DC Motor (WHEELCHAIR)	Brushless DC Motor (WHEELCHAIR)
Worm gear – worm screw	Worm gear – worm screw	Cycloidal reducer	Worm gear – worm screw	Spiral Bevel Gears
Aluminum and ABS for non-structural parts	LiPo Battery	Aluminum and ABS for non-structural parts	Aluminum and ABS for non-structural parts	Topological design
Hybrid architecture	Modular architecture	Modular architecture	Hybrid architecture	Modular architecture
Cycloidal	Worm gearbox	Harmonic	Cycloidal	Planetary
Permanent magnet DC motor (WIPER)	Permanent magnet DC motor (WIPER)	Stepper DC motor	Permanent magnet DC motor (WIPER)	Stepper DC motor
Composite materials (fiberglass, carbon)	Structural optimization	Composite materials (fiberglass, carbon)	Composite materials (fiberglass, carbon)	Lightweight motors and reducers
6 DOF	6 DOF	6 DOF	5 DOF	7 DOF
Hybrid architecture	Modular architecture	Modular architecture	Modular architecture	Modular architecture
Cycloidal reducer	Worm gearbox	Worm gearbox	Cycloidal reducer	Worm gearbox
Topological optimization	Topological optimization	Topological optimization	Aluminum and ABS for non-structural parts	Topological optimization
DC mechanical linear actuator	DC mechanical linear actuator	DC mechanical linear actuator	DC mechanical linear actuator	DC mechanical linear actuator

Each criterion was weighted relative to its importance; for example, weight and safety were considered as essential criteria. The solutions were compared using a scoring system where 0 was assigned if the criterion was less important, 1 if it was equally important, and 2 if it was more important than other criteria compared. After detailed evaluation, the results showed that Solution 2 obtained the highest score with 24.76 points, standing out for its adequate balance among all the criteria evaluated. This solution proved to be the most effective, followed closely by Solution 4 with 23.81 points. Solution 3, focused mainly on low weight and speed, received the lowest score with 11.9 points, reflecting limitations in safety and autonomy. Solution 1 and Solution 5 had intermediate performances with scores of 23.33 and 16.19 respectively, each showing strengths and weaknesses in specific areas such as ergonomics and maneuverability.

After the comparative evaluation of the solutions based on technical criteria, in this phase, a modularity assessment is carried out to ensure the functional independence of each component. This includes verifying estimated weight, torque, and speed to ensure proper system performance, the stability of the center of mass under different operating conditions, and Failure Mode and Effects Analysis (FMEA).

The diagram in Fig. 5 illustrates the connections and dependencies between the modules. Fig. 6 shows the final model of the virtual prototype, which provides the ability to efficiently separate and swap modules (thus optimizing the robot's maintainability, scalability, and adaptability to changing environments). In this implementation, the track chassis can be replaced by another locomotion system such as wheels if necessary.

The main objective is to verify whether the current design allows for a significant weight reduction compared to the previous version. Table 6 shows the weight of each component. These results were obtained using SolidWorks 3D modeling software. The methodology used provides an approximate calculation of the total weight of the robot and is the basis for verifying operational requirements and optimizing system performance.

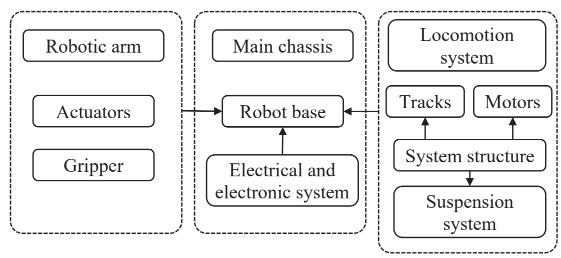

Fig. 5. JVC 0.3 modular distribution

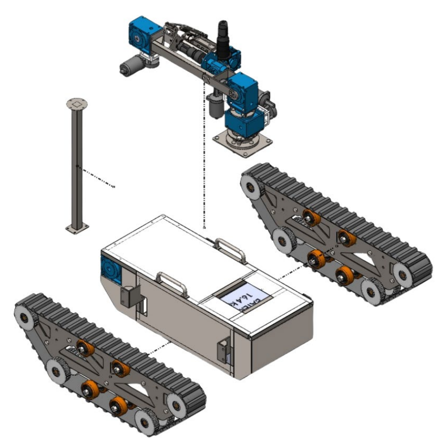

Fig. 6. Final model of the JVC 0.3 prototype

Table 6

Weight per module of JVC 0.3

Module	Quantity (units)	Unit weight (kg)	Weight per module (kg)
Chassis	1	37.8	37.8
Locomotion system	2	12.2	24.4
Robotic arm	1	21.6	21.6
Total weight	4	71.6	83.8

Based on the methodology described for torque and speed determination, a free body diagram is used to represent the forces and torques on the robot in a critical situation (an inclined surface at 30°) Fig. 7. Speed is our input variable (a minimum speed of 1 km/h is required). This speed is used to determine the speeds required for the gearmotor.

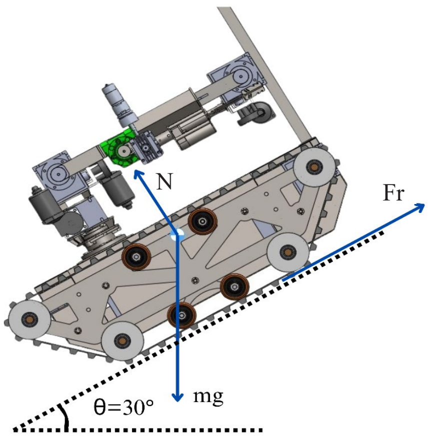

Fig. 7. Free body diagram robot explosive ordnance disposal

With the required torque and speed, the motor that meets these two characteristics can be selected. According to (1)–(3), the tangential speed (*Vt*), torque (*T*) and power (*P*), The motor power must be greater than 76.3 W. The results of these calculations are summarized in Table 7, which details how the various motor configurations respond to torque and speed requirements under different operating scenarios.

Table 7

Speed and torque required for different scenarios

Features	Flat surface (0°)	Inclined surface (30°)
Power (W)	76.3	65.5
Torque (N·m)	13.7	23.5
Speed (rpm)	53.1	26.2

The evaluation of stability concerning the center of mass was done by positioning the robot arm in different configurations, both on sloping terrain and flat surfaces. Fig. 8. shows a critical scenario using SolidWorks software, where the change in weight due to the arm position was considered.

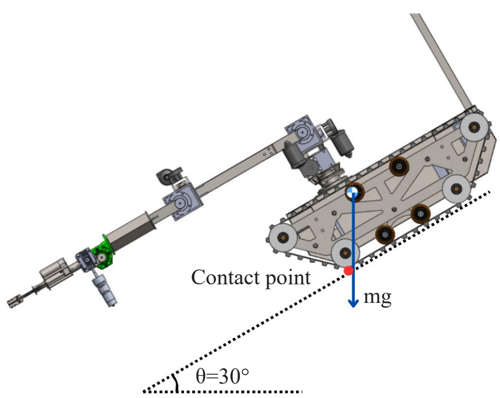

Fig. 8. Validation of stability in the most critical arrangement

The method for evaluating the stability of an EOD robot on an inclined plane is based on the theory of stroke polygons, also known as equilibrium polygons. This method draws vertical lines from the last point of contact between the robot's center of gravity and the inclined plane. The polygon formed by these lines defines the limits of the robot's contact area with the inclined.

If the red vertical line of the center of mass is within this polygon, the robot is in equilibrium. In this case, the line of the center of mass in front of the last gear indicates that the robot is balanced on the slope and ensures the robot's stability when working on the slope. In the Table 8 shows the final specifications of JVC 0.3, which mainly relate to mechanical properties, robot motion, power system, and handling.

Table 8

Technical specifications of JVC 0.3

Specification	Value
Denomination	JVC 0.3
Dimensions	0.60*0.98*0.60 m
Total weight	83.8 kg
Unpacking and assembly time	360 min
Locomotion system	Tracks
Maximum speed on flat surface	1 km/h
Maximum payload	10 kg
Power source	Lithium polymer batteries
Manipulator	6 DOF
Arm length	130 cm
Payload with extended arm	5 kg

The table above presents the technical specifications of the JVC 0.3, highlighting key features such as its dimensions, optimized weight, and load capacity. The design includes a track-based locomotion system to ensure stability and maneuverability in varied terrain, a top speed suitable for a fast approach to the operating site, and a six-degree-of-freedom handling system that enhances handling and adaptability to different operating situations.

5. 3. Risk assessment with FMEA

The FMEA analysis in Tables 9, 10 (based on the Technical Prevention Standard-NTP 679: Failure Mode and Effects Analysis) allows to anticipate and mitigate risks to ensure that our prototype performs with high reliability and safety in explosive ordnance disposal.

For the first "Low Weight" failure mode, the effect of this failure was determined as "4 policemen are required to transport it", and then the cause was determined as "Chassis Weight." This failure mode is scored based on three criteria: the failure severity criterion (*G*), the probability of occurrence criterion (*O*), and the non-detectability criterion (*D*). Each criterion is assigned a score from 1 to 10: very low (1), low (2 to 3), medium (4 to 5), frequent (6 to 7), high (8 to 9), and very high (10). The scores for the "low weight" failure mode are $G=10$, $O=8$, and $D=9$; this score is used to obtain the number of risk priorities (NPR), G×O×D=NPR, where NPR is 720, an NPR above 100 requires intervention to improve the prototype, as seen in Fig. 9, in this case the recommended actions are "Optimize the structure and use lightweight batteries (LiPo).

Table 9

Failure mode and effects analysis part 1 (FMEA)

No.	Failure mode	Effect	Causes	G	O	D	NPR
1	Low weight	Requires 4 policemen to transport	Elevated weight of chassis, arm, and electronics (115 kg)	10	8	9	720
2	Speed	Having a low speed prolongs the operation time to several hours due to slow mobility	Maximum robot speed on flat terrain of 10 to 11 cm/s	4	8	5	160
3	Ergonomics	Police officers experienced fatigue and even injuries when transporting the robot	Poor location of transport handles. Pronounced and exposed edges	6	8	5	240
4	Safety	Explosive device detachment during transport	Lack of mechanical brake in gripper rotation. High robot vibrations during locomotion	7	9	9	567
5	Maintainability	Difficulty in assembly and disassembly of robotic arm, motors, and reducers	Poor design of couplings combined with manufacturing inaccuracies	8	8	8	512
6	Autonomy	Robot battery duration of 1 hour	Robot operation time exceeds 1 hour due to its slow displacement speed	5	6	5	150
7	Maneuverability	Track system jamming. Instability and abrupt inertia movements when crossing irregular terrain and steep slopes	Track detachment. Elevated robot center of mass and weight	8	8	6	384

Table 10

Failure mode and effects analysis part 2 (FMEA)

No.	Proposed Actions	Actions Taken	G′	O′	D′	NPR′
1	Optimize structure and use lightweight batteries (LiPo). Weight limit to consider is 70 kg, which is lower than the RoboCup recommendation (77.5 kg), distributed as follows: – chassis weight limit of 45 kg; – locomotion system limit of 30 kg; – arm weight limit of 20 kg	Optimized robot design with ASTM A36 structural steel and lightweight LiPo batteries: – chassis software weight: 37.8 kg; – locomotion system: 24.4 kg; – arm software weight: 21.6 kg; – total weight of 83.8 kg	3	4	7	84
2	Implement DC brushless motors to achieve a speed of approximately 28 cm/s (1 km/h)	Brushless motors were implemented in the locomotion system design, resulting in: – speed on flat terrain: 32 cm/s	2	3	5	30
3	Implement lateral transport handles aligned with the center of mass	Lateral handles were implemented and aligned with the center of mass calculated by software	4	6	5	120
4	Implement screw worm gear locking system for gripper rotation. Implement linear actuator to eliminate mechanical failures in the gripper	A worm gear aluminum wheel was implemented for mechanical gripper locking, and also a linear actuator. Actuator alignments were verified through motion simulation	5	5	6	160
5	Design robot with modular architecture for easy and quick disassembly	Robot modularity was verified through assembly and disassembly simulation in software	5	4	7	140
6	Implement LiPo batteries	LiPo batteries were implemented in the design	2	3	3	18
7	Robot weight was distributed to maintain a low center of mass. Design track in trapezoidal configuration. Implement suspension system to robot tracks	Design stability was verified with software, resulting in stability at 30° inclined positions. Robot locomotion was simulated in various environments (flat terrain, slopes, and stairs) to verify robot maneuverability, as well as obtaining point cloud data of the arm to determine its range of action	5	6	6	180

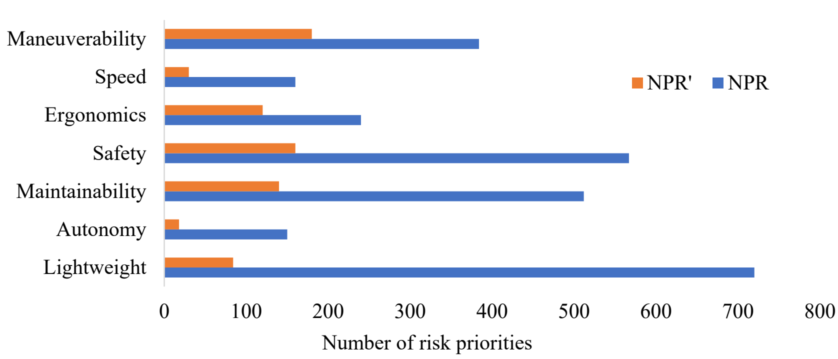

Fig. 9. Failure mode and effects analysis in bar chart (The NPR is calculated on a scale from 0 to 800, where higher values indicate more critical failure modes)

Fig. 9 shows the NPR obtained by the failure modal analysis for both the JVC 02 and JVC 03 models. The orange bars represent the JVC 02, while the gray bars refer to the JVC 03. The most critical values identified besides light weight, are safety, maintainability and maneuverability, whose NPR's are 567; 512 and 384 respectively, having been reduced by improvement actions in the virtual model of the JVC 03, whose NPR′ were reduced to 140; 160 and 180, demonstrating a remarkable progress in the optimization and robustness of the design.

5. 4. Comparison of performance between JVC 0.3 and JVC 0.2

The evolution of the EOD robot design in our research has been marked by incremental improvements since the introduction of the first version, "JVC-01", in 2021. The development of "JVC-01" began with a thorough analysis of UDEX requirements, which included EOD procedures, frequency, and ordnance characteristics. This initial model was equipped with a drive system powered by two 12 V, 1.2 kW DC motors and presented several operational challenges during field testing, such as difficulties in overcoming steep terrain and problems with the tempering control system.

These technical challenges identified in "JVC-01" led to the development of the upgraded version "JVC-02" in 2022, which introduced a flexible trapezoidal rail system and a manipulator arm with significant improvements. Despite the advances, "JVC-02" also faced difficulties, including mechanical failures in the motor joints on steep slopes and problems in track maintenance, highlighting the need for further design review.

These learnings were crucial to the development of "JVC-0.3", which not only addressed the previous problems but also implemented substantial improvements in weight, modularity, and maneuverability. The JVC-0.3 version benefited from structural optimization techniques, the use of lighter motors and propulsion systems, and lighter batteries, achieving a 27.13 % weight reduction compared to the JVC-0.2 as shown in Table 11, and increasing the operating speed to 1 km/h among other technical improvements.

Table 11

Comparison of capabilities of the JVC 0.3 with the JVC 0.2

Features	JVC 0.2	JVC 0.3
Weight (kg)	115	83.8
Speed (cm/s)	11	27.7
Modularity	Semi modular	Modular
Maneuverability	Tracks only	Tracks and suspension system
Load capacity (kg)	10	15
Extended arm distance (mm)	1200	1300

Table 11 shows a comparative table highlighting the improvements between the versions, where the JVC 0.3 not only improves in terms of technical specifications but also in terms of adaptability and operational efficiency, evidencing the success of the design methodologies applied and the iterative approach towards the optimization of the EOD robot.

6. Discussion of the results of the study of EOD robot prototype optimization using quality function deployment and failure mode and effects analysis methodologies

Based on the research, robust methods such as Quality Function Deployment (QFD) and Failure Mode and Effects Analysis (FMEA) must be integrated to optimize the design of Explosive Ordnance Disposal (EOD) robots, ensuring that the results meet user requirements, mainly related to robot weight, speed, maneuverability, and modularization. Through the application of QFD, the needs and expectations of UDEX technicians can be effectively translated into technical engineering specifications. At the same time, FMEA can identify and mitigate the most critical failure modes, making the robot lighter, faster, and more maneuverable.

Comparing the JVC 0.3 in Table 11 with its predecessor, the JVC 0.2, the main results are significant, with a weight reduction of 27.13 % and an increase in operating speed to 27.7 cm/s, topological optimization performed in SolidWorks software identified areas of the chassis where material could be reduced without affecting the stiffness of the system. This, along with the incorporation of lithium polymer (LiPo) batteries, which offer high energy density with lower weight compared to traditional batteries. Likewise, the use of structural steel in critical components provided an optimal strength-to-weight ratio, while materials such as ABS and aluminum were used in non-structural parts, achieving a significant decrease in overall mass. These directly address the needs of the users in Table 4, reflecting the effectiveness of the approach. Furthermore, the results demonstrate how the introduction of a modular design Fig. 6, the optimization of the weight Table 6, and the stability of the EOD robot Fig. 8, directly contribute to improving its functionality. Regarding the FMEA analysis in Tables 9, 10, the weight limit to be considered was 70 kg, lower than that proposed by LLR (77.5 kg); this weight is distributed as follows: chassis weight: 45 kg, arm weight: 20 kg, locomotion system: 30 kg. These measurements were performed during the development of the virtual robot prototype and led to the following results: Optimized robot design with ASTM A36 structural steel and lightweight LiPo batteries. Chassis software weight: 37.8 kg, arm software weight: 21.6 kg, locomotion system software weight: 24.4 kg, total weight: 83.8 kg. With these improvements, a new evaluation was performed based on the above criteria. The NPR result is 84, i.e., no intervention is required, as the NPR is less than 100, indicating that the failure mode has been adequately addressed. This analysis was applied to all eight failure modes. Also, the results shown in Fig. 11, extracted from Tables 12, 13, show that lightness (84), speed (30), and reach (18), with NPR values below 100, do not require intervention, but maneuverability (180), maintainability (140), safety (160) and ergonomics (120), with NPR values above 100, do require intervention for the virtual robot prototype to meet the UDEX requirements. These results are in accordance with previous studies, such as the one conducted in [17] on improving the reliability and quality of mechanical robots using QFD and FMEA, this study confirms that the integration of these methodologies can result in substantial improvements in the design and performance of EOD robots. Furthermore, unlike other approaches that might focus only on technical aspects, this study also considers the operational and maintenance needs of end users, ensuring that the proposed solutions are not only technically feasible but also practical and adaptable in the field. The JVC 0.3, unlike the JVC 0.2 model [8], which focused solely on improving mobility and grippability, offers a balance between weight reduction and stability. This balance is made possible by the joint application of QFD and FMEA, which allowed multiple aspects of the design to be addressed simultaneously. In addition, the use of detailed simulations in SolidWorks provided a competitive advantage, allowing to quickly iterate on the design and validate each component prior to physical implementation.

The application of this proposed QFD/FMEA methodology shows a clear improvement with respect to the previous design, which was a basis for further evaluation and comparison. For example, the JVC 0.3 has a modular design that allows for maintenance in less time, which is an improvement over similar models such as the SCOBOT-200. Unlike the Nexis R-5, which faced mobility challenges, the JVC 0.3's locomotion system provides improved stability and maneuverability, especially in different terrains. The lightweight materials and optimized design further distinguish the JVC 0.3 from other EOD robots, making it more suitable for local operating conditions, such as Arequipa. The importance of this methodological framework is the systematization, from the classification of the requirements, prioritization of the same until a further layer of refinement with the Kano model, this allows a global analysis, where argumentative biases are avoided. However, one of the disadvantages of this study lies in the verification of the results mainly through virtual simulation. Although these simulations allow obtaining valuable data such as stress evaluation of the materials under extreme conditions. Although the selected materials showed promise, in situ tests are required to confirm the effectiveness of the improvements in real working conditions, which is a limitation due to the availability of resources. This practical validation is crucial for further research to ensure that the proposed solutions are not only technically feasible, but also practical and adaptable in the field. In summary, to promote future research in this area, it is important to introduce more frequent feedback to end users and to expand field testing. In addition, the integration of usability technologies can improve the implementation of user interfaces and natural user interfaces [27–30]. Research into new materials and fabrication methods can also help to further optimize designs, reduce costs, and improve overall robot performance.

Looking ahead, the features presented in this document will form the basis for the project's next phase, the construction of the prototype. In this phase, the mechanical properties will be verified and tested in real working environments, allowing to evaluate the performance and effectiveness of the EOD robot.

7. Conclusions

1. The implementation of the QFD/FMEA design methodology based on the "Design For X" concept for the development of the JVC 0.3 EOD robot prototype proved to be an effective procedure that allows collaborative development between the engineering area and the end users. This approach met the first objective of analyzing and gathering UDEX user requirements, identifying and prioritizing these needs to translate them into accurate technical specifications.

2. The target specifications were effectively achieved through the creation of a virtual 3D model developed in SolidWorks: a weight reduced to approximately 80 kg, a speed close to 1 km/h on flat ground, and a modular architecture allowing assembly and disassembly in less than 360 minutes. These achievements validate the creation of the JVC 0.3 virtual prototype and directly address the requirements of modularity, weight, torque, speed and stability, aligning with the objectives set to improve the quality and reliability of the design.

3. The solution defined in the concept phase and evaluated using a morphological matrix, stands out for its modularity, a robotic arm with 6 degrees of freedom and a crawler motion system. This solution confirms the validity of the methodology to anticipate and identify failures through FMEA analysis.

4. The methodology was successfully validated using the JVC 0.3 virtual prototype, achieving a weight reduction of 27.13 % and a speed increase up to 1 km/h on flat terrain compared to the JVC 0.2. In addition, direct comparison of the performance between JVC 0.3 and JVC 0.2 confirmed substantial improvements in quality and reliability.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this re-search, whether financial, personal, authorship or otherwise, that could affect the re-search and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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