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Kinematic calibration of serial robots using low-cost tools

Calibración cinemática de robots seriales usando herramientas de bajo costo

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Abstract

This paper presents the kinematic calibration of an open-chain robot using low-cost tools to measure the position of its end-effector. These tools include a smartphone video camera and an open-access online video analysis program. The methodology involves developing the robot's direct kinematic and identification models, executing motion trajectories, and recording them in two perpendicular planes. The videos extract the kinematic position variables required for the identification model. This section explains the calibration process, including axis alignment, reference points, and length measurements. It also details how the position variables can be obtained either manually or automatically using the video analysis program. Next, the dimensions of the robot's links are identified and validated by applying the calibrated dimensions to a trajectory different from the one used during calibration. When applied to an simulated ABB IRB120 robot, this methodology successfully identified the link dimensions with low errors. However, the precision achieved exceeded the specifications provided in the robot's catalog. The use of the video analysis program allowed for the automated determination of the robot's end-effector positions, significantly reducing human intervention in the calibration process. The proposed methodology is simple, cost-effective, and suitable for systems that do not require high precision.

Keywords: modeling; kinematic; identification; dimensional calibration; video analysis; ABB robot.

Resumen

Este artículo presenta la calibración cinemática de un robot de cadena abierta utilizando herramientas de bajo costo. Estas herramientas incluyen la cámara de vídeo de un smartphone y un programa de análisis de vídeo en línea de libre acceso. La metodología consiste en desarrollar los modelos cinemáticos directos y de identificación del robot, ejecutar trayectorias de movimiento y grabarlas en dos planos perpendiculares. Los vídeos extraen las variables cinemáticas de posición necesarias para el modelo de identificación. En esta sección se explica el proceso de calibración, incluida la alineación de los ejes, los puntos de referencia y las mediciones de longitud. También se detalla cómo obtener las variables de posición de forma manual o automática mediante el programa de análisis de vídeo. A continuación, se identifican las dimensiones de los eslabones del robot y se validan aplicando las dimensiones calibradas a una trayectoria distinta de la utilizada durante la calibración. Cuando se aplicó a un robot ABB IRB120 simulado, esta

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metodología identificó con éxito las dimensiones de los eslabones con un margen de error bajo. Sin embargo, la precisión alcanzada superó las especificaciones proporcionadas en el catálogo del robot. El uso del programa de análisis de vídeo permitió la determinación automatizada de las posiciones del efector final del robot, reduciendo significativamente la intervención humana en el proceso de calibración. La metodología propuesta es sencilla, rentable y prometedora para sistemas que no requieren una gran precisión.

Palabras clave: modelado; cinemática; identificación; calibración dimensional; análisis de video; robot ABB.

1. Introduction

In industrial robotics, the deviations between the mathematical model used in the controller and the manipulator's actual geometry significantly affect the system's accuracy. To minimize these deviations, manufacturing tolerance, permissible adjustments, and clearances must be rigorously controlled during the design, manufacturing, and assembly of the physical components. Moreover, the mathematical model must accurately represent the robot's actual configuration, necessitating kinematic calibration. This process involves determining and adjusting the geometric and kinematic parameters of mechanical systems. Specifically for robots, this procedure corrects the actual parameters of the kinematic model, such as link lengths, joint angles, and joint positions. Despite its clear advantages, calibration presents challenges including environmental variability, mechanical wear, and manufacturing tolerances. These factors require engineers to develop robust methods to adapt to such conditions and ensure consistent performance over time. Robot calibration is typically classified into three levels based on its focus:

- Level 1: Ensures the accuracy of joint measurements and aligns the signal from displacement transducers with actual joint displacements.
- Level 2: Involves calibrating the robot's complete kinematic model to verify link dimensions and joint angle relationships, ensuring precise correspondence between the model and the robot's actual behavior.
- Level 3: Addresses the robot's dynamic response, focusing on its performance under varying operational conditions [1].

Calibration can be divided into four sequential operations: Modeling, Measurement, Identification, and Implementation.

Modeling establishes the theoretical basis for the kinematic behavior of the robotic system. Two basic forms of modeling can be implemented on any robot or manipulator:

The direct kinematic model calculates the end-effector's pose given the displacement of the motors at the joints. For serial robots, there is a unique relationship between the joint transducer displacements and the pose.

The inverse kinematic model determines the set of joint displacements required to achieve a given pose. Deriving this model can be challenging for serial robots, as no universal methodology applies to all robot geometries.

The second step in calibration is *measurement*, which aims to accurately determine the pose of the end-effector for various joint displacements. This involves moving the robot to specific locations within its workspace, recording the joint displacements, and using an external measurement system to determine the pose. The selection of a measurement system is critical, as each system has distinct characteristics, such as accuracy, speed, and ease of use. Careful observation strategy planning is essential to minimize time and human error during the measurement process.

Different techniques can be used to collect the data required for calibration, and metrology systems can be categorized based on the number of position elements they measure. Measuring systems for robot kinematic calibration fall into two groups [2]:

- *Complete pose measurement*, which determines three position coordinates and three orientation angles (Euler angles), providing maximum information for a given configuration.
- *Partial pose measurements*, which typically only determines the position of the end-effector.

Partial measurement uses devices such as instrumented ball bars [3], linear potentiometers [4], and laser displacement meters [5]. For systems measuring two components, the use of theodolites is common [6]. Recently, 2D vision systems have been employed to measure positioning errors in robotic drilling and other industrial activities [7].

The laser tracker is the most widely used equipment in complete pose measurement due to its large measurement range, convenient installation, and high precision, although it can be somewhat expensive [8]. In [9] a manipulator robot using position measurements obtained with a telescopic ball bar equipped with laser technology. In [10] used a laser tracker, a three-dimensional (3D) scanner, and a reflector tool to obtain the position and orientation of the end-effector during the calibration of a robotic machining system. The same methodology is used by [11] in their calibration-based least-squares vector regression for industrial robots. Another approach, demonstrated by [12], involved using a touch panel as a measuring device for calibrating industrial robot cells. This method exhibited good repeatability and accuracy while also automating and accelerating the entire calibration process.

The identification stage in kinematic calibration is critical for adjusting the parameters of the mathematical model to accurately reflect the system's actual behavior. Experimental data are first collected using sensors and measurement tools to record the robot's actual positions and movements during operation. These data are then compared with the predictions of the mathematical model, exposing discrepancies that may result from manufacturing tolerances, wear and tear, or structural deformations.

To minimize these discrepancies, fitting algorithms, such as the least squares method, are employed from an optimization perspective. The model parameters are iteratively adjusted until the discrepancies are minimized. It is essential to validate the fitted model using data sets that differ from those used during the identification process. This ensures the model's generality and prevents overfitting to a specific dataset. Achieving the desired accuracy may require multiple iterations, involving additional data collection, model fitting, validation, and refinement.

In the implementation stage, the information obtained during the identification process is used to enhance the manipulator's performance. The calibration process produces an accurate kinematic model with well-defined parameters, enabling a precise relationship between the joint variables and the tool pose.

This study aims to evaluate the use of low-cost technologies such as smartphone video cameras and free video analysis applications, in the kinematic calibration of a simulated ABB IRB-120 robot. It is recognized that an in-silico implementation simplifies real operating conditions, including variations caused by assembly clearances and wear, while also introducing discrepancies due to the numerical methods used in the simulation. However, in a simulated model, dimensional variations can be incorporated a priori, allowing the study of sensitivity to deviations and dimensional tolerances of a specific manufacturing process and their impact on system performance. Additionally, in a simulated robot, the level 1 calibration issue does not occur, whereas it would need to be ensured if the methodology were applied to a real robot. For this purpose, the kinematic modeling stage of the robot is initially addressed. Next, the measurement process using these low-cost tools is detailed. Finally, the results of the calibration process are presented and discussed.

2. Methods and materials

This section outlines the step involved in the calibration process. Since the main objective of this work is to evaluate the use of simple and low-cost technological tools, the calibration will be performed on a simulated IRB-120 robot, allowing clearances and dimensional discrepancies, similar to those present in real systems, to be easily incorporated.

2.1. Modeling

In the kinematic calibration, the direct kinematic model is used to adjust the robot's dimensional variables. Its determination by applying the Denavit-Hartenberg (D-H) formulation is simple and is based on determining the homogeneous transformation matrix of the robot T as a series of rotations and translations between reference systems associated with each link of the robot, from its base to its end effector [13]. A schematic representation of the robot is shown in Figure 1 and its D-H parameters are in Table 1.

This homogeneous transformation matrix contains information about the location of the robot's end-effector in terms of its joint and dimensional coordinates. This matrix is derived by multiplying the individual transformation matrices A, corresponding to each D-H parameter [13]:

$$A_{i-1}^{i}=\begin{bmatrix}\cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i\\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i\\ 0 & \sin\alpha_i & \cos\alpha_i & d_i\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (1)$$

For a robot with six degrees of freedom, the product of six transformation matrices results in the overall transformation matrix T_0^6. This matrix describes the relationship between the base frame and the reference frame associated with the end-effector. It includes unit vectors (n, o, and a) representing the orientation, and the position vector of the effector's reference frame. The transformation matrix is determined as follows:

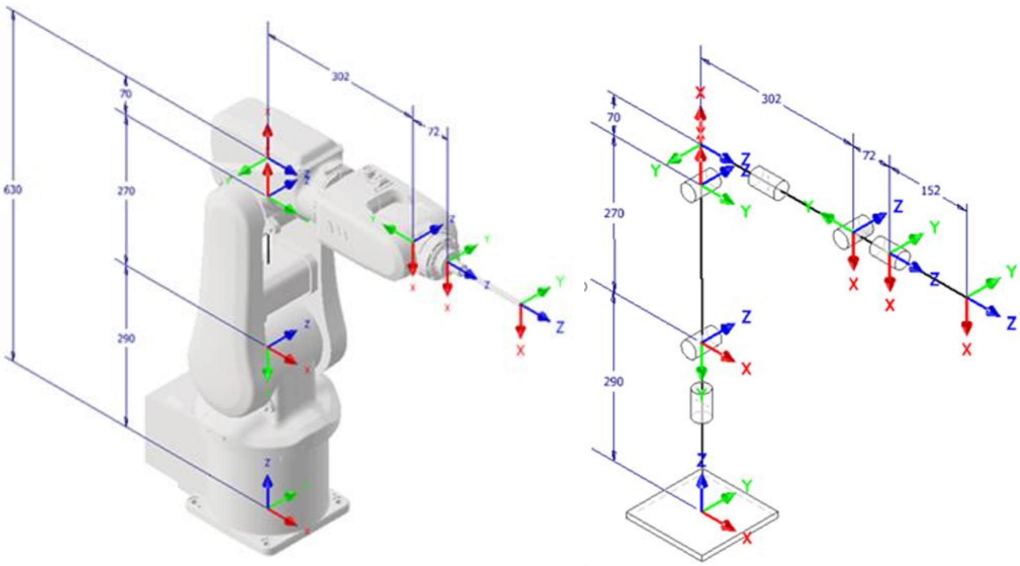

Figure 1. ABB IRB 120 robot reference system. Source: Own elaboration.

$$T_0^6 = A_0^1 A_1^2 A_2^3 A_3^4 A_4^5 A_5^6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Table 1. D-H parameters for IRB 120 robot

Join	α_i [rad]	a_i [mm]	θ_i [rad]	d_i [mm]
1	$-\frac{\pi}{2}$	0	q_1	l_1
2	0	l_2	$q_2 - \frac{\pi}{2}$	0
3	$-\frac{\pi}{2}$	l_3	q_3	0
4	$-\frac{\pi}{2}$	0	$q_4 + \pi$	l_4
5	$\frac{\pi}{2}$	0	q_5	0
6	0	0	q_6	l_4+l_h

Source: Own elaboration.

p_x, p_y and p_z correspond to the position of the robot's end effector and are determined by:

$$\begin{aligned} p_x = {} & \cos q_1[l_4 \cos(q_2+q_3) + l_2 \cos q_2 + \ldots \\ & l_3 \sin(q_2+q_3)] - \ldots \\ & (l_5 + l_h)[\sin q_1 \sin q_4 \sin q_5 + \ldots \\ & \cos q_1 (\sin(q_2+q_3) \cos q_4 \sin q_5 - \ldots \\ & \cos(q_2+q_3) \cos q_5)] \end{aligned} \quad (3)$$

$$\begin{aligned} p_y = {} & \cos q_1[l_4 \cos(q_2+q_3) + l_2 \sin q_2 + \ldots \\ & l_3 \sin(q_2+q_3)] - \ldots \\ & (l_5 + l_h)[\sin q_5 (\cos q_1 \cos q_4 \sin(q_2+q_3) + \ldots \\ & \sin q_1 \sin q_4) - \cos q_1 \cos(q_2+q_3) \cos q_5] \end{aligned} \quad (4)$$

$$\begin{aligned} p_z = {} & (l_1 - l_4) \sin(q_2+q_3) - \ldots \\ & (l_5 + l_h)[\sin(q_2+q_3) \cos q_5 + \ldots \\ & \cos(q_2+q_3) \cos q_4 \sin q_5) + \ldots \\ & l_2 \cos q_2 + l_3 \cos(q_2+q_3)] \end{aligned} \quad (5)$$

From the above, the linearity of the expressions concerning the dimensional variables of the links can be observed, and therefore they can be rewritten to obtain a model for identification:

$$\begin{bmatrix} px \\ py \\ pz \end{bmatrix} = \begin{bmatrix} p_{xl_1} & p_{xl_2} & p_{xl_3} & p_{xl_4} & p_{xl_5} \\ p_{yl_1} & p_{yl2} & p_{yl_3} & p_{yl4} & p_{yl_5} \\ p_{zl_1} & p_{zl3} & p_{zl_3} & p_{zl4} & p_{zl5} \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ l_5 + l_h \end{bmatrix} \quad (6)$$

where:

$$p_{xl_1} = 0$$

$$p_{xl_2} = \cos q_1 \sin q_2$$

$$p_{xl_3} = \cos q_1 \sin(q_2+q_3)$$

$$p_{xl_4} = \cos q_1 \cos(q_2+q_3)$$

$$p_{xl_5} = \cos q_1[\cos(q_2+q_3)\cos q_5 - \cos q_4 \sin q_5 \sin(q_2+q_3) - \sin q_1 \sin q_4 \sin q_5]$$

$$p_{yl_1} = 0$$

$$p_{yl_2} = \sin q_1 \sin q_2$$

$$p_{yl_3} = \sin q_1 \sin(q_2+q_3)$$

$$p_{yl_4} = \sin q_1 \cos(q_2+q_3)$$

$$p_{yl_5} = \sin q_1 \cos(q_2+q_3)\cos q_5 + \sin q_5[\cos q_1 \sin q_4 - \sin q_1 \cos q_4 \sin(q_2+q_3)]$$

$$p_{zl_1} = 1$$

$$p_{zl_2} = \cos q_2$$

$$p_{zl_3} = \cos(q_2+q_3)$$

$$p_{zl_4} = -\sin(q_2+q_3)$$

$$p_{zl_5} = -\sin(q_2+q_3)\cos q_5 - \cos(q_2+q_3)\cos q_4 \sin q_5$$

2.2. Measurement

The level of kinematic calibration to be achieved is established, with the objective of this work being a level 2 calibration. For level 1, the calibration process outlined in the robot's product manual must be used, where calibration of the axes and the updating of the revolution counters are addressed. This ensured that the actual displacement of the joints matched the signal generated by the sensors. For the level 2 calibration, the focus shifts to establishing geometric parameters, such as the lengths of the links, to ensure an accurate kinematic model.

2.2.1. Type of Trajectory

Since the robot operates in three dimensions, the trajectory must maximize joint excitation to cover a wide range of movements. Ideally, this would involve a three-dimensional trajectory. However, given the proposed measurement system -a smartphone camera- perspective distortion, which affects the perceived size of objects based on their distance from the camera, presents a challenge. To mitigate this complexity, a two-dimensional trajectory is proposed instead. This approach simplifies the measurement process by analyzing points moving with a known plane relative to the robot's frame of reference. To capture data in all three Cartesian dimensions, trajectories are performed in two perpendicular planes XZ and YZ, as illustrated in Figure 2.

In this trajectory, the orientation of the end-effector remains constant throughout, which simplifies the process by requiring orientation to be captured only once. The choice between the trajectory options depends on the availability of initial information and the balance between resource constraints and the accuracy required for calibration.

In general, selecting a trajectory or a set of points for accurately identifying unknown parameters requires defining a criterion to validate the estimation. To achieve this, various trajectory optimization approaches are employed, such as minimizing parameter variance and/or improving system conditioning.

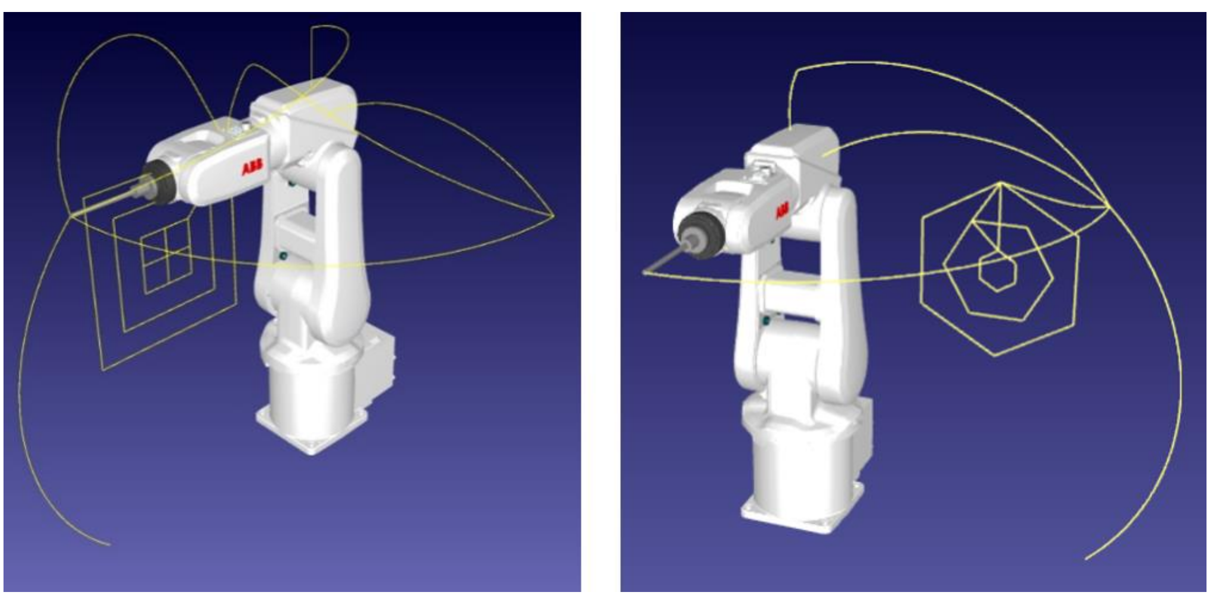

Figure 2. Trajectories to be used in the kinematic calibration process (XZ plane and YZ plane). Source: Own elaboration.

Algorithms like Sequential Quadratic Programming, used in [14] to optimize trajectories in low-mobility systems, and the DETMAX algorithm, applied in [15] to maximize the observability of the matrix in machine tool calibration, have proven to be effective strategies, albeit with a high computational cost.

In this study, although an explicit optimization of the set of points was not performed, numerical conditioning was verified to be adequate. Specifically, the condition number of the observation matrix is 9.7 for the trajectory in the XZ plane, while for the trajectory in the YZ plane, it is 14. These values fall within the conditioning range of approximately 20, as reported in the literature for six-degree-of-freedom serial robots [16].

2.2.2. Camera Position

Proper camera positioning is critical, as any misalignment or unconsidered factor can impact the accuracy of data acquisition. Sensors integrated into smartphones, such as the gyroscope, and additional tools like the camera grid, can assist in achieving optimal alignment, as shown in Figure 3.

The camera must be centered on this point, ensuring that the smartphone is parallel as possible to the plane being recorded. This point is determined by considering the limits of the trajectory and the limits of the X and Z axis, as shown in Figure 4.

2.2.3. Video Capture

When recording video, stability is crucial for ensuring accuracy. A tripod or another form of support can help maintain the camera in a predefined, stable position. To prevent unwanted movements during recording, the following steps are recommended:

- Be recording before initiating the trajectory
- Confirm that the camera is correctly positioned
- Once confirmed, proceed with the trajectory movement.

Additionally, check smartphone settings, such as resolution, frame rate (FPS), and battery level. Recording conditions, including lighting and ambient noise, should also be considered.

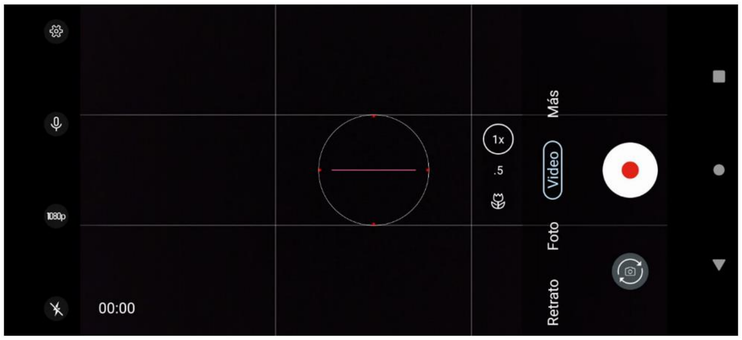

Figure 3. Motorola G22 Cell Camera Interface. Source: Own elaboration.

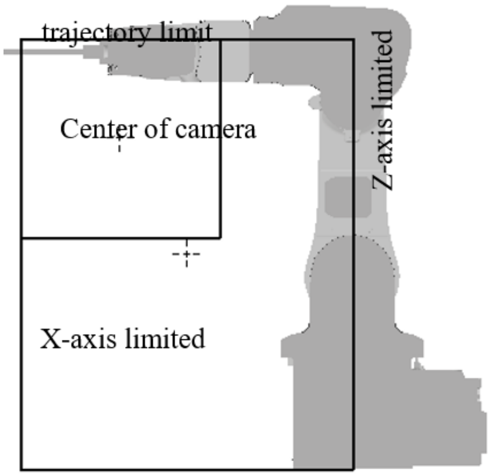

Figure 4. Camera center position. Source: Own elaboration.

These precautions help ensure high-quality video recording, facilitating the subsequent analysis process.

2.2.4. Calibration of reference points and axes

To enable correlation between robot coordinates and camera-captured data, an absolute reference frame $[X_0, Y_0, Z_0]$ must be established during video analysis. Generally, dimension adjustments are based on known length, such as a tool attached to the end-effector, as shown in Figure 5a. This adjustment should occur in a position where the actual length is visible within the recorded plane -in this case, the XZ plane. If the tool's measurement is uncertain, two reference points can be used for measurement, as depicted in Figure 5b.

Axis calibration is performed by identifying two points from the robot's HOME or initial along the axis to be calibrated. Figure 6a and Figure 6b show the calibration of the Z and X axes, respectively, within the XZ plane of the first trajectory video.

2.2.5. Data Acquisition

After calibrating the axes in each video, the program proceeds to data acquisition for the executed trajectories. Two modes are available: manual and automatic. In manual mode, the user selects points frame by frame or approximates the position of a single frame point to be measured (Figure 7). In automatic mode, the user initially selects the starting point, and the program automatically traces the trajectory by selecting subsequent points. Figure 8 illustrates part of this process.

2.3. Identification

The objective of this stage is to determine the link lengths that enable the kinematic model to align optimally with reality. From equation (3) - (6) we observe an indeterminate system with more unknowns than equations. To address this, the system must be extended by increasing the number of measurements, thereby creating an overdetermined linear system:

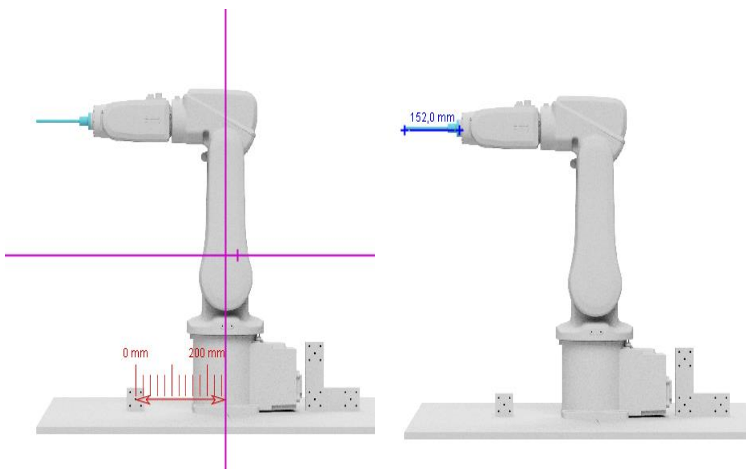

Figure 5. Definition of distances in the video analysis program Tracker®. Source: Own elaboration.

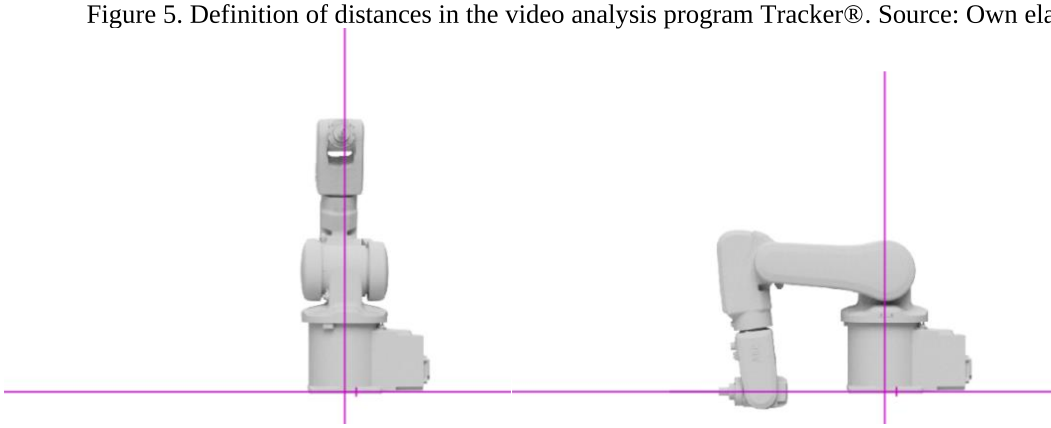

Figure 6. Calibration of the axes in the video analysis software Tracker®.Source: Own elaboration.

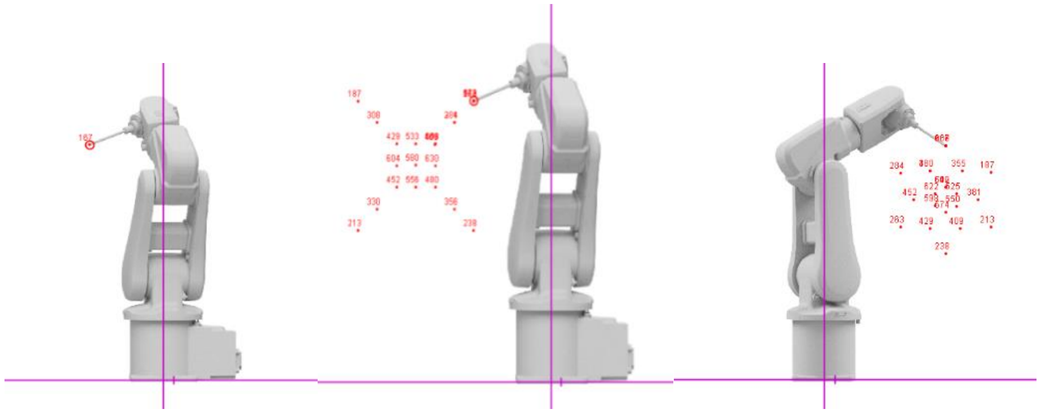

Figure 7. Manual data acquisition in the XZ plane. Source: Own elaboration.

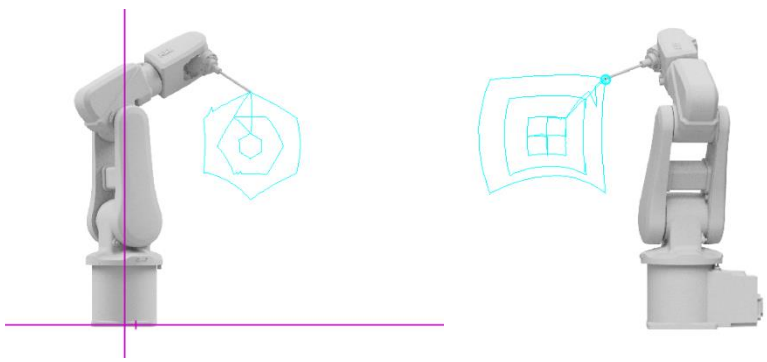

Figure 8. Automatically obtained points on the XZ plane trajectory. Source: Own elaboration.

$$\begin{bmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ l_5 + l_h \end{bmatrix} = \begin{bmatrix} p_1xl_1 & p_1xl_2 & p_1xl_3 & p_1xl_4 & p_1xl_5 \\ p_1yl_1 & p_1yl_2 & p_1yl_3 & p_1yl_4 & p_1yl_5 \\ p_1zl_1 & p_1zl_2 & p_1zl_3 & p_1zl_4 & p_1zl_5 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ p_nxl_1 & p_nxl_2 & p_nxl_3 & p_nxl_4 & p_nxl_5 \\ p_nyl_1 & p_nyl_2 & p_nyl_3 & p_nyl_4 & p_nyl_5 \\ p_nzl_1 & p_nzl_2 & p_nzl_3 & p_nzl_4 & p_nzl_5 \end{bmatrix}^{-1} \begin{bmatrix} p_{1x} \\ p_{1y} \\ p_{1z} \\ . \\ . \\ . \\ p_{nx} \\ p_{ny} \\ p_{nz} \end{bmatrix} \quad (7)$$

where n is the number of measurements performed.

2.4. Implementation

In this phase, the previously obtained dimensional parameters are incorporated into the direct kinematic model for simulation and result comparison. To assess the calibration method, the error is calculated as the difference between the theoretical value and the value obtained from the calibrated model, as follows:

$$\text{relative error}[\%] = \left| \frac{\text{obtained value}}{\text{real value}} \right| \cdot 100 \quad (8)$$

3. Results and discussion

From the values given by the video analysis program both manually and automatically for the trajectory in the XZ plane, the lengths of the links are determined using equation (7), as shown in Table 2. The length of L_h is known to be 152 mm.

The table clearly shows that the identified parameters exhibit minimal discrepancies compared to the theoretical (catalog) parameters. When the identified values are applied to the direct kinematic model for the same joint coordinates used in the XZ plane trajectory, a relative error of 0.103% is observed for the manual method and 0.0932% for the automatic method. These results are expected, as the same trajectory was used for identification. Additionally, a lower error is observed when using data obtained through the program’s automatic tracing.

By performing the calibration process using two trajectories, corresponding to the XZ and YZ planes, the values present in Table 3 are obtained.

Table 2. Parameters identified for the trajectory in the XZ plane

Link	Theoretical value	Value by manual mode calibration	Value by automatic mode calibration
L_1	290 mm	289,7964 mm	289,9840 mm
L_2	270 mm	270,7448 mm	270,1027 mm
L_3	70 mm	69,9620 mm	69,8843 mm
L_4	302 mm	302,5973 mm	302,3615 mm
$L_5 + L_h$	224 mm	224,3394 mm	224,3323 mm

Source: Own elaboration.

Table 3. Parameters identified using the XZ plane and YZ plane trajectories

Link	Theoretical value	Value by automatic mode calibration
L_1	290 mm	290,0406 mm
L_2	270 mm	269,6773 mm
L_3	70 mm	69,9104 mm
L_4	302 mm	302,0298 mm
$L_5 + L_h$	224 mm	224,2168 mm

Source: Own elaboration.

As shown in the table, increasing the number of points and incorporating both planes reduces the differences between the identified values and the catalog values. When these values are applied to the direct kinematic model of the first trajectory, a relative error of 0.0888% is observed for the manual method and 0.0793% for the automatic method. This demonstrates an improvement over the previous simulation, highlighting that the trajectory plane or the trajectory itself significantly influences the results. However, a maximum pose accuracy deviation of ± 1.13 mm and an average pose accuracy of ± 0.24 mm were observed when the point selection is performed manually. In automatic selection a maximum deviation of ±0.43 is reached in the Z-coordinate, while in the X and Y coordinates the average deviations are ±0.065 and ±0.23 respectively. These results indicate that the calibrated model reproduces the trajectory with an average accuracy of 0.25 mm. However, it is important to clarify that the manufacturer reports a repeatability of ±0.02 mm for the ABB IRB 120 robot, which refers to its ability to return to the same position under identical conditions (repeatability) rather than its absolute accuracy. Therefore, these values are not directly comparable.

Adding errors to the CAD model

To simulate real effects, the CAD model of the robot is modified and the XZ plane trajectory is run with the joint coordinates set for the ideal model. This will succeed in simulating a mismatch, making the position of the end effector different from that predicted by the ideal kinematic model. As can be seen in Figure 9, three misalignments are made to the CAD model. The first one is between the junction of links 1 and 2, the second misalignment is between links 3 and 4, and the last misalignment is between links 5 and 6. All of them with a discrepancy of 0.5 mm, simulating a variation in the dimensions of the links.

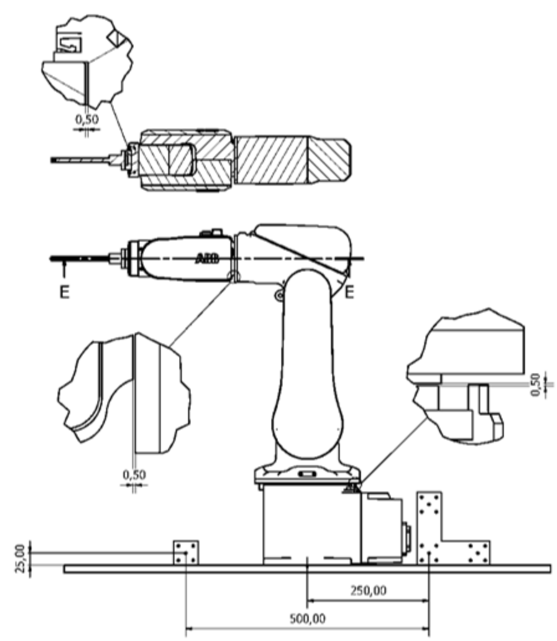

Figure 9. CAD model misalignment. Source: Own elaboration.

Again, taking data from the videos of the robot with clearances and performing the identification process, the dimensional parameter values in Table 4 are obtained.

To validate the values obtained, a new trajectory different from those used in the calibration process is simulated, Figure 10. For this new trajectory, direct kinematics is applied with the dimensional values obtained in Table 4 and compared with those obtained from the theoretical model. With these new parameters, the error between the ideal model and the one identified is 1.44 %.

Table 4. Parameters identified for the model with clearances

Link	Value by automatic mode calibration
L_1	290,426 mm
L_2	270,050 mm
L_3	69,9875 mm
L_4	302,3841 mm
$L_5 + L_h$	224.5037 mm

Source: Own elaboration.

4. Conclusions

In this work, we proposed a method for kinematic calibration using low-cost tools. A non-conventional measurement approach was implemented, leveraging a smartphone video camera and an open-access video analysis program.

The development of the methodology and the use of open-access video analysis software, such as Tracker, simplify the application of this method. Tracker's user-friendly interface and intuitive design facilitate video analysis. Moreover, its ability to enable automatic data acquisition minimizes errors compared to manual method, demonstrating the efficiency of reducing human intervention in the calibration process. The choice of a smartphone as a measurement device further enhances accessibility by eliminating the need for complex sensors, capitalizing on the widespread availability of smartphones today.

This proposed methodology, characterized by its simplicity, significantly reduces costs and streamlines the measurement phase in the kinematic calibration process. However, the approach has limitations in achieving high accuracy in the executed trajectories. For its application in a real-world setting, photogrammetric adjustments should be considered and validated through physical experiments to ensure the robustness of the method. Additionally, the use of high-resolution cameras is recommended, as video analysis software is sensitive to frame resolution and image contrast. Nevertheless, the method offers a promising solution for applications where extreme accuracy is not required.

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Autor Contributions

L. A. Mejía-Calderón: Conceptualization, Formal Analysis, Methodology, Project administration, Validation, Visualization, Writing –review & editing. C. A. Romero-Piedrahita: Conceptualization, Formal Analysis, Supervision, Writing –review. C. D. Borrero-Vélez: Conceptualization, Formal Analysis, Methodology, Investigation, Software, Validation.

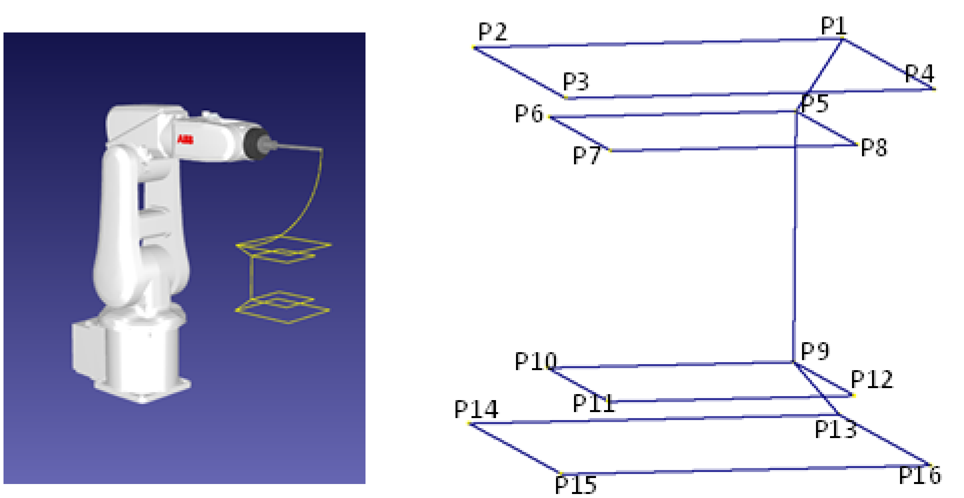

Figure 10. Trajectory used for validation. Source: Own elaboration.

Conflicts of Interest

The authors declare that there is no conflict of interests of any kind regarding the publication of the results of our research work.

Institutional Review Board Statement

Not applicable.

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Not applicable.

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