

Static and Thermal Analysis Using the CFD-FEA Method of the Electronic Enclosure for an EOD Robot

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Abstract—Currently, Explosive Ordnance Disposal (EOD) operations are more reliable and safer due to the incorporation of EOD robots. These robots typically operate in uneven urban terrain with obstacles, as well as in extreme temperature conditions, which cause severe damage to the robots' control and operating systems. This article presents the modeling and analysis of an Electronic Enclosure for EOD robots adapted to uneven terrain and extreme thermal conditions. The JVC-02 robot, developed collaboratively by the National University of San Agustín (UNSA) and the Arequipa Explosive Ordnance Disposal Unit (UDEX-AQP), was taken as a case study. Taking as a reference the characteristics of the control and operation system of this robot, to develop a first prototype of an Electronic Enclosure based on aluminum profiles, which allowed the identification of technical problems caused by impacts and vibrations of the chassis when passing through uneven terrain accompanied by extreme thermal conditions. An improved Electronic Enclosure was then modeled and adapted to the requirements of the JVC02 robot. This version has a modular design that facilitates maintenance, as well as an open structure for adequate ventilation of the components and a system that cushions impacts and vibrations during the robot's locomotion. The model was analyzed using the Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) methods, which allowed critical stresses and thermal loads to be identified in the prototype. The results show that adopting an Electronic Enclosure with the CFD-FEA method offers a viable solution for protecting the control and operating systems of EOD robots against impact loads and thermal effects, as well as providing maintenance improvements due to its modularity.

Keywords—electronic enclosure, Explosive Ordnance Disposal (EOD), robot, Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), design, modular

I. INTRODUCTION

Explosive device attacks continue today, causing global human and economic losses. According to the United Nations General Assembly, in 2023, there were 3237

victims of explosive devices in 25 countries, with 68% of victims identified as civilians [1]. The organization Action On Armed Violence (AOAV) described the use and impact of explosive devices in the period 2015–2024 in 94 countries, recording 10,376 incidents, which resulted in 83,529 civilian casualties [2], with 94% of civilian casualties occurring in populated areas [3]. 2024 was the most damaging year for the world's population, with 67,026 victims of explosive weapons, 41% (24,147) of whom were civilians. Last year, there was a 29% increase in global incidents [4]. In response to these situations, several countries have established organizations specializing in Explosive Ordnance Disposal (EOD) [5–7]. In Peru, the Explosive Device Deactivation Unit (UDEX) was created in response to the internal armed conflict against terrorist groups, which claimed more than 69,280 victims between 1980 and 2000, with the use of explosive devices being one of the methods employed by these groups [8]. The UDEX, in collaboration with the Peruvian Armed Forces (FFAA), eradicated the threat posed by terrorist groups. However, in recent years, the emergence of criminal groups focused on extortion using explosive devices represents a new and growing threat, which has put the UDEX on alert, reporting more than 1200 cases involving explosive devices [9]. Likewise, the National Superintendency for the Control of Security Services, Arms, Ammunition, and Explosives for Civil Use (SUCAMEC) destroyed more than 600 explosive devices that put the safety of thousands of Peruvians at risk [10]. According to UDEX, extortion groups are using more advanced methods of remote-controlled explosives devices [11], which results in higher-risk EOD operations, endangering Explosive Ordnance Disposal Technicians (TEDAX) and the general public.

In response to this situation, robotics has evolved for use in EOD operations, eliminating the risk of direct exposure of bomb disposal experts to the accidental detonation of explosive devices. Bećirspahić *et al.* [12] designed an EOD robot based on the Minimum Viable Product (MVP)

criteria, capable of complying with US guidelines for the deactivation of explosive devices. In China, Jiang *et al.* [13] developed the FC-EODR, an innovative centaur-type robot with two humanoid arms that performs operations in rough terrain and with advanced explosive devices. In Colombia, Ramírez *et al.* [14] presented the evolution of the VALI robot for neutralizing explosive devices using an iterative method. Similarly, in Peru, a series of EOD robots called JVC were developed, which were designed to meet the requirements of the UDEX [15–17]. As seen in previous studies, the incorporation of EOD robots into explosive ordnance disposal units resulted in a considerable decrease in casualties among TEDAX and citizens. However, these robots operate in irregular urban environments with obstacles [18] and are also exposed to external conditions such as extreme temperatures [19], causing severe damage to the control and operation systems of EOD robots.

On the other hand, in robotics applied to operations in extreme environments, the use of electronic enclosures has been integrated in order to provide greater protection to robot control and operation systems. Muktadir *et al.* [20] designed a robot with a lead-shielded electronic enclosure to protect its electronics in radioactive environments. Song *et al.* [21] presented an underwater robot with an electronic enclosure that protects the electronics even from waves. NASA developed a modular SpaceCube adapted to protect electronics in robotic operations in space missions [22]. While these studies demonstrate the use of electronic enclosures in extreme environments, their application in EOD robotics has not been sufficiently addressed in the literature. These works demonstrate the potential of enclosures to protect control and operation systems in robots exposed to extreme conditions, such as EOD robots.

Computer-Aided Engineering (CAE) is also widely used in industry for the design of complex products [23], with different types of analysis depending on the studies required, such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) [24]. FEA analysis allows the structural strength and deformation of mechanical components to be evaluated to manufacture using a finite element model [25, 26]. CFD analysis allows fluid flow and heat transfer to be simulated based on the Navier-Stokes equations, which is ideal for designing ventilation and heat dissipation systems [27–29]. Militao *et al.* [30] evaluated the thermal performance of a submarine system enclosure using CFD. Kowalski and Radmehr [31] performed a precise thermal analysis using CFD in the design of a complex electronic enclosure. Wróbel and Warzyńska [32] used CFD to analyze the cooling of an acoustic enclosure. While these studies address thermal and structural aspects, they do not consider the mechanical impact conditions and thermal demands specific to EOD operations. These studies reinforce the application of enclosures in EOD robots, implementing FEA and CFD analysis for greater performance and precision in meeting the requirements of explosive ordnance disposal units.

This article presents the design and FEA-CFD analysis of a novel Electronic Enclosure for EOD robots, adapted to external operating conditions. First, the EOD robot JVC02 developed by the National University of San Agustín de Arequipa (UNSA) in collaboration with the Arequipa Explosive Ordnance Disposal Unit (UDEX-AQP) is taken as a case study. Next, the characteristics of the robot's control and operation system are analyzed, along with an initial experimental version of the electronic enclosure, based on aluminum profiles, which helped identify the design requirements for electronic enclosures for EOD robots. Subsequently, a second version of the electronic enclosure is virtually designed and optimized. The simulation methodology using a hybrid FEA-CFD approach is then presented. The FEA analysis determines the resistance and deformation against impact loads that would be generated on the robot's chassis when passing over uneven terrain, followed by the application of CFD analysis to determine the thermal effects caused by the external thermal conditions of EOD operations. Finally, the results obtained are presented and discussed, highlighting the structural and thermal performance of the proposed design.

II. PROBLEM DEFINITION

A. Case Study: JVC-02 EOD Robot-UDEX

For this work, the research team based its findings on the characteristics of the electronic components of the JVC-02 Explosive Ordnance Disposal (EOD) robot, see Fig. 1, which was developed by the National University of San Agustín in collaboration with the Explosive Ordnance Disposal Unit (UDEX).



Fig. 1. EOD robot version JVC-02.

In recent years, UDEX has optimized its explosive device disposal protocols to make operations more effective and safer for both Explosive Ordnance Disposal Technicians (EODT) and the public, thanks to the implementation of EOD robots. The first UDEX robot was the Canadian-made Vanguard MK-II [33], which, after several years of service, began to experience technical failures in its cameras and robotic arm control due to damage to electronic components caused by impacts

during movement. Then, in collaboration with researchers from UNSA, they developed a series of EOD robots called JVC [15–17], which were adapted to the requirements of UDEX technical personnel. These robots also experienced technical problems in their electronic control and operating components due to impact loads when crossing obstacles, as well as overheating due to exposure to high temperatures.

For this reason, the electronic components of the control and operation system of the JVC-02 EOD robot were reviewed, comprising eight types of components and a total of 23 parts, as shown in Table I. The weights and dimensions are shown in Table II, and the interconnection

of the components for the robot's operation can be seen in Fig. 2.

TABLE I. LIST OF ELECTRONIC COMPONENTS OF THE JVC-02 CONTROL AND OPERATION SYSTEM

Item	Component	Quantity
01	Socket TCP/IP Access Point AC1750	1
02	Raspberry Pi3	1
03	ESP32	1
04	NVR DS-7600	1
05	ATmega328	9
06	Drivers BTS7960	4
07	Drivers Cytron MD20A	4
08	Drivers L293D	2

TABLE II. ELECTRONIC COMPONENT CHARACTERISTICS

Item	Component	Unit Weight (g)	Dimensions L × W × H (mm)
01	Socket TCP/IP Access Point AC1750	200	160.0 × 100.0 × 40.0
02	Raspberry Pi3	41	86.9 × 58.5 × 19.1
03	ESP32	2	18.0 × 25.5 × 3.1
04	NVR DS-7600	1000	385.0 × 315.0 × 52.0
05	ATmega328	4	24.0 × 9.0 × 7.0
06	Drivers BTS7960	66	50.0 × 50.0 × 43.0
07	Drivers Cytron MD20A	43	86.0 × 52.0 × 18.0
08	Drivers L293D	10	40.0 × 35.5 × 12.5

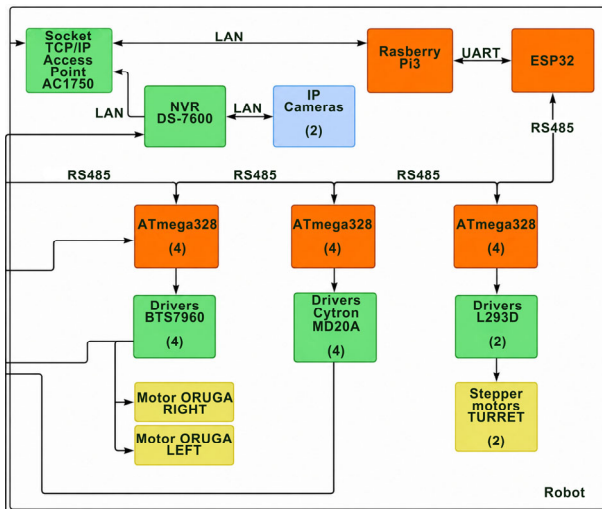


Fig. 2. Diagram of the electronic control and operations system of the JVC-02 EOD robot [19].

B. Experimental Electronic Enclosure

After reviewing the electronic components and their characteristics in the previous section, a first version of the electronic enclosure was developed that brings together the components in a structure, as shown in Fig. 3, and was implemented in the chassis of the JVC-02 EOD robot. This device provided an understanding of the technical requirements that must be considered in the design of an electronic enclosure for EOD robots.

The electronic enclosure was designed using aluminum angle profiles. It is a single cube-shaped structure measuring 300 × 280 × 250 mm. The electronic components are distributed across five levels. The access point is located on the top level, with its antennas

perpendicular to the base and protruding from the structure. The total weight of the electronic enclosure and electronic components is 4500 g. This device was installed inside the chassis of the JVC-02 robot, located in an available space measuring 390 × 350 mm, together with the batteries and motors, which generate a high-temperature environment combined with the heat of the environment, causing overheating and damage to the components. The robot chassis has a height of 250 mm, which translates into a high center of mass, causing instability during locomotion, mainly when passing over obstacles. High-impact loads are also generated, causing damage to the electronic systems. Although the structure of the electronic enclosure is open, allowing for inspection of the electronic components, in practice, the engineering team encountered difficulties in maintenance and assembly, which could suggest a modular structure.

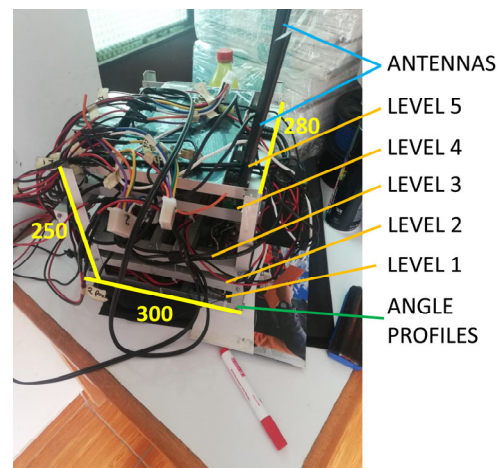


Fig. 3. Electronic enclosure based on aluminum profiles.

TABLE III. LIST OF REQUIREMENTS FOR THE DESIGN OF AN ELECTRONIC ENCLOSURE

Requirements	Description
Structural design	Open structure for adequate ventilation, easy inspection, and component maintenance. TCP/IP Access Point AC1750 antennas perpendicular to the base of the robot.
Rigidity and strength	Resistance to impact loads caused by robot movement without causing significant deformation to the structure of the electronic enclosure.
Thermal dissipation	Material that supports the thermal load of electronic components. Structural design that allows for adequate heat dissipation.
Damping	Shock absorption system to minimize impacts on electronic components during robot movement.
Stability	Low electronic enclosure height, for an overall robot center of mass that ensures stability during operation and EOD operations.
Modularity	Modules organized for easy assembly and disassembly for easy maintenance.

Based on the findings from the implementation of the first version of the electronic enclosure in the chassis of the JVC-02 EOD robot, the requirements for future designs were determined, as shown in Table III.

III. VIRTUAL DESIGN AND ASSEMBLY

Based on the requirements determined in the previous section, a virtual version of the electronic enclosure was designed, as shown in Fig. 4.

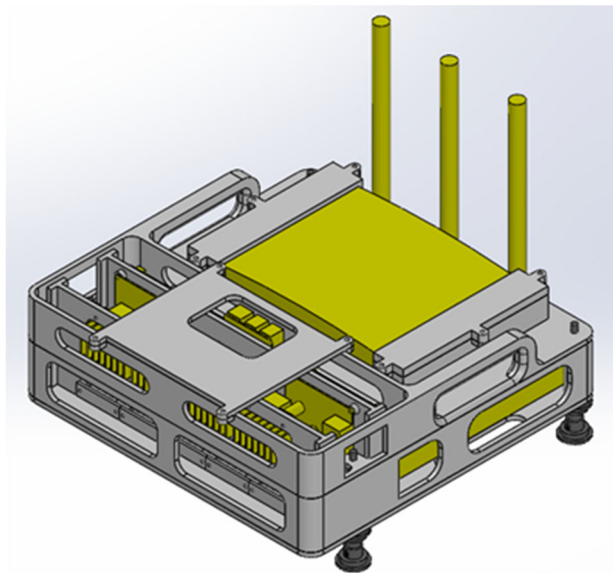


Fig. 4. Isometric view of the 3D model of the electronic enclosure.

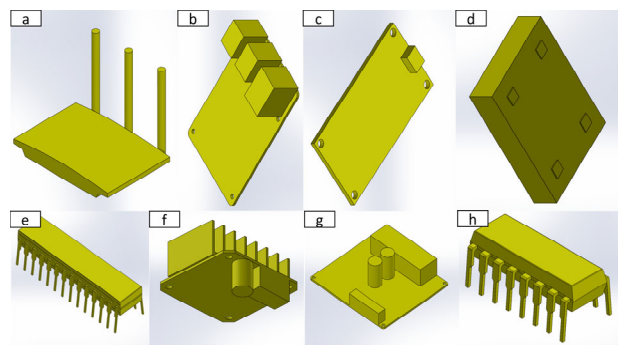


Fig. 5. Electronic control and operating components of the JVC-02: (a) Socket TCP/IP Access Point AC1750, (b) Raspberry Pi3, (c) ESP32, (d) NVR DS-7600, (e) ATmega328, (f) Drivers BTS7960, (g) Drivers Cytron MD20A, (h) Drivers L293D.

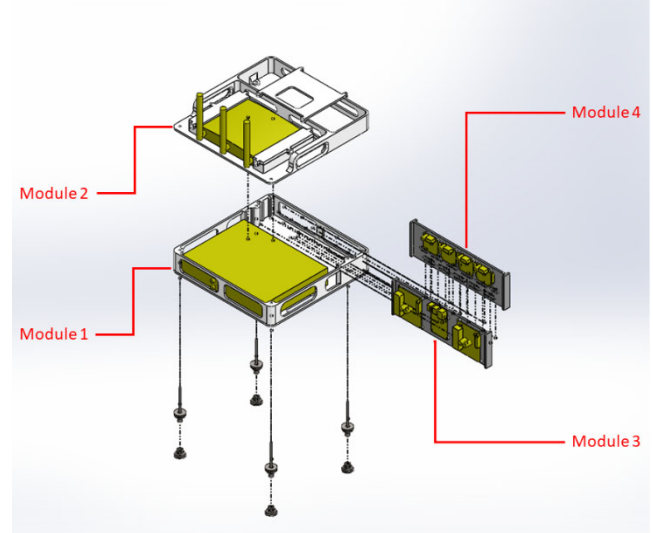


Fig. 6. Exploded view of electronic enclosure.

First, Fig. 5 shows the 3D model of the electronic components listed in Table I. Next, the structure of the electronic enclosure was designed according to the dimensions of each electronic component, dividing it into four modules and a damping system, as shown in Fig. 6. Module 1 is the lower and side casing that mainly houses the DS-7600 NVR. It also has two parallel and vertical rails to which modules 3 and 4 can be easily attached. These modules are removable for inspection and repair, even while the robot is in operation. These modules integrate the electronic components: Raspberry Pi3, ESP32, ATmega328, BTS7960 drivers, Cytron MD20A drivers, and L293D drivers. Module 2 is the upper casing that houses the AC1750 TCP/IP Access Point. This structure allows the antennas of this component to protrude from the chassis perpendicular to the base of the robot. It also has a cover that, when opened, allows for quick removal of modules 2 and 3. Two handles were designed on the sides of module 2 to move the electronic enclosure safely and stably. Finally, at the bottom of module 1, a damping system was designed consisting of four shock absorbers, each of which comprises a compression spring with a sliding guide bar and another screw-on bar that allows the electronic enclosure to be attached to the base of the chassis. The modular configuration also contributes to the overall robustness of the design by reducing the enclosure height by 40% (from 250 mm to 150 mm), lowering the robot's center of mass, and improving stability during locomotion on uneven and inclined terrain.

The damping system integrated at the base of Module 1, comprising four shock absorbers with compression springs and guide bars, minimizes the transmission of impact loads and vibrations to the electronic components during continuous robot operation. All modules were designed with openings on their surface for adequate ventilation and to facilitate maintenance.

IV. SIMULATION METHODS

A. FEA Analysis of the Electronic Enclosure

This section presents the configuration of the Finite Element Analysis (FEA) simulation used to evaluate the structural behavior of the electronic enclosure under impact loads generated by locomotion on uneven terrain typical of EOD operations.

First, the boundary conditions and load assumptions were defined based on the conditions observed during locomotion tests of the EOD robot JVC-02 on uneven terrain and inclined surfaces. The critical situation that causes the greatest impact load on the 115 kg robot was identified in the locomotion of the JVC-02 robot, occurring at the end of the ascent up stairs or slopes of 20° [17]. The last point of contact of the robot's track before completing the ascent is 29 cm from the center of mass. At the moment of impact, a deformation of the structure and synthetic rubber tracks estimated at 1 cm is considered, and the maximum deformation of the electronic enclosure springs is also 1 cm, resulting in a total deformation of 2 cm. Then, to calculate the force of the fall, these values are first substituted into Eq. (1), where r is the distance between the point of contact and the center of mass, α is the angle of inclination, and h is the vertical distance traveled by the center of mass from the end of the ascent until the robot is in a horizontal position.

$$h = r(1 - \cos \alpha) \quad (1)$$

The value of 0.0175 m was obtained for h ; then the values were substituted into Eq. (2), where m is the total mass of the robot, g is gravity, and E is the energy generated by the robot's fall.

$$E = mgh \quad (2)$$

A value of 19.74 J was obtained for E . Finally, the values were substituted into Eq. (3), where d is the deformation in the wheels, structure, and springs when the robot's falling force is applied, and F is the falling force.

$$F = E/d \quad (3)$$

The result of the fall force is 981 N. The impact force of 981 N was obtained from the potential energy generated during the critical locomotion phase of the EOD robot and the estimated total deformation of the structure, tracks, and damping system during the impact observed in the JVC-02 tests.

B. CFD Analysis of the Electronic Enclosure

This section presents the configuration of the Computational Fluid Dynamics (CFD) simulation used to evaluate the thermal behavior of the electronic enclosure under the thermal conditions associated with EOD operations.

First, the parameters for the initial CFD simulation configuration were identified, considering the location of the electronic enclosure inside the chassis, as well as the environmental conditions of the city of Arequipa. The parameter values are shown in Table IV. The electronic enclosure is installed inside the chassis of the EOD JVC-02 robot. Then, the chassis structure was configured with slots and holes for air intake/exit, and the computational domain was defined as shown in Fig. 7.

TABLE IV. PARAMETERS FOR INITIAL CFD SIMULATION CONFIGURATION

Parameters	Values
System of units	SI (m, kg, s, K)
Type of analysis	Internal
Physical Features	Heat conduction in solids only
Project fluid	Air
Solid material by default	Steel Stainless 321
Heat transfer coefficient	10 W/m ² ·K
External fluid temperature	20.05 °C
Absolute atmospheric pressure	77 000 Pa
Initial internal temperature	20.05 °C

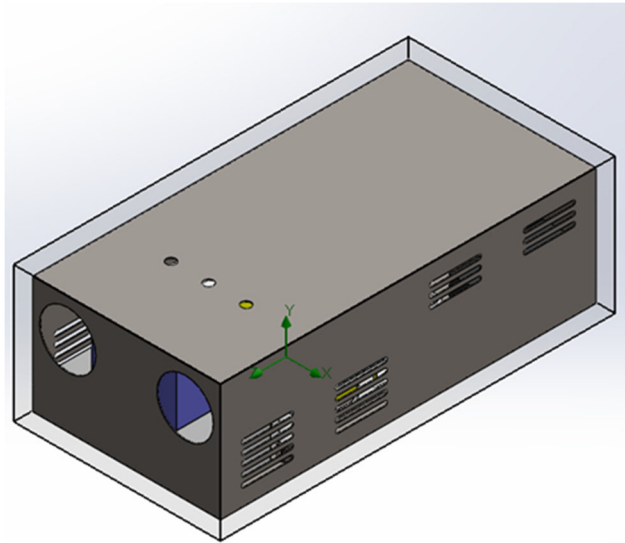


Fig. 7. Computational domain.

The ventilation parameters are shown in Table V below; these values were obtained based on the values of common and standard fans for applications similar to the one that is required to be analyzed in this work [34].

TABLE V. FAN PARAMETERS

Fan Parameter	Value
Diameter	120 mm
Thickness	25 mm
Nominal speed	1600 RPM
Maximum flow	160 m ³ /h (0.045 m ³ /s)
Maximum static pressure	65 Pa

The geometric and flow field conditions of the CFD simulation are summarized as follows. The electronic enclosure (Version 2.0), with dimensions of $340 \times 340 \times 150$ mm and an open modular structure with ventilation openings, is installed within the JVC-02 robot chassis in an available space of 390×350 mm. The chassis structure was configured with slots and holes for air intake and outlet, defining the boundaries of the computational domain for the internal flow analysis, as shown in Fig. 7. The working fluid is air, with an absolute atmospheric pressure of 77,000 Pa and an initial temperature of 20.05 °C for both the interior and exterior of the system, both adjusted to the real altitude conditions of the city of Arequipa. The flow is driven by a standard 120 mm fan operating at 1600 RPM, with a maximum flow rate of 160 m³/h (0.045 m³/s) and a maximum static pressure of 65 Pa. These conditions produced a mean air velocity of 0.31 m/s and a mean outlet static pressure of 77,000.70 Pa. From a fluid mechanics perspective, the velocity

trajectories reveal that air circulates at a speed that does not allow efficient thermal load absorption, and that, due to the current geometric configuration of the enclosure openings, a significant portion of the airflow fails to effectively penetrate the enclosure interior, which explains the high residual temperatures observed in the critical components.

The materials for analysis were then defined, with ABS plastic being the main material for the structure of the electronic enclosure. This material was selected for its ease of manufacturing, which allows for the creation of customized designs tailored to EOD robots. Furthermore, this choice helps keep the weight low due to the material's lightness. However, its thermal conductivity is lower than that of metallic materials, an aspect that was subsequently evaluated using CFD analysis. Next, stainless steel was used for the chassis and FR4-PCB (epoxy-glass) for the electronic components. The properties of each material are shown in Table VI.

TABLE VI. MATERIAL PARAMETERS FOR CFD ANALYSIS

Properties	Materials		
	Steel Stainless 321	ABS Plastic	FR4-PCB (epoxy-glass)
Density (kg/m ³)	7920	1050	1850
Thermal conductivity (W/m·K)	16.00	0.20	0.30
Specific heat (J/kg·K)	500	1300	1200
Melting point (K)	1725	533	780
Emissivity	0.80	0.95	0.90

V. SIMULATION RESULTS

A. FEA Results of the Electronic Enclosure

This section presents the results obtained from the Finite Element Analysis (FEA) of the electronic enclosure, including the evaluation of structural strength and rigidity under impact loads generated during locomotion on uneven terrain.

Subsequently, this calculated force was applied to the simulations of resistance and rigidity of the electronic enclosure structure using FEA analysis in SolidWorks software. ABS material was used for the simulation, and the safety factors and maximum deformations for each structural component were obtained, as can be seen in Table VII.

TABLE VII. STRESS AND STRAIN RESULTS OF THE ELECTRONIC ENCLOSURE WITH FEA ANALYSIS

Component of the Electronic Enclosure 2.0	Safety Factor (SF)	Maximum Deformation (mm)
Laterals	4.292	0.8067
Bottom	3.368	0.1585
Top	2.633	0.3218

For the lateral structure, the maximum stress of 13.35 MPa (FS = 4.292) is located at the rounded corners of the lateral openings, as shown in Fig. 8(a), while the maximum deformation of 0.8067 mm is located at the bottom beam of the lateral openings, as shown in Fig. 8(b). For the lower structure, the maximum stress of 17.01 MPa (FS = 3.368) is located at the holes in each corner, as shown in Fig. 8(c). The maximum deformation of

0.1585 mm is also located at the holes, as shown in Fig. 8(d). For the top structure, the maximum stress of 21.76 MPa (FS = 2.633) is located in the holes at each corner that connect to the other structures, as shown in Fig. 8(e). The maximum deformation of 0.3218 mm is also located in the same holes, as shown in Fig. 8(f). The following observations were made from the results obtained through FEA analysis:

- The critical safety factor (SF = 2.633) of the electronic enclosure occurs in the top structure and the maximum deformation (0.8067 mm) in the lateral structure; both values indicate structural integrity in terms of strength and rigidity.
- Critical areas can be clearly identified, with the holes in the corners being the area that requires attention due to possible structural failures.
- The beam of the lateral structure reaches a maximum deformation of 0.8067 mm in the electronic enclosure; however, this value is compensated by the support it receives when assembled with the upper and lower structures.

Finally, to verify the reliability of the results obtained from the FEA analysis, a mesh independence verification was performed on the critical components. The critical component in terms of deformation is the lateral structure, while the top structure is the one that exhibits the critical stress. Fig. 9 shows the convergence for both the critical deformation in the lateral structure, with a convergence rate of 0.944%, and the convergence for the critical stress in the top structure, with a convergence rate of 0.668%.

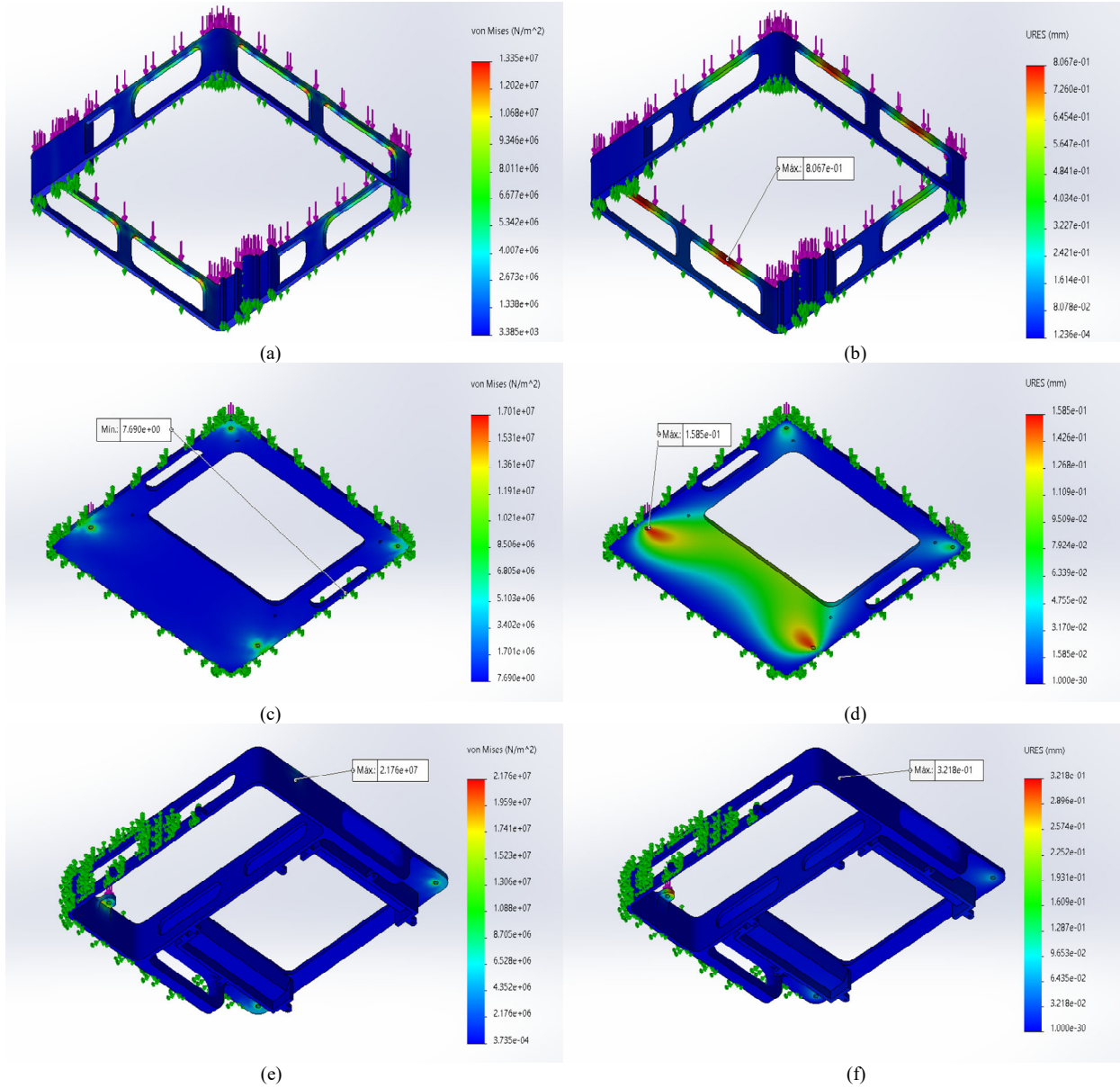


Fig. 8. FEA analysis results for the electronic enclosure: (a) stress in lateral structure, (b) deformation in lateral structure, (c) stress in bottom structure, (d) deformation in bottom structure, (e) stress in top structure, and (f) deformation in top structure.

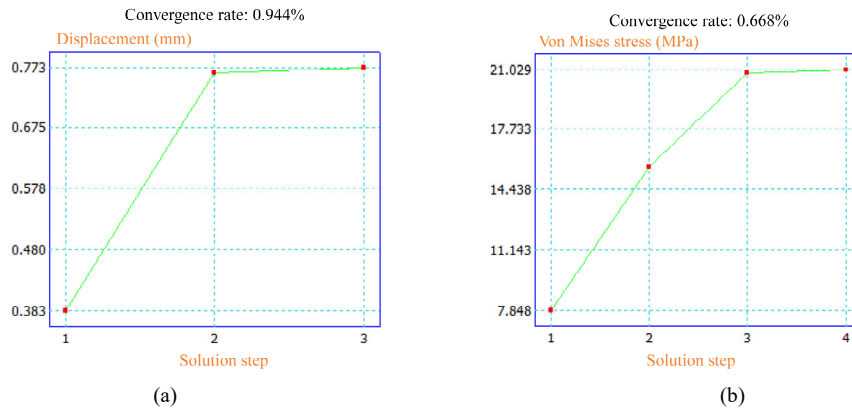


Fig. 9. Mesh independence study in critical components (a) deformation convergence in lateral structure and (b) stress convergence in top structure.

Table VIII below compares the results obtained in the original finite element analysis with those obtained in the mesh independence study. The maximum differences

observed were 4.18% for the deformation in the lateral structure and 3.46% for the safety factor in the top structure. These variations are less than 5%, confirming

that the results show adequate convergence and that the mesh size used provides consistent results. Therefore, the

credibility of the simulation results for evaluating the structural behavior of the electronic enclosure.

TABLE VIII. COMPARISON OF RESULTS FROM THE ORIGINAL FEA STUDY AND THE MESH INDEPENDENCE STUDY FOR THE CRITICAL COMPONENTS

Component	Parameter	Preliminary Study	Mesh Independence Study	Variation (%)
Laterals	Stress (MPa)	13.35	13.54	1.42
	Deformation (mm)	0.8067	0.7730	4.18
	FS	4.292	4.231	1.42
Top	Stress (MPa)	21.76	21.03	3.35
	Deformation (mm)	0.3218	0.3126	2.86
	FS	2.633	2.724	3.46

B. CFD Results of the Electronic Enclosure

This section presents the results obtained from the Computational Fluid Dynamics (CFD) analysis of the electronic enclosure, including the evaluation of temperature distribution and airflow behavior under the thermal conditions associated with EOD operations.

Next, the CFD simulation was run with the parameters presented in this section, as shown in Fig. 10. The global values were then defined as those results most relevant to

this study, reaching convergence after iteration number 102 for average static air outlet pressure and 152 for maximum electronic component temperature. The values for each result are shown in Table IX. In the electronic enclosure, the maximum temperature is 236.27 °C in the critical components, which is transferred to the designed structure until it is heated to a maximum temperature of 199.07 °C. The average air temperature is 24.99 °C and travels at an average speed of 31 cm/s.

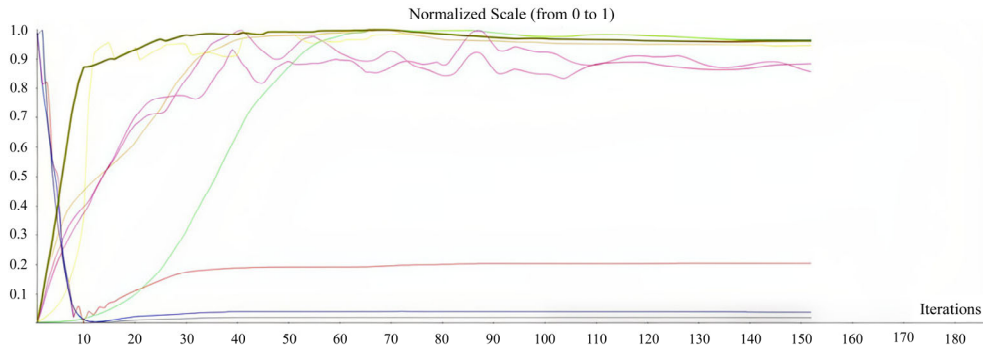


Fig. 10. Iteration and results of global values.

TABLE IX. RESULTS OF OVERALL VALUES

Global Values	Iteration No.	Value
Maximum temperature of the electronic box	138	199.07 °C
Maximum temperature of electronic components	152	236.27 °C
Average static pressure of the air intake	102	77000.60 Pa
Average air temperature	109	24.99 °C
Average air velocity	126	0.31 m/s
Average static air outlet pressure	102	77000.70 Pa

The following observations were made from the results obtained through CFD analysis:

- The temperatures of electronic components, such as the structure of the designed electronic enclosure, are reaching values that jeopardize the integrity of the device.
- The air temperature and velocity indicate that it is passing very quickly through the electronic components, absorbing little thermal load. Fig. 11 also shows the air trajectory, and it was identified that much of the air did not enter the electronic enclosure.
- In the electronic components, the maximum temperatures are found in the Raspberry Pi 3, as shown in Fig. 12(a), and in the L293D drivers, as shown in Fig. 12(b).

The extremely high temperatures predicted in the CFD simulation (236.27 °C in critical components) are

attributed to the combined effect of several factors. First, the airflow is inefficient: the simulation results indicate that air passes too quickly through the components, preventing adequate thermal absorption, and a significant portion of the air fails to enter the electronic enclosure, leaving critical components without effective cooling. Second, the enclosure is installed inside the JVC-02 robot chassis, sharing space with the batteries and motors, which generates a high-temperature environment that, combined with the heat dissipated by the electronic components themselves, contributes to overheating. Third, the ABS plastic used for the enclosure structure has a low thermal conductivity (0.20 W/m·K) compared to metallic materials, which limits heat dissipation to the exterior. These factors collectively explain the thermal behavior observed in the Raspberry Pi 3 and the L293D drivers as the most critical components.

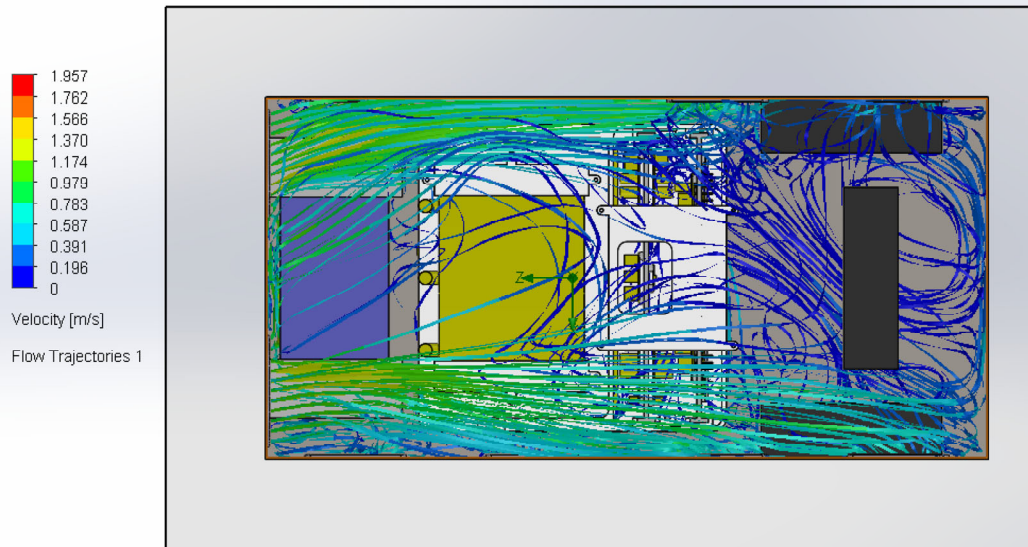


Fig. 11. CFD simulation of velocity trajectories.

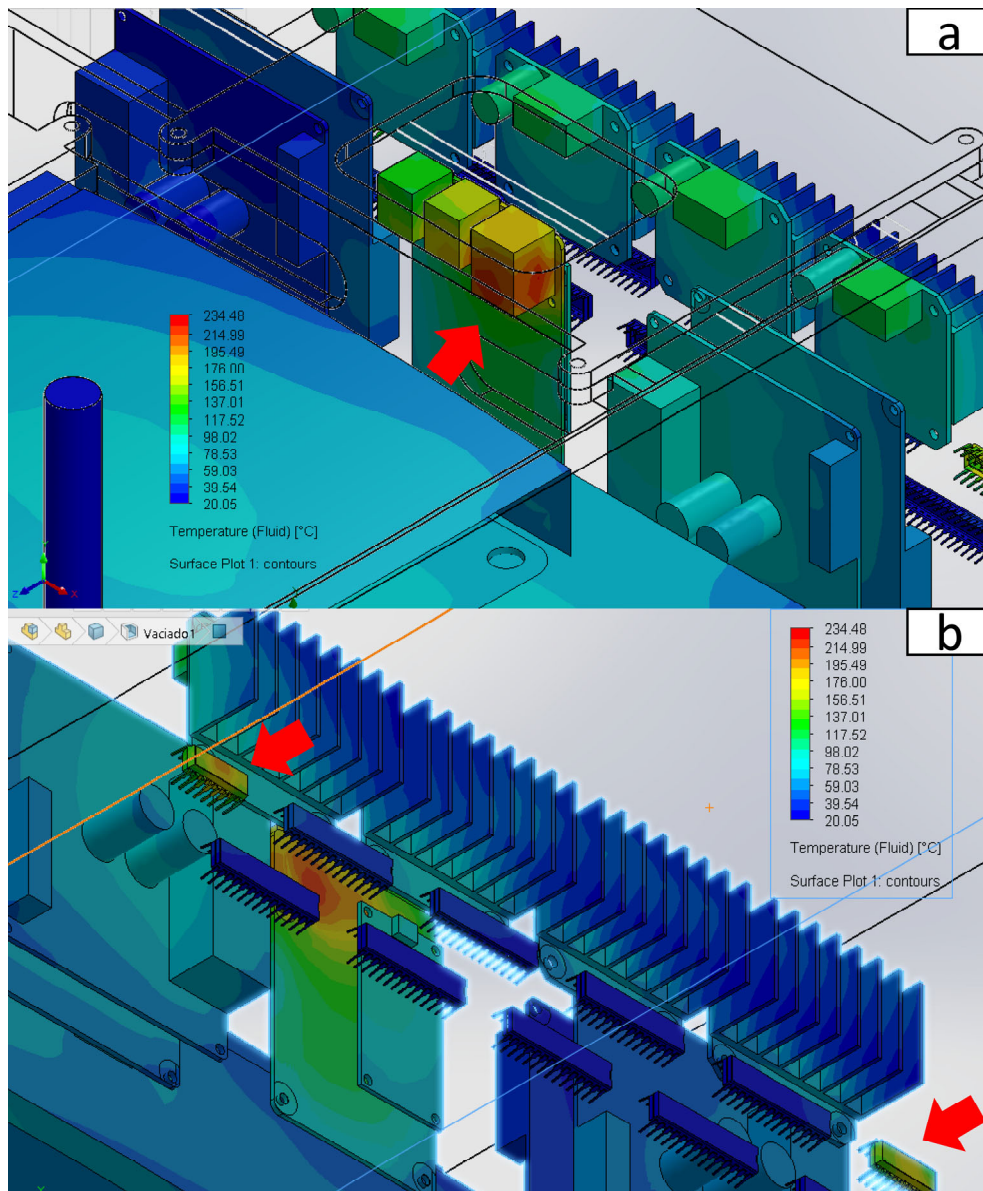


Fig. 12. Critical temperatures from CFD simulation: (a) Raspberry Pi 3 and (b) L293D drivers.

VI. DISCUSSION

This chapter analyzes the information from case study JVC-02, the requirements obtained based on the design of the first experimental version of the electronic enclosure, the results of the design of the second version of the device, as well as the review of mechanical aspects and the results of the CFD and FEA analyses, up to a comparison of the two versions of the electronic enclosure and, subsequently, a comparison with electronic enclosures reported in the literature.

The evaluation of the JVC-02 robot as a case study provided information for designing an electronic enclosure that meets the requirements of EOD operations.

The development of an experimental electronic enclosure provided a better understanding of what is required in EOD operations, generating up to six requirements, which are: structural design, rigidity and strength, thermal dissipation, damping, stability, and modularity.

The application of reverse engineering to the electronic components in the case study and the use of the SolidWorks tool enabled the creation of a precise mechanical design that met the requirements, with an open structure for ventilation and ease of inspection and maintenance, a damping system that minimizes impacts and damage to electronic systems, a low-height design that reduces the center of mass and provides greater stability to the chassis and robot in general, and four removable modules that provided modularity to the design and allowed for easy assembly and disassembly during maintenance.

The FEA analysis identified the critical values and areas of the mechanical design with the critical impact load that occurs in EOD operations, with a minimum safety factor of 2.633 in the top structure and a maximum deformation of 0.8067 mm in the lateral structure. The critical areas occur in the corner holes of all components that are directly coupled to the damping system, indicating that greater attention should be paid to these areas. This analysis demonstrated the structural integrity of the proposed design.

It should be noted that a direct quantitative comparison with existing commercial EOD robot enclosures was not possible in this study, as performance and durability data for such enclosures are not publicly available in the

literature. CFD analysis allowed for thermal evaluation and identification of critical values and components of the electronic enclosure under the thermal conditions of EOD operations. Parameterization with real values from the case study provided a reliable CFD simulation, identifying the Raspberry Pi 3 and the L293D driver as critical components. The simulation also demonstrates that the design requires a directed ventilation system to redirect airflow toward the critical components, particularly the Raspberry Pi 3 and the L293D drivers. The high temperatures predicted are a consequence of inefficient airflow, the thermally demanding environment inside the chassis shared with batteries and motors, and the low thermal conductivity of ABS plastic (0.20 W/m·K). Addressing these factors through directed ventilation or the use of materials with improved thermal properties is, therefore, a mandatory consideration for future design iterations to ensure the integrity of the electronic components under EOD operating conditions.

Next, a comparative analysis was performed of the improvements offered by the new electronic enclosure design, analyzed with FEA and CFD methods (version 2.0), with respect to the experimental version (version 1.0) as shown in Table X. The height of the electronic enclosure was reduced to 150 mm, reducing the height by 40%. The base was expanded to 115,600 mm², increasing the footprint by 37.62%. The total volume was reduced to 17,340,000 mm³, reducing the volume by 17.43%. The total weight was reduced to 4408.67 g, representing a reduction of 2.03%. The following observations can be made from these results:

- The reduction in height allows the robot's center of mass to be closer to the base, offering a design with greater stability when moving over rough and sloping terrain. On the other hand, the expansion of the footprint indicates better use of the base area available in the chassis. This variation in dimensions results in an overall reduction in volume, demonstrating that a compact design can be achieved.
- Although the weight was reduced only minimally, the use of materials such as ABS allowed for customization of designs and provided modularity.
- The use of CFD and FEA methods allowed us to design an electronic enclosure with characteristics closer to those required in EOD operations.

TABLE X. COMPARISON OF PARAMETERS OF ELECTRONIC ENCLOSURE VERSIONS 1.0 AND 2.0

Parameters	Electronic Enclosure Version	
	1.0	2.0
Dimensions (mm)	300 × 280 × 250	340 × 340 × 150
Footprint (mm ²)	84,000	115,600
Volume (mm ³)	21,000,000	17,340,000
Material	Aluminum	ABS plastic
Total weight (g)	4500.00	4408.67
Structural verification (strength)	NO	SI
Structural verification (rigidity)	NO	SI
Thermal verification	NO	SI

Finally, in addition to comparing versions 1.0 and 2.0 of the electronics enclosures presented in this paper, a comparison was made with electronics enclosures used in

radiological monitoring robotics, submarine robotics, and CubeSat space systems, as shown in Table XI. The

comparison was based on the design requirements for EOD operations, as shown below:

- **Structural design:** The Radiological Electronic Enclosure [20], the Underwater Electronic Enclosure [21], and the SpaceCube system [22] were developed for their specific applications. In contrast, the proposed housing has an open structure that facilitates ventilation, inspection, and maintenance of the electronic components during EOD operations.
- **Rigidity and strength:** Unlike previous designs, such as the Radiological Electronic Enclosure, where the focus was on increasing the housing's thickness to provide greater rigidity, the Electronic Enclosure EOD 2.0 was verified through FEA analysis under impact loads representative of the JVC-02 robot's operation, demonstrating its structural integrity.
- **Heat dissipation:** The Underwater Electronic Enclosure [21] and SpaceCube [22] take into account thermal aspects such as the thermal stability of their components and thermal paths, respectively; however, this study used CFD simulations to identify critical components and evaluate thermal behavior under conditions representative of EOD operations.
- **Shock Absorption:** Unlike the revised enclosures, the proposed enclosure incorporates a shock absorption system designed to minimize the impact forces that could affect the electronic components while the robot is in motion.
- **Stability:** Reducing the height of the chassis and repositioning internal components lowers the center of mass of the JVC-02 robot, improving its stability on uneven and sloped terrain. Similarly, the Radiological Electronic Enclosure [20] takes into account the design and placement of the electronic enclosure within a rover to contribute to the system's stability.
- **Modularity:** While SpaceCube [22] uses a modular architecture based on interchangeable cards and the Underwater Electronic Enclosure [21] integrates functional modules for navigation and sensing, the Electronic Enclosure EOD 2.0 uses removable modules specifically designed to facilitate assembly, disassembly, and maintenance during EOD operations.

TABLE XI. COMPARISON OF ELECTRONIC ENCLOSURES BASED ON EOD DESIGN REQUIREMENTS

Design Requirement	Radiological Electronic Enclosure [20]	Underwater Electronic Enclosure [21]	Space Cube [22]	Electronic Enclosure EOD 2.0
Structural Design	Partial	Partial	Partial	Yes
Stiffness and Strength	Partial	NR	NR	Yes (FEA)
Heat Dissipation	NR	Partial	Partial	Partial (CFD)
Damping	NR	NR	NR	Yes
Stability	Partial	NR	NR	Yes
Modularity	Partial	Partial	Yes	Yes

Note: NR: Not Reported in the referenced study. Partial: The requirement was partially addressed or considered for purposes different from EOD operations.

VII. CONCLUSION

In this study, a novel electronic enclosure was designed and evaluated from an application perspective for the external conditions of EOD robot operations, using an FEA-CFD analysis method.

The design was based on a case study of a JVC-02 EOD robot from UDEX to develop a first version of an experimental electronic enclosure. Then, based on locomotion tests under thermal conditions common in EOD operations, the requirements for optimizing subsequent designs were determined.

Subsequently, a second version of the electronic enclosure was designed to meet the requirements and was first evaluated using FEA, obtaining a safety factor of 2.633 and maximum deformations of 0.8067 mm, values that guarantee the structural integrity of the design. It was then evaluated using CFD, which identified the Raspberry Pi 3 and the L293D driver as the thermally critical components.

Finally, in the comparative analysis of the electronic enclosure versions, it was possible to reduce the volume by 17.43% and the height by 40%, demonstrating that the design of EOD robot electronics enclosures can also be compact, improving the stability of locomotion in EOD operations.

Future research should consider the following recommendations:

- Analyze the design of a thermal dissipation system that efficiently redirects airflow to critical components.
- The design was evaluated using ABS material; however, studies using other materials with better thermal characteristics should be considered.
- The results of this study, obtained through numerical simulation, must be corroborated through a three-stage verification process: (1) physical manufacturing of the Version 2.0 prototype; (2) laboratory testing in controlled environments to compare real structural and thermal behavior against the FEA and CFD simulation predictions; and (3) field validation on a real EOD robot, verifying that the enclosure withstands impact loads on uneven terrain and the extreme thermal conditions characteristic of EOD operations in environments such as Arequipa. This staged process, from virtual model to prototype, and from laboratory to field, will ensure the reliability of the design before operational implementation.
- In future research, experimental thermal validation studies and a mesh independence study should be conducted to further ensure the reliability of the CFD results presented in this study
- A dedicated dynamic vibration analysis should be conducted in future research to further validate the robustness and vibration resistance of the proposed modular design under continuous EOD robot operation conditions.

- Future research should evaluate the following specific ventilation and active cooling strategies to mitigate the thermal issues identified in the CFD results: (1) redesign the ventilation system to direct airflow specifically toward the critical components identified in the simulation, namely the Raspberry Pi 3 and the L293D drivers, avoiding circulation through thermally inactive zones of the enclosure; (2) optimize the geometry and placement of the enclosure openings to improve air penetration into the modular structure, given that the current configuration allows a significant portion of the air to bypass the enclosure interior; and (3) evaluate enclosure materials with higher thermal conductivity than ABS (0.20 W/m·K), as the current material acts as a thermal insulator and limits heat dissipation to the exterior.
- A quantitative comparison of the proposed enclosure design with existing commercial EOD robot enclosures should be conducted in future research, once technical performance and durability specifications become publicly available, in order to further validate the competitiveness of the proposed design.

These recommendations will be addressed in future research to optimize the design, analysis, and development of electronics enclosures applied to EOD operations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

EGM and WH performed the main designs, simulations of the electronic enclosure versions, and drafted the manuscript. YLS and EVF reviewed and corrected the manuscript for submission. All authors have approved the final version of the manuscript.

ACKNOWLEDGMENT

The authors would like to thank the National University of San Agustín in Arequipa for its support in designing the electronic enclosure. They would also like to thank the Arequipa Explosive Ordnance Disposal Unit (UDEX) for its support in providing information on the explosive ordnance disposal robot.

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