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Original Article

Automation in Automotive Mechanical Industry: Design and Evaluation of a Tool-Organizing Robotic Arm with Artificial Intelligence

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Abstract - *This article shows the design and evaluation of a robotic arm with artificial intelligence capable of performing organisation functions, the selection and evaluation of the state of tools in the automotive sector, and the design implemented due to the need to increase efficiency and time in terms of production. A robotic arm designed based on inverse and direct kinematics will be put into operation and simulated in MATLAB after implementation; the manufacture of a control circuit and programming will be done in ESP32 and ESP32-CAM modules as main microcontrollers. The evaluation of this design guarantees productivity in the sector due to its weight, reach, maneuverability and easy adaptability to other industrial sectors since the use of neural networks implemented in its programming makes it more versatile.*

Keywords - *Industrial automation, Robotic arm, Artificial Intelligence, Neural Networks, Production optimization five.*

1. Introduction

Peru's industrial and automation sector has been advancing significantly in areas such as welding, metalworking, assembly, chemistry, warehousing, etc. Maximizing production using autonomous or semi-automated equipment improves the sustainability of these companies, where productivity is very important. Despite the benefits of using this equipment, accessibility and cost are very scarce in the market. It must be programmed by an operator who will provide the respective conditions for each type of use or desired industrial application. Industrial robotics in applications such as the mechanical industry is a field where electronic and electromechanical engineering deals with the design and control of these devices, performing the programming and mechanical design for production needs such as fixed or flexible, having a deficit in each need in terms of each required application, since it requires the intervention of the human factor to perform the corresponding algorithms in their programming to perform movements in each axis, the clear example shown in [3] making the comparison of application with sampling algorithms depends on planning; therefore the implementation of artificial intelligence facilitates the development of the system to be implemented by obtaining required data and memorizing procedures which allow this does not depend on a constant intervention of the operator. It is proposed the use of a robotic arm capable of performing autonomous actions and running independently, achieving an adaptation in the mechanical sector for different applications since it will not depend on reprogramming or human manipulation in parallel to the operation of the robotic arm, as it develops learning capabilities according to the needs of the task to be performed using artificial intelligence. The evolution in the assembly industry with the use of robotic arms in [5] for different applications stands out for its high performance and accuracy, compared to the human factor that could generate delays in decision-making and generate disorder due to the use of multiple tools in a mechanical sector.

Thus, even the recognition of tools, materials, objects, etc., using artificial intelligence with Deep Learning in [2] for the application of the autonomous system as the robotic arm obtained experimental data such as the position and type of tool to be selected by learning from captured images, according to the algorithms and information stored in the device. This study focuses on the design and evaluation of a robotic arm with artificial intelligence used to organize tools after cutting or manipulations a piece of equipment on a worktable in an automotive mechanical sector due to the need to occupy time for order at the end of a workday, and this could be used to perform other tasks. The objective is to increase production by optimizing labour time in the cutting or new assembly, contributing to the company's sustainability by making it more productive. The robotic arm could be implemented in other sectors, such as the food industry, agriculture or pharmaceuticals, fulfilling required functions since it has artificial intelligence and is easily adaptable.

2. Related Works

The idea is to implement robotic arms for different sectors such as agriculture, automotive, mechanical, pharmaceutical, etc. They are beneficial and feasible, as in the case of [1], where a robotic arm is manufactured to perform the harvesting of fruits in the agricultural sector; this has an artificial vision that serves to identify and select the different hydroponic fruits in the crop, it is specified that this uses the YOLOv8 algorithm to perform the recognition of such fruits.

Likewise, in [2] it is mentioned the implementation of a robotic arm with neural networks for cotton harvesting, showing the discussion about the efficiency in terms of harvesting this material, acquiring a learning based on each harvesting performed, a new application of these robotic arms mentioned in [3] the innovation of using them as maintenance devices in the electrical industry operating in 10kV electrical distribution lines showing significantly high results compared to the human factor due to the fact that it has sampling algorithms based on RAPIDLY EXPLORING RANDOM TREES (RRT) and RTT-Connect, results show that its success rate is 90% in RRT-Connect compared to RRT reducing the planning time of 155ms demonstrating excellent reliability and operational efficiency, improving safety in terms of maintenance manipulations in the distribution network, additionally in the application of artificial intelligence techniques such as Deep Q Network were used, Artificial Neural Network and Artificial Deep Q Network described in [4] for classification accuracy processes, obtaining an increase in learning as the number of iterations is increased, thus improving the Q network as its artificial neural network implemented in the programming of robotic arms, in [5] the types of inverse and direct kinematics are used for the design of a robotic arm with artificial intelligence where it performs executions of programmed desired trajectories, using MATLAB as simulation software for obtaining detailed process, activity, type of trajectory and quality, regarding the implementation of precision and improvement of errors per trajectory in a 6-joint robotic arm affecting the accuracy of machining, this approach is described in [6] using as an error compensation technique based on the decomposition of the movement of each axis in the robotic arm, using WHALE optimization algorithm (CIWOA) and adaptive chaotic mapping clustering approach to improve efficiency and global optimization, using the latest advances in robot vision and trajectory tracking for robotic arms, is explained in [7] where tracking algorithms are mentioned, focusing on the importance of model prediction control applied in autonomous robots and unmanned aerial vehicles, as well as in [8] where multiple input-output systems are controlled through the Lagrangian, Lyapunov dynamic model, as a verification step a prototype controller called CSPACE-RT is developed which would allow new developers to focus directly on numerical simulation and experimental results. Other implementations and methods used in different industrial sectors include the MAKO robotic arm [9], which is used for the purpose of revision after hip surgery in the medical industry, applications such as the use in the oil industry [10] used as a support in drilling which adapts to its environment in pipes.

As can be seen, the implementation of robotic arms in the industry is of vital importance for the precision and effectiveness of the functions entrusted, highlighting the automotive industry as one of the sectors with the problem to be addressed in this article, shown in [11] the design of a robotic arm to meet the needs of precision and transport of heavy loads, obtaining variables in terms of lags by deformations in its structure and conditions of weight lifting with loads, adding the use of artificial intelligence using neural networks to optimize the behavior of the robotic arm in [12] through the use of cardan joints and Artificial Neural Network (ANN) architectures.

3. Methodology

This article presents the development, design and evaluation of a robotic arm with artificial intelligence for the automotive mechanical sector to organize workshop tools such as wrenches, screwdrivers, screwdrivers, screwdrivers, etc. The objective of this development arises due to the lack of time to generate an order and selection of tools evaluating their status or losses; the main features of the robotic arm with artificial intelligence are:

- Speed of selection and order regarding tools used to cut diesel combustion engines.
- Low implementation and manufacturing costs.
- Dimensions of 1.6m x 1.8m x 0.45m and weight of 11Kg.
- Parts based on resin and fiberglass are light materials compared to the use of metals.

Table 1. Components used

Type	Model	Quantity
Position sensor	XCKJ10511	1
VGA camera	OV2640	1
Stepper motors	NEMA	4
Drivers motors PAP	A4988	4
Controller	ESP32	1
Camera controller	ESP32-CAM	1
Micro motor	Pololu 41 RPM	2
ON-OFF switch	KCD4-16A	1
Power supply	24V-5A	2
Camera cable	RJ45 Extension	1

The artificial intelligence developed in the device will allow it to learn autonomously each type of tool used and place it in the right place established on the board. The union of parts of the robotic arm was performed in SOLIDWORKS software, and the implementation of the control circuit was performed on the WOKWI platform as a means of electronic simulation for the axes of the robotic arm and the implementation of neural networks in the ESP32 and ESP32-CAM modules was performed in MATLAB and ARDUINO IDE software.

Its operating logic is represented in Figure 1, where the ON/OFF switch provides power to the control PCB and evaluates the state or short circuit in the robotic arm. An organization will perform the command control start selector or switch start conditioned with the positioning sensor. The selection variables such as tools, status or losses will determine the actions directly on the robotic arm. At the same time, it performs the respective order and will provide a report of damage or loss. The processing is performed by PCB control, having as feedback generated images and data captured from previous selections implemented in its artificial intelligence for direct decision making in the type of drive as degrees of movement in axes of the robotic arm, generating a bidirectional communication between ESP-32 on PCB control and ESP32-CAM (Figure 1).

The robotic arm has a robust system that corroborates the effectiveness of positioning and power required for the placement of tools by integrating a PID control for each axis with the use of ZIEGLER-NICHOLS control tuning; the motors use the A4988 driver known for its practicality of use and easy replacement in case of failure, to finish the PCB control was performed in the EAGLE software.

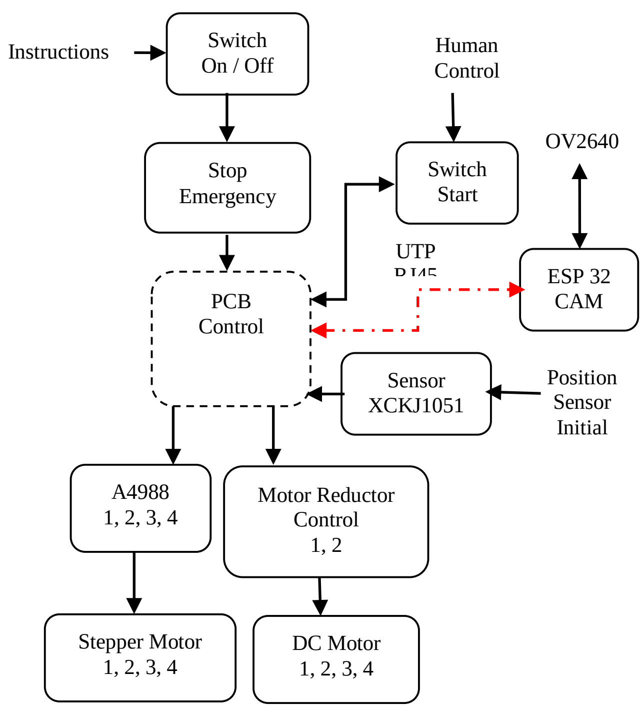


Fig. 1 Equipment block diagram

4. Development System

The electronic design consists of the ESP32 and ESP32-CAM module, which control the axes of the robotic arm, performs autonomous processing due to the implemented neural networks and a vision of the objects to be selected through the camera in the ESP32-CAM, which can be monitored storing data such as absence of tools and indicate conflict due to poor location of tools, thanks to the easy control of the stepper motors implemented the axes of freedom of the robotic arm are 360 ° which will allow a precise rotation without limitations and can even reach more distant spaces where the tool could be found, Its operating logic is based on the detection of objects by means of the integrated camera, this will evaluate the status of the tool before placing it in the initial place prior configured order, the robotic arm together with the artificial intelligence will define this problem to later be placed in the indicated place and generate a visual report of variables obtained due to a built-in peripheral.

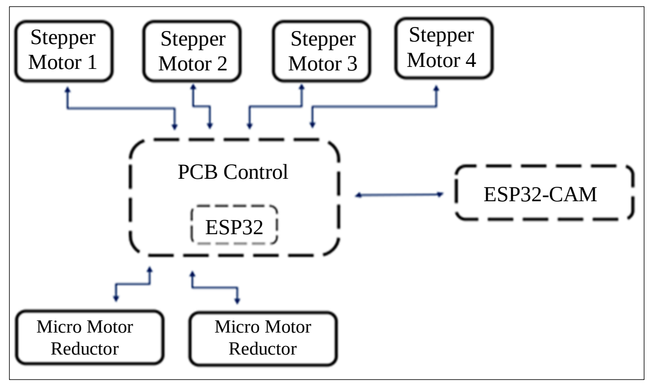
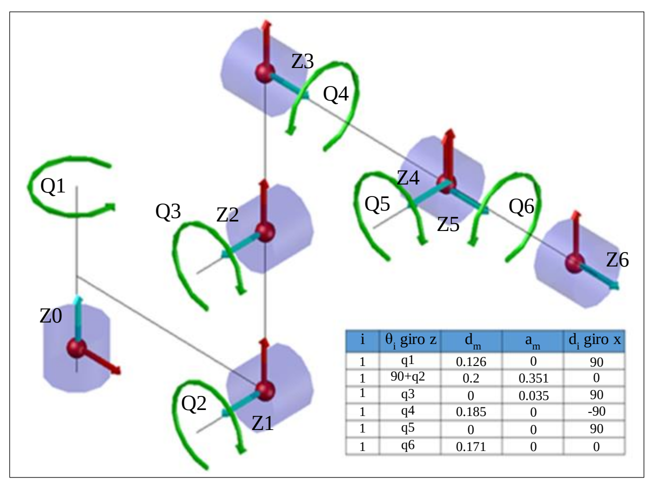


Fig. 2 Actuators block diagram

Starting from the main actuators, the movement of each axis is performed with the A4988 drivers together with the NEMA 17 stepper motors and micro-geared motors (See Figure 2), to perform the model of the same, the direct kinematics was performed using the Denavit-Hartenberg algorithm (Figure 3).



i	θ_i giro z	d_m	a_m	d_i giro x
1	q1	0.126	0	90
1	90+q2	0.2	0.351	0
1	q3	0	0.035	90
1	q4	0.185	0	-90
1	q5	0	0	90
1	q6	0.171	0	0

Fig. 2 Direct kinematic algorithm

The design of the main control PCB of the device was made subject to the needs of maximum control of 4 stepper motors and 4 micro motor reducers; for this case, the PaP (stepper) motors are controlled directly from the ESP32, which will have the programming for a routine movement if it is used for other applications semi or non-automated, the control PCB uses the industrial voltage of 24V for the management of actuators, in this case, the 4-wire bipolar stepper motors and the A4988 driver, the control voltage is isolated from the device and conditioned with logic gates which indicate possible failures such as excessive load or inadequate detection of objects, conditions to be evaluated from the ESP32-CAM installed in the last axis point of the robotic arm, the bypass voltages for the control PCB are 24V, 12V, 5V and 3. 3V (Figure 4) is constituted by linear regulators except for the voltage by a 3.3V switched source so that the logic signals are not unbalanced by high power consumption or voltage drop, besides being more susceptible to data loss due to the logic performed.

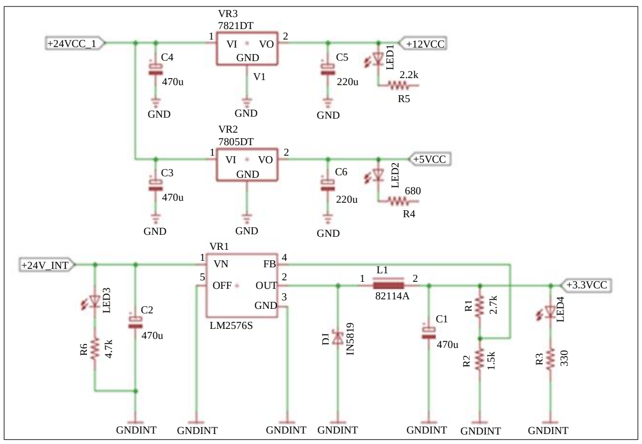


Fig. 4 Power supplies on control PCBs

The conditions made in the integrated protection as the CD4093B and CD40106B are mostly for logic validation and no electrical noise or signal interference that could not validate the correct operation of the robotic arm (Figure 5) are configured in such a way that the 3 operating conditions are in the required range, of which the first is to validate the logic power supply voltage in stepper motors, the signal obtained is a logical value of +5V in normal conditions and 0V before failures, the second is to verify the initial position of the robotic arm at the end of its routine organization (Figure 6) using a limit switch sensor to know the initial position, the choice of this sensor must be of industrial character and withstand moisture, dust and particle projections such as the sensor XCKJ10511 which meets the industrial needs required by the standard EN 60204-1, as a third operating condition is the sensing of high current in control driver, using the maximum amperage signal from the trimpot of the driver A4988.

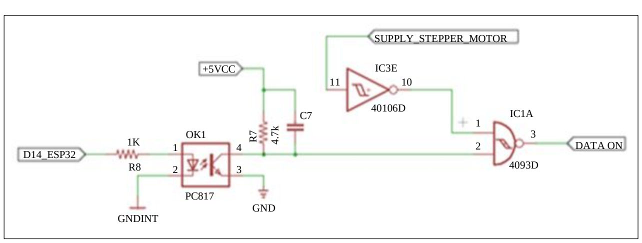


Fig. 5 Validation circuit 1

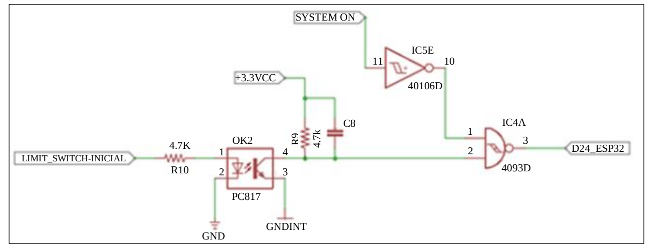


Fig. 6 Validation circuit 2

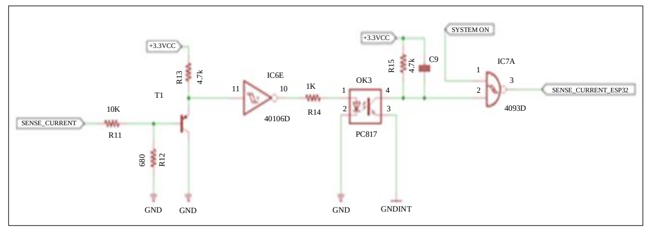


Fig. 7 Validation circuit 3

The logic must be integrated with the ESP-32 module, which will carry the programming with neural networks for object detection, including an artificial vision which was programmed in the ARDUINO IDE software in C++ language; the control PCB and the ESP32-CAM work together as their data are sent directly (Figure 8), validating the actions in this mode the I2C connection was made as slave mode for the ESP32-CAM and master mode in ESP32 of the control PCB; likewise the connections between the two modules will be made by UTP cable to improve data transmission and noise isolation.

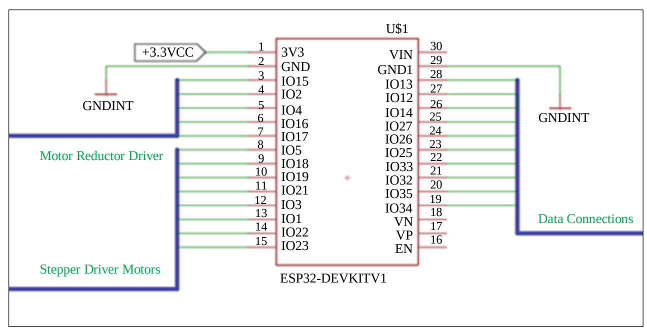


Fig. 8 Derivations in PCB control

The elaboration of the simulation of the robotic arm was made from the data obtained with the Denavit-Hartenberg algorithm, which was included in the programming itself to define the degrees and angular position of movement in each part of the robotic arm, the functionality of using the MATLAB software allows us to simulate the direct and inverse kinematics, since once the data is obtained according to the formulas included in the program, we can obtain the different positions that the robot can use to reach the griper being this the final point where the tool should take (Figure 9) for this we use the inverse kinematic method of Pieper since the final axes of the robotic arm coincide with a common point. This procedure makes it suitable for its corresponding algebraic calculation (Figure 10).

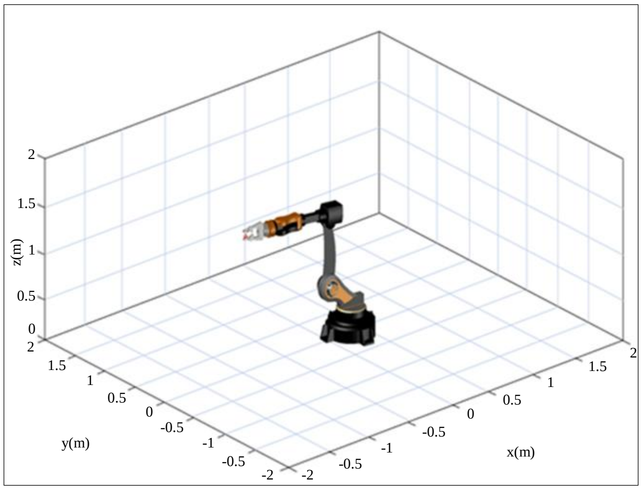


Fig. 9 Simulation of robotic arm in MATLAB

$$ {}^{3}R_{6} = \begin{pmatrix} C_4C_5C_6 - S_4S_6 & -C_4C_5S_6 - S_4C_6 & C_4S_5 \\ S_4C_5C_6 + C_4S_6 & -S_4C_5S_6 + C_4C_6 & S_4S_5 \\ S_5C_6 & S_5S_6 & C_5 \end{pmatrix} $$

Fig. 10 Formula for obtaining orientation

As for the tuning was performed ZIEGLER NICHOLS control theory to test open loop with STEP command pulse to generate the following characteristic curve (Figure 11).

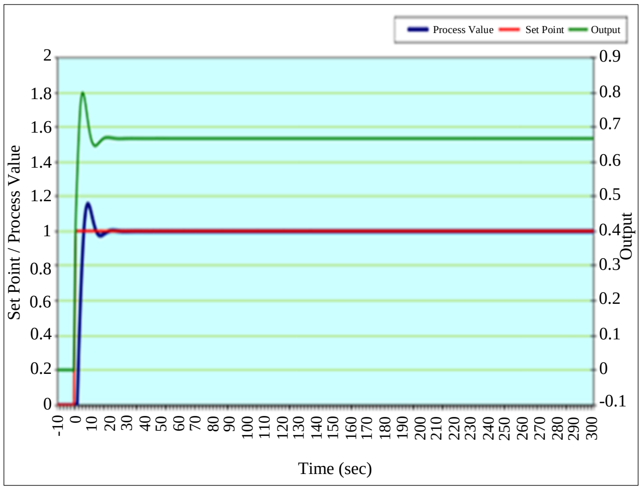


Fig. 11 Initial reaction curve

Obtaining the tuning of new values by reaction curve using the table of KP, TI, TD and pulse time without delay; performing the respective tuning values are obtained for closed loop according to the following table and obtaining the characteristic curve for PaP motors, similarly tuning for geared motor (Figure 12).

Implementing the robotic arm containing an artificial vision is achieved by programming patterns of identification of mechanical tools such as a considerable variety of wrenches, screwdrivers, screwdrivers, etc. Necessary for the disassembly of an engine or a piece of equipment on the worktable, identification of a work table with disordered tools was taken as a sample, identifying 30% of a maximum of 5 tools in a first test due to the terrible conditions found (Figure 13).

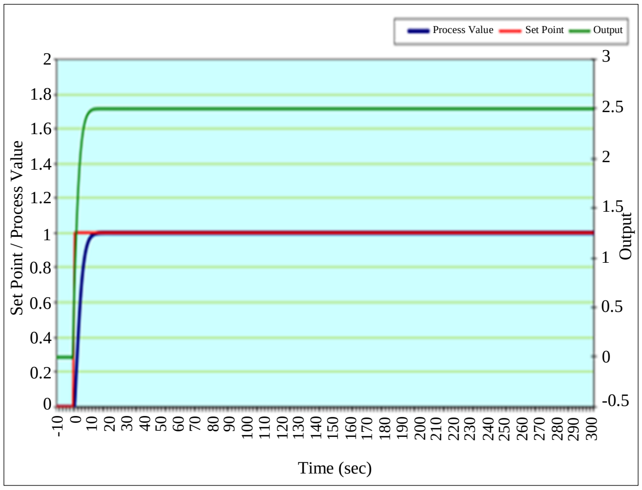


Fig. 12 Reaction curve with tuning

Fig. 13 Detection of test tools 1

The following tests were performed on a board with an established standard for the correct organization of these tools, and the ESP32-CAM camera is relatively medium quality; therefore, a waiting time of only seconds facilitates the detection of objects, improving the selection by 95%, in turn, this manages to store the data and make comparisons of a tool in good condition, damaged or damaged (Figure 14).

Fig. 14 Detection of test tool 2

Once the detection tests were completed, we proceeded to simulate the space in which the equipment would be located for its operation, considering the reach that it could have throughout the space of the worktable and be able to reach the tabletop to organize the tools found, a space of 2x2x2. 5m to perform all functions in terms of engine parts and small assemblies where a considerable variety of tools are required, the simulation of short and long-distance reach was performed on the workbench in the SOLIDWORK software, which provided an optimal result in terms of unforced approaches for the collection and organization on the tool table (Figure 15).

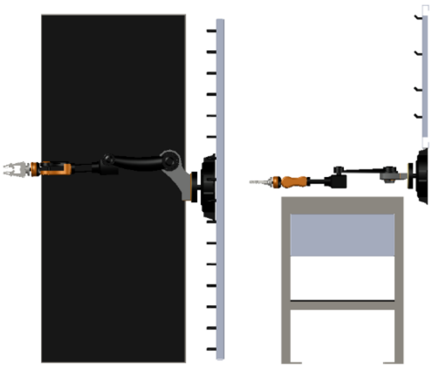
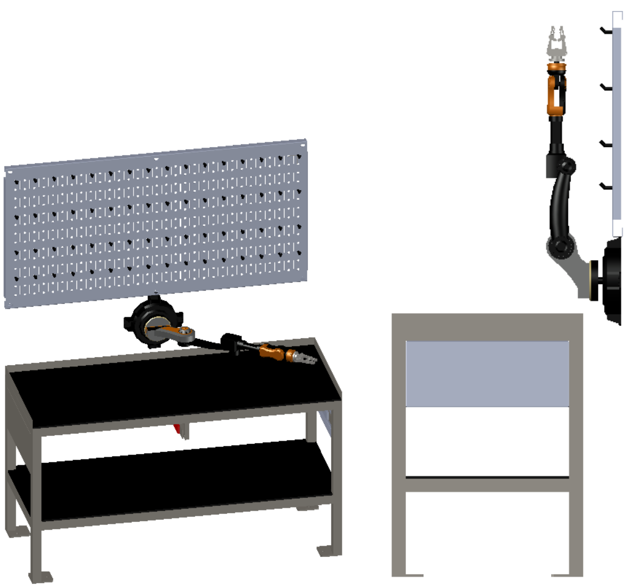


Fig. 15 Top and side view of the robotic arm

The robotic arm was configured to extend its reach by utilizing the projection on the q2 axis. This configuration was saved to enable the arm to access tools located at greater distances in future operations (Figure 16).



(a) **(b)**

Fig. 16 Maximum distances of the robotic arm

At the end of the simulation stage and subsequent implementation in the respective workspace, some adjustments had to be made, such as the table and board measurements, since they were designed empirically; in this case, we proceeded to manufacture them so that the robotic arm can function correctly according to the model presented. This implementation was carried out in a mechanical workshop specialized in repairing diesel engines located in the automotive repair area in Paucarpata, Arequipa. According to the sketch presented (Figure 17), the operation of the robotic arm is beneficial since the mechanic has the necessary time to distribute his tasks in other areas, different from repair or cutting.

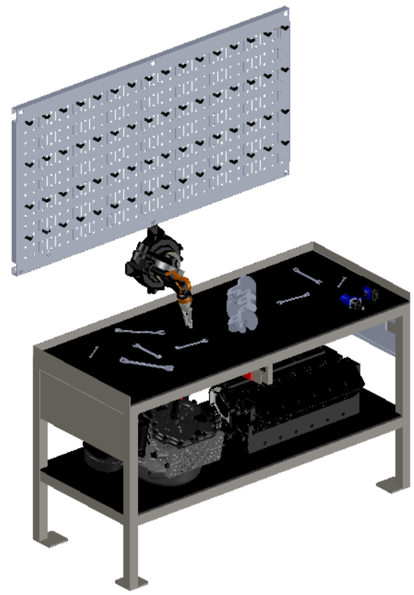


Fig. 17 Implementation sketch

5. Tests and Results

To evaluate the project's effectiveness and the time savings proposed as the main objective, the implementation was carried out in the automotive workshop already mentioned, using a mechanic with years of experience in the disassembly and assembly of engines. Likewise, the correct operation was corroborated with weights greater than it could support, obtaining the desired alerts mentioned in its operation due to a high amperage consumption and versatility in terms of decision-making of the robotic arm. The experienced mechanic's organisation was compared in terms of the order and location of the tools, compared to the robotic arm that showed more speed using a stopwatch, in addition to generating a report of missing and damaged tools displayed on its peripherals. According to the comparisons in terms of time, tools found, selected and organized from a total of 30 of them according to its database, an improvement in terms of speed of 83% was achieved compared to the one performed manually (Figure 18).

The same comparison of this process was obtained thanks to the simultaneous function that the robotic arm performs, comparing with the decision-making of the human factor, which gives possible types of functionalities focusing on the correct selection of these tools; the efficiency in the selection of tools such as wrenches, screwdrivers and electrical cutting equipment was evaluated, occupying the same time since while performing the selection and order it can evaluate its condition, using only the 10 minutes mentioned above, compared to the experienced mechanic who requires an exhaustive evaluation of each tool, taking 25 minutes to make decisions from a total of 30 organized tools (Figure 19). In addition to these data, the functionality of the electrical parts was evaluated, as well as the continuous use of the camera installed in the ESP32-CAM, concluding that the equipment requires preventive maintenance of not less than 6 months of operation since the mechanical working conditions impair its correct functionality by jamming or loss of power, due to the environment which influences by falls of oils, grease or dust, causing delays in the robotic arm by requiring more torque in its axes and selection chamber obstructed by the contaminating agents mentioned. Finally, the time savings generated with the use of the robotic arm should be highlighted since the artificial intelligence programmed in the ESP32 allows the selection of these tools to be more direct in comparison to a human choice; therefore, there is better control in terms of damages generated and evaluation of a possible replacement, this process carried out as a consequence of the learning process that the artificial intelligence of the robotic arm opts for.

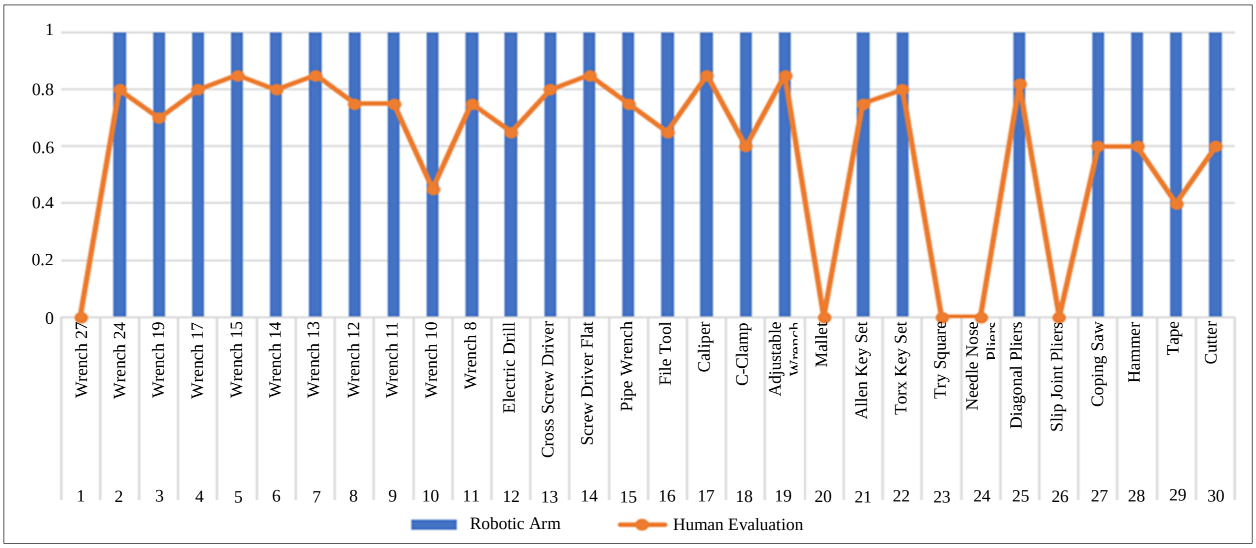


Fig. 18 Comparison between human and robotic arm performance

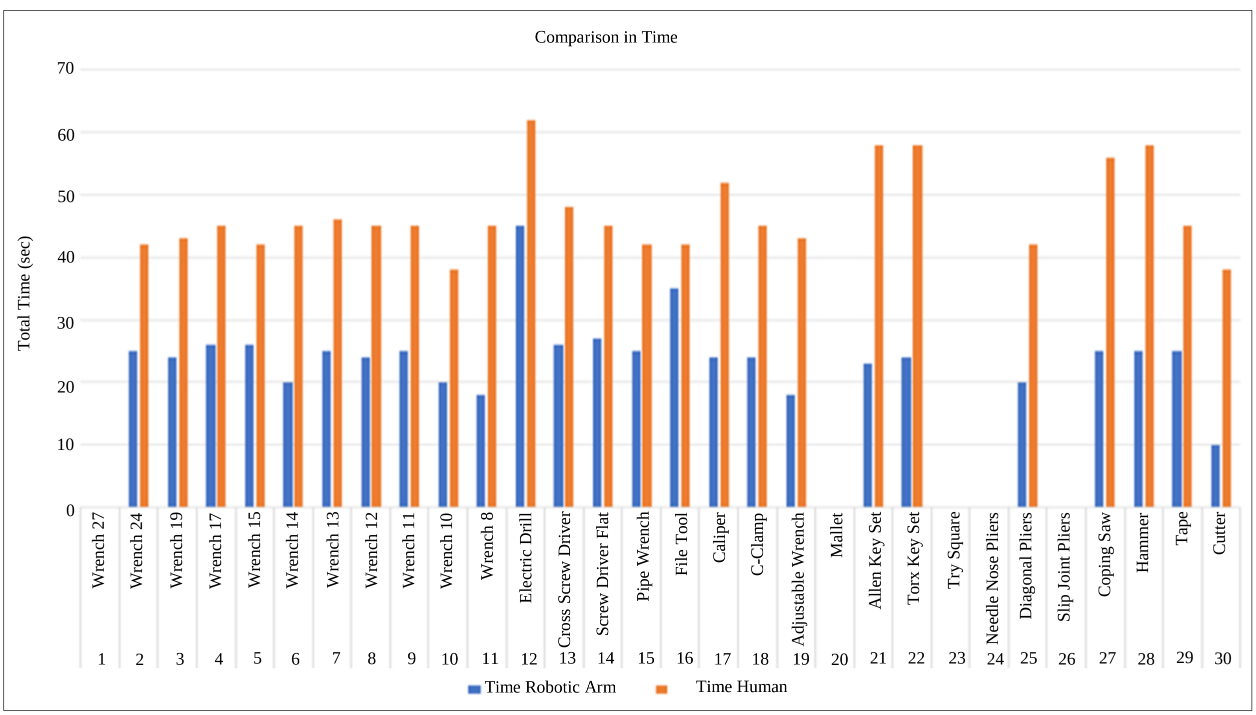


Fig. 19 Comparison of order and selection

6. Conclusion

This study shows the efficiency in saving considerable time directly influencing the production of cutting, assembly and order of the applied automotive mechanical sector, establishing a robotic design according to the required need, based on efficient tests to what is required by the user considering as the main problem the time used to perform the organization of tools on a work table; because it has artificial intelligence this can increase even more the speed of organizing depending on the condition of tools used. The results obtained show the efficiency and time savings achieved after implementation, in addition to reporting on the status of the tools, time used and reporting lost or absent tools.

It is concluded that the development and adaptability of this robotic arm allows the automotive mechanical sector to offer greater efficiency and sustainability in terms of factors such as time savings and tool status selection, thus improving performance and productivity in an automotive mechanical environment, contributing to making this sector more sustainable.

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References

[1] Haider Ali Khan et al., "Design and Development of Machine Vision Robotic Arm for Vegetable Crops in Hydroponics," *Smart Agricultural Technology*, vol. 9, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Naseeb Singh et al., "In-Field Performance Evaluation of Robotic Arm Developed for Harvesting Cotton Bolls," *Computers and Electronics in Agriculture*, vol. 227, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Kening Mi et al., "Research on Path Planning of Intelligent Maintenance Robotic Arm for Distribution Lines Under Complex Environment," *Computers and Electrical Engineering*, vol. 120, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[4] Tianci Gao, "Optimizing Robotic Arm Control Using Deep Q-Learning and Artificial Neural Networks through Demonstration-Based Methodologies: A Case Study of Dynamic and Static Conditions" *Robotics and Autonomous Systems*, vol. 181, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Fausto A. Valenzuela-Domínguez et al., "Design of a Two-Degrees-Of-Freedom Robotic Arm for Monitoring Applications for Teaching Robotics and Artificial Intelligence Technology," *Computer Applications in Engineering Education*, vol. 32, no. 6, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Xuejian Zhang et al., "Research on Six-Joint Industrial Robotic Arm Positioning Error Compensation Algorithm Based on Motion Decomposition and Improved CIWOA-BP Neural Network," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 238, no. 21, pp. 10439-10459, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Eleftheria Poulianiti et al., "Recent Developments in Robotic Vision and Path Following in Robotic Arms and Autonomous Robots," *International Conference Series on ICT, Entertainment Technologies, and Intelligent Information Management in Education and Industry*, Aizuwakamatsu, Japan, vol. 3220, no. 1, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Shengchao Zhen et al., "Robust Trajectory Tracking Control Design for the Robotic Arm with Uncertainty and Experimental Validation" *Journal of Vibration and Control*, vol. 30, no. 19-20, pp. 4351-4367, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[9] Konstantinos Dretakis, Konstantinos Raptis, and Christos Koutserimpas, "The Use of the Robotic Arm-Assisted System (MAKO) for Hip Revision Surgery," *Archives of Bone and Joint Surgery*, vol. 12, no. 8, pp. 608-611, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Qing, Luo, Feng Yanwei, and Ma Haohao, "Parametric Modeling of The Two-Story Platform Robotic Arm of An Oil Drilling Rig," *Proceedings of the 2024 3rd International Conference on Networks, Communications and Information Technology*, China, pp. 87-92, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] P.C. Arunakumara et al., "Design and Analysis of Robotic Arm for Serving Material in Automotive Industry," *International Journal of Vehicle Structures and Systems*, vol. 14, no. 2, pp. 215-218, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Aydin Azizi, "Applications of Artificial Intelligence Techniques to Enhance Sustainability of Industry 4.0: Design of an Artificial Neural Network Model as Dynamic Behavior Optimizer of Robotic Arms," *Complexity*, vol. 2020, no. 1, pp. 1-10, 2020. [CrossRef] [Google Scholar] [Publisher Link]