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Development of an EOD Robot for the Arequipa Explosive Disposal Unit

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***Abstract*—The JVC 0.2 is an Explosive Ordnance Disposal (EOD) robot with tracks, a 5 Degrees of Freedom (DOF) arm, and a two-finger gripper developed by the National University of San Agustin (UNSA) and the Explosive Ordnance Disposal Unit of the Police of Arequipa (UDEX) in response to the technical needs of adequate weight for manual transport in compliance with the law 29,088 in force in Peru, urban multi-terrain locomotion skills, robotic arm control and handling of explosive objects with sizes and weights registered in the UDEX database. The objective of this document is to develop and test the robot for maneuverability, locomotion, and arm strength based on National Institute of Standards and Technology (NIST) standards adapted to the needs of UDEX to safeguard the lives of Explosive Ordnance Disposal Specialists (TEDAX). The test procedures were carried out to evaluate the robot's capabilities in terms of maneuverability and were designed to time the transport of objects simulating explosives at different inclinations to a container. The tests showed us that the actuation time of the robotic arm was improved, that it can climb stairs with a maximum inclination of 20°, that the locomotion speed measured on flat ground was 10.94 cm/s and that the load capacity at the extended arm is 9 kg. Finally, we conclude that it is necessary to update the design of the robot to reduce the weight to meet the safety standards at work, increase the load capacity up to 10 Kg, and improve mobility; so that, it becomes of daily use by the TEDAX.**

***Keywords*—Explosive Ordnance Disposal (EOD) robot, robotic arm, gripper, explosive, design, tracks**

I. INTRODUCTION

According to the Statistical Yearbook of Crime and Citizen Security for 2011–2016 of the National Institute of Statistics and Informatics (INEI), 1,739 people have been sentenced for crimes against public security in Peru under the modality of manufacturing and illegal possession of weapons, ammunition, and explosives [1]. To neutralize these threats to the public and institutions in Peru [2–6], the explosives handling technicians (TEDAX) of the Explosives Disposal Unit (UDEX) detect, effectively and safely isolate and deactivate Improvised Explosive Devices (IEDs), ammunition, etc. [7]. To reduce the risk of physical damage from TEDAX during the deactivation of explosives without compromising the speed and precision of the intervention, the UDEX together with the National University of San AgustÍn (UNSA) of Arequipa developed the technology for the local construction of Explosive Disposal Robots (EOD).

The first EOD robot product of this collaboration, JVC 0.1 [8], is a design conformed by an Unmanned Ground Vehicle (UGV) driven by caterpillar tracks, a 4 Degrees of Freedom (DoF) robotic arm and a three-finger gripper shown in Fig. 1. This robot is built with local materials and equipment from the city of Arequipa, the results of its exhaustive evaluations based on the National Institute of Standards and Technology (NIST) standards of performance in the field testing and simulation in urban terrain are the basis of the following versions following the iterative method of development and testing. As a result of the tests, the need for a new iteration of design evaluating the UGV's portability, weight, maneuverability, powertrain range, and manipulator to satisfactorily meet the requirements of the UDEX-Arequipa becomes apparent.

Fig. 1. Robot JVC 0.1 [9].

To satisfy the technical needs of UDEX, in this new iteration, the performance of EOD robots around the world has been evaluated, which are built, designed, and evaluated under their requirements with their rigorous technical tests.

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These designs have evolved to meet the specific needs of their nations, states, and institutions, for example, the design of some robots focused on the payload-to-weight ratio to make it more portable for ground personnel [10, 11], and others in offering a good perspective for the operator and facilitating robot control by increasing the Human-Robot Interaction (HRI) [12, 13], finally, designs focused on improving and adapting a robotic arm have been explored, designed for handling objects surrounding the explosive and the explosive with the strength, precision, and delicacy necessary for its handling, safeguarding the integrity of TEDAX and its counterparts around the world [14, 15]. The VALI robot (Light Anti-explosive Vehicle) [16] is an example of the technological development of EOD robots in Latin America in a line of research similar to that developed by UNSA. This project had technical problems related to control and maneuvering in its first versions, these technical defects were corrected by improving its load-weight ratio, its stability, the perspective of its operator with the camera system installed at key points and a Wide Dynamic Range (WDR) gripper that has some protection against rain, dust, humidity, and solar radiation, making it suitable for service to the Colombian Armed Forces (FFAA) in its commercial version called Rodex EOD 1.0 [17–19].

The JVC 0.2 is the second iteration of this program, it is equipped with a track-driven UGV, lighter than its predecessor, an arm with five degrees of freedom, and a two-finger gripper (See Fig. 2). Its design, based on JVC 0.1 flaws, has shown increased technical capabilities over this version in team-designed tests based on NIST and American Society for Testing and Materials (ASTM) testing [20–24] fully oriented to robots that respond to emergencies in object manipulation skills, rotating test targets geometrically designed based on the most common Improvised Explosive Devices (IEDs) according to UDEX statistics [25], UGV dexterity when climbing stairs and an inclined plane in a controlled environment, simulating the usual work area of TEDAX personnel, moving in a simulated environment, opening doors and using speed tools. The result of these tests contrasted the technical differences between both designs and will also be the basis for a third model.

Fig. 2. Robot JVC 0.2.

This document aimed to develop and evaluate the JVC 0.2 EOD robot on portability, Human-Robot Interaction (HRI), locomotion dexterity, and work of the robotic arm and manipulator together, using the results of JVC 0.1 to meet the technical needs of the UDEX Arequipa and lay the foundations for a future version.

II. METHODOLOGY

The development of this document follows a design sequence (Fig. 3), which begins with the collection of requirements based on the needs of UDEX considering the safety and health at work regulations of the law in force in Peru 29088, then various design concepts were proposed and through a qualitative-quantitative qualification method the best scoring concept was selected, then the mechanical design of the EOD robot was performed with the assistance of SolidWorks software, for subsequent kinematic analysis, torques and components by Finite Element Analysis (FEA). Finalizing the construction and testing of the robotic prototype with different skill tests and the Failure Mode and Effects Analysis (FMEA) matrix. Following a design methodology based on Bauhaus.

The industrial design movement [26] Bauhaus is characterized by emphasizing beyond functionalism, the importance of geometry, precision, simplicity, and economy of design [27], which is why in the development of the JVC 0.2 robot these principles are applied by dividing the methodology according to the technical needs of the TEDAX and logistics of the UDEX.

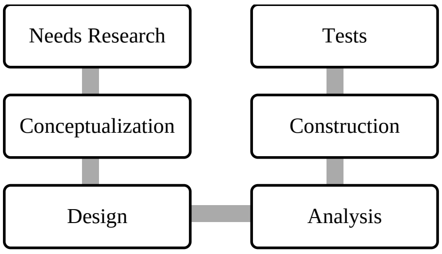


Fig. 3. Design sequence for JVC robot 0.2.

(1) Investigation of needs: In this chapter, the technical design requirements are obtained from interviews with the TEDAX, DHS recommendations, and current legislation in the Peruvian territory.
(2) Conceptualization: This chapter presents a design concept resulting from an iteration of technologies used in similar projects.
(3) Design: Respond to the needs and the concept of the previous chapters. This chapter details the design of the robotic gripper, the UGV, the robotic arm, and the selection of materials.
(4) Analysis: Before the construction, it is necessary to simulate the robot arm to evaluate the behavior of the links and the gripper in a critical work situation.
(5) Construction: The robot has been built with slight modifications to the original model that solved the problems that appeared while it was being assembled.

(6) Tests: To evaluate and compare the technical capabilities of the robot and its predecessor JVC 0.1, designed tests, based on international standards, have been submitted.

III. INVESTIGATION OF NEEDS

In this second iteration, the list of UDEX requirements was updated, as well as the latent, hidden, and explicit needs of the institution to be covered, and the current occupational health and safety regulations in Peru were considered. With all this information, the needs to be met with this design are listed (see Table I).

TABLE I. UDEX-AREQUIPA TECHNICAL NEEDS

Technical Needs	**Description**
Weight	Less than 100 kg
Workspace	1m from UGV chassis
Load Capacity	10 kg to the extended arm
Gripper	Adaptable to the IED geometry
Kinematic Chain	Maneuver 15% faster than JVC 0.1 with 5 DOF
UGV Mobility	Off-road at a speed greater than or equal to 1 km/h

(1) Weight: The robot must be light and easy to transport to be carried by hand by a team of 4 people, to comply with the requirements of the Occupational Health and Safety Law in force in Peru, Law No.° 29088 [28] must not exceed 100 kg.
(2) Workspace: The kinematics of the arm must be able to maneuver 1 m from the limit of the chassis [29].
(3) Load capacity: The arm must be capable of lifting loads of 10 kg at arm's length, this value represents 97% of all explosive devices found in Arequipa in the period 2013–2020 [25] and data from the Department of Homeland Security (DHS) [30, 31].
(4) Gripper: This should easily adapt to the geometry of cylindrical and spherical objects that are generally used in the design of grenades, dynamite sticks, etc. In the first version of the robot, deficiencies were observed in the 3-finger gripper separated by 120°, considerably reducing its effectiveness by varying the angle of attack [32–34].
(5) Kinematic chain: Considering the robotic arm a kinematic chain that will have the explosive ordnance handler mounted at the end, the design has been inspired by a human arm with two degrees of freedom at the shoulders, one at the elbow, two in the wrist, resulting in the value of 5° of freedom [35–37].
(6) UGV travel speed: The speed of the JVC 0.1 is 1.2 km/h which was considered acceptable, the new design should move at a minimum of 1 km/h according to the NIST recommendations and the UDEX staff user experience.
(7) Maneuvering speed of the kinematic chain: The average speed of the arm actuation must be at least 15% higher than that of the JVC 0.1 as required by the UDEX staff.

IV. CONCEPTUALIZATION

The concept of the JVC 0.2 robot stems from the technology applied in rescue robots, object handlers, and other EOD robots. In this chapter, different design concepts for the robot modules are compared, and the one that best suits the needs of the Arequipa UDEX is selected, using a qualitative-quantitative rating method, scoring the collected concepts according to their level of affinity with the requirements of Section III.

A. Design Requirements

The requirements of Table I become target technical specifications for each module of the robot that is made up of which are UGV, the object manipulator, and the robotic gripper. Fig. 4 groups the needs that are related to each other through the module that will be designed to meet them.

(1) UGV: The design will be lightweight with the ability to overcome terrain, obstacles, and working conditions of a stochastic nature at an average speed of 1 km/h.
(2) Robotic Arm: It will be at least 15% faster than the JVC 0.1 with a range greater than 1 m and 5 DOF.
(3) Gripper: Its design will adapt to the different explosives that could be found.

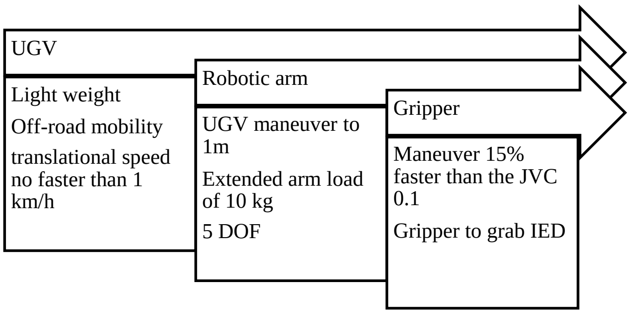


Fig. 4. Relationship between technical needs and aims.

This project is aligned with the concepts of modular architecture due to the facilities it offers regarding the parallel work of efficient design and construction of all the robot modules [38]. The operation of each JVC 0.2 module is defined by its contribution to the final task of moving explosives safely, about this (see Fig. 5).

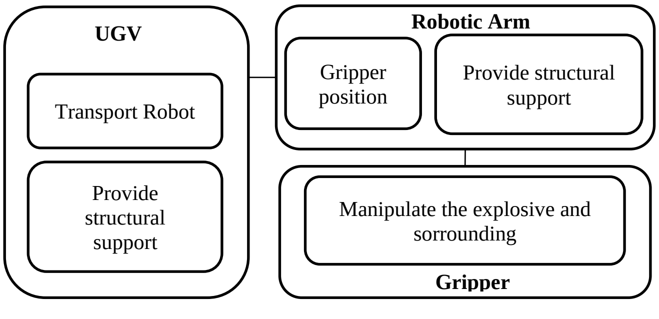


Fig. 5. JVC design architecture 0.2.

(1) The UGV is in charge of moving the robot and providing structural support to all the other modules.
(2) The robotic arm positions the gripper and provides it with structural support
(3) The gripper is responsible for manipulating the explosive and the surroundings.

B. *Compilation of Solutions*

UGV: To fulfill the task of moving the robot, it is considered that the robot has to be stable throughout the entire journey due to the volatility of the Improvised Explosive Devices (IED) that it will lift and carry in the gripper, it must be maneuverable and adaptable to the terrain of dynamic geometry. The technological concepts of symmetrically distributed wheels asymmetrically distributed wheels, and caterpillars are considered for their capabilities and technical advantages, which are:

(1) Symmetrically distributed wheels: This technology provides better stability and balance to the robots, maneuverability, efficient rotation on its axis, reduction of mechanical efforts, and ease of control, however, they are limited in terrain complex, less stable on sloping terrain and have a capacity of load limited by the variation that this causes to the center of gravity.
(2) Asymmetrically distributed wheels: A robot with asymmetrically distributed wheels has an agility advantage in complex terrain, superior traction by placing the wheels in strategic places, and an optimization of the payload that could help to distribute better the weight of the arm when in motion next to the explosive, however, the complexity of the design is increased, along with the demand for control precision and load sensitivity.
(3) Tracks: Tracked robots have advantages with excellent traction, stability and load capacity, good maneuverability, and uniform weight distribution, however, their speed is limited, they consume a lot of energy and they are complex systems that have many parts and subsystems to repair.

ROBOTIC ARM: When designing a robotic arm, the complexity of the movements required for the task to be executed must be considered, in addition, it must be taken into account that increasing the degrees of freedom also increases the design costs or, manufacture and, maintenance of the final product. For this work, 3°, 4°, and 5° of freedom have been considered as they are the most frequently found in robots that manipulate objects geometrically similar to the explosives considered for the design.

GRIPPER: The 2-finger grippers have a smaller gripping surface; however, they can adapt to any geometrical space and due to their reduced number of parts they are more frequently used. While the 3-finger grippers, depending on the angle between the fingers, will adapt to different objects, the 120° are the most common and adapt only to regular objects.

According to the design architecture in Fig. 5, a product of the literature compilation of different technologies applied in rescue and EOD robots, these technologies were organized into 3 groups (moving the robot, positioning the gripper, and manipulating the explosive and its environment) as shown in Table II, where the technologies of asymmetrically distributed wheels, symmetrically distributed wheels, and tracks are ideal concepts for locomotion in rough terrain, the technologies of gripper positioning frequently used to correctly position the gripper are 4, 5, and 6 DOF, symmetrically distributed and crawler technologies are ideal concepts for locomotion in rough terrain, the gripper positioning technologies frequently employed to correctly position the gripper are 4, 5, and 6 DOF, finally the 2 and 3 finger gripper technologies are the best performing for handling explosive ordnance. This is used as a basis for combining and deriving design concepts (see Table II).

TABLE II. COMBINATION OF CONCEPTS

Module Tasks	Technology Concepts
Robot Movement	Asymmetrically distributed wheels [39, 40].
	Symmetrically distributed wheels [41–43].
	Tracks [44–47].
Position the clamp	4 DOF [10, 48–50] 5 DOF [51]. 6 DOF [35, 52]
Handle the Explosive	2-finger gripper [10, 53, 54]. 3-finger gripper [55–58]

C. *Concept Selection*

We reviewed and evaluated 3 off-road mobility concepts (tracks, asymmetrically distributed wheels, and symmetrically distributed wheels), 3 robotic arm concepts (4.5 and 5 DOF), and 2 gripper concepts (Gripper with 2 and 3 fingers) on a concept assessment matrix (Table III).

TABLE III. CONCEPT EVALUATION AND SELECTION TABLE

Selection Criteria	**UGV**			**Robotic Arm**			**Gripper**	
	Wheels asymmetrically distributed	Wheels symmetrically distributed	Caterpillars	4 DOF	5 DOF	6 DOF	2 fingers	3 fingers
Maintenance	2	3	3	3	2	1	3	2
Manufacture	1	3	2	3	2	1	3	1
Maneuverability	1	3	3	3	2	1	3	2
Light	1	3	3	3	2	1	3	2
Adaptable to the environment	3	1	2	1	2	3	2	3
Cost	2	3	3	3	2	1	3	2
Punctuation	10	16	16	16	12	8	17	12

For the evaluation of the concepts, the following selection criteria were applied:

(1) Maintenance: Ease of being able to perform maintenance and repair activities on all components.
(2) Manufacturing: Refers to the availability of parts and the level of difficulty for the construction and assembly of the components.
(3) Maneuverability: Ease at carrying out different maneuvers by the user.
(4) Light: Refers to the weight of the assembled set and must be as light as possible for ergonomic and energetic reasons.
(5) Adaptable to the surroundings: Easy to move through different surroundings and handle explosive objects of varied geometry.
(6) Cost: It refers to the cost of the required parts and manufacturing service available in the local market.

Table III shows that the selection criteria were placed in the first column, and at the top of the table are the concepts proposed for each component of the robot, for the qualification of the concepts, a scale from 1 to 3 was used. where 1 is Not Recommended, 2 is Regular, and 3 is Recommended.

After giving the rating respectively to each concept, the sum of the rating of each criterion is made and it was concluded that for UGV it is advisable to design a chassis with a caterpillar locomotion system (Score: 16), for the robotic arm. it is recommended to design it with 4 DOF (Score: 16) and for the gripper, 2 fingers are recommended (Score: 17).

V. DESIGN

A. *Design Concepts and Architecture*

The robot design update is mainly based on the results obtained from the EOD JVC 0.1 robot, in addition to the requirements requested by UDEX and the ordinary resources present in this institution and in the Peruvian market. The new robot will comply with the following list of requirements summarized in Table IV.

TABLE IV. REQUIREMENTS OF DESIGN FOR THE NEW ROBOT

Requirements	Description
Structure	Weight less than 100 kg
Workspace	Range from 0 to 1m from the chassis
Load Capacity	10 kg to the extended arm
Gripper	2 fingers
Freedom degrees	5
Conditioning System	12V DC motors with mechanical brake gearboxes
Action Speed	Overcome in 15 percent to the JVC01

B. *Mechanical Design of the Robot*

The robot has been divided into two subsystems that comprise the two functional parts of the robot that work together to move the robot through the terrain and manipulate the explosive device and its environment (Fig. 6). The first subsystem is the manipulation subsystem that has the objective of manipulating the explosive devices, this subsystem comprises the joint work of the robotic arm and the gripper that in their interaction fulfill this objective. The second subsystem is locomotion, it has the objective of moving the robot through complicated environments taking the IED to a safe zone of deactivation or explosion, this comprises the work of traction of the tracks and the structural support of the chassis in their interaction fulfill this objective.

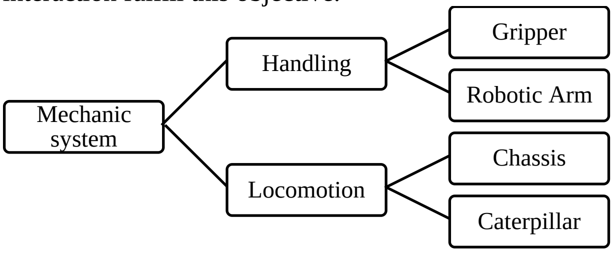


Fig. 6. Mechanical system division.

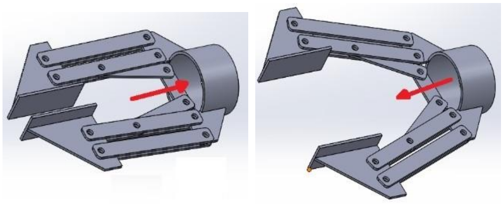
C. *Handling Subsystem*

The robotic gripper is in charge of handling the explosive, therefore it must have a good grip, prevent slippage, and be able to easily adapt to different geometries. Two-finger robotic grippers are the simplest and most effective for handling cylindrical and spherical objects, as well as being easy to manufacture and low cost [34]; The gripper in Fig. 7 was designed to overcome the required load considering a load of 15 kg carrying out the calculation of the minimum gripping force assuming a coefficient of friction of 0.3 at 245 N. Generally, in a mechanism a smaller number of possible elements is expected, however, in this gripper 12 joints and 13 rigid elements were used to keep the planes that come into contact with the target with an opening parallel at all times. maximum of 150 mm considering that the grip area is covered with EVA rubber for better adaptability to objects, to keep loads evenly distributed on the gripper structure, and to provide acceptable accuracy for operators.

Summarizing the technical characteristics in Table V.

TABLE V. GRIPPER TECHNICAL CHARACTERISTICS

Characteristics	Parameters
Displacement (screw)	30 mm
Clamp opening	150 mm
Clamping force	245 N
Maximum load	15 kg



(a) (b)

Fig. 7. Gripper: (a) Closed; (b) Open.

The robotic arm has been designed to move, rotate, and position the object handler for the correct grasp and transfer of the explosive device.

The concept to be developed must have the following characteristics: 5 DoF with 4 rotational articulations of one DoF each (Fig. 8). Support a load of 10 kg in the end effector and use of low-cost motors coupled to gearboxes with mechanical brakes.

Fig. 8. Robotic arm.

D. Locomotion Subsystem

The chassis is the component on which the robotic arm and the locomotion system are installed, it is also the one that receives all the loads coming from the mass of the vehicle circle, mass of explosives, wheel drive, shock, and vibration.

The locomotion system is responsible for providing translational movement to the EOD robot, and it must be able to resist the dynamic loads generated by the movement of the robot and the transmission system, it must also move at such a speed that the risk of unintentional explosions of the explosive device is minimized.

To meet the technical requirements of the chassis, a design that adapts to the requirements is the one developed in Colombia, where the EOD VALI 1.0 robot was developed, whose chassis is composed of a topologically optimized duralumin sheet, in its next version EOD VALI 2.0 the structure was changed to a cast aluminum one, also with topological optimization [7], the proposed robot will be of a design with topological optimization made up of structural profiles with welded joints which allows a significant weight reduction compared to the first JVC-01 model (See Fig. 9).

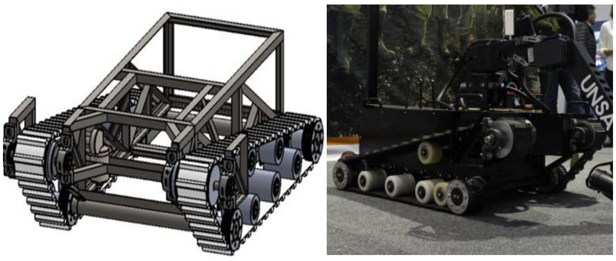


Fig. 9. Locomotion subsystem.

E. Material Selection

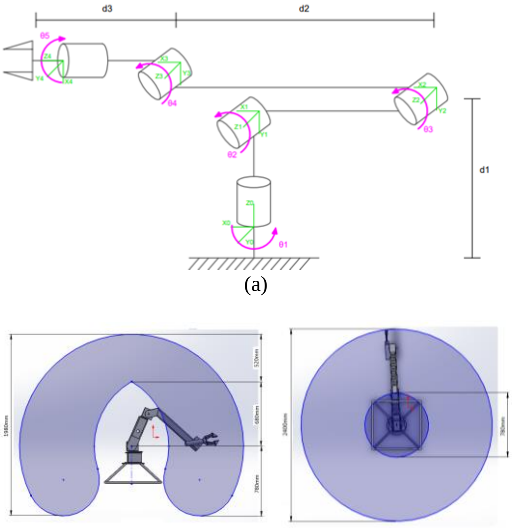
The material with the mechanical and chemical properties [25] that best adjusts to the stiffness-weight ratio required to support the required load of 10 kg at arm's length and its weight, easy to machine and welded, low cost, and high availability is ASTM A36 [25]. The profile used in the links was selected to give the necessary space to the circuity, controllers, sensors, etc. Therefore, it can be mentioned that the concept of the JVC 0.2 robot tries to surpass its predecessor (JVC 0.1 robot) in technical capabilities, satisfactorily responding to the requirements of the design of the robotic gripper, the links of the arm and the chassis, where kinematic analysis, torque analysis, and finite element analysis are used to check the effectiveness of the design.

VI. ANALYSIS

In this section, the proposed robot is analyzed in three aspects: kinematic analysis to find the workspace, torque analysis for motor selection, and component analysis to corroborate the mechanical resistance of the critical parts.

A. Kinematic Analysis

To determine the working space of the robotic arm, kinematic analysis was developed using the Denavit Hartenberg method, which can be controlled by adjusting the dimensions or limiting the angles between links to achieve the desired working space [59] (see Fig. 10).



(a)

(b)

(c)

Fig. 10. Kinematic analysis, (a) Kinematic diagram; (b) Workspace side view; (c) workspace plan view.

First, the relative reference systems in the joints and links of the robotic arm were assigned as seen in the kinematic diagram (Fig. 10(a)). Then the rotation and translation of each reference are estimated by 4 basic transformations and the D-H parameters are determined, see Table V. The result of these parameters and equations is represented in a point cloud as shown in Fig. 10(b)–(c).

Fig. 10(b) shows the lateral view, showing the vertical and horizontal range. In Fig. 10(c), the workspace is observed in a plan view, where the robotic arm performs its work in the form of a ring around the chassis.

TABLE VI. D-H PARAMETERS

Articulation	θ	di	a	α
1	$\theta 1$	$d1$	0	270°
2	$\theta 2$	0	$d2$	0
3	$\theta 3$	0	$d3$	0
4	$\theta 4 + 90°$	0	$d4$	90°
5	$\theta 5$	0	0	0

B. *Torques Analysis*

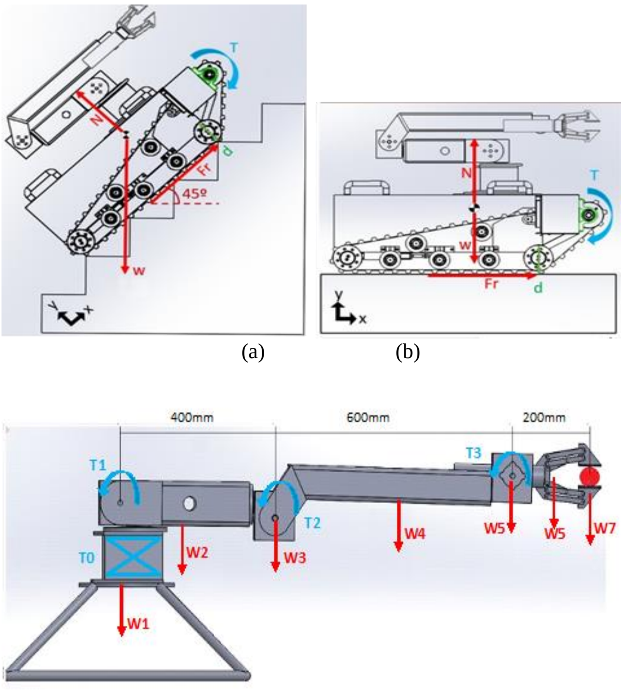
For the analysis of torques of the locomotion system, 2 scenarios were considered, the first one is to ascend a 45º staircase according to the technical standard A.010 of the National Building Regulations (RNE) (Fig. 11(a)) and the second one is to move along a horizontal plane (Fig. 11(b)). Considering a total robot mass of 100kg and a friction coefficient of 0.8 [59–63], the force required for the first scenario is 1248N and for the second is 785 N, considering that the drive wheel is 50 mm in diameter and that they are 2 caterpillars, the torque required for locomotion in scenario 1 is 31.2 NM in each motor and for scenario 2 is 19.6 NM. It is concluded that each motor of the robot requires at least 31, 2 NM for locomotion, see Table VII.

TABLE VII. TORQUES REQUIRED

Torques Required	**Description**	**Torque Parameters (*Nm*)**
Torques of Caterpillar Locomotion	Inclined plane 45° Horizontal plane 0°	31.2 19.6
Torques in the Robotic Arm	T0 T1 T2 T3	548.0 592.0 235.0 20.1

C. *Component Analysis*

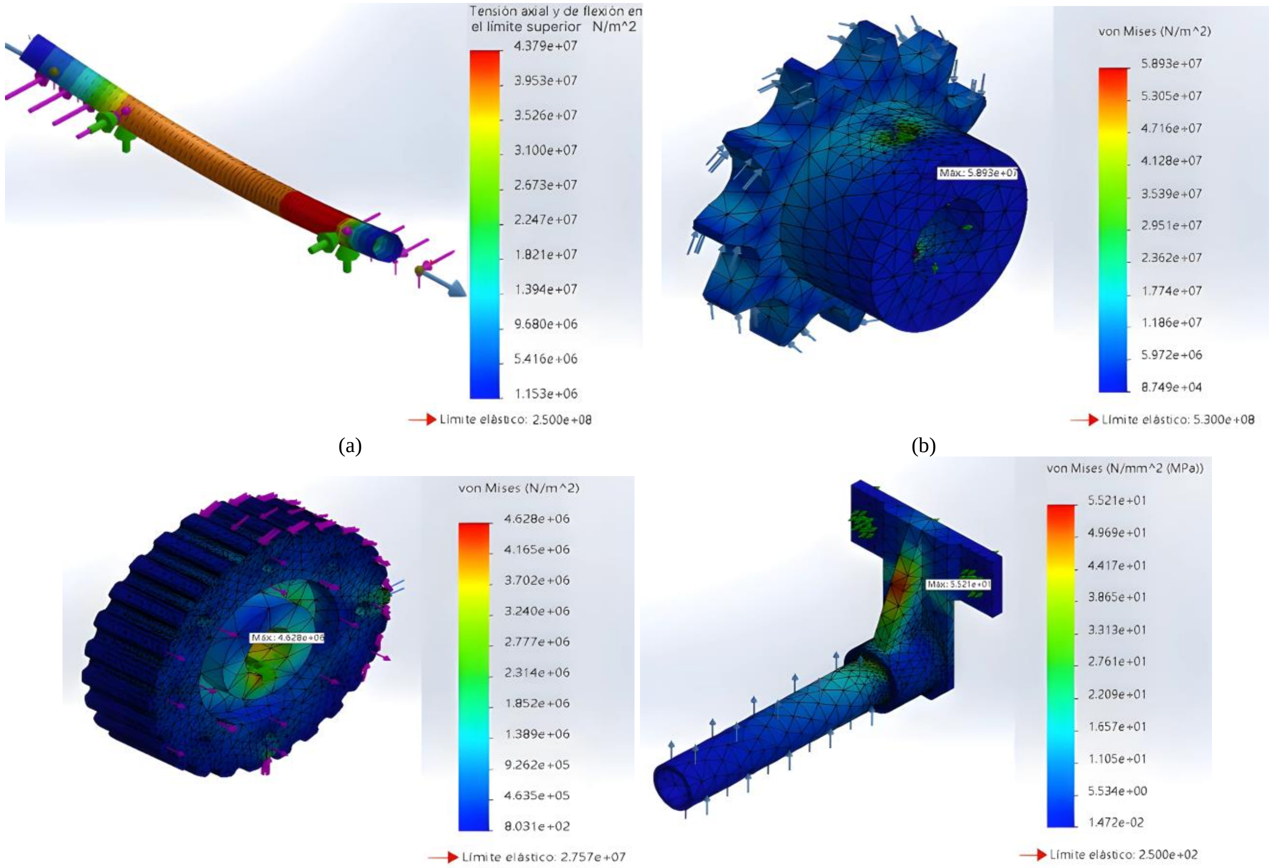
The finite element analysis was carried out on the components that will withstand the greatest stress generated by walking on uneven terrain and climbing and descending stairs. It is evaluated only using the Von Misses criteria, finding the F.S. (safety factor), which must be higher than the F.S. of the Pugsley tables of 2.88. All the components as shown in Fig. 12 comply with the above safety factor which assures us a low possibility of failure.



(a) (b)

(c)

Fig. 11. Free body diagram, (a) Stairs 45°, (b) Plane, (c) Arm Fr: Friction, N: Regular Strength, T: Required Torques, W: Weight of links, motors and gearboxes.



(a) (b)

(c) (d)

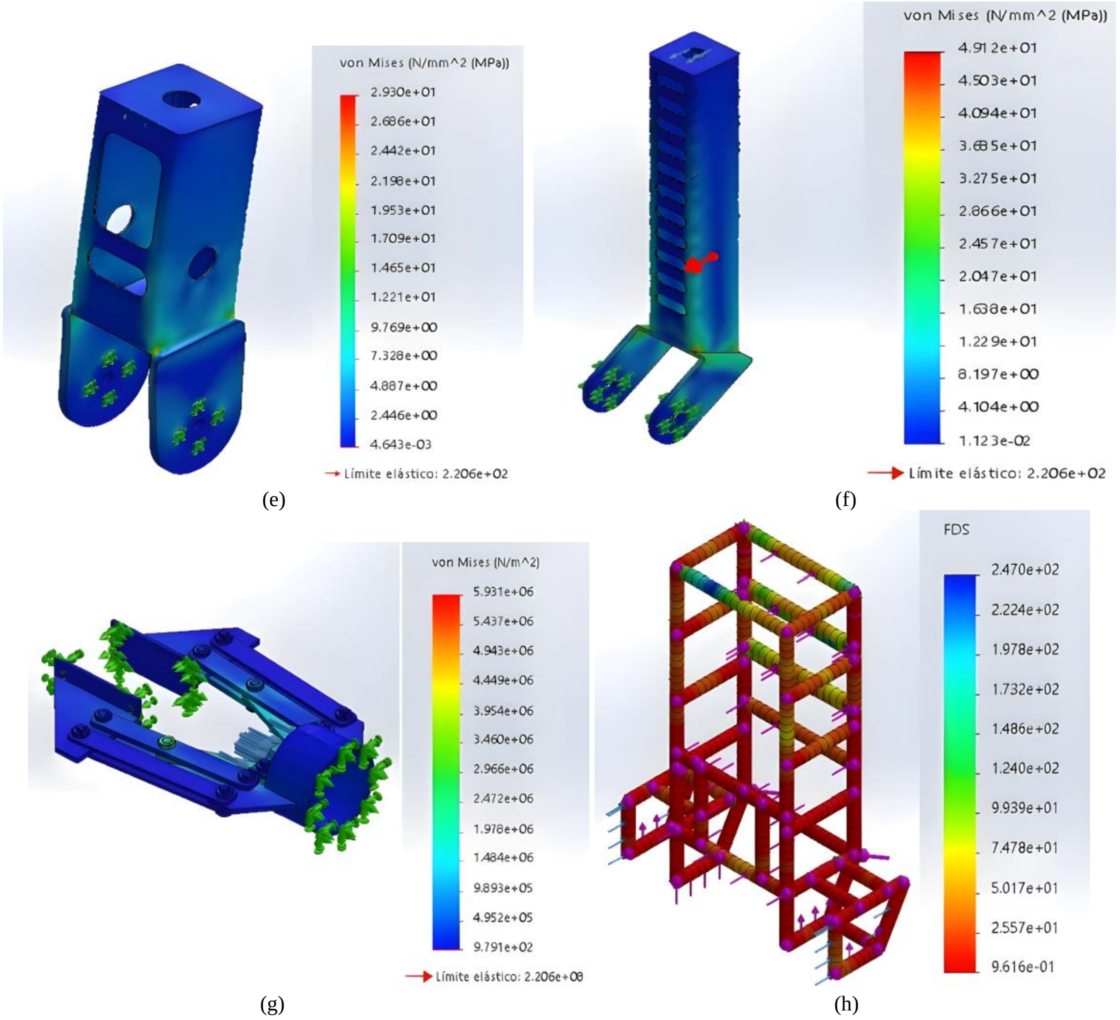
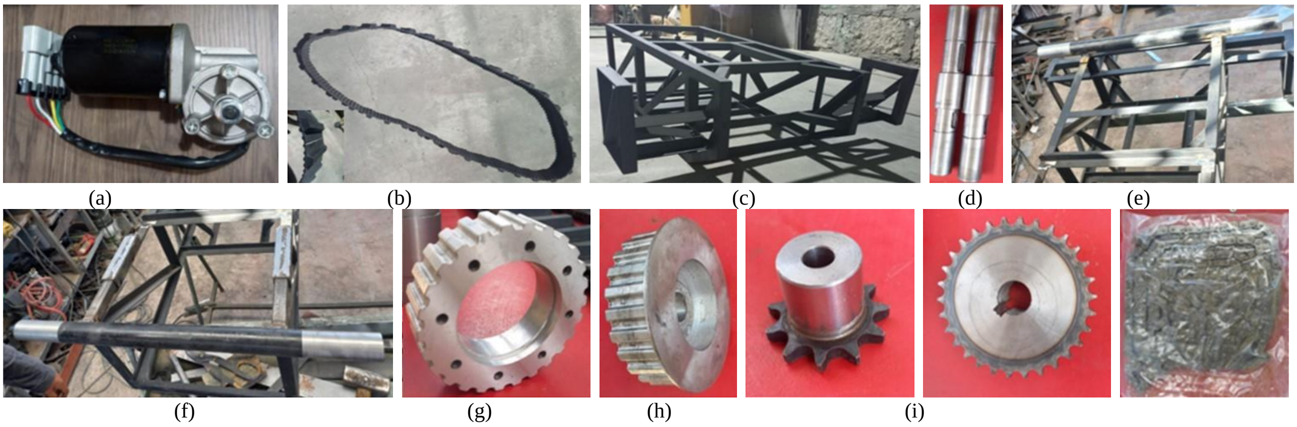


Fig. 12. Von-Misses strain analysis; (a) Axle; (b) Sprocket; (c) Traction wheel; (d) rollers; (e) Link 1; (f) Link 2; (g) Gripper, (h) chassis.

VII. CONSTRUCTION

The construction of the JVC 0.2 robot took place in the facilities of the Universidad Nacional de San Agustín with equipment from the laboratories, technical consultancy from professors and UDEX personnel. This chapter describes the construction process of each module, its difficulties, and necessary modifications to the original model. The team took 3 months to assemble the UGV, 2 months to manufacture the robotic arm, and 1 month to build the gripper. The manufacturing process is shown in Fig. 13, where each of the parts belonging to the three components and their subsequent assembly has been adapting parts of the robot design as it was being developed (See Table VIII).



(j) (k) (l)

Fig. 13. Construction JVC 0.2; (a) Wiper motor-DC; (b) Rubber tracks; (c) Structure chassis; (d) Axle; (e) Front fixed shaft; (f) Fixed shaft with tempering system; (g) secondary and traction sprocket; (h) Catalina 11T and Catalina 30T; (i) Chains p=3/4; (j) Nylon roller; (k) Handling subsystem assembly; (l) Locomotion subsystem assembly.

TABLE VIII. MANUFACTURING PLANNING AND PROTOTYPE ASSEMBLY

Prototype Name	**Robot EOD JVC 0.2**
Manufacturing sequence and assembly of the UGV (Period: 3 months)	Selection of DC electric wiper motors
	Manufacture of vulcanized rubber tracks
	Manufacture of primary and secondary sprockets
	Manufacture of nylon rollers
	Manufacture of the rotary axis
	Selection of transmission system by sprockets and chains
	Manufacture of front fixed axle
Manufacturing sequence and robotic arm assembly (Period: 2 months)	Manufacture of fixed shaft with tempering system
	Manufacture of structural profile chassis
	Selection of DC electric wiper motors
	Selection of endless gearboxes-toothed wheel
	Manufacture of a robotic arm with a square tube
Gripper manufacturing and assembly sequence (Period: 1 month)	Manufacture of a metal base with steel plates
	Selection of DC electric wiper motors
	Selection of transmission system by Catalinas and chains
	Manufacture of power screw for gripper opening/closing
	Manufacture of manipulator
	Manufacture of metallic gripper support

VIII. TESTS

In this chapter, we evaluate the robotic arm in terms of dexterity to extract and place objects, because with this, we demonstrate effectiveness in EOD tasks. For this, we use standard test methods for response robots from NIST, consisting of a test module in which the objectives are placed modifying the distance variables, height, and orientation so that we will have to grip different shapes of objects. These tests were carried out for the previous version JVC 0.1 and the one designed in the present one.

A. Preparation of the Test Module

(1) The test module was built according to the dimensions given by the RoboCup Rescue Robot League 2022.
(2) The test module, designed to evaluate the two models under position and maneuver conditions, was installed.
(3) A container was placed on the side of the module for the collection of targets.
(4) The objects to be moved were installed in the test module as shown in Fig. 14.
(5) After the test module is prepared, JVC 0.1 and JVC 0.2, robots are tested.

(a) (b)

Fig. 14. Robots on the field test; (a) JVC 0.1 test; (b) JVC 0.2 test

B. Dexterity Tests with Linear Object

The linear object is set to the required location and orientation like Fig. 14. The container starts at the side of the module; however, the robot is free to move the object container and to move in any direction, without protruding from the test module. Then the robot is prepared in the starting square and the task of transferring the objectives from the module to the collector begins, taking the time from the beginning of the operation until finishing with the 5 locations with the linear rail. When the robot has completed the dexterity task at the current location, the robot will disconnect from the apparatus and return to the start to continue with the other module positions. Finally, the results obtained are recorded in the evaluation sheets, taking into account the evaluation regulations of the RoboCup Rescue Robot League 2022. To evaluate the performance of each robot, 1 point is scored if the target is picked with the robot's gripper and receives a bonus of 4 additional points if the target is successfully placed in the container, for a total of up to 25 points. The average values of the scores obtained, the time required, and the rates of the task are shown in Table IX.

TABLE IX. TEST OF ROBOT SCORE

Robot version EOD	**SCORE**	**Maneuver time**	**Task rate**
JVC 0.1	16	12 m 13 s	1.33
JVC 0.2	25	8 m 45 s	2.78

From Table IX, it can be deduced that the effectiveness of the task to remove and place objects outperforms its predecessor by twice the task rate, which demonstrates a breakthrough thanks to the proposed new design. This is because the average time required to extract the 5 targets could be reduced to 3 min 28 s and the score indicates that the JVC 0.2 could easily adapt to the different positions of the linear object while the JVC 0.1 had great difficulties in the objectives located at 45°. Then, we will look at the feedback that was obtained from the operators when running the tests with both robots.

C. Test of Strength

The purpose of this test is to quantitatively evaluate the load capacity of the manipulator so that the robot can meet one of the requirements established by UDEX Arequipa. In addition to complying with the design parameter of the robot, it can lift to 10 kg without inconvenience. Each weight is lifted by the robot starting with the weight of 8 kg and having increments of 1 kg, the observations are recorded in a table as well as the successful and failed attempts, for this test the time that each attempt takes is not considered. For an attempt to be successful, each robot angle of the elbow and shoulder must be raised 45°. The results obtained are shown in the following table, where it can be seen that the robot has difficulties from 9 Kg at arm's length. On the other hand, at medium distance, it manages to exceed expectations, lifting loads of up to 15 kg. These results show that the prototype complies with the UDEX requirements, and the design parameters initially raised (see Table X).

TABLE X. STRENGTH TEST SCORE

Weight (Kg)	**Extended arm distance**	**Average distance**	
	Shoulder	**shoulder**	**elbow**
8	Yes	yes	yes
9	Difficulties to lift	yes	yes
10	no	yes	yes
11	no	yes	yes
12	no	yes	yes
13	no	yes	yes
14	no	yes	yes
15	no	yes	no

D. Test of Flat Terrain

The purpose of this test is to evaluate the locomotion capacity of the UGV quantitatively and quantitatively so that the robot meets the requirements established by UDEX Arequipa for maneuverability and speed on flat terrain.

The robot travels a distance of 3 m and at the end of the section, it turns 180º to repeat the same route 10 times as recommended by the NIST. This operation was carried out for slab, grass, and dirt at an inclination of 0º (see Table XI).

The results obtained are shown in the table, where it can be seen that the robot manages to pass the test on the slab without problems, in addition to having an acceptable speed according to the requirements, however on grass and dirt the robot gets stuck during the turn, it was noted overexertion of the engines, accompanied by detachment of the caterpillar belt and being stranded (see Table XI).

TABLE XI. RESULTS ON FLAT GROUND

Ground Type	**Test Completion**	**Average Speed (cm/s)**	**Observations**
Slab	YES	10.49	Full turn
Grass	NO	10.61	Caterpillar jam incomplete turn Detachment of caterpillar belts Overexertion of UGV engine
Dirt	NO	10.94	Caterpillar jam incomplete turn Detachment of caterpillar belts Overexertion of UGV engine

E. Test of Stairs

The purpose of this test method is to quantitatively evaluate stair climbing and descending capabilities, coordinated climbing behaviors, and tread surface vulnerabilities.

For its procedure, the robot is placed in the initial position facing the obstacle (stairs of 15º, 20º, and 30º). The timer is started when the robot starts and captures the total in the elapsed time. It is repeated for different step surfaces and the inclination of the ladder is increased until it is unsuccessful in one of the repetitions. The results obtained are shown in the table, where it can be seen that the robot manages to overcome the obstacle up to 30º, which is when the robot overturns due to loss of contact between the caterpillar and the ladder and the pin that couples the motor with the caterpillar shear failure. Also, during the ascent and descent of the different stairs, instability, and impacts were observed in the front and rear of the UGV causing damage to the electronics (see Table XII).

TABLE XII. RESULT ON STAIRS

Inclination	**Direction**	**Test Completion**	**Observations**
15°	Ascending	YES	Strong frontal impact at the end of the stairway Overexertion of UGV engines
15°	Descending	YES	Strong posterior impact at the end of the stairway Turret Chamber Damage Instability and with a high possibility of overturning during the stairs haul
20°	Ascending	YES	Frontal impact during the stairs haul Strong impact at the end of the stairway Overexertion of UGV engines
20°	Descending	YES	Instability and with a high possibility of overturning during the stairs haul Strong posterior impact at the end of the stairway
30°	Ascending	NO	UGV left engine pin mechanical failure The robot overturned due to the loss of contact of caterpillars with the stairway
30°	Descending	NO	Test not completed due to mechanical failure while climbing stairs 30º

F. Operator's Feedback

JVC 0.1: For this version, the wireless control from a control panel was the user's interface, presenting ergonomic problems for the operator, however, the movement of two motors at the same time is allowed. The operator, already familiar with this design, began with the tests in the module and commented the following: "Imprecision of the entire arm, it was difficult to position to catch the object, especially the rotation of the tower", to Objects located at 45° to the sides were difficult since the gripper did not rotate, did not adapt to the object and caused sudden movements in the entire structure of the test bench when extracting the object.

JVC 0.2: For this version the wireless remote control Dualshock 4 controller is the control due to its ergonomic and familiar design for the user, however, it only admits the operation of a single motor at a time. The training regarding the handling of the model the operator for the tests was in charge of the team, after the tests the operator made the following comment: "It had good precision and ease of maneuver, it extracted the objects without sudden movements in the test bench and the gripper picked up the object from any angle", He also mentioned that each different position had different ways of approaching with the gripper, so it was easier at ground level, but it was getting more complicated when the test bench was raised.

IX. ANALYSIS WITH FMEA MATRIX

The FMEA matrix is a method used to analyze a product during the design phase [64], in this case, this analysis was already carried out on the EOD JVC 0.1 robot [8], however, it is necessary to provide feedback on improvements recommended in said analysis and compare it with the new robot EOD JVC 0.2 (See Table XIII and Fig. 15).

TABLE XIII. MANUFACTURING PLANNING AND PROTOTYPE ASSEMBLY

Function	Nº	Failure Mode	Effect	Causes	G	F	D	RPI	Proposed Actions	Carried-out actions	G	F	D	RPI
Inspections and Measurements	1	Weight	Hard to move	Material excess Lead-acid battery oversized motors	9	8	5	360	Change the materials aluminum construction. Use lithium batteries. Reduce engine power.	The material used ASTM A36 with a lightened structure, power of motors adjusted to design	7	7	2	98
Inspections and Measurements	2	Dimensions	Hard to move	Lost requirements	6	8	3	144	Reduce the size of JVC 01 closer to MK2. Design arm in rest position.	Dimension reduction, designation of the robotic arm to rest on the chassis	4	5	2	40
Analysis of the locomotion system	3	Motors	Electric energy waste	Oversized engines	5	7	6	210	Reduce power of the engines	Implementation of engines with service factor 1.2	4	7	3	84
Analysis of the locomotion system	4	Caterpillar	Robot stranded	Link tensioners lost	6	6	5	180	Design system of caterpillars with tensioners.	Tensioners Design shared rear axle	3	3	3	27
Analysis of the locomotion system	5	Chassis	Unnecessary material	Too heavy structure	4	6	5	120	Reduce material Distribute weights for outstretched armload	Chassis design with structural sections	3	5	3	45
Analysis of the locomotion system	6	Workspace	Reduction of workspace objects near the chassis cannot be caught	Limited joints due to motors adapted to linear	9	8	6	432	Switch to a gear system worm screw.	Implementation of gearboxes endless sprocket	4	3	3	36
Analysis of the locomotion system	7	Driving Time	Too long operations	Linear adapted motors	9	9	3	243	Increase motor speed.	Implementation of motors with adequate speed	2	3	3	18
Analysis of the locomotion system	8	Robotic Gripper	Objects that cannot be easily grabbed	Poor gripper design gripper lacks rotation	9	7	7	441	2-finger gripper redesign increase freedom, freedom to turn the gripper	2 finger grippers Implementation of 1 DoF for the twist of the gripper	3	3	5	45
Analysis of the handling system	9	Load Capacity	Waste of electrical energy necessary material	Oversized engines and structures	7	8	5	280	Lighten the structure of links. Motors sized appropriately up to 10 kg arm extended	Light structure Implementation of motors with gearboxes endless sprocket	5	4	3	60

As can be seen in Table XIII, an action taken was applied to each component, and a new score was given according to its severity (G), frequency (F), and detection (D), these values are multiplied and result in the ´Index of Risk Priority (RPI), the comparison of the results of JVC 0.1 and JVC 0.2 are displayed in the figure, being able to notice a significant improvement in the characteristics of the robot, however, the weight and dimensions components still have results higher than 100 RPI, so for future versions, it will be important to consider weight reduction using lightweight materials (aluminum or plastics) as well as software-assisted design techniques such as Topological Optimization and the dimensions will have to continue to be reduced mainly in width since that in the tests during the start-up the TEDAX agents had complications to be able to place and transfer the robot in the UDEX vans.

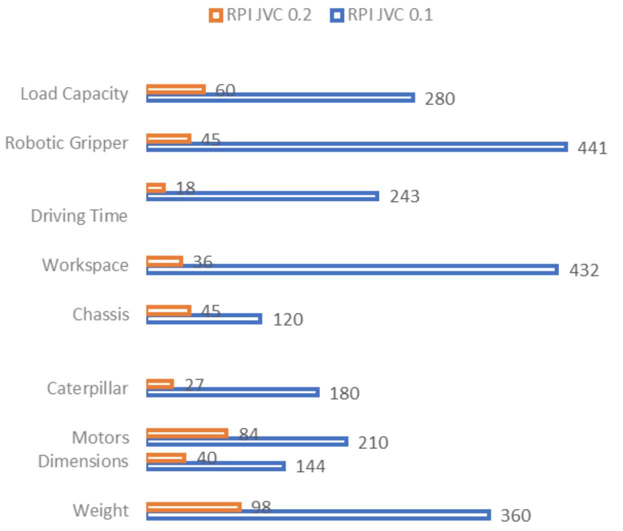


Fig. 15. Comparison FMEA de JVC-0.1 con JVC-0.2.

X. CONCLUSION

In this paper, the EOD robot JVC 0.2 was developed and evaluated for portability, HRI, locomotion dexterity, and joint work of the robotic arm and manipulator using tests based on NIST standards, these tests were adapted to the needs of UDEX and improved the characteristics of the previous EOD robot version JVC 0.1. This evaluation is detailed below:

The overall weight of the robot was reduced, maintainability was improved, the all-terrain capability of the UGV was enhanced and the maneuverability of the robotic arm was increased at a low manufacturing cost; however, it requires improvements to meet the needs of the UDEX and the Peruvian regulations in force. The application of the Bauhaus design methodology in the development of the EOD robot JVC 0.2 showed significant improvements in functionality, precision, and cost compared to its previous version JVC 0.1. In the analysis, it was demonstrated that using kinematic analysis, a previous manipulator workspace can be determined, the torque analysis proved to be effective in determining the necessary torques for the selection of motors and reducers, also the analysis using finite elements verified the robot resistance. The robot was built with locally available materials, such as carbon steel and DC electric wiper motors, allowing lower manufacturing costs and ease of maintenance. The tests were performed on the JVC 0.2 according to NIST recommendations, two tests were performed for the UGV; flat terrain (slab, grass, and earth) and stairs (15°, 20° and 30°), having as most important events detachment of the caterpillar belt in turns on earth and grass, mechanical failure due to shearing of the pin in stairs of 30°, instability when climbing stairs and front and rear impacts of the UGV at the time of completing the ascent and descent of stairs, despite demonstrating better characteristics of locomotion and handling compared to the JVC 0.1. For the robotic arm and gripper two tests were executed; maneuverability of the arm where the operation time was 8 min 45s and load capacity where a maximum of 9 kg was reached, however, what is required is 10 kg, therefore it is not yet considered a stable version to enter into real operations.

Therefore, for future work, it is recommended to use lightweight materials (aluminum and plastics) to optimally apply software-assisted topological optimization in the design of the chassis, robotic arm, gripper, and tracks to reduce the weight and dimensions of the robot, move the robot's center of mass as close to the ground and also start considering the implementation of a suspension system on the tracks to cushion impacts.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

J.M.G., M.A.C., and M.A.B. gathered the requirements; D.M. performed the conceptualization; J.M.G. and E.V.F. performed the design and analysis; M.A.B. supervised the construction; J.M.G., M.A.C., and E.V.F. performed testing; D.M., Y.L.S., and J.L.A. wrote the article; Y.L.S. managed the project; J.L.A. obtained funding. All authors approved the final version.

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