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Presentation of Content

In the first article we present, *Maintenance and energy management of photovoltaic systems: strategies for energy efficiency and cost optimization*, by MORENO-NUÑEZ, Ismael, SALOME-BAYLON, Joel and JIMENEZ-ZAVALA, José Armando, with adscription in the Universidad Tecnológica de Manzanillo; as the next article we present, *Prototype of a sustainable electricity generation system in an indigenous Mazahua community*, by MENDOZA-SOTELO, Rubén, RUIZ-GARDUÑO, Jhacer Kharen, JIMÉNEZ-ALFARO, Abraham Jorge and GONZÁLEZ-RAMÍREZ, Claudia Teresa, with adscription in the Tecnológico Nacional de México campus Zitácuaro and *Tecnológico Nacional de México campus Superior de Ecatepec*; as the next article we present, *Reconstruction of the rotor output signal of a direct current motor using numerical approximation*, by CAMACHO-ALTAMIRANO, Ulices, MARTÍNEZ-CARRILLO, Irma and JUÁREZ-TOLEDO, Carlos, with adscription in the Universidad Autónoma del Estado de México; as the last article we present, *Industrial robots programming based on augmented reality posture estimators*, by NÚÑEZ-HERNÁNDEZ, Luis Fernando & CANALES-SILLER, Horacio, with adscription in the Centro de Ingeniería y Desarrollo Industrial.

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Maintenance and energy management of photovoltaic systems: strategies for energy efficiency and cost optimization

Maintenance and energy management of photovoltaic systems: strategies for energy efficiency and cost optimization

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Abstract

This work explores the synergy between the maintenance and management of photovoltaic systems to enhance energy efficiency and optimize costs. An advanced architecture for real-time energy management focused on power generation is introduced, integrating the Internet of Things (IoT), cloud computing, and data visualization. Empirical results and detailed analysis are presented as a significant contribution to the field of industrial maintenance and renewable energies.

Photovoltaic systems (PS), Energy efficiency, Internet of things (IoT), Artificial intelligence, Predictive maintenance

Resumen

En este trabajo se explora la sinergia entre el mantenimiento y la gestión de sistemas fotovoltaicos para mejorar la eficiencia energética y optimizar costos. Se introduce una arquitectura avanzada para la gestión de energía en tiempo real, enfocada en la generación de energía, que integra el Internet de las Cosas (IoT), computación en la nube y visualización de datos. Los resultados empíricos y análisis detallados se presentan como una contribución significativa al campo del mantenimiento industrial y energías renovables.

Sistemas fotovoltaicos (SF), Eficiencia energética, Internet de las cosas (IoT), Inteligencia artificial, Mantenimiento predictivo

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Introduction

Energy efficiency and sustainability have become critical issues on the global agenda, particularly in the context of photovoltaic systems [1],[2],[3],[4]. In Mexico, especially for Small and Medium Enterprises (SMEs), optimizing energy management has become an economic and environmental priority. This study aims to present maintenance and management strategies for photovoltaic systems to improve efficiency and reduce operational costs.

The increasing reliance on renewable sources to address the climate crisis makes efficient management of these systems crucial [5]. To meet these challenges, this study proposes an integrated approach encompassing preventive and corrective maintenance and advanced management and monitoring of energy consumption. The need for this research stems from the importance of optimal management and maintenance to maximize the performance of photovoltaic systems.

The structure of this work is organized as follows: we begin with a review of related works, followed by the adopted methodology. Details on implementation and obtained results are then presented. Finally, we offer conclusions and recommendations for future research in this field.

This study aims to fill gaps in existing research by introducing an IoT and cloud computing-based architecture, allowing for real-time energy demand management and offering a more integrated and effective solution for managing photovoltaic systems.

Related work

The quest for efficient and sustainable energy management has motivated significant research into integrating IoT, cloud computing, and data visualization techniques. Studies like those presented in [6] and [7] focus on intelligent energy management systems, employing IoT and cloud computing for real-time data collection, storage, and visualization.

However, despite advancements in the field, gaps remain in scalability, security, privacy, and cost-effectiveness. This work seeks to address some of these issues by offering an architecture that not only optimizes energy efficiency but also focuses on cost reduction.

Interoperability and standardization of protocols allowing seamless integration between different components and systems are also relevant [8],[9],[10]. These challenges are addressed in our proposed architecture by adopting widely accepted communication and data standards.

Furthermore, previous studies have not thoroughly explored the impact of preventive and corrective maintenance on the efficiency of photovoltaic systems. This research contributes to this field by investigating how maintenance practices directly affect both efficiency and operational costs.

Methodology

The study is conducted through an experimental design integrating IoT sensors for real-time data collection, edge computing for data preprocessing, and Amazon AWS for cloud storage and data analysis. The methodology also includes implementing a real-time visualization dashboard developed in Grafana.

To measure the system's efficiency, metrics like the photovoltaic system's energy generation efficiency over time, system latency, and total operational cost are used. A predictive analysis approach is adopted to determine the relationship between maintenance practices and system efficiency. Reinforcement learning techniques are used to optimize energy consumption management.

Regarding security and privacy evaluation, encryption and authentication techniques are applied to protect data integrity and confidentiality. The system's scalability is assessed through stress tests simulating different energy demand scenarios.

The methodology also focuses on the system's adaptability, conducting tests in various industrial sectors such as hospitality, manufacturing, and schools, to evaluate its versatility and effectiveness in different applications.

Results

The implementation is based on a four-layer architecture encompassing the collection, storage, and visualization of data on energy consumption and generation. For the data collection layer, various hardware devices such as energy meters, photovoltaic inverters, and Raspberry Pi devices for edge computing are used.

The implementation is based on a four-layer architecture encompassing the collection, storage, and visualization of data on energy consumption and generation. For the data collection layer, various hardware devices such as energy meters, photovoltaic inverters, and Raspberry Pi devices for edge computing are used.

The visualization layer employs Grafana to develop a real-time dashboard providing intuitive information on energy consumption patterns. This facilitates real-time decision-making and better control over the system.

Additionally, a web alert system is implemented, notifying users of critical events, like fluctuations in system efficiency or potential equipment failures, thus allowing quick interventions for corrective or preventive maintenance. Figure 1. Cloud-IoT based Energy Management architecture. The dataset analyzed consists of energy generation from a photovoltaic plant comprising 5 power inverters recording generation data. The dataset contains the following columns:

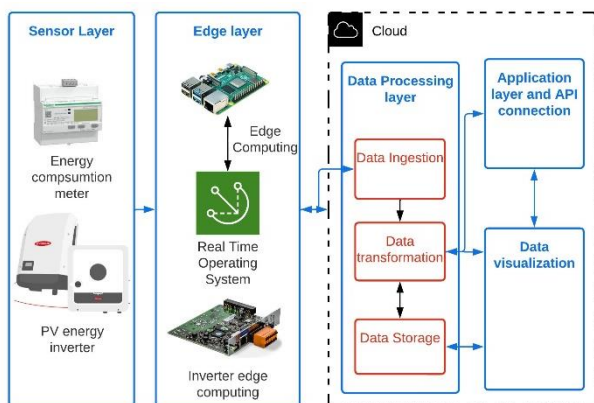


Figure 1 Cloud-IoT based Energy Management architecture

- DATE_TIME: Date and time of each observation.

- PLANT_ID: Plant ID (appears constant in this snippet).
- SOURCE_KEY: Inverter ID.
- DC_POWER: Direct current power generated.
- AC_POWER: Alternating current power generated.
- DAILY_YIELD: Daily production.
- TOTAL_YIELD: Total production to date.

Figure 2 shows the AC power of the 5 inverters over approximately 30 days.

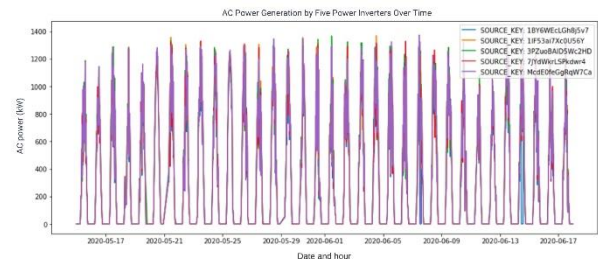


Figure 2 Energy production from a PV system, 5 power inverters. AC power (kW)

To detect faults or anomalous conditions in the inverters, we can use a Long Short-Term Memory (LSTM) model, a variant of recurrent neural networks (RNN). These models are particularly good at dealing with data sequences, like time series.

We will apply the following methodology:

- Data Normalization: We will normalize the AC power data so that the values are within a more manageable range for the LSTM model.
- Data Preparation for LSTM: We will create fixed-length data sequences to train the model.
- LSTM Model: We will train an LSTM model to predict the next AC power observation based on a previous sequence.
- Anomaly Detection: We will use the error between the prediction and actual values to detect possible faults or anomalies.

For one of the inverters, we have 3134 data sequences of length 20 and 3134 corresponding output labels.

Now that our data are prepared, we can proceed to build and train the LSTM model. We will use the Keras library for this. We will train a model for each inverter and evaluate its performance in anomaly detection. Figure 3 shows the training error.

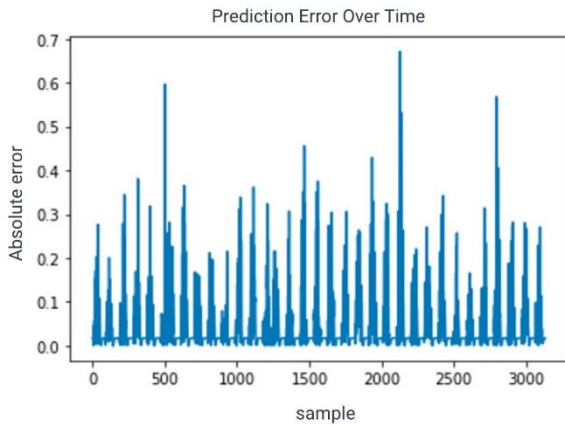


Figure 3 Training error

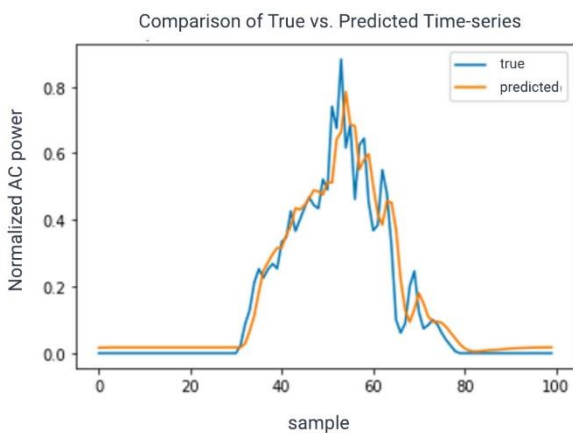


Figure 4 AI model's prediction of power generation versus actual value

With the trained model, we can detect if an inverter shows low performance or potential failure. To illustrate this, we can simulate a scenario where an inverter shows lower energy production than expected according to a hypothetical model. Figure 5 shows such a simulation. If we design a failure threshold, we can obtain an alarm scheme, i.e., when the prediction vs. actual generation is greater than a failure threshold, then an event can be triggered that may fire an alarm for potential failure or low performance.

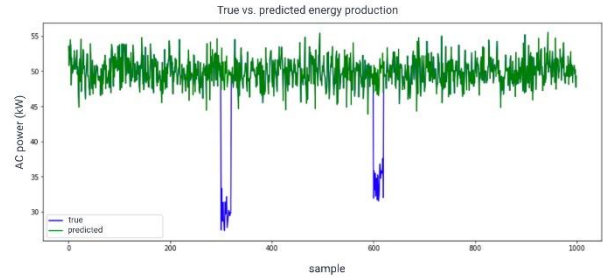


Figure 5 Simulation of a failure in an inverter (blue line) vs. the trained LSTM model's energy generation prediction

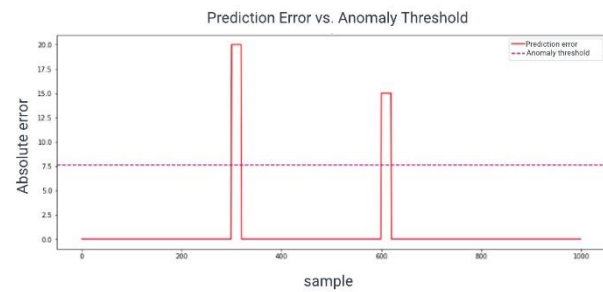


Figure 6 Exemplification and design of failure threshold

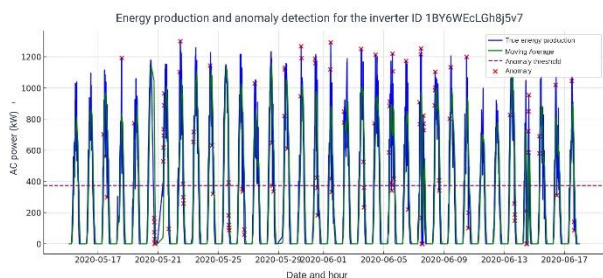


Figure 7 Anomaly detection using the failure threshold approach, with a predictive model based on moving average

To demonstrate the LSTM model's performance, we will analyze the failure threshold using data from the first inverter in the dataset and apply a moving average window to simulate what the predictions of a more advanced model like an LSTM might be. Then, we calculate prediction errors and define a threshold to identify anomalies.

The graph in Figure 7 shows the actual energy production (in blue) and a 10-point data moving average (in green) for the first inverter in the dataset. The points in red represent detected anomalies, which are moments when the prediction error (the difference between actual energy production and the moving average) exceeds an anomaly threshold (dotted purple line).

It's important to note that this is a simplified approach using a moving average instead of a more advanced LSTM model. Now we will apply the same analysis, but with the trained LSTM model, to obtain more accurate results.

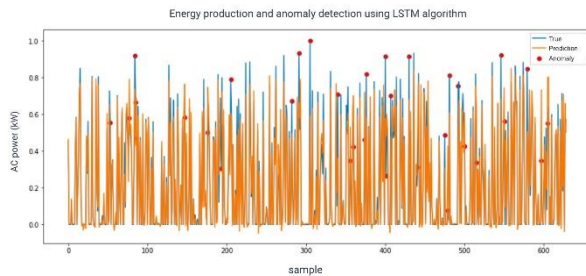


Figure 8 Anomaly or low performance detection, using the trained LSTM model and the failure threshold approach

In Figure 8, we observe that LSTM estimates allow for fewer event points compared to the moving average approach. The LSTM model shows better performance, however, this model requires identifying what type of failure might be occurring in the equipment to provide more context in the detection of the event and possible alarm.

Conclusions

This study presents a Long Short-Term Memory (LSTM) sequence model-based approach for detecting anomalous or low-performance conditions in energy generation system inverters. The performance of the LSTM model is compared to a simplified approach based on a moving average window.

Figure 7 illustrates the moving average approach, where anomaly detection is performed using a threshold calculated based on the prediction error between actual energy production and the moving average. Although effective for an initial approach, this method lacks the sophistication necessary to adapt to more complex patterns in the data.

In contrast, Figure 8 demonstrates the superior performance of the LSTM model in identifying anomalous events. There is a reduction in the number of false positives, indicating more accurate anomaly detection. However, it is important to note that while the LSTM model shows better performance in detection, it lacks the ability to specify the type of anomaly or failure that might be occurring in the inverter.

For future research, it would be valuable to incorporate a more detailed diagnosis that can classify the type of anomaly or failure being detected. Additionally, the model could be improved by incorporating more features and optimizing hyperparameters.

In summary, preliminary results suggest that LSTM models offer a powerful tool for the detection of anomalous conditions in power generation systems, although further research is needed to make the system more descriptive in the type of anomalies it detects.

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Prototype of a sustainable electricity generation system in an indigenous Mazahua community

Prototipo de un sistema generador de energía eléctrica sustentable en una comunidad origen Mazahua

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Abstract

This study proposes the design and development of a prototype electrohydraulic microgenerator to provide a sustainable energy source for the community of Manzanillos, Michoacán. Specific objectives include analyzing the state of the art of similar systems in Mexico and the community, as well as identifying requirements in accordance with the UN's 2030 Agenda. The methodology encompasses various stages: analyzing requirements and hydraulic resources, preliminary design considering technical and environmental aspects, compliance with regulations and standards, community involvement for feedback and adjustments, prototyping, and testing to evaluate performance and efficiency. An agile modeling approach is adopted, allowing for iterations and improvements based on feedback. The study falls within the scope of an exploratory applied research and aims to align with the Sustainable Development Goals of the 2030 Agenda, contributing to energy efficiency, renewable energy, and equitable access to energy. In collaboration with the San Juan Zitácuaro council and the Zitácuaro Technological Institute, the project seeks to create a prototype that addresses the community's energy needs in a sustainable and viable manner in the long term, while promoting community participation and local development.

Electrohydraulic microgenerator, Energy sustainability, Energy needs

Resumen

Este estudio propone el diseño y desarrollo de un prototipo de microgenerador electrohidráulico con el fin de proporcionar una fuente de energía sustentable a la comunidad de Manzanillos, Michoacán. Los objetivos específicos incluyen el análisis del estado del arte de sistemas similares en México y en la comunidad, así como la identificación de requisitos según la Agenda 2030 de la ONU. La metodología abarca diversas etapas: análisis de requisitos y recursos hidráulicos, diseño preliminar considerando aspectos técnicos y ambientales, cumplimiento de regulaciones y normativas, participación comunitaria para retroalimentación y ajustes, creación de prototipos y pruebas para evaluar rendimiento y eficiencia. Se adopta un enfoque de modelado ágil, permitiendo iteraciones y mejoras basadas en retroalimentación. El estudio se enmarca en una investigación aplicada de tipo exploratorio y busca alinearse con los Objetivos de Desarrollo Sostenible de la Agenda 2030, contribuyendo a la eficiencia energética, energías renovables y acceso equitativo a energía. En colaboración con el comisariado San Juan Zitácuaro y el Tecnológico de Zitácuaro, el proyecto busca crear un prototipo que aborde las necesidades energéticas de la comunidad de manera sustentable y viable a largo plazo, a la vez que promueve la participación comunitaria y el desarrollo local.

Microgenerador electrohidráulico, Sostenibilidad energética, Necesidad energética

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Introduction

Sustainable and reliable access to energy is a crucial factor for the development and well-being of communities, especially in rural and marginalised areas. In this context, the implementation of sustainable power generation systems becomes relevant as a promising solution. This article focuses on the design of a prototype electro-hydro microgenerator with the purpose of providing sustainable energy to the community of Manzanillos, a community of Mazahua origin in Zitácuaro, Michoacán.

The objectives of this study are to analyse the current situation of micro-hydroelectric generators in Mexico and specifically in the community of Manzanillos. In addition, it seeks to examine the design requirements of the micro-generator in line with the principles of the UN 2030 Agenda. The study also aims to delimit the scope for the design and development of the prototype in the Manzanillos community, as well as to employ agile modelling techniques for its development. To ensure sustainability and alignment with the 2030 Agenda, essential requirements for the microgenerator have been established. These include maximising efficiency in the conversion of hydropower to electricity to harness resources and reduce waste. In addition, the microgenerator is prioritised as a renewable and clean energy source, contributing to Goal 7 of the 2030 Agenda. It is considered crucial to minimise the environmental impact, ensuring the conservation of biodiversity and avoiding alterations to natural habitats. Accessibility and adaptability of the design are fundamental for its implementation in rural environments and with limited electricity infrastructure [2]. Operational safety and reliability are priorities, as is long-term economic sustainability. In addition, integration with existing systems, community empowerment and alignment with other Sustainable Development Goals (SDGs) of the 2030 Agenda are sought.

Rationale

Access to reliable and sustainable energy sources is a fundamental factor for social and economic development, playing a crucial role in improving the quality of life, promoting education, health care and general community well-being.

However, in many rural and marginalised areas, the lack of accessible and affordable energy options remains a significant challenge, perpetuating cycles of poverty and hindering progress. This underscores the critical need for innovative and localised solutions to address energy deficits and promote sustainable development [1]. The proposed design and development of a prototype micro-hydroelectric generator for the community of Manzanillos in Zitácuaro, Michoacán, emerges as a timely and impactful initiative. The current energy landscape in the community is characterised by limited access to reliable electricity, which inhibits educational opportunities, health services and economic activities. In addition, the construction of alternative electricity generators, supported by existing materials and technologies, provides the feasibility of optimising resources and minimising costs; reliance on non-renewable energy sources contributes to environmental degradation and increases vulnerability to climate change. [3]

The importance of this project lies in its potential to address multiple dimensions of sustainable development. The design of the micro-generator aligns perfectly with the principles of the UN 2030 Agenda, in particular focusing on Goal 7 (Clean and Sustainable Energy), Goal 13 (Climate Action) and Goal 1 (End Poverty). By harnessing the region's water resources, the prototype will contribute to the diversification of energy sources, reducing dependence on fossil fuels and minimising greenhouse gas emissions. In addition, the incorporation of agile modelling techniques allows for community participation and adaptation, improving the inclusivity and long-term viability of the project.

Methodology

This study is framed within an exploratory applied research and focuses on the design and development of a prototype electro-hydro micro-generator with the objective of providing a sustainable source of electricity to the community of Manzanillos, in Zitácuaro, Michoacán. The methodological process is divided into several stages ranging from the identification of requirements to prototyping and functional testing.

Considering the size of the project, it was divided into three phases, which are described in Phase 1.

Requirements Analysis and State of the Art. It starts with a comprehensive analysis of the state of the art of micro-hydro systems both nationally and in the community of Manzanillos. Similar implementation cases are examined and information is gathered on technologies, designs, efficiencies and lessons learned.

Identification of Technical and Environmental Requirements

In collaboration with engineering experts from the academic science faculty in computer systems engineering, electronics, mechanics and robotics, the technical requirements of the microgenerator are identified. Parameters such as generating capacity, output voltage, electrical frequency and physical dimensions are defined. In addition, the environmental and geographical characteristics of the location are considered in order to optimise the use of hydropower.

A detailed analysis of the flow of the river in the community of Manzanillos and the reservoir at the Tecnológico de Zitácuaro is carried out. By means of in situ measurements and analysis of historical data, the height of fall and the available flow are estimated. These data are essential to determine the power generated by the microgenerator.

Preliminary design of the microgenerator

Based on the technical requirements and resource assessment, a preliminary design of the microgenerator is developed. Key components such as the turbine, generator and power conversion system are defined. The design is adjusted to maximise efficiency and minimise environmental impact.

Compliance with Regulations and Legal Requirements. Local regulations and standards related to the installation of power generation systems are reviewed. The design of the microgenerator is adapted to meet established safety and environmental standards.

Community Participation and Feedback. A series of meetings are organised with the Manzanillos community to obtain their opinions and expectations about the prototype. Feedback from the community is essential to ensure that the design fits their needs and values. Prototyping and Testing. Rather than waiting to complete the entire design, rapid prototypes and mock-ups are developed based on the preliminary design. These prototypes allow preliminary testing to evaluate the performance and efficiency of the microgenerator under controlled conditions.

Iteration and Continuous Improvement. Test results and feedback from the community and experts are used to iterate on the design. Adjustments and improvements are made to the prototype design to ensure its functionality, efficiency and alignment with the objectives. functionality, efficiency and alignment with sustainability objectives.

Results

The design of a micro hydropower generator in its functional and detailed prototype phase of the energy generating system. This prototype includes all the necessary components to convert the available hydropower into usable electrical energy in an efficient and sustainable manner. Table 1 below shows the key elements that are part of the prototype.

Action	Description	Achievement
Power Generation Components	Generation mechanisms that transform the kinetic energy of water into mechanical energy.	100%
Mechanical Transmission System	Transmission system that connects the generation mechanism with the electric generator.	100%
Electric generator	Electric generator that converts mechanical energy into electrical energy.	100%
Regulation and Control:	Control system that adjusts water flow and generator speed to optimize power generation.	100%
Energy Storage System	Energy storage system, such as batteries, to store excess energy generated and release it when needed.	100%
Diagrams	Diagram illustrating the configuration and operation of the micro hydroelectric generator	100%

Table 1 Elements for the conversion of hydraulic-electric energy

Source: Own elaboration

The prototype of a hydroelectric microgenerator that was proposed in this project represents a comprehensive solution for the efficient and sustainable generation of electrical energy from hydraulic resources available in the community of Manzanillos. This device will consist of several key components meticulously designed to ensure optimal performance and reliable operation.

First, the Power Generation Components were designed and specified, which may include turbines and propellers. These components are responsible for converting the kinetic energy of the water flow into usable mechanical energy. The precise choice and design of these elements is essential to maximize the efficiency of the conversion and, therefore, the generation of energy. To ensure efficient transmission of the mechanical energy generated, a Transmission System was considered. Mechanically, this system will connect the generation mechanism with the Electrical Generator, which will be responsible for converting mechanical energy into usable electrical energy.

The design and specifications of this generator are crucial to the overall efficiency of the system. In addition, a Regulation and Control system was implemented, which is the system that will monitor and adjust the water flow and the speed of the generator to optimize energy generation based on the changing conditions of the water resource.

Ensuring consistent and efficient performance of the microgenerator in different hydrological situations.

Regarding energy storage, a Storage System, such as batteries, will be considered to capture and store the excess energy generated.

This will allow energy to be released when needed, providing a reliable power source even during times of reduced or intermittent water flow.

In all areas, 100% achievement was obtained, allowing us to move on to the next level of assessment of additional results, which strengthen continuity in the next Phase 2.

Together, these components and systems form a complete microhydroelectric generator prototype that, once implemented and tested in the community of Manzanillos, will serve as a potentially scalable model to address sustainable energy needs in similar communities, thus promoting local development and energy sustainability.

In Table 2, you can see identified factors that contribute to the great value of the prototype for its continuity, providing valuable feedback.

Action	Description	Achievement
Demonstrated Energy Efficiency	Measurements of the amount of energy generated in relation to water flow and drop height, allowing actual performance to be evaluated	100%
Environmental Impact and Sustainability	Life cycle analysis and environmental impact studies to evaluate how the microgenerator affects the surrounding ecosystem and how it meets sustainability and biodiversity conservation objectives.	100%
Design and Technology Validation	Validation of the design and technology used in the prototype	100%
Cost Evaluation	Carry out an accurate evaluation of the real costs of implementation, operation and maintenance of the microhydroelectric generator.	100%
Experience in Agile Modeling	Use of an agile modeling approach during design, gaining experience in successful application in sustainable energy project methodology.	100%
Community Participation and Awareness Raising	The community was involved in the design and development process, results of greater community awareness about sustainable energy and the use of local resources were obtained.	80%
Knowledge Transfer	Collaboration with academic institutions and local organizations helps in the transfer of knowledge and technical skills to the community, which in turn has a positive impact on local development.	90%

Table 2 Factors in the design of the prototype hydroelectric generator

Source: Own elaboration

The micro hydroelectric generator prototype offers a series of significant results that support its effectiveness and usefulness. Firstly, its Energy Efficiency is demonstrated through quantitative data showing its ability to generate energy efficiently under various hydrological conditions. These precise measurements relate the amount of energy produced to variables such as water flow and drop height, allowing an accurate assessment of the actual performance of the device. In addition, a thorough Environmental Impact and Sustainability analysis is carried out, through life cycle studies and assessments of how the micro-generator affects the surrounding ecosystem. This ensures that the project meets the objectives of bio-diversity conservation and sustainability.

The results also validate the Design and Technology employed in the prototype, supporting the feasibility of implementing similar systems in other communities with comparable hydrological characteristics. A more accurate assessment of implementation, operation and maintenance costs is obtained, which is fundamental for future projects.

The experience in Agile Modelling becomes a valuable asset, showing how this methodology can be successfully applied in sustainable energy projects. Community Involvement and Awareness Raising contribute to greater community awareness on sustainable energy, although it shows an achievement of 80%, it is due to the security situation that arose in the city, while Knowledge Transfer with 90% to the community and academic partners promotes local development, due to participation in events to be held in the first half of the year 2024.

Conclusions

The demonstrated energy efficiency of the prototype supports its ability to generate electricity efficiently and sustainably, which has a positive impact on cost reduction and effective use of available natural resources. Compliance with the principles of the 2030 Agenda, such as renewable energy, environmental conservation and the promotion of economic and social sustainability, underlines the importance of this approach in future energy generation projects in similar communities.

In addition, active community participation and the transfer of know-how improve the awareness and capacity of local communities to manage and maintain their own sustainable energy systems, thus contributing to local development and self-reliance. The project sets a positive precedent for the design and development of micro-hydropower generators in rural communities, highlighting their effectiveness, sustainability and ability to empower local communities to manage their own energy, encouraging the continuation of similar projects to address energy challenges in marginalised areas and contribute to the advancement of global sustainability goals.

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Reconstruction of the rotor output signal of a direct current motor using numerical approximation

Reconstrucción de la señal de salida del rotor de un motor de corriente directa utilizando aproximación numérica

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Abstract

In many areas of technology and research, who study behavior process have increasingly relied on mathematical models. Most of the time the mathematical model is used, representing the important aspect of a dynamic system. Sometimes the mathematical model does not have an appropriate structure and it can be loss the relevant information, nevertheless output signal characterization based on an input signal using laboratory measurements in real time can keep the relevant information, which it is not contemplated in the mathematical model because they involve losses or disturbances. In this work the speed of the rotor magnetic field with respect to the stator magnetic field for a dc motor in real time is showing, the data will be processed and a polynomial approximation is depicting and can effectively trigger with the mathematical model. Finally, a stability analysis is present, it shows the regions or system stability points (pre-fault, fault and post-fault), and the direction from which stability is reached through time.

Numerical integration, Stability analysis, Phase plane portrait

Resumen

El estudio y análisis de los modelos matemáticos para conocer el comportamiento ideal de fenómenos en diversas áreas de la ciencia y la tecnología, son de gran interés. La mayoría de las veces se parte de un modelo matemático el cual contiene la mayor información sobre el comportamiento dinámico del sistema. La caracterización de una señal de salida a partir de una señal de entrada mediante la obtención de mediciones en tiempo real en el laboratorio, contiene información relevante que no está contemplada en un modelo matemático ideal, ya que se involucran pérdidas o perturbaciones que pudieran estar presentes. En este trabajo se modela la velocidad de un rotor de un motor de corriente continua (cd), mediante mediciones en tiempo real obtenidas de una base de datos experimentales de laboratorio que serán procesados usando la teoría de integración numérica y herramienta de Matlab, para obtener una aproximación polinomial de orden n, se comparará con el modelo matemático del sistema original para conocer sobre la precisión del método propuesto. Finalmente se concluirá con un estudio de las regiones de estabilidad (pre-falla, falla y post-falla).

Integración numérica, Análisis de estabilidad, Plano de fase

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Introduction

Electric motors in the industrial field, are the main elements that convert electrical energy into mechanical, however, due to the different and prolonged times of use make them vulnerable to operational problems. According to Rairán (2011) the main function of motors is based on controlling processes in industry such as adjusting temperature, current, voltage, torque, speed and position.

Fernández (2007) states that, in order to make any modification in the parameters of a dynamic system composed of electric motors, measurements of the main parameters must be made by means of sensors and, subsequently, the controller can be designed. The control process starts with the comparison between the sensor reading and the reference value considered as the expected value and the error signal is based on the comparison of previously evaluated readings considered as the controller input.

Revuelta (2016) states that by modifying the control parameters of an electric motor, the theoretical losses can be determined and the purpose of the modification is almost always to know the ideal behaviour.

According to Sánchez (2008) the purpose of reconstruction is to convert a set of data or points into a digital model, maintaining a representation of its physical characteristics, the use of reconstruction techniques through interpolation is used because they provide greater accuracy and control of adjustment.

The purpose of this work is to reconstruct the output signal of a direct current (dc) motor with a step input signal from experimental data, in order to subsequently evaluate and design a polynomial system (numerical model).

This model represents the original dynamic behaviour of study, consecutively the proposed methodology is compared with the output response of the mathematical model of the dc motor checking the approximation of the method. The methodology to be used is described in figure 1.

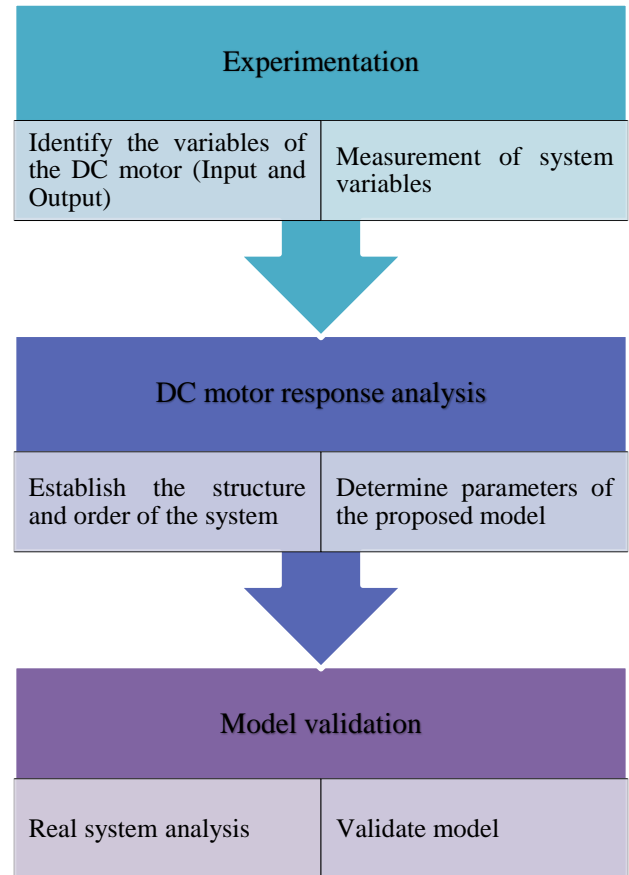


Figure 1 Proposed methodology
Source: Own elaboration

DC motor dynamics under load

The dynamic behavior of a DC motor like the one shown in Figure 2 is represented with a set of differential algebraic equations whose transforms in the Laplace domain are the transfer function in Dorsey (2004).

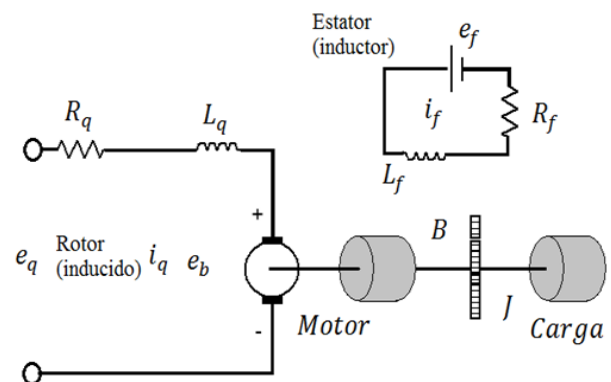


Figure 2 DC motor considering the load
Source: Valdivia (2012)

The motor model considering the load can be described with the following transfer equations:

$$\frac{\theta(s)}{E_q(s)} = \frac{k_m}{[s^2 + (\frac{B}{J})s + \frac{k_r}{J}](s + \frac{R_q}{L_q}) + k_e k_m s} \tag{1}$$

Being

$$G(s) = \frac{k_m}{\left[s^2 + \left(\frac{B}{J}\right)s + \frac{k_r}{J}\right]\left(s + \frac{R_q}{L_q}\right)} \quad (2)$$

and

$$H(s) = k_e k_m s \quad (3)$$

The accuracy of the model depends on the detailed representation of the phenomena involved in the physical parameters corresponding to the real values of the engine, in Figure 2, equations (2) and (3) are described in Table 1 (Chapman, 2005).

Parameter	Description	Units
e_q	Armature voltage	V
R_q	terminal resistance	Ω
L_q	rotor inductance	H
B	friction torque	Nms
J	motor inertia	gcm ²
τ_m	Mechanical time constant	s
k_e	Counter electromotive force constant FEM	V /rpm
k_m	Torque constant	Nm/A
I_0	No-load motor current	mA
n_0	Rated angular speed of the motor without load	rpm
M_N	Rated torque	Nm
τ_e	Electrical time constant.	s

Table 1 DC motor parameters considering load
Source: Chapman, (2005)

Conventionally, the study and analysis of the mathematical model of equation (1) is considered ideal, that is, disturbances within the system are not involved. In this study, the output response to a disturbance of a DC motor of the real model is analyzed by means of polynomial approximations.

The block diagram representation of equation (1) is shown in Figure 3.

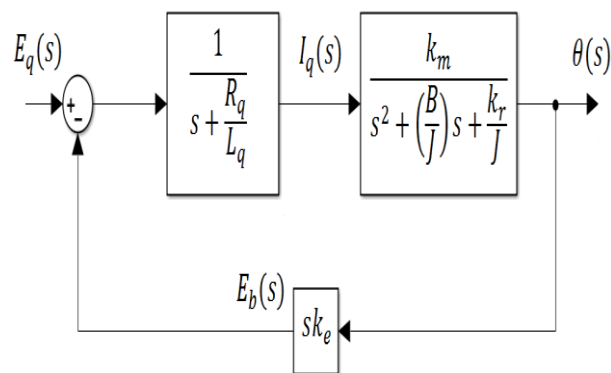


Figure 3 Block diagram of a DC motor
Source: Own elaboration

with $E_q(s)$ and $\theta(s)$ being the input and output signal respectively. It can be seen in Figure 3 that the feedback block of the system is dependent on the constant k_e

In real models, the motors are subject to small disturbances inherent to the system. Figure 4 shows the block diagram of the original system with a disturbance $N(s)$ not contemplated within the initial operation of the study model.

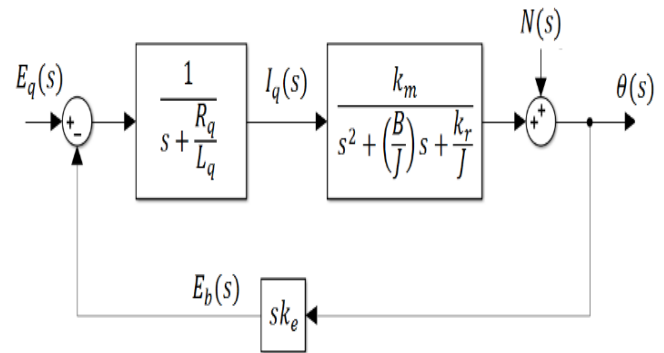


Figure 4 Block diagram with disturbance of a DC motor
Source: Own elaboration

Starting from the assumption of the diagram in Figure 4 where a disturbance of the mechanical torque is involved within the motor parameters, the representative model of the system will then be designed.

Lab tests

To obtain the laboratory measurements where the recorded data set is used for the proposed model, an interface of a motor mechanically coupled to a load was designed and built as shown in figures (5) and (6).

$$\{\Delta^0 f(x_i) = f(x_i), \Delta^k f(x_i) = \Delta^{k-1} f(x_{i+1}) - \Delta^{k-1} f(x_i)\} \quad (4)$$

Where $\Delta^k f(x_i)$ It is called order difference $k \in N \cup \{0\}$ of f in the point x_i .

The forward difference approximation of the first derivative of a function $f(x_i)$ sand defines as:

$$\begin{aligned} \Delta y_i &= y_{i+1} - y_i \\ i &= 0, \dots, n - 1 \end{aligned} \quad (5)$$

where y_i is obtained by evaluating the function $f(x_i)$.

The differences obtained are called first-order differences of the function $f(x)$ on the interval function (x_0, x_n) . To define second-order differences, equation (5) is written as:

$$\begin{aligned} \Delta^2 y_i &= \Delta(\Delta y_i) = \Delta y_{i+1} - \Delta y_i \\ i &= 0, \dots, n - 2 \end{aligned} \quad (6)$$

In general, for differences of the k th order, we have:

$$\begin{aligned} \Delta^k y_i &= \Delta^{k-1} y_{i+1} - \Delta^{k-1} y_i \\ i &= 0, \dots, n - k \end{aligned} \quad (7)$$

In Camacho (2017) equation (8) represents a way to rewrite the differences forward using the following system

$$\begin{aligned} y_2 &= y_1 + \Delta^1 y_1 \quad y_3 = y_1 + 2\Delta^1 y_1 + \Delta^2 y_1 \quad y_4 = \\ &= y_1 + 3\Delta^1 y_1 + 3\Delta^2 y_1 + \Delta^3 y_1 \quad y_5 = y_1 + \\ &= 4\Delta^1 y_1 + 6\Delta^2 y_1 + 4\Delta^3 y_1 + \Delta^4 y_1 \end{aligned} \quad (8)$$

in compact form

$$\begin{aligned} y_2 &= (1 + \Delta)y_1 \quad y_3 = (1 + \Delta^2)y_1 \quad y_4 = (1 + \\ &= \Delta^3)y_1 \quad y_5 = (1 + \Delta^4)y_1 \end{aligned} \quad (9)$$

such that k th order, simplifies into the equation (7)

$$y_{k-1} = (1 + \Delta)^k y_1 \quad (10)$$

Newton's binomial theorem is an arrangement by which the development of the positive powers of a binomial can be written.

Where the k combinations of a set of j elements define the equation:

$$\begin{aligned} y_{k+1} &= (k \ 0) y_{i+1} + (k \ 1) \Delta^1 y_1 + \\ &= (k \ 2) \Delta^2 y_1 + (k \ 3) \Delta^3 y_1 + \dots + \\ &= (k \ k) \Delta^k y_1 \end{aligned} \quad (11)$$

Equation (12) is the binomial coefficient formula, as stated in Cheng-I and Yeong-Chin (2016).

$$(k \ j) = \frac{k!}{j!(k-j)!} \quad (12)$$

Equation (13) shows that if $j=0$ then for any k the value corresponds to

$$(k \ 0) = \frac{k!}{0!(k-0)!} = \frac{k!}{(k)!} = 1 \quad (13)$$

Simplifying the above expression into the recursive polynomial of equation (11), it follows that

$$\begin{aligned} y_{k+1} &= y_1 + (k \ 1) \Delta^1 y_1 + (k \ 2) \Delta^2 y_1 + (k \ 3) \Delta^3 y_1 + \\ &= \dots + (k \ k) \Delta^k y_1 \end{aligned} \quad (14)$$

In Hernandez, (2015) the j -th differences of the points of a constant tabulated function in $(k \ j)$ is a polynomial in k of degree j , so that y_k , can be expressed as

$$y_{k+1} = a_0 + a_1 k + a_2 k^2 + \dots + a_j k^j \quad (15)$$

If a function is continuous at $a \leq x \leq b$, it can be approximated to a polynomial $P_n(x_i)$, undergraduate n .

$$P_n(x_i) = a_0 + a_1(x) + a_2(x^2) + \dots + a_n(x^n) \quad (16)$$

Because the system has n defined points the resulting n -order polynomial has the following form:

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \dots + a_n x^n \quad (17)$$

where (a_0, a_1, \dots, a_n) correspond to the unknowns described in Juárez (2016).

Results

The application of the proposed method was implemented on the engine in figure 5 and 6 with nominal plate values given in table 2.

Parameter	Value
e_g	12 V
R_g	1.9 Ω
L_g	65 μH
B	1.18 μNms
J	5.7 gcm^2
τ_m	6 ms
k_e	1.4 mV/rpm
k_m	13.4 mNm/A
I_0	75 mA
n_0	8100 rpm
M_N	17 mNm
τ_e	34.21 μs

Table 2 Motor nameplate ratings model 2342L012CR: DC-Micromotors
Source: Faulhaber (2022)

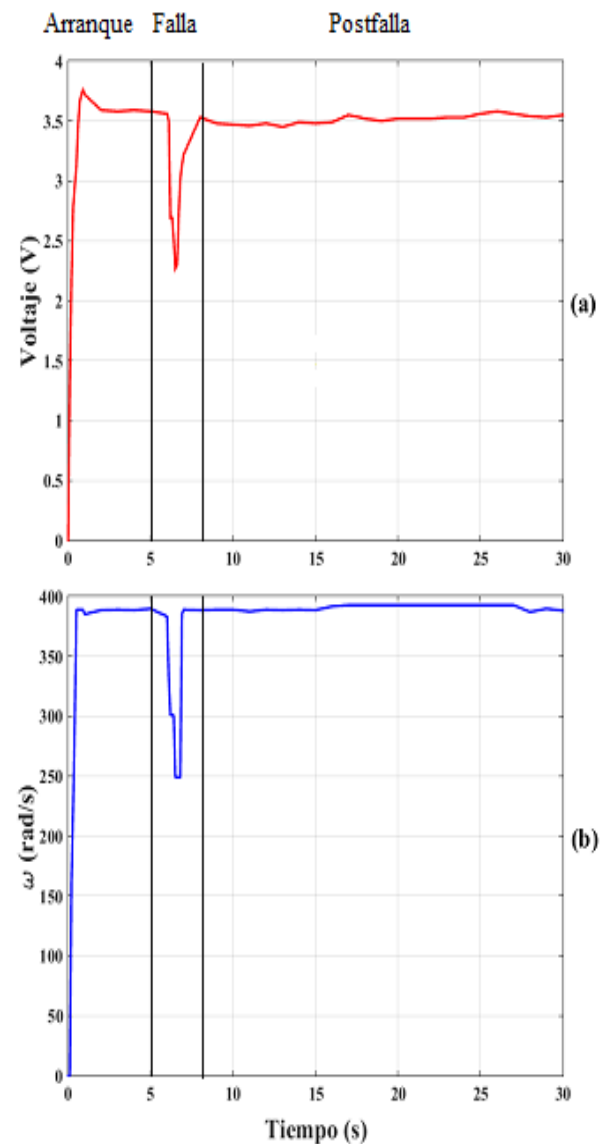
The measurements obtained are shown in table 3, at a time interval of 30 seconds.

Time (s)	Angular velocity (ω en RPM)
0	0
0.1	0
0.2	1553.57
0.3	2142.85
0.4	2850.00
0.5-0.9	3712.87
1	3676.47
2-3	3709.45
4	3712.87
5	3720.37
6	3658.80
6.1	3171.42
6.2-6.4	2871.42
6.5-6.8	2378.57
6.9	3676.47
7	3712.87
8	3698.31
9	3713.02
10	3712.94
11-12	3709.23
13-14	3712.94
15	3709.45
16	3738.93
17-27	3750.00
28	3694.82
29	3720.59
30	3705.66

Table 3 Laboratory data
Source: Own elaboration

Graphic 1 shows the input and output signal corresponding to the system corresponding to table 3.

For the purposes of the study, the transformation of revolutions per minute (RPM) to radians per second (rad/s) corresponding to the angular velocity (ω) is carried out. The three stages of the system during the study period can be observed, the first being the start-up, followed by the voltage change and finally the stabilization zone.



Graphic 1 (a) output signal, (b) input signal
Source: Own elaboration

Graph 1 identifies the stages of the dynamic behavior of the system under study as follows:

Start-up or Pre-fault: the speed and voltage start from the origin and tend to stabilize.

Fault: voltage and speed drop due to the disturbance.

Post-fault: the system has slight oscillations until a new equilibrium point is found.

During the evolution of the trajectory of the laboratory data, the phases of the dynamic behaviour of the motor can be clearly observed.

Numerical solution

The approximation or interpolation methods reconstruct signals by approximating the data set obtained in laboratory tests. Polynomial interpolation provides a practical solution to the behaviour of the rotor system in comparison with the mathematical model.

The aim of the present work is to obtain an accurate, concise and approximate description of the real system behaviour. In the following, the polynomials generated in the reconstruction of the angular velocity (ω) in different cases are presented.

The sectioning of the laboratory curve for the validation of the proposed method is expressed in equation (18), which includes three stages.

$$x \in [a, b] \rightarrow R y \{n_0, n_1, \dots, n_m\} \quad (18)$$

where m is the total number of elements of angular velocity ω .

$$\begin{aligned} x_1 &= [n_1, n_2, \dots, n_k] & x_2 &= \\ [n_{k+1}, n_{k+2}, \dots, n_p] & \dots & \\ [n_{q+1}, n_{q+2}, \dots, n_m] & & \end{aligned} \quad (19)$$

so that equation (19) corresponds to the number of times the real model will be sectioned.

Case 1

Using equation (16), the polynomial of degree thirteen is calculated which corresponds to the best approximation to the real model, so it is described as

$$P_{13}x = a_0 + a_1t + a_2t^2 + \dots + a_{12}t^{12} + a_{13}t^{13} \quad (20)$$

The points in table 3 corresponding to the data collection that satisfy the above expression, the coefficients $[a_0, a_1, \dots, a_n]$ are shown in table 4.

Coefficient	Result
a_0	-42.06
a_1	1280.82
a_2	-1389.80
a_3	764.94
a_4	-245.11
a_5	49.40
a_6	6.58
a_7	0.59
a_8	0.03
a_9	1.64×10^{-3}
a_{10}	-4.88×10^{-5}
a_{11}	9.38×10^{-7}
a_{12}	-10.55×10^{-9}
a_{13}	5.267×10^{-11}

Table 4 Coefficients of equation 21

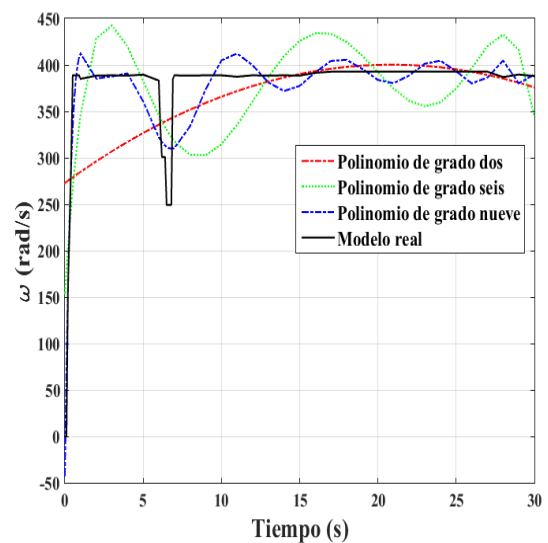
Source: Own elaboration

Equation (21) shows the resulting polynomial obtained with the data shown in table 4.

$$\begin{aligned} f(x) = & -42.06 + 1280.82t - 1389.80t^2 + \\ & 764.94t^3 - 245.11t^4 + 49.40t^5 - \\ & 6.58t^6 + 0.59t^7 - 0.03t^8 + \\ & 1.64 \times 10^{-3}t^9 - 4.88 \times 10^{-5}t^{10} + \\ & 9.38 \times 10^{-7}t^{11} - 10.55 \times 10^{-9}t^{12} + \\ & 5.26 \times 10^{-11}t^{13} \end{aligned} \quad (21)$$

The curve corresponding to the real model without splitting the system behaviour into stages and the representation of the equation (21) of the polynomials of degree three and six are incorporated in figure 2.

$x_l =$



Graphic 2 Real model, Polynomial degrees 2, 6, 13

Source: Own elaboration

Case 2

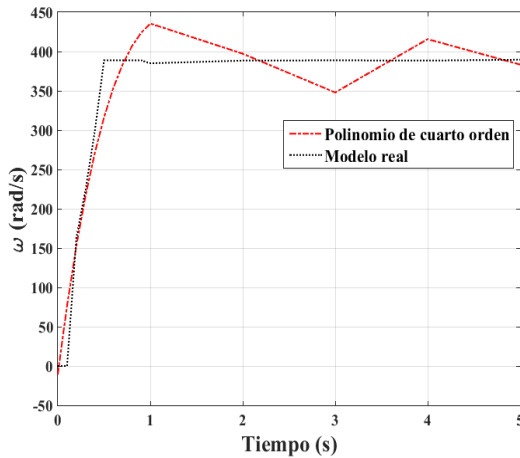
By dividing the behaviour of the system, three polynomials are obtained, comprising start-up, voltage change and stabilisation. Graphs 3, 4 and 5 show the behaviour of the stages. Again making use of equation (16) the resulting polynomials are:

$$f(x_1) = -10.01 + 9.32x10^2t - 6.37x10^2t^2 + 1.65x10^2t^3 - 14.38t^4 \tag{22}$$

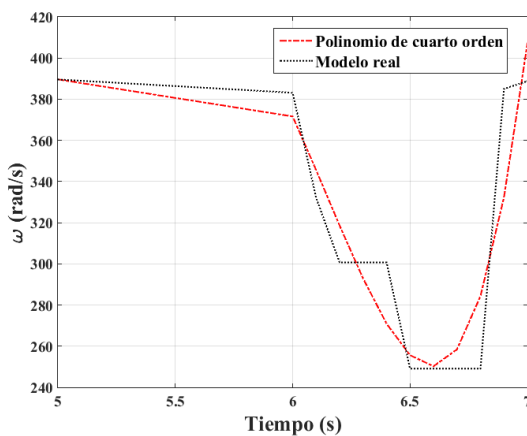
$$f(x_2) = 1.49x10^5 - 1.09x10^5t + 2.98x10^4t^2 - 3.58x10^3t^3 + 1.60x10^2t^4 \tag{23}$$

$$f(x_3) = 4.12x10^2 - 6.25t + 0.53t^2 - 1.68t^{-2} + 1.70x10^{-4}t^4 \tag{24}$$

The polynomial $f(x_1)$ of equation (22) corresponding to the start-up stage of the system, the behaviour of which is depicted in Figure 3.



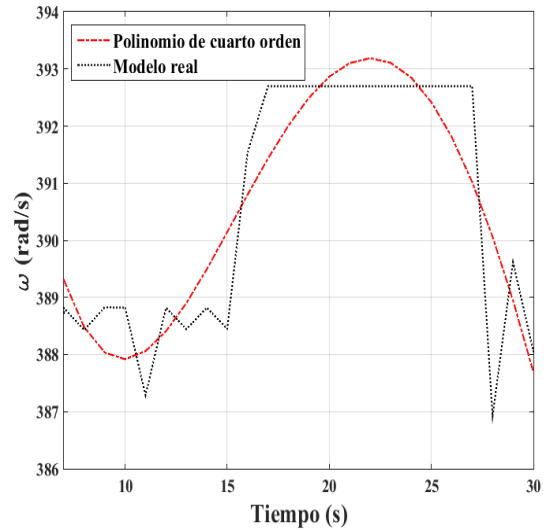
Graphic 3 Stage one of the system and fourth order polynomial
Source: Own elaboration



Graphic 4 Stage two of the system and fourth order polynomial
Source: Own elaboration

Graph 4 shows the voltage change established as stage two or system failure, represented by equation (23) and the polynomial $f(x_2)$.

Finally, graph 5 shows the polynomial $f(x_3)$ of equation (24), belonging to the stabilisation or post-fault stage of the system..



Graphic 5 Stage three of the real model and fourth order polynomial
Source: Own elaboration

Acknowledgements

The authors are grateful to the Consejo Mexiquense de Ciencia y Tecnología with grant ESYCA2023-14929.

Conclusions

As can be seen in graph 1, the dynamics of direct current motors are very varied, so that an algebraic model must contemplate the maximum possible variables of the real system, while the numerical method based on polynomial equivalents can approximate the graphical model 2.

The graphs 3-5 show that by dividing the phenomenon into time windows (pre-fault, fault and post-fault) the fourth-degree polynomial approximation improves.

In the article polynomials of different degrees are exposed in order to check:

Equations 22, 23 and 24 corresponding to the staged classification show a behaviour that tends to minimise the degree of error between the real model and the polynomial one.

The higher the degree of a polynomial, the better approximation to the curve of the real model is obtained.

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Industrial robots programming based on augmented reality posture estimators**Programación de robots industriales a partir de estimadores de postura con realidad aumentada**

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Abstract

Given the high level of training required to program robots, their utilization has historically been confined to high production volumes. In response to this challenge, several efforts have been made to simplify the programming process. One particularly notable approach involves the use of *Augmented Reality (AR)* to present both information and interactive virtual objects, thereby facilitating more intuitive programming. Building on this, the present paper introduces a method for calibrating posture estimators using *AR* on mobile devices. It also presents an interface that allows users to define, view, and execute welding routines on a robot. This method enhances the accuracy of the posture estimators and reduces the error when compared against a reference. Consequently, it achieves a level of accuracy closer to the one required in practical applications. The results of this work can be used to develop *AR* interfaces that enable *in-situ* robot programming.

Augmented reality, Robotics, Programming, Interfaces, Mobile, Calibrate, Accuracy, Production**Resumen**

Dado el alto nivel de formación tradicionalmente requerido para programar robots, su utilización históricamente ha estado limitada a volúmenes de producción elevados. En respuesta a este desafío, se han realizado varios esfuerzos para simplificar el proceso de programación. Un enfoque particularmente destacado implica la utilización de *Realidad Aumentada (RA)* para presentar información e interactividad con objetos virtuales, facilitando así una programación más intuitiva. Basándose en esto, el presente artículo introduce un método para calibrar estimadores de postura utilizando *RA* en dispositivos móviles. También presenta una interfaz que permite a los usuarios definir, visualizar y ejecutar rutinas de soldadura en un robot. Este método mejora la precisión de los estimadores de postura y reduce el error al compararlo con una referencia. En consecuencia, logra un nivel de precisión más cercano al requerido en aplicaciones prácticas. Los resultados de este trabajo pueden ser usados para desarrollar interfaces de *RA* que permitan la programación de robots *in-situ*.

Realidad aumentada, Robótica, Programación, Interfaces, Móvil, Calibrar, Exactitud, Producción**Citation:** NÚÑEZ-HERNÁNDEZ, Luis Fernando & CANALES-SILLER, Horacio. Industrial robots programming based on augmented reality posture estimators. *Journal of Technological Prototypes*. 2023. 9-23:23-33.

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Introduction

The rising interest in robotic arms can be attributed to their high accuracy, precision, and convenience. However, their deployment is far from simple, necessitating specialized training and costly equipment. Additionally, the act of programming these arms is intricate and labor-intensive. This has spurred the quest for more user-friendly and cost-effective methods for programming these devices.

A favored strategy involves the incorporation of user-friendly interfaces and cloud-supported programming utilities, enabling users to operate robotic arms without extensive technical expertise. Emerging technologies like machine learning and computer vision are also contributing to the automation of specific tasks. According to Larkin et al. (2017), further automating the robot programming process could minimize or even eradicate the need for human intervention, make it more practical to use robots for small-scale operations, enhance the autonomy of robots, and cut down on operational downtime. Nevertheless, there remains a discernible gap in both knowledge and available resources, particularly in less developed regions.

While the use of *Augmented Reality (AR)* in industrial robotics has primarily been explored in academic settings, it has yet to transition into a commercial product. In this landscape, mobile-based *AR* solutions for robot programming have largely been eclipsed by *head-mounted displays (HMD)*. This predominance is because *HMDs* provide a more immersive and real-time programming experience, thereby enabling users to interact with robots more effectively. Furthermore, *HMD*-based solutions grant users greater freedom of movement and a more intuitive interaction with robots, consequently enhancing both the efficiency and effectiveness of programming tasks. Despite this, a market niche still exists for mobile-based *AR* solutions, particularly in scenarios where increased portability and accessibility are required.

One proposal for implementing *AR* in robotics is offered by Ong et al. (2019), which presents a robot programming system for welding tasks assisted by *AR*. This system simplifies the definition of the welding path and allows for the placement of weld seams between a flat surface and a surface perpendicular to it, as well as the orientation of the robot's end effector. This is achieved using a handheld pointer, which is tracked by a motion capture system.

Similarly, Zhang et al. (2020) present an *AR* application that uses *Vuforia* and markers to display a virtual robot. This application allows manual control of the rotation axes of the virtual robot, thereby teaching the real robot by aligning the end effector with real objects located near the marker. This application also allows for the control of aspects of the robot or its programming with touch controls on a mobile interface. Which is similarly done in this work, as described in section *Trajectory parametrization*.

In a related development, an *AR* tool introduced by Lotsaris et al. (2021) uses a *Hololens* device to assist in the operator's interaction with the robot in production systems. It is calibrated with a *QR* code, located in a fixed and known position. And allows to teach a robotic gripper, using gestures to manipulate a virtual version of it. The use of a *QR* code in a known position is an aspect also applied in the present study, by using a calibration marker that is placed in a fixed position in relation to the robot, as shown in section *Calibration of the fixed marker*.

Bertolo et al. (2019) discusses the limitations and future directions of *AR*-assisted surgery, where the poor registration of *AR* is denoted as its major limitation. This area is highlighted as in need of urgent technical improvements. Considering this, the current work introduces a method for averaging poses with the intention of increasing the accuracy achievable with *AR*.

This work focuses on the use of *AR* techniques and trajectory parametrization to simplify robot programming in welding applications, aiming to achieve sufficient accuracy for practical use in low-volume production. This is done through the development of a method that enables the mobility of industrial robots by determining the posture of objects within their reach. In this study, the development of *AR* technology for the industry is presented, in which it is verified whether determining the posture of objects with augmented reality, accompanied by calibration paradigms, allows for sufficient accuracy to support industrial robot welding operations.

Posture estimation of augmented reality markers

Ong et al. (2020) point out that although mobile *AR* allows users to move freely within the work cell and provides a first-person view, it requires them to use at least one hand to hold the device,

thus limiting their ability to interact with the environment. Therefore, it is important to develop mobile AR interfaces with this limitation in mind. To address this challenge, this work presents a mobile AR interface that employs two AR markers to define the robot's trajectories. These are based on a pair of posture estimator sets specifically designed for welding applications. The interface was developed using the *Unity* game engine (Unity Documentation, n.d.) and the *Vuforia* AR framework (Vuforia Library, n.d.). Notably, this AR interface requires one marker to be placed in a fixed and calibrated position relative to the robot's base, while a mobile marker facilitates the definition of parameter-based trajectories and postures for the robot.

These trajectories are subsequently defined through a mobile application designed for the *Android* platform. They are then read via *Android Debug Bridge (ADB)* over *Wi-Fi* (Android Debug Bridge, n.d.) by a *Python* script executed on a computer. This script, in turn, utilizes the *RoboDK API* to interact with *RoboDK* (ROS-Industrial, n.d.), thereby generating a program in a language that the robot can execute.

In terms of data representation, the results showcased in this work were converted from *Unity's* coordinate system to a right-handed Cartesian coordinate system with the z-axis pointing upwards.

The proposed method uses two of the AR targets provided by *Vuforia*, an *Image Target* and a *Model Target*. *Image Targets* represent images that *Vuforia* can detect and track (Image Targets, n.d.), while *Model Targets* do the same with objects if a 3D model is provided (Model Targets, n.d.). Both targets can be used to display content like any AR marker. Specifically, the *Image Target* is used as an initialization marker located in a fixed and known position relative to the robot's base and allows the application to estimate the transformation between its local frame and the robot's global frame. Conversely, the *Model Target* is used as a mobile marker, which helps define and place a parametric trajectory pattern in the world relative to the global frame.

To facilitate this, *Vuforia Target Manager*, which is a web tool for creating and managing target databases (Vuforia Target Manager, n.d.), was employed to create the *Image Target* from the black and white image of rocks shown in Figure 1a. This was chosen because it has many details that give *Vuforia*

more features to work with, thereby improving tracking accuracy.

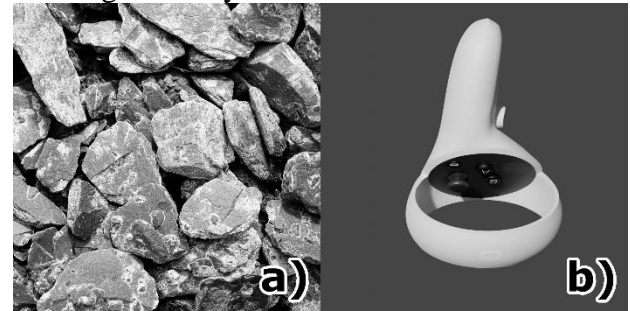


Figure 1 AR markers created with *Vuforia* used in this work. a) Image used to create the fixed calibration marker (*Image Target*). b) Render of the 3D model of the mobile marker (*Model Target*)

Source: Own elaboration.

While, the *Model Target* was created using the desktop application *Model Target Generator* (Model Target Generator User Guide, n.d.), based on the right controller of the *Meta Quest 2* and its 3D model found on the *Oculus* site (Oculus Developer Center, n.d.), which is presented in Figure 1b. To properly align the mobile marker on the grid, the marks shown in Figures 2a and 2b were used to define the center and a line between them that represents the center of the mobile marker and the forward orientation.

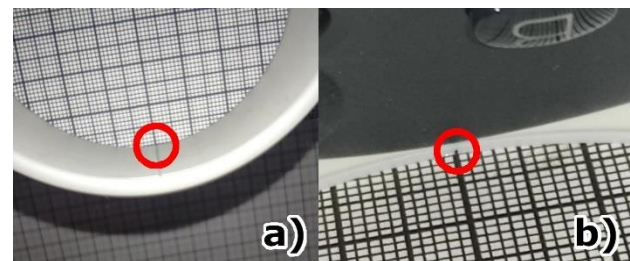


Figure 2 Marks on the right controller of the *Meta Quest 2*, used for aligning it on the grid, the mark in the image on the left defines the center of the marker

Source: Own elaboration.

For this method, an AR application for *Android* devices was developed, which estimates the posture of a mobile marker relative to a reference frame, using *Unity 2021.3.5f1* and *Vuforia 10.7.2*. This mobile AR application was tested to calibrate it, modify it, and test its accuracy, as well as its proper functioning with a *Universal Robots UR3e* robot. The application was executed on a device with a *Snapdragon 732G*, a 64 Mpx camera, a 2 Mpx depth sensor, and 6 GB of RAM; this device is compatible with *Google's ARCore*.

Figure 3 presents a diagram of the posture estimation of this method and its necessary transformations, which are described below:

- Camera to global: The transformation between the fixed marker and the base of the robot.
- Posture of the fixed marker relative to the initial smartphone: The posture of the device relative to the fixed marker at the last moment it was being directly tracked.
- Current posture relative to the initial posture of the smartphone: The posture of the device relative to the initial posture of the camera.
- Posture of the mobile marker relative to the current smartphone: The posture of the mobile marker estimated by the application using the device's camera.

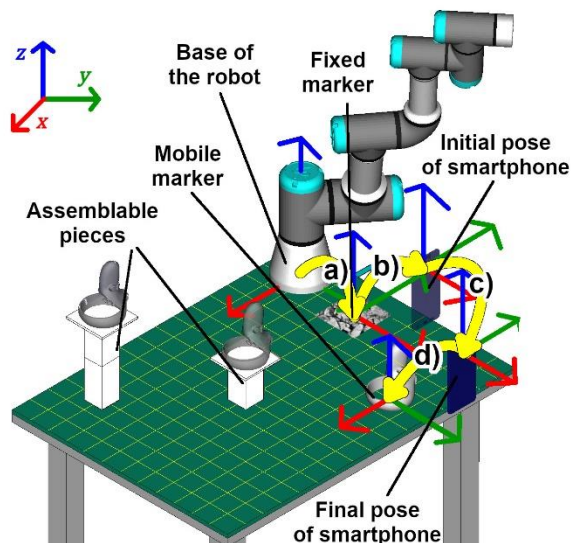


Figure 3 Diagram of the method and necessary transformations

Source: Own elaboration.

Calibration

Calibration of the mobile marker

Given that the center and orientation of the 3D model of the mobile marker did not align with those of the real object, an experiment was conducted to calibrate it. Specifically, the aim was to estimate the transformation between the real and virtual mobile marker. To accomplish this, the experimental setup depicted in Figures 4a, 4b, 4c, and 4d was utilized. In these figures, the mobile marker is observed traversing different postures. The purpose of this setup was to obtain estimates of the posture of the mobile marker relative to the fixed marker and to contrast these with a reference coordinate system. This reference system consists of a printed paper with millimeter graduation affixed to a table, which includes a pattern and the fixed marker. The grid on this paper defined a reference coordinate system, whose origin was defined as the center of the fixed marker.

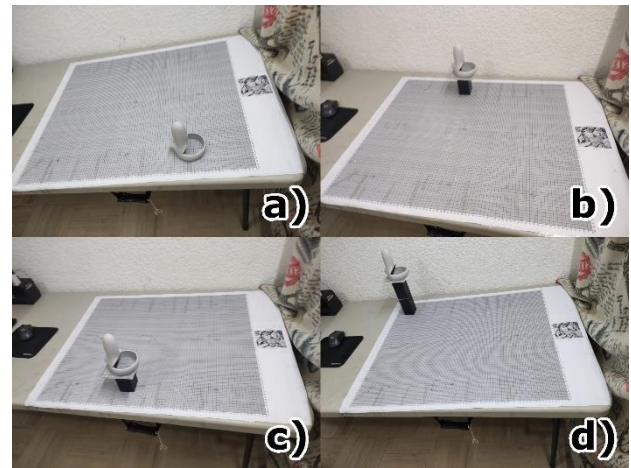


Figure 4 Experimental setup used to calibrate the mobile marker with a workspace of 66 x 82 cm

Source: Own elaboration

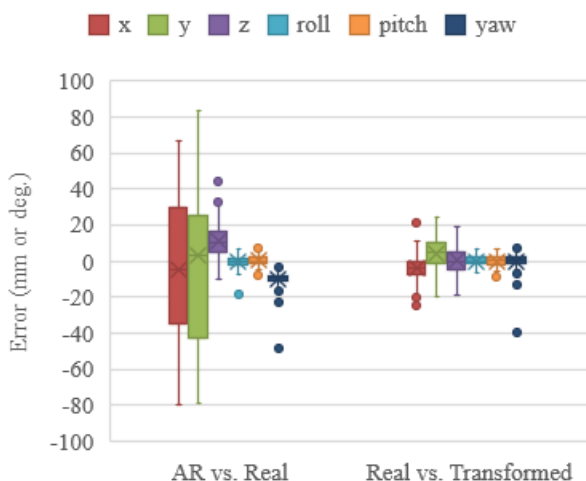
For the experiment, a $3^3 \cdot 4$ factorial design with two replicates was employed; the factors studied were the position in x , y , and z , each with three levels; and the orientation, which was accounted for by taking 90° rotation steps around the z axis. The first two factors were defined on the grid; additionally, a 3D-printed, assemblable piece was used to vary the z height of the mobile marker. Utilizing *Unity* and *Vuforia*, an AR application was created that estimated the posture of the mobile marker relative to the fixed marker, furthermore, *ARCore* was used for extended device tracking. This application was run on the *Android* device previously mentioned.

During the experimental process, the fixed marker is placed in a fixed and known relative position with respect to a reference frame. Initially, the application detects the fixed marker; and calibrates itself in relation to the reference frame using the camera of the device to estimate the posture of the fixed marker. Subsequently, the device is tracked through *Vuforia's VISLAM* implementation until the mobile marker is visible. From that point on, if the fixed marker remains in tracking, the application estimates the posture of the mobile marker relative to the fixed marker, and consequently in relation to the reference frame.

The obtained posture estimate is then transmitted through a data array comprising six values, corresponding to the position in x , y , and z , and the orientation represented with Euler angles for each coordinate, via *ADB* over *Wi-Fi*. Next, the data is read by an *ADB* command on a computer and stored in a file that allows each observation to be identified.

These files are then read by a *Python* script, which calculates the estimate of the transformation between the virtual and physical mobile markers. For this, posture estimates are converted from *Unity's* coordinate system to a right-handed coordinate system with *z* as up, allowing the use of *RoboDK's Python API* to calculate the transformation between each observation and the corresponding reference postures.

In the data analysis phase, outliers among the six sets of posture values are removed. This is done by setting an upper and lower value based on the median plus or minus 1.5 times the interquartile range for each set. This step aims to minimize errors from data sampling. The translations of these transformations are then averaged to obtain an estimate of the translational component, while the rotational component is estimated by converting individual rotations to quaternions and averaging them, as per Markley et al. (2007). Both components are subsequently converted back to *Unity's* Euler angles and axis conventions.



Graphic 1 Boxes diagram of the error before and after calibration

Source: Own elaboration

In the box plot of the results before and after calibration shown in Graph 1, it can be observed how calibration improves accuracy in the *x* and *y* axes, mainly caused by a yaw rotation error, as well as accuracy in the *z* axis and Euler angles by reducing the error in positioning the tool.

In Table 1, it can be observed that the *Mean Absolute Error (MAE)* is reduced in all three spatial dimensions and that the *Mean Orientation Error (MOE)*, defined as the average (Markley et al., 2007) of the orientation error between each observation and reference, presented as the Euler angles of an intrinsic *xyz* rotation, is reduced approximately to zero.

This is due to the rotation of the applied transformation being the *MOE* of the postures obtained with *AR*.

		AR	Transformed (from AR)
MAE (mm)	<i>x</i>	32.58	6.41
	<i>y</i>	34.24	7.56
	<i>z</i>	11.69	6.04
MOE (degrees)	<i>roll</i>	-0.34	0.00
	<i>pitch</i>	0.16	0.00
	<i>yaw</i>	-9.9	0.00

Table 1 Mean Absolute Errors (MAE) and Mean Orientation Errors (MOE) of the mobile marker's postures against reference before and after the calibration
Source: Own elaboration.

To conclude, the transformation parameters are assigned in the *Unity* editor to a child object of the mobile marker, which is used as the calibrated virtual mobile marker.

Calibration of the robot tool

In order to evaluate the level of accuracy attainable through the method proposed in this work, experiments were carried out using a *Universal Robots UR3e* robot. This robot was securely affixed to a table, and reference images compatible with the *AR* software were calibrated within the lab setting.

To enhance the precision of the measurements, a custom tool, as depicted in Figure 5a, was designed. This tool is engineered to screw into one of the four threads located on the *UR3e* robot's tool flange, which is illustrated in Figure 5b. Subsequently, the tool underwent calibration via the teach pendant interface.

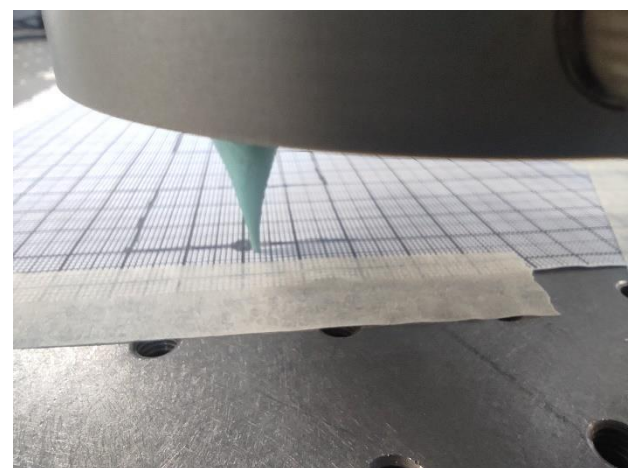


Figure 5 Custom tool that screws into one of the threads of the *UR3e* robot's tool flange

Source: Own elaboration

Calibration of the fixed marker

The fixed marker was secured to the table, and using a calibrated tool, the four corners of the square marker shown in Figures 6a, 6b, 6c, and 6d were measured relative to the robot's base frame.

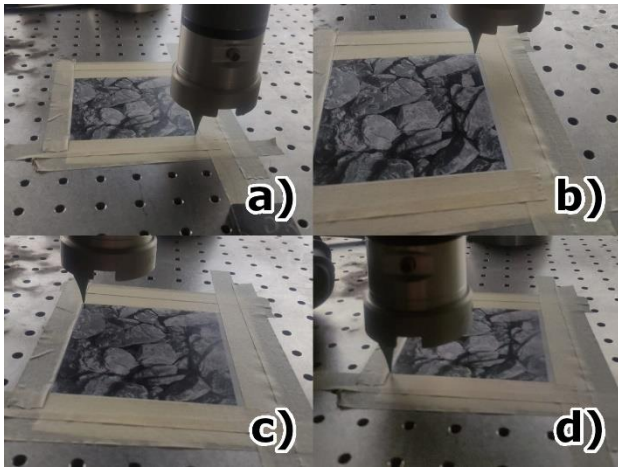


Figure 6 Four points measured using the robot with the calibrated tool, used to calibrate the fixed marker in relation to the robot
Source: Own elaboration

Based on these points, the posture of the robot's base relative to the fixed marker was determined. The position was calculated as the intersection of the diagonals of the square, and the orientation by the angle of one of its sides. With this information, the robot's base was added as a child object of the fixed marker in the Unity editor. The posture of the calibrated mobile marker was defined from this point on in relation to the virtual robot's base.

Trajectory parametrization

After the calibration of the robotic tool, the fixed marker, and the mobile marker were successfully completed, the application underwent another round of modifications. These changes allowed the define, visualize, and send the parametric trajectories to a computer, in relation to the mobile marker and thus also with respect to the robot's base. As illustrated in Figure 7a, the initial step involves estimating the posture of the cellphone based on the fixed marker; this posture is then continuously tracked using Vuforia's extended tracking feature.

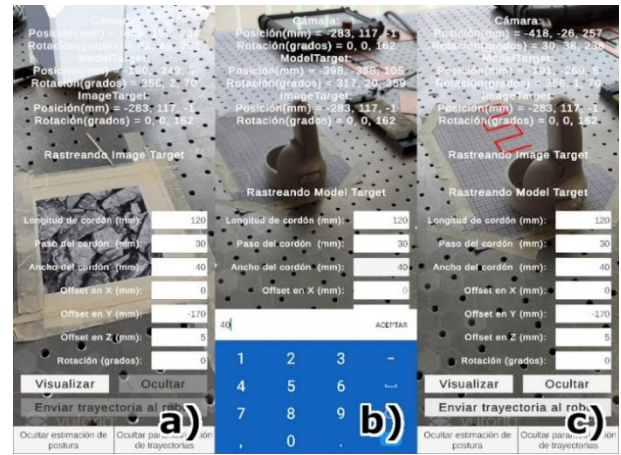


Figure 7 Interface of the AR application that allows defining and visualizing trajectories in relation to the mobile marker
Source: Own elaboration

Regarding customization, the application offers seven editable parameters for generating the program that simulates the trajectories for applying a weld seam. These parameters include the length, width, and step of the seam, displacement in x, y, and z axes, and yaw rotation. These can be edited through the on-screen interface of the application as seen in Figure 7b. By default, the trajectories follow a square zigzag pattern that moves toward y+. The application only allowed sending the trajectories to a computer if both the fixed and mobile markers were being tracked, as shown in Figure 7c.

Functionality tests with robot

The application was employed to generate trajectories on a surface, which were subsequently executed on a Universal Robots UR3e robot. These trajectories were contingent upon observation of a single posture of the mobile marker, which was relative to marks in three magnitude patterns that were placed on the robot's table. To aid in visualization, the trajectories were specifically defined based on various parameters and were superimposed over these magnitude patterns.

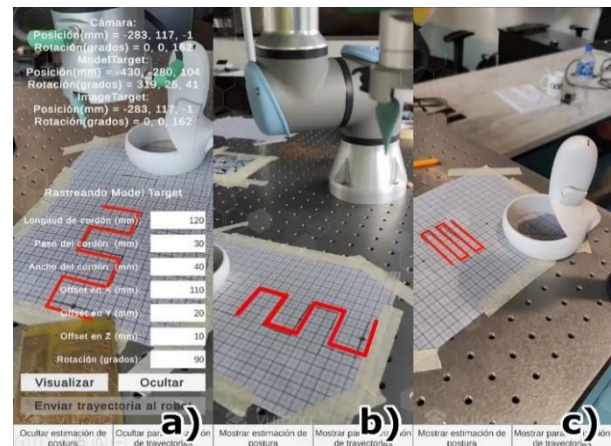


Figure 8 Tests with robots viewed through the application interface
Source: Own elaboration

For data transmission, the application utilized a Python script on a computer to read via *Wi-Fi ADB* the data sent by the application. This data consisted of the coordinates of the trajectory relative to the posture of the mobile marker. Subsequently, the *API* of *RoboDK* is employed to generate programs for the trajectories, specifically for a *Universal Robots UR3e*, using a robot-specific post-processor (ROS-Industrial, n.d.). Figures 8a, 8b, and 8c show some of these programs being executed on said robot, to verify the method's functionality.

Accuracy measurement with robot

Three magnitude patterns were strategically placed on the robot's table, and two points were defined along one of the lines of each pattern. Using the robot's custom tool, these three pairs of reference points corresponding to the three magnitude patterns were measured. This process enables the acquisition of the actual position of each pair of points as well as the angle formed between them, thereby revealing the orientation of the lines of each pattern. This approach is analogous to the definition of a plane by three points, commonly used in robot calibration. However, in this specific context, only two points are required since all points reside on the same table where the robot is located and are coplanar in the *xy* plane of the robot's base frame.

As illustrated in Figures 9a and 9b, a pair of points is shown with the mobile marker aligned over the lines of the magnitude pattern. The mobile marker was carefully positioned over each point and parallel along the lines of the pattern it resides on. From this setup, the work object was subsequently inferred. A set of *n* individual postures were obtained based on each reference posture; each group of postures was called $p_i = [p_{i,1}, p_{i,2}, \dots, p_{i,n}]$, which together form the postures $P = [p_1, p_2, \dots, p_m]$ that were averaged for each reference posture using the method described earlier in section *Calibration of the mobile marker*, obtaining the *m* averaged postures $\bar{P} = [\bar{p}_1, \bar{p}_2, \dots, \bar{p}_m]$.

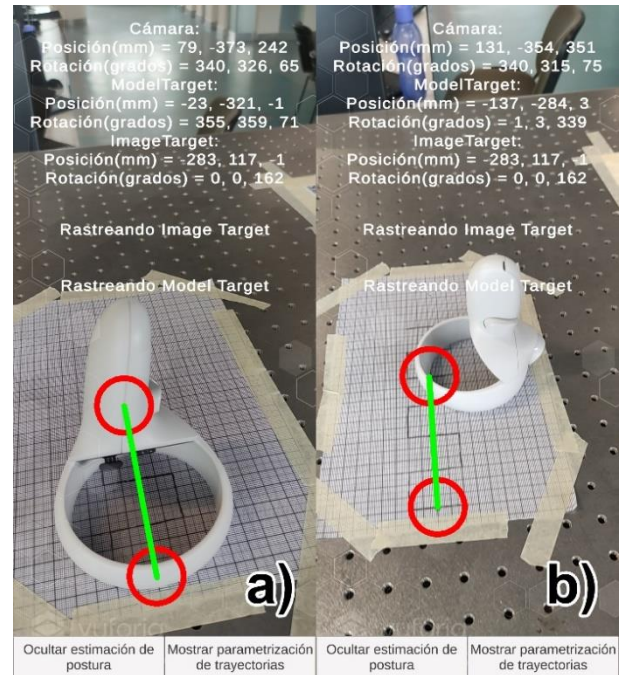


Figure 9 Points measured using the robot as a reference and the line formed between them

Source: Own elaboration

Given the inherent variation in sampling with the camera, which arises from a continuous flow of processed data, outlier values from each group p_i were removed. Statistical measures such as the standard deviation of the distances (SD_{dist}) and the mean of the three standard deviations of the Euler angle axes (SD_{ang}) were calculated using the mobile marker's calibration data.

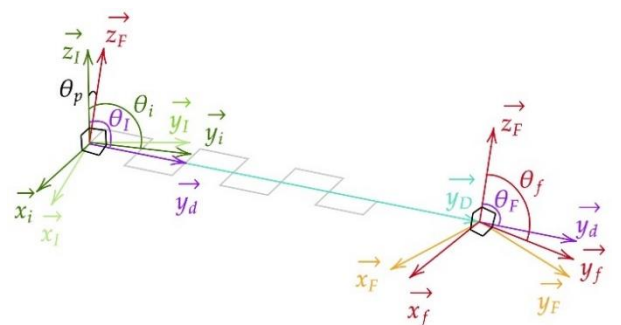


Figure 10 Diagram of the postures generated from 2 mobile markers and of the trajectories generated from these postures

Source: Own elaboration

Criteria were established to discard individual postures that deviated significantly from the group. Specifically, postures that had a minimum distance to another point greater than 1.5 times SD_{dist} , or a Euler angle axis whose minimum absolute difference with another angle of the same axis exceeded than 1.5 times SD_{ang} , were excluded. If none of the individual postures meet the requirements, the posture was discarded.

Utilizing \bar{P} , simulations were conducted to define trajectories using two mobile markers, denoted as $\hat{P} = [\hat{p}_1, \hat{p}_2, \dots, \hat{p}_k]$. The order of the mm postures was selected according to the permutations $\bar{P}(m, 2)$. The initial and final postures were designated as \bar{p}_I and \bar{p}_F , respectively, with corresponding rotation matrices and translation vectors R_I , t_I , and R_F , t_F .

$$[\vec{x}_I \ \vec{y}_I \ \vec{z}_I] = R_I, \quad [\vec{x}_F \ \vec{y}_F \ \vec{z}_F] = R_F \quad (1)$$

First, it was verified that they were approximately parallel, taking this as an angle θ_p and a minimum distance of 6 times SD_{ang} and a minimum distance of 6 times SD_{dist} to consider them different points.

$$\theta_p = \cos^{-1}(\vec{z}_I \cdot \vec{z}_F) \quad (2)$$

\vec{t}_F was subtracted from \vec{t}_I and the result was normalized to obtain a unit vector \vec{y}_d with the direction from \bar{p}_I to \bar{p}_F :

$$\vec{y}_d = \frac{\vec{t}_I - \vec{t}_F}{\|\vec{t}_I - \vec{t}_F\|} \quad (3)$$

Two vectors \vec{x}_i y \vec{x}_f , the first perpendicular to \vec{y}_d and \vec{z}_I , and the second perpendicular to \vec{y}_d and \vec{z}_F , were calculated as the cross and product of:

$$\vec{x}_i = \vec{y}_d \times \vec{z}_I, \quad \vec{x}_f = \vec{y}_d \times \vec{z}_F \quad (4)$$

The angles between \vec{y}_d and \vec{z}_I , and \vec{y}_d and \vec{z}_F were calculated:

$$\theta_I = \cos^{-1}(\vec{y}_d \cdot \vec{z}_I), \quad \theta_F = \cos^{-1}(\vec{y}_d \cdot \vec{z}_F) \quad (5)$$

If any of the angles were equal to π or $-\pi$, the posture is discarded. The vectors \vec{z}_I and \vec{z}_F were rotated along the axes \vec{x}_i y \vec{x}_f with angles θ_i and θ_f respectively, to obtain the vectors \vec{y}_i and \vec{y}_f :

$$\theta_i = -\frac{\pi}{2} \text{sgn}(\theta_I), \quad \theta_f = -\frac{\pi}{2} \text{sgn}(\theta_F) \quad (6)$$

The matrices R_i y R_f are formed by orthogonal column vectors, these represent the approximate orientation between the two mobile markers:

$$R_i = [\vec{x}_i \ \vec{y}_i \ \vec{z}_i], \quad R_f = [\vec{x}_f \ \vec{y}_f \ \vec{z}_f] \quad (7)$$

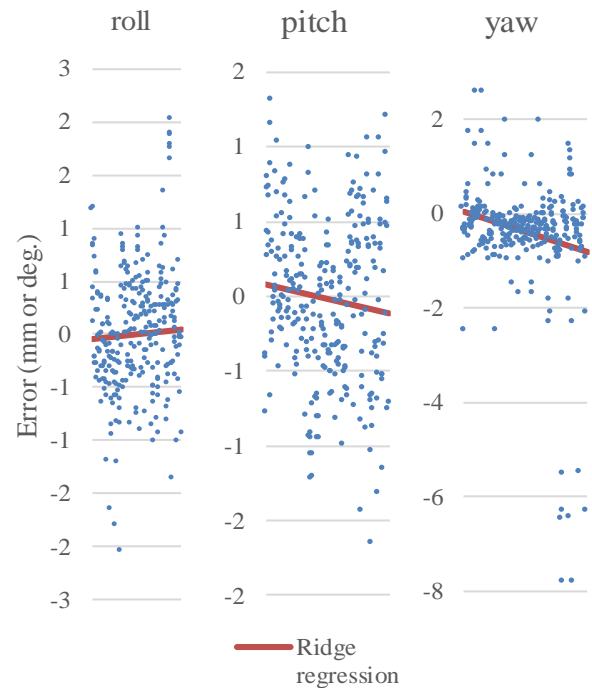
To know if they are pure rotation matrices or have reflections, the determinants of R_i and R_f , which if having a value of -1 , the columns of \vec{x}_i or \vec{x}_f are multiplied by -1 , respectively.

Then, these matrices are converted to quaternions, averaged with the previous algorithm, and converted back to the rotation matrix R ; which was then multiplied by \vec{y}_d to check if the absolute value of the last element of the resulting vector was greater than $1.5\sqrt{3}SD_{dist}$ to verify if they are approximately coplanar in the xy plane defined by the orientation, if this is the case the posture is discarded. Being R the orientation and t_i the translation defined by the two postures, called \hat{p}_w . This process of obtaining a posture from two mobile markers is graphically shown in the diagram of Figure 10.

$$[\vec{x} \ \vec{y} \ \vec{z}] = R \quad (8)$$

Results

To validate the method delineated in previous sections, a total of 23 postures \bar{P} were collected, out of which 19 were deemed acceptable. 342 postures \hat{P} were generated to represent the direction of simulated trajectories. Ridge linear regressions were then executed with a regularization factor of 0.001, specifically on the rotation axes of the error when simulating two mobile markers. The trends of these errors are illustrated in Graph 2.



Graphic 2 Rotation errors in postures that simulate two mobile markers

Source: Own elaboration

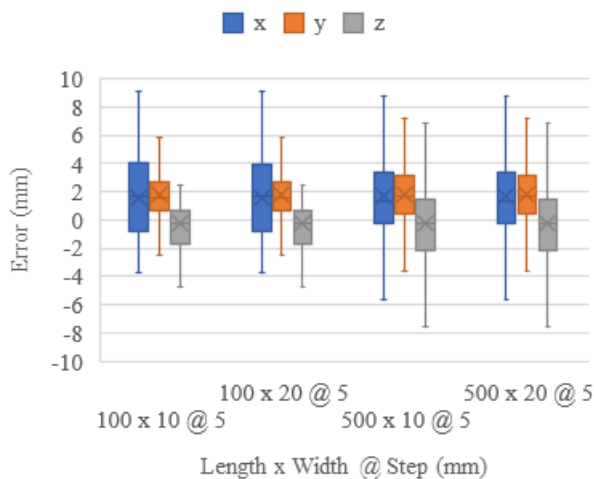
Next, both Positional and orientation errors for P , \bar{P} and \hat{P} were calculated. The results are displayed in Table 2, where a notable improvement in precision is evident upon averaging. Importantly, since the \hat{P} postures use the same positions as \bar{P} , they have virtually identical positional accuracy.

		Unique	Averaged	2 mobile markers
MAE (mm)	x	6.94	2.72	2.69
	y	6.46	2.32	2.12
	z	5.56	1.78	1.63
MOE (deg.)	roll	-0.05	-0.08	0.00
	pitch	-0.23	-0.04	-0.02
	yaw	0.09	0.00	-0.25

Table 2 Mean Absolute Errors (MAE) and Mean Orientation Errors (MOE) of the unique postures, averaged, and simulating 2 mobile markers using the robot as a reference

Source: Own elaboration

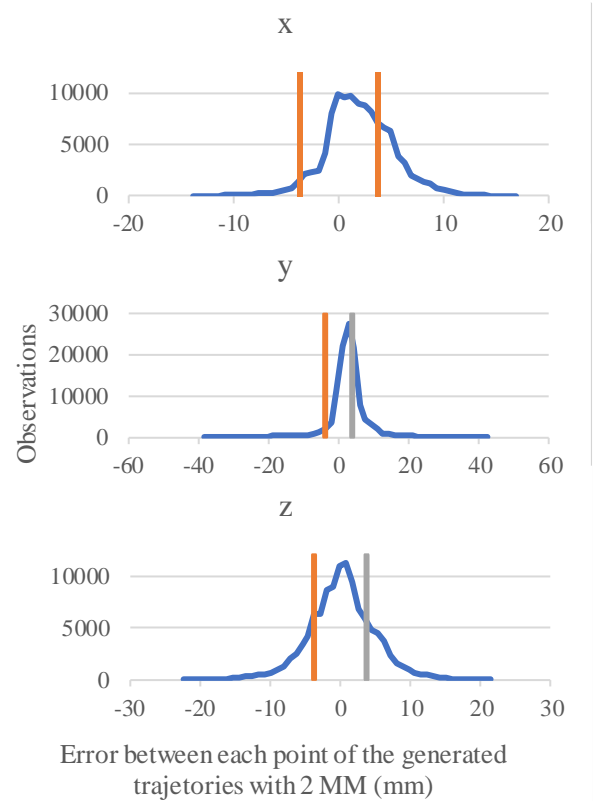
Building on this, parameter-based trajectories were simulated from the postures \hat{P} . These trajectories progressed in the \vec{y} vector given by each posture. The error between each corresponding point of the trajectories generated from \hat{P} and the reference was computed. These errors are encapsulated in box plots presented in Graph 3. Within this context, it was observed that the most significant factor contributing to error was the length of the trajectories. Conversely, changes in width did not exert a significant influence, owing to their smaller magnitude.



Graphic 3 Box plot of the error between each corresponding point of the trajectories compared to the reference

Source: Own elaboration

Graphic 4 showcases the probability distributions of the error of the corresponding points of the trajectories generated by this method. These distributions are based on the postures simulating two mobile markers with the largest parameters for length, width, and step. In this graph, the values of ± 3.74 millimeters on each of the axes are highlighted, corresponding to a p -value less than 0.05. This is under the null hypothesis that the magnitude of the error exceeds this value.



Graphic 4 Histogram of error between each corresponding point of the trajectories generated using the postures simulating two mobile markers (MM). Length:1000 x Width:20 @ Step:5 mm

Source: Own elaboration

Acknowledgements

Access to a *Universal Robots UR3e* robot was provided by the *Center for Engineering and Industrial Development (CIDESI)* in Queretaro. This access facilitated the execution of critical experimental tests. The authors received assistance for learning the operational intricacies of the robotic system and for the calibration of both the tool and the marker.

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Conclusions

Efforts have been made to automate aspects of programming and enhance the interaction between the operator and the robot. One approach of these studies is to use *AR* to display interactive virtual information and objects over the environment, allowing the operator to program the robot more easily and intuitively, leveraging the unique advantages offered by this technology.

Despite its promise, the approach faces several challenges in adoption. Recent advancements in trajectory estimation and the use of *AR* platforms like *Vuforia*, *ARCore*, *ARKit*, *Unity*, among others, can help overcome these obstacles.

The portability of the method can be improved using different mobile devices, and the accuracy of trajectory estimation can be increased through improvements in object tracking technology (Seiskari et al., 2022) and integration with additional sensors. Moreover, the need for a precise reference system, to compare and correct the estimates, could contribute to achieving greater accuracy of the method. The results obtained with the method presented in this work could also be improved with the use of *LIDAR* sensors or depth cameras.

In the current study, mobile *AR* is employed to estimate the posture of objects and to develop a more accurate calibration model by juxtaposing it with a reference coordinate system. This implementation effectively minimizes the error between the estimated and the reference values. Importantly, the method can be readily deployed in a robot using simple components: a cellphone, a fixed marker, and a mobile object, which serves as a mobile marker.

This research introduces the concept of averaging *AR* postures to enhance accuracy. While additional evaluation is needed to quantify the extent of improvement achievable through averaging multiple postures, a noticeable increase in accuracy is already evident with just three observations per posture of the mobile marker.

Given that accuracy in registration remains a major limitation in the adoption of *AR* for robotic applications, sectors where accuracy is less critical may serve as initial adoption points for *AR* technology. This early adoption could provide a platform for *AR* to demonstrate its utility, thereby incentivizing further research aimed at crucial improvements in registration.

The results presented in this work can be used to create *AR* interfaces that allow for on-site robot programming, facilitating the repair of large-scale components and addressing other applications, where calibrating the robot with respect to critical objectives is a significant challenge.

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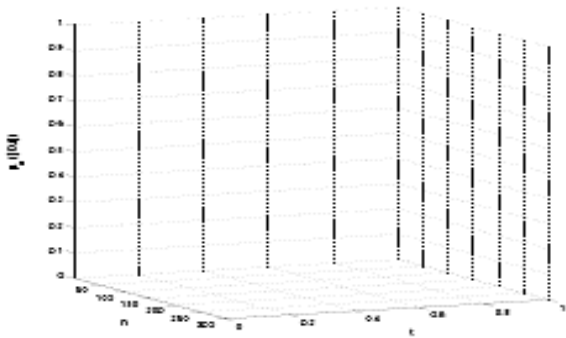
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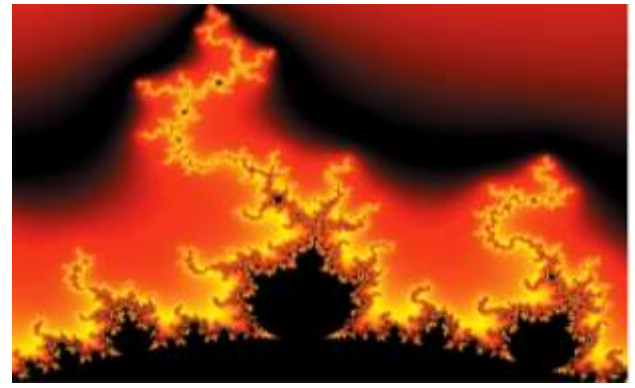


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