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METHODS

Kinematic Compensation Algorithm for Reducing Errors in a Closed-Loop Manufacturing System

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ABSTRACT During the manufacturing process of a piece, different factors influence the process so that errors of a systematic and random nature are added, affecting both the dimensions and the final geometry. The strategy presented in this research seeks to identify, monitor, and computationally control the errors arising from the arrangement of the actuators that can be derived from errors in assembly, wear of the components, and thermal deformations. This article proposes an algorithm to prevent and correct geometric and dimensional errors in manufacturing parts as a compensation strategy. The algorithm obtains the references of the manufacturing process and estimates the process's deviation, calculating the manufactured part's error concerning the projected piece. Error compensation is performed through reference points that alter the location of the target points in the opposite direction to the resulting error to nullify it kinematically. The validation of the strategy is carried out through the computational implementation of kinematic algorithms of a machine tool with a Cartesian structure of two degrees of freedom on which position and orientation errors are induced. The presented results allow for verifying the proposed algorithm's effectiveness against tests with significant errors. The compensation strategy presented allows projecting this algorithm as an online software calibration method, reducing the number of stops due to mechanical maintenance of the CNC machine and making closed-loop manufacturing possible with real-time compensation.

INDEX TERMS Advanced manufacturing, closed-loop manufacturing, STEP-NC, error compensation, digital manufacturing.

I. INTRODUCTION

Within the demands placed by the digital era on manufacturing processes, there is a constant challenge to obtain sustainable manufacturing. Sustainable manufacturing is strongly related to smart manufacturing, where methods can automatically decide the course of their operations. In this exposed scenario of integration and interoperability of systems, the concept of closed-loop manufacturing, known as CLM, takes on great relevance; more than a concept, it is a method that enables data feedback to CAx (Computer-aided technologies) systems that can continuously influence and improve the manufacturing process [1]. The feedback data can be both information acquired from the manufacturing conditions and dimensional and geometric measurement results of already manufactured parts [2].

The variability and uncertainty of manufacturing processes impair the balance between the quality and productivity of the fabrication. The dimensional and geometric inspection of manufactured parts can solve this problem, since the data obtained provide essential information about how they were manufactured and the sources of errors inherited from the machine tool [3]. The objective of analyzing the inspection data is to reduce the uncertainty values and maintain the geometric and dimensional characteristics within the projected specifications in the design [4].

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Analyzing the dimensional and geometric inspection data will allow for obtaining an approximate error model [5]. The geometric error in machine tools directly influences the position of the tool, producing dimensional and geometric defects in manufacturing [6]. There are several ways to analyze when solving the problem; The first option is to carry out a physical intervention on the machine, which means stopping the operation and generating other complications. Modifying the design and adjusting tolerances in the project of the part to be manufactured could be another feasible option; however, the traceability of the project is lost [7]. Another option is to compensate for the deviation directly on the machine's control system, which is more feasible with an open system [8].

The integration architecture is necessary for manufacturing systems to obtain autonomous processes with a physical connection of the elements, bidirectional communication under the same data structure, and disturbance control by expert systems. The architecture that operates with a closed-loop manufacturing integrates the different phases of the product life cycle: design, manufacturing, and measurement through a neutral data structure, extensible and interpretable by other technologies associated with the various stages of the life cycle of the product [9]. An architecture in CLM allows for the optimization of the process and promotes sustainable systems [10].The execution requirements change progressively in this digital age, but it is still essential to implement integration and maintain interoperability between CAx systems [11].

This document proposes a feedback control architecture with measurement data to compensate for errors detected in manufacturing algorithmically. Section II presents a brief literature overview to contextualize the contribution as a compensation strategy operating in closed-loop manufacturing. Section III presents the operation architecture and the feedback strategy. Section IV contends the error compensation method used to calculate the deviation. Section V presents a typical case study to check the flow of information within the architecture. Finally, section VI presents the conclusions and suggestions for future studies.

II. LITERATURE OVERVIEW

Thinking about contributions and developments for the future of manufacturing consists of envisioning efficient processes that operate with a balance between productivity and quality while simultaneously meeting specific needs in an increasingly sustainable way [12]. Analyzing the data of the manufacturing process and providing feedback on the results provides us with knowledge of manufacturing conditions, generating helpful information to make decisions and propose strategies to improve manufacturing conditions [13], [14].

The search for recent information found different research papers that address this line and present a contribution. Works such as [15] and [16] address the concept of closed-loop manufacturing, used as a generalized solution to keep under control the parameters that can affect the manufacturing process. The notable difference in each job consists of how the data flows between the systems involved and how the integration of the systems occurs. The ISO10303 standard can support the Integration of CAD/CAPP/CAIP/CAM/CAI systems as a basis for exchanging information through a neutral file that works with homogenized entities for different contexts within the life cycle of a product [17], [18]. This is demonstrated by research such as [19] and [20].

The main problem with automating decision-making in closed-loop manufacturing lies in the integration and interoperability of measurement systems. They are challenging to automate, require human intervention, and the technologies used are only partially accessible. Mears et al. [21] present a review of the use of coordinate measuring machines in machining processes. The investigation shows technological advances of CMM, as well as integration strategies of measurement systems in machine tools. Some problems resulting from the integration of the systems are reported, such as the case of integrating the CMM directly with the machine tool related to the measurement and calibration error due to the difference between the inspection reference system and the reference of the process of machining on the machine, causing CNC machine errors to affect inspection [22].

Gaha et al. [23] pose challenges to using dimensional measurement in digital environments. These challenges are being addressed through simulation, error compensation, rapid calibration techniques, and the incorporation of new detection technologies. It also presents a set of functionalities and opportunities for measurement systems within the industry 4.0 paradigm.

According to Saif et al. [24] Closed-loop Inspection (CLIM) and computer-assisted inspection planning (CAIP) have become relevant and have become a method to improve the product. The work presents a systematic review of the literature that analyzes articles on inspection and using CLIM together with CNC machines. The results of this study provide a taxonomy and definition in terms of and characteristics of this emerging technology.

During manufacturing, different factors interact so that errors of a different nature (static, dynamic, and progressive) are added to the process. Different investigations address this line, managing to classify the geometric errors in parts manufactured in CNC machining centers according to their nature: systematic, progressive, and random. The geometric errors in the parts processed when machining with CNC machines can be attributed to four sources of error: machine tool, NC programming, machining process, and other factors.

Zhen et al. [25] relate how the dynamic limitations of the CNC machine tool lead to errors during its operation and affect the precision of the machining of the parts. The paper highlights the importance of reducing errors and presents a review of the methods focused on this line, emphasizing advantages and disadvantages. The article suggests future studies that minimize contouring errors in parts machined with a CNC machine.

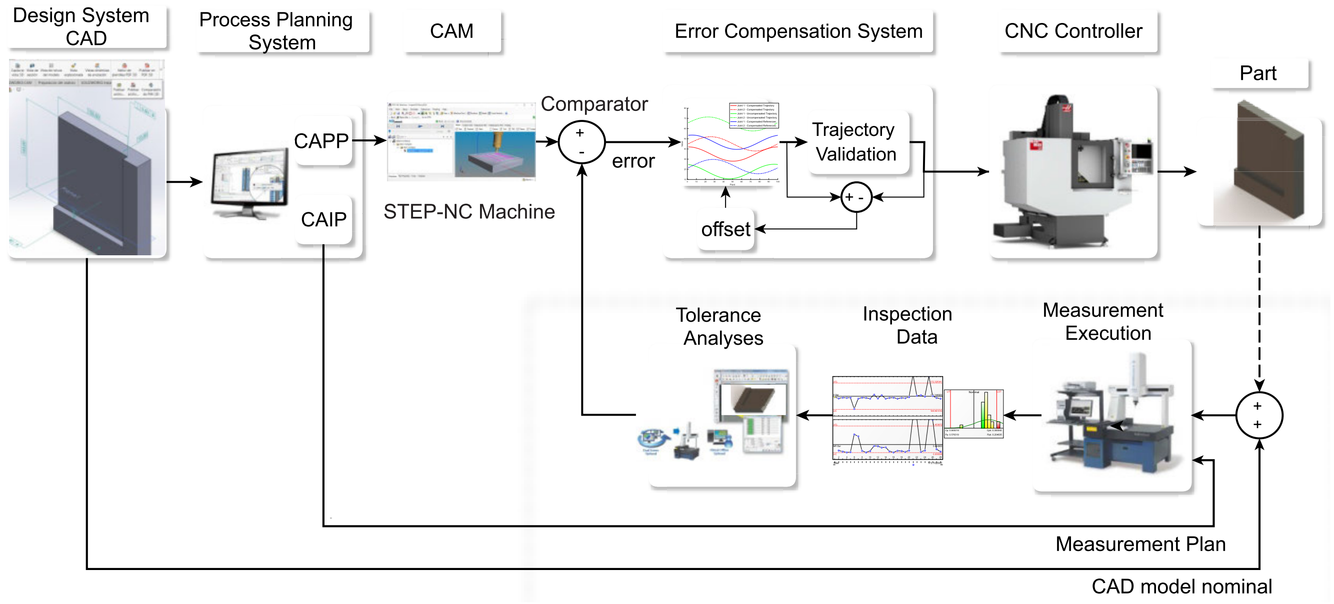


FIGURE 1. Closed-loop manufacturing architecture.

In the search for research that addresses architectures for closed-loop manufacturing, there is a notorious tendency to use solutions that adhere to the ISO10303 standard known as STEP-NC [26]. Works developed in this line [27], [28], [29] describe strategies to converge an extensible and open neutral solution through the standard. The ISO 10303 standard, also known as STEP (Standard for the Exchange of Product model data), provides a mechanism for structuring information that can be used within a closed-loop manufacturing architecture [30]. The standard defines a structure within the object-oriented perspective for data representation and information exchange between systems involved in the life cycle of a product [31], [32]. The concept of features is considered within the standard as an integral component used within the different possible contexts such as design, manufacturing, and measurement; this concept is syntactically and semantically homogenized between each of the processes involved in the life cycle of production of a piece [33], [34]. The STEP standard provides a neutral format for defining product data and exchanging information between processes [35].

Hu et al. [16] present an architecture of a STEP-NC compliant closed-loop robot machining system, including its function model and information stream. The closed-loop robot machining system was implemented based on an open STEP-NC interpreter that interprets the high-level information in STEP-NC directly to reduce the machining robot programming time.

III. INTEGRATED INSPECTION SYSTEM

This section describes the closed-loop inspection architecture and the feedback strategy to compensate for manufacturing errors. As a requirement, an interoperable architecture is defined with a bidirectional data flow and integrated with the different CAD/CAPP/CAIP/CAM/C NC/CAI systems, using a neutral file STEP (Standard for the Exchange of Product model) with support for layers: application, logic, and physics.

Fig. 1 shows the study scenario, and the scope of the architecture presented. The physical configuration and the data flow between the CAx systems involved in the compensation strategy are present.

The encoding in a STEP file of the toolpath of the CNC machine is carried out through a framework developed in JAVA to read, write, and update files compatible with the ISO10303 standard. The framework generates a neutral STEP interchange file in AP238 format that contains the project, main Workplan, and Workingstep with paths for facing operation. Other additional information relevant to the manufacturing process is included through STEP-NC Machine after importing the generated step file into the framework. Fig. 2 shows the working environment of the STE-NC Machine; the project structure is shown on the left panel.

A. FRAMEWORK FOR STEP FILE ENCODING

This section explains how the proposed method for error compensation in manufacturing processes adheres to the ISO 10303 standard, STEP (Standard for the Exchange of Product model data). A Model-View-Controller (MVC) architecture was used to develop the STEP interpreter. This architecture is supported by three main logical components: the model, the view, and the controller. Each of these components is designed to handle specific development aspects of an application. The model contains the dynamic data structure of the application, which is the core where the knowledge of

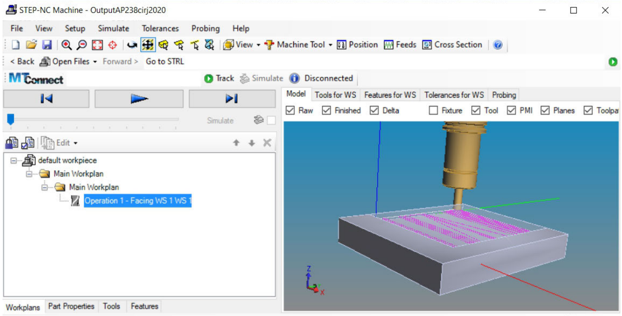
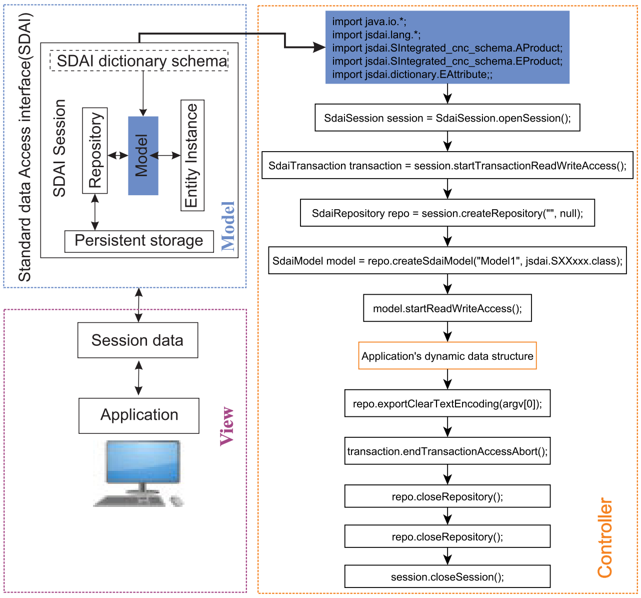


FIGURE 2. Step file project for manufacturing environment.

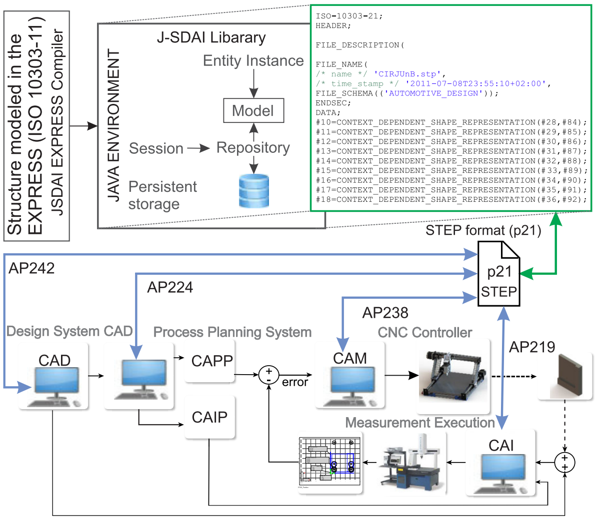


```
import java.io.*;
import jsdai.lang.*;
import jsdai.SIntegrated_cnc_schema.AProduct;
import jsdai.SIntegrated_cnc_schema.EProduct;
import jsdai.dictionary.EAttribute;;
SdaiSession session = SdaiSession.openSession();
SdaiTransaction transaction = session.startTransactionReadWriteAccess();
SdaiRepository repo = session.createRepository("", null);
SdaiModel model = repo.createSdaiModel("Model1", jsdai.SXXxxx.class);
model.startReadWriteAccess();
Application's dynamic data structure
repo.exportClearTextEncoding(argv[0]);
transaction.endTransactionAccessAbort();
repo.closeRepository();
repo.closeRepository();
session.closeSession();
```

FIGURE 3. Model-view-controller architecture for the development of the STEP interpreter.

the STEP standard is necessary for application development. The controller manages the program's execution, creates the project, receives events, implements the actions to supply data to the model, and manages the creation of the STEP interchange file. The view is the user interface layer. Fig. 3 shows the sequential structure of the file carried by the execution thread, in which an SDAI session is created, manages the repository, and encodes the STEP exchange file with the information generated during the execution of the program.

Integrating information within the Closed-loop inspection requires a robust and interoperable data structure to be compatible with the different CAx systems. ISO 10303 has a description method in EXPRESS language specified in ISO 10303-11 that facilitates the interpretation of information models and application protocols. The EXPRESS language defines in a neutral and technology-independent manner a logical structure, restrictions, rules, functions, and procedures for each entity, which facilitate the development of applications with a diverse context of use.



```
ISO-10303-21;
HEADER;

FILE_DESCRIPTION(

FILE_NAME(
/* name */ 'CIRJUnB.stp',
/* time_stamp */ '2011-07-08T23:55:10+02:00',
FILE_SCHEMA(('AUTOMOTIVE_DESIGN'));
ENDSEC;
DATA;
#10=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#28,#84);
#11=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#29,#85);
#12=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#30,#86);
#13=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#31,#87);
#14=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#32,#88);
#15=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#33,#89);
#16=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#34,#90);
#17=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#35,#91);
#18=CONTEXT_DEPENDENT_SHAPE_REPRESENTATION(#36,#92);
```

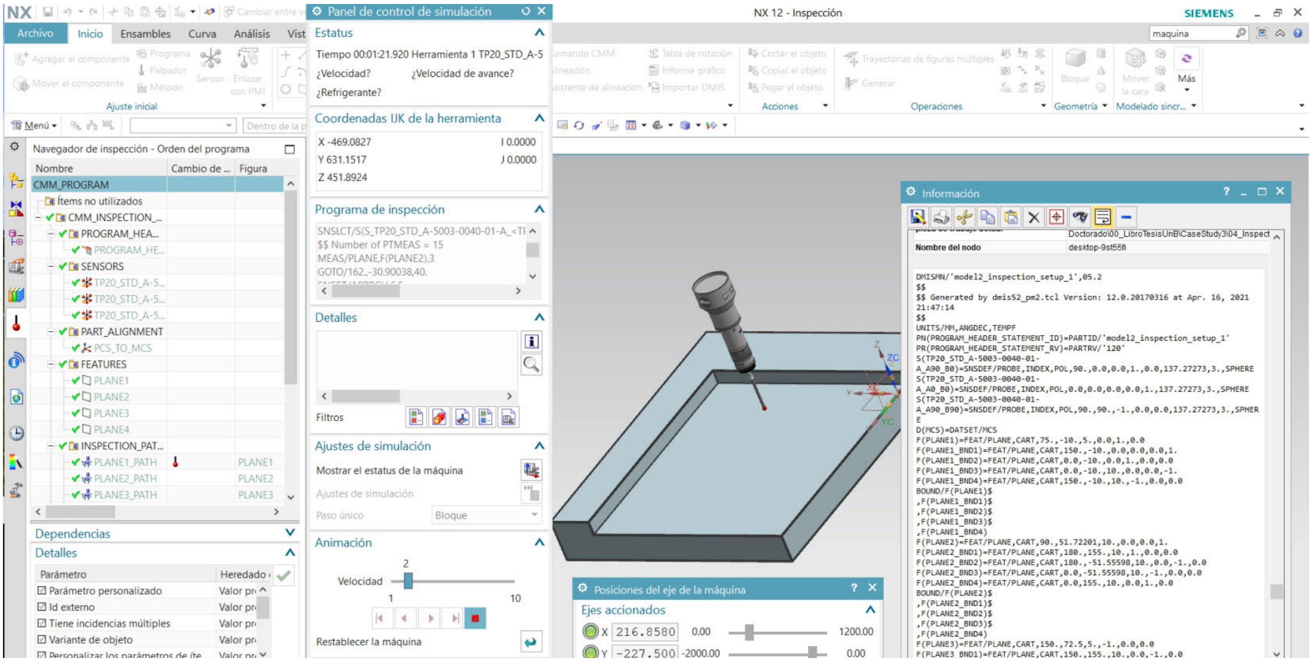
FIGURE 4. Approach for Interoperable data access, adherent to STEP standard.

JSDAI is an Application Programming Interface (API) for read-write and run-time manipulation of object-oriented data defined by an EXPRESS data model. The JSDAI tools enable the use of data structures modeled in the standard data element type language EXPRESS (ISO 10303-11), PLIB (ISO 13584), and IEC61360. JSDAI can store and exchange data with STEP applications in various forms, such as STEP XML - ISO 10303-21 (part 21) and STEP XML - ISO 10303-28 STEP XML, among other formats. JSDAI can organize and control application data, such as physical separation in repositories and logical grouping between instances and schemas.

The Fig. 4 shows a data flow scheme that supports the integration of information in CAx systems and the pillars supporting this application's computational development. Through the EXPRESS schemes provided by ISO 10303, a series of application protocols support each phase of the life cycle of a CAD/CAPP/CAIP/CAM/CAI product. The protocols share an entity but are used in different contexts. The developed framework has the function of reading, writing, and updating values of these entities according to the results obtained in the compensation strategy to modify the original design executed by the CNC and compensate for manufacturing errors. After modifying the sensitive entities with tool positioning information, a new STEP file is created in p21 format, which contains the necessary actions to compensate for the design that allows compliance with the quality standards according to the capacity of the process.

B. DIMENSIONAL AND GEOMETRIC INSPECTION PLAN

Nx-Siemens provides an environment to plan the dimensional and geometric inspection of the part. The objective is to simulate the measurement of the project and generate a program for a measurement environment that identifies the design specifications and their tolerances, the selection of



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¿Refrigerante?

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Y 631.1517 J 0.0000
Z 451.8924

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21:47:14
$$
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E
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F(PLANE1_BND2)=FEAT/PLANE,CART,0.0,-10.,0.0,1.,0.0,0.0
F(PLANE1_BND3)=FEAT/PLANE,CART,0.0,-10.,10.,0.0,0.0,-1.
F(PLANE1_BND4)=FEAT/PLANE,CART,150.,-10.,10.,-1.,0.0,0.0
BOUND/F(PLANE1)$
,F(PLANE1_BND1)$
,F(PLANE1_BND2)$
,F(PLANE1_BND3)$
,F(PLANE1_BND4)
F(PLANE2)=FEAT/PLANE,CART,90.,51.72201,10.,0.0,0.0,1.
F(PLANE2_BND1)=FEAT/PLANE,CART,180.,155.,10.,1.,0.0,0.0
F(PLANE2_BND2)=FEAT/PLANE,CART,180.,-51.55598,10.,0.0,-1.,0.0
F(PLANE2_BND3)=FEAT/PLANE,CART,0.0,-51.55598,10.,-1.,0.0,0.0
F(PLANE2_BND4)=FEAT/PLANE,CART,0.0,155.,10.,0.0,1.,0.0
BOUND/F(PLANE2)$
,F(PLANE2_BND1)$
,F(PLANE2_BND2)$
,F(PLANE2_BND3)$
,F(PLANE2_BND4)
F(PLANE3)=FEAT/PLANE,CART,150.,72.5,5.,-1.,0.0,0.0
F(PLANE3_BND1)=FEAT/PLANE,CART,150.,155.,10.,0.0,-1.,0.0
```

FIGURE 5. Inspection program execution.

suitable touch probes, the generation of trajectories without collisions, and the adequate programming of the order in which they are executed those trajectories. When the simulations are carried out, and the configurations applied in the CAIP are approved, a DMIS output file is generated to perform the measurement process. Fig. 5 shows the inspection planning process performed in NX-Siemens. NX™ CMM inspection programming software exports the inspection program in the industry standard Dimensional Measurement Interface Specification (DMIS) format.

The developed inspection plane presented in this section enables obtaining valid measurement results for the error compensation strategy; the following section details how the acquired data is used to measure dimensional and geometric features.

IV. ERROR COMPENSATION METHOD

This section presents the development of an algorithm to compensate for manufacturing errors derived from assembly problems or wear in the actuators of a Computer numerically controlled (CNC) machine. The compensation algorithm uses position references extracted from the Computer Aided Manufacturing (CAM) system to determine the deviation produced in manufacturing parts. With the error result obtained, the algorithm generates a system compensation to correct the perpendicularity and parallelism errors. The compensation acts on the kinematic model of the machine, redefining the location of the manufacturing system actuators and preventing the actual deviation from affecting the manufacturing. Reference compensation consists of altering the location of the target points in the opposite direction to the resulting error to cancel it. The compensation is carried out through the kinematic algorithms that intervene in controlling a CNC machine with two degrees of freedom, using the differences in position and the errors in orientation. It verifies the compensation of the algorithm exposed in this article through tests with significant parallelism and perpendicularity errors. The results allow projecting this algorithm as an online software calibration method, reducing the number of stops for mechanical maintenance of the CNC machine.

For this research, a CNC machine hybrid was built with a Cartesian configuration and open control architecture, designed for applications in machining, additive manufacturing, and laser cutting processes that allow validating the error compensation strategy within a safe environment and with the possibility of including disturbances. to the process. The Fig. 6 shows the most essential components of the CNC machine.

The Cartesian configuration has three prismatic actuators; in machine tools, these actuators determine the trajectories and the degrees of freedom for manufacturing parts. A model is proposed to estimate the errors produced in manufacturing using machine tools with a Cartesian configuration. In this model, the linear actuators are located at a point other than the origin of the reference system. Fig. 7 (b) shows a representation of a CNC machine, highlighting two of its three degrees of freedom determined by the linear actuators that define the path in the X-axis and Y-axis.

The representation model is built for the machine shown in Fig. 7 (a), for which the analysis is carried out using a Euclidean coordinate system as a reference. All machines or

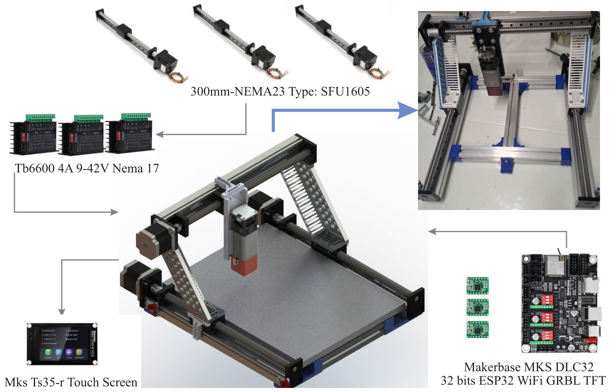


FIGURE 6. **Experimental CNC machine.**

movement systems have differences between the projected movement and the actual movement they perform due to the assembly of their actuators.

In the assembly, a fictitious error was made so that the actuators are not entirely perpendicular, and their location does not coincide with the origin of the reference system. The model will consider that the actuators have an orientation error. Fig. 7 (b) shows a representation of the actual location of the actuators in a CNC machine, representing the actuators in their initial position. It must be taken into account that the CNC machine is to be modeled as a serial configuration, where the first joint corresponds to the X-axis and the second to the Y-axis.

Ideally, the machine would work according to the XY system defined by the unit vectors i and j. However, in the model proposed for analysis, the actuator that defines the trajectory on the X-axis is located in the position defined by the vector O_{xr}; the unit vector i_r determines its orientation. Analogously, the Y-axis actuator is located at the position defined by the vector O_{yr}, and the unit vector j_r defines its orientation. The components of these vectors are illustrated below in Eq. (1).

$$O_{xr} = \begin{bmatrix} O_{xri} \\ O_{xrj} \end{bmatrix}; O_{yr} = \begin{bmatrix} O_{yri} \\ O_{yrj} \end{bmatrix}; i_r = \begin{bmatrix} i_{rx} \\ i_{ry} \end{bmatrix}; j_r = \begin{bmatrix} j_{rx} \\ j_{ry} \end{bmatrix}; \quad (1)$$

Since the vectors i_r and j_r are not perpendicular, using a vector analysis representing non-orthogonal systems is necessary. The position error of the actuators makes it necessary to generate a new reference point that can be considered the origin of the non-orthogonal coordinate system. The reference point of the proposed model is established at the projection intersection of the X and Y-axis, determined by the current location of the actuators (represented through a circle in Fig. 7.

The difference between the positions of the actuators O_{yr} and O_{xr} define the vector ΔO_r (see Eq. (2)). On the other hand, ΔO_r is XY's base of the coordinate system.

$$\Delta O_r = O_{yr} - O_{xr} \quad (2)$$

The intersection point of the actuator's projected axes is calculated by expressing Eq. (2) in terms of the unit vectors i_r and j_r, as shown in Eq. (3). Note that m_x is the distance between the origin of the X-axis actuator and the point of intersection. Similarly, m_y is the distance of the other actuator concerning the same point.

$$-m_x i_r + m_y j_r = \Delta O_r \quad (3)$$

Equation 3 can be expanded by expressing the components of the vectors i_r, j_r, and ΔO_r concerning the reference system XY. See Eq. (4).

$$-m_x \begin{bmatrix} i_{rx} \\ i_{ry} \end{bmatrix} + m_y \begin{bmatrix} j_{rx} \\ j_{ry} \end{bmatrix} = \begin{bmatrix} \Delta O_{rx} \\ \Delta O_{ry} \end{bmatrix} \quad (4)$$

Eq. (4) can be rewritten to express the equation as a system of matrix equations. Note that the unknown variables are m_x and m_y as expressed in Eq.(5).

$$\begin{bmatrix} -i_{rx} & j_{rx} \\ -i_{ry} & j_{ry} \end{bmatrix} \begin{bmatrix} m_x \\ m_y \end{bmatrix} = \begin{bmatrix} \Delta O_{rx} \\ \Delta O_{ry} \end{bmatrix} \quad (5)$$

By generating the inverse matrix of dimensions 2×2 on the right side of the equality of Eq. (5), through the multiplication of both sides by the inverse matrix, we arrive at Eq. (6), which expresses the solution of the variables m_x and m_y. These variables fully define the intersection point of the actuators' axes.

$$\begin{bmatrix} m_x \\ m_y \end{bmatrix} = \begin{bmatrix} -i_{rx} & j_{rx} \\ -i_{ry} & j_{ry} \end{bmatrix}^{-1} \begin{bmatrix} \Delta O_{rx} \\ \Delta O_{ry} \end{bmatrix} \quad (6)$$

The next step is to calculate the direct kinematics of the structure, which consists of determining the values of the position of the final effector of the CNC machine defined by the vector P (see Eq. (8)) concerning the coordinate system XY from the known coordinates of the actuators and defined by the vector P_r, see Eq. (7).

$$P_r = \begin{bmatrix} P_{ir} \\ P_{jr} \end{bmatrix} \quad (7)$$

$$P = \begin{bmatrix} P_i \\ P_j \end{bmatrix} \quad (8)$$

Fig. 8 illustrates the relationship between the position of the end effector concerning the actuators and the XY coordinate system. Fig. 8 shows that the orientation error in the actuators will generate perpendicularity errors in the manufactured parts. The fact that the actuators have zero error due to not starting at the exact origin reduces the machine's workspace. Fig. 8 represents the structure of a CNC machine whose actuator that defines the path on the X-axis is fixed to the base, and the Y-axis actuator is serially connected to the previous one.

Fig. 8 defines the strategy to relate the position of the end effector and the XY coordinate system. The strategy consists of moving from the XY system origin along the vector O_{xr} to the origin of the X-axis actuator. Next, a translation of magnitude P_ir is performed along the direction i_r (defined by the orientation of the actuator). Subsequently, it moves in

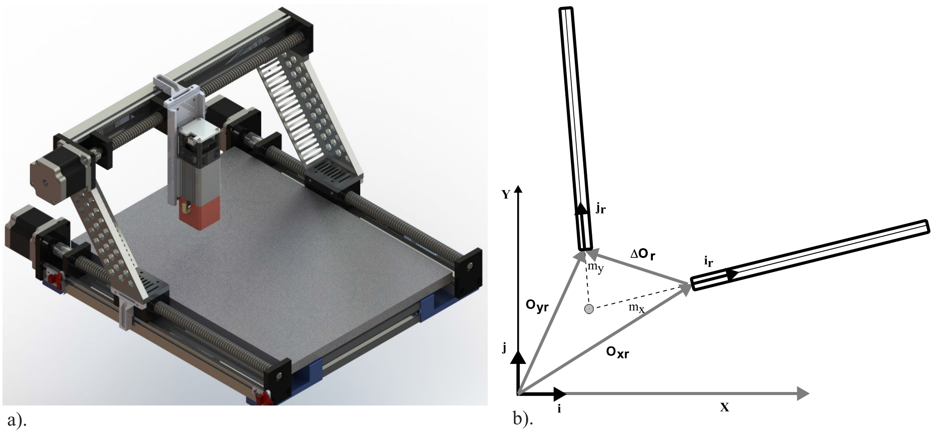


FIGURE 7. The actual location of the actuators in a CNC machine: (a) Cartesian configuration machine; (b) Geometric representation.

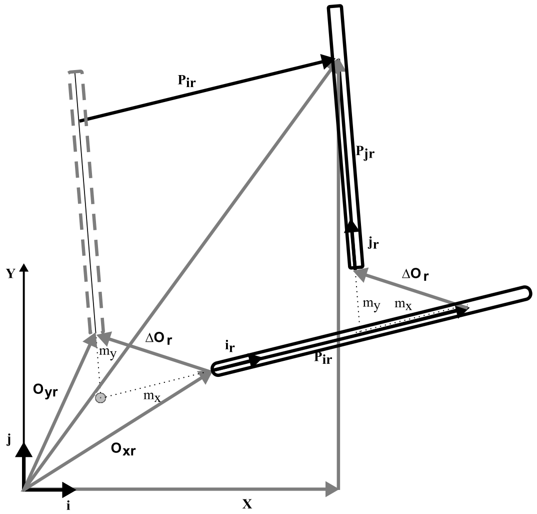


FIGURE 8. The Kinematic diagram relates the actuators' position concerning a CNC machine's XY coordinate system.

the direction and magnitude of ΔO_r, where this displacement corresponds to the position error of the Y-axis actuator to the origin of the X-axis actuator. After that, move in the direction of the second actuator defined by j_r, a distance equal to P_{jr}. This magnitude corresponds to the displacement of the actuator of the Y axis. This path can be represented by Eq.(9).

$$P = O_{xr} + i_r P_{ir} + \Delta O_r + j_r P_{jr} \tag{9}$$

Eq.(9) corresponds to the direct kinematic model of the machine according to its Cartesian configuration. This model allows calculating or simulating the actual position reached by the end effector or tools when each actuator's joint coordinates and the position and orientation errors are known.

In constructing the kinematic compensation algorithm for reducing errors in the CNC machine, the inverse kinematic model of the previously described Cartesian configuration is proposed as the basis of the solution. This model allows calculating the correct joint coordinates to correct errors in the location of the actuators. Eq. (9) can be rewritten in the form expressed in Eq. (10) to organize the terms of the joint coordinates on the left side of the equation.

$$i_r P_{ir} + j_r P_j r = V_1 \tag{10}$$

where:

$$V_1 = P - O_{xr} - \Delta O_r \tag{11}$$

Equation 10 can be expressed in a matrix as equation 12, where all terms are defined based on the XY frame of reference.

$$\begin{bmatrix} i_{rx} P_{ir} + j_{rx} Pjr \\ i_{ry} P_{ir} + j_{ry} P_{jr} \end{bmatrix} = \begin{bmatrix} V_{1x} \\ V_{1y} \end{bmatrix} \tag{12}$$

Equation 12 can be rearranged as the product of a 2 × 2 matrix representing a non-orthogonal transformation matrix that multiplies the vector of actuator coordinates to obtain vector V_1. See equation 13.

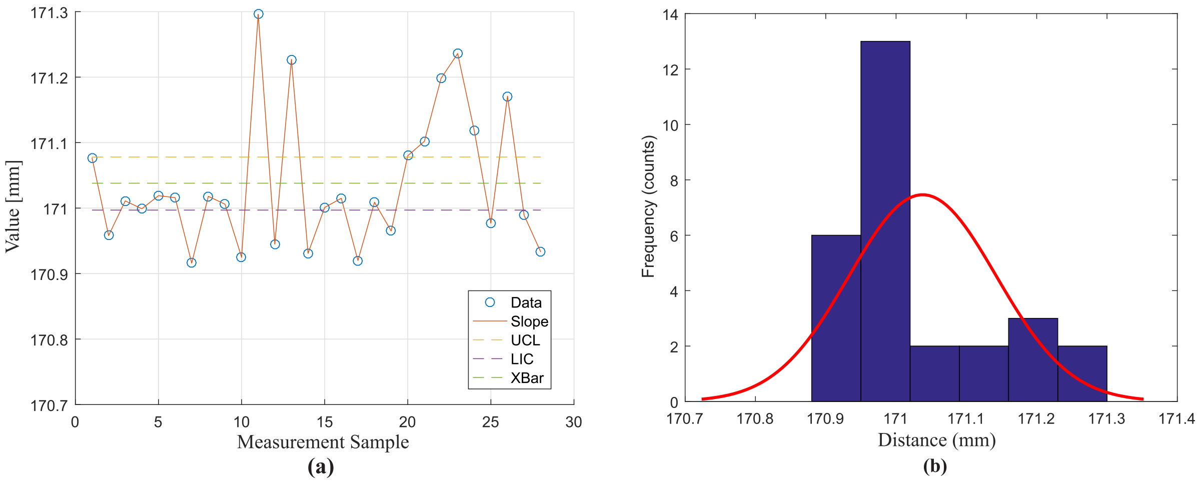
$$\begin{bmatrix} i_{rx} & j_{rx} \\ i_{ry} & j_{ry} \end{bmatrix} \begin{bmatrix} P_i r \\ P_j r \end{bmatrix} = \begin{bmatrix} V_{1x} \\ V_{1y} \end{bmatrix} \tag{13}$$

Once the equation is rearranged, it is rewritten in its compact form, as illustrated in equation 14.

$$\begin{bmatrix} i_r & j_r \end{bmatrix} P_r = P - O_{xr} - \Delta O_r \tag{14}$$

Finally, utilizing its inverse, we pass the non-orthogonal transformation matrix to the right side of the equation. With this, the inverse kinematic model of the machine represented in Eq. (15) is obtained. Note that this model has the reference positions of the tool as input parameters and considers the errors in orientation and the actuator's position. This equation will allow the correct coordinates of the actuators to be calculated to reduce manufacturing errors.

$$P_r = \begin{bmatrix} i_r \; j_r \end{bmatrix}^{-1} [P - O_{xr} - \Delta O_r] \tag{15}$$



(a) **(b)**

FIGURE 9. **Measurement graph for the variable: (a) Chart inspection data; (b) Distance histogram.**

A. ERROR CALCULATION

Product dimensional management is necessary to balance productivity and quality for industrial manufacturing processes. The closed-loop inspection presented in this document brings the process closer to the ideal product quality while maintaining high productivity. The relevant issue to be resolved within this case study is to avoid overestimated dimensional specifications in the design since they lead to manufacturing problems that are difficult to solve because they require greater capacities in machines and adjusted processes to meet the demanding ones. In other words, parts with demanding specifications are better quality but more challenging to manufacture, affecting productivity. Another aspect of this problem is that relaxed geometric, and dimensional specifications increase productivity but sacrifice quality in the final result. The closed-loop inspection architecture seeks a zone or interval of dimensional compliance that balances productivity and quality, seeking continuous process improvement.

The central limit theorem is an appropriate method to estimate the behavior of random variables as it happens in manufacturing parts. The theorem states that when the size of a sample and the number of parts manufactured is large enough, the distribution of the mean follows an approximately normal or Gaussian distribution. This distribution causes samples to accumulate around the mean, and the pieces with values far from the mean are at their extremes. This distribution is what we call the confidence interval for geometric conformity. Operating manufacturing processes with dimensional conformity fosters a robust system against dimensional variations in manufacturing and correct control of errors in production processes.

The inspection results obtained through a part production follow-up are used for this analysis. The dimensional inspection was performed on a Mitutoyo Crysta-Plus M 574 CMM, and the results exported from MeasurLink are used to identify the causes of particular variations within the process. The measurement is made on the critical characteristics that must be monitored and a statistical study that allows relating the errors and the causes that cause them. It also determines the capacity of the machine to manufacture these types of parts. Measurements are made on two linear features of the piece that can provide relevant information about the process. These characteristics represent the functional characteristics of the workpiece under control.

In this case, a statistical study is carried out to relate the errors with the causes that cause them. The applied process also determines the capacity of the machine to manufacture this type of part. Measurements are made on two controlled features of the part that can provide relevant information about the process.

The case of process control is defined between the limits of 6σ. The variability measure is associated with considering the Gaussian result where the $\mu \pm 3\ \sigma$ range includes approximately 99.7% of the characteristic values. The range limits define natural tolerances as intrinsic to the process. The Lower Specification Limit (LSL) and Upper Specification Limit (USL) are considered to define the range of permissible values of the variables that are forced. The objective defined by the mean value μ will be centered on the specification limits. The capability index (C_p) is defined as:

$$C_p = USL - LSL/6\sigma \tag{16}$$

$$Tolerance_{Natural} = (UCL_{\bar{x}} - LCL_{\bar{x}})\sqrt{n} \tag{17}$$

where,

$UCL_{\bar{x}}$: Upper Control Limit.
$LCL_{\bar{x}}$: Lower Control Limit.
n: Sample size or number of observations.
A_2 :Constant to adjust the control limit based on expected variability.

TABLE 1. **Quality control references.**

Indicator	6σ	σ	C_p	C_{pk}	$\bar{X}$	$\bar{R}$
Dx	3,4702	0,5783	0,8450	0,3000	171,1449	0,4449
Dy	2,7533	0,4588	0,8408	0,7911	170,4408	0,4471
*Ly*_1	3,8667	0,6444	0,6805	0,6646	170,5233	0,5524
*Ly*_2	4,4777	0,7462	0,6013	0,5647	170,5608	0,6252
*Lx*_1	3,5157	0,5859	0,8430	0,3711	171,0598	0,4459
*Lx*_2	3,4685	0,5781	0,8229	0,2388	171,2097	0,4568

TABLE 2. **Manufacturing errors found with inspection results.**

Indicator	$Error_{Sis}$	${\sigma_x}^2$	${\sigma_y}^2$	${\sigma_{xy}}^2$	$y = mx + b$	ϕ
Dx	-0,6449	0,3345	–	0,5451	$y = 170,7698 + 0.00428x$	1,4818
Dy	0,0591	–	0,2105	0,5451	$y = 170,2022 + 0,233x$	1,3381
*Lx*_1	-0,5598	0,3433	–	0,7586	$y = 170,7224 + 0,0232x$	1,3329
*Ly*_1	-0,0233	–	0,4153	0,7586	$y = 170,8090 + 0,0276x$	1,5827
*Lx*_2	-0,7097	0,3341	–	0,8911	$y = 170,1995 + 0,0223x$	1,2794
*Ly*_2	-0,0608	–	0,5569	0,8911	$y = 170,2082 + 0,0243x$	1,3927

If μ and σ are known, then the construction of the graph of media is immediate from its definition:

$$UCL_{\bar{x}} = \bar{x} + A_2 * \bar{R} \tag{18}$$

$$LCL_{\bar{x}} = \bar{x} - A_2 * \bar{R} \tag{19}$$

where,

A_2: Constant to adjust the control limit based on expected variability.
$\bar{x}$: Mean of the process subgroups.
$\bar{R}$: Average range of process subgroups.

Figure 9 (a) presents a graphical result of means. An analysis of the results is necessary to obtain more information on the behavior of the process. Indeed, from the dispersion of the sample values, it is possible to estimate the dispersion of the process and follow the evolution. The standard deviation σ measures the dispersion of the values of a population, and the most frequently used sample estimators are the path R (Graph R) and the sample standard deviation S (Graph S).

Table 1 presents a summary of the measurement result returned by Measurlink that presents standard deviation (σ), natural process variability (6σ), and process capability (Cp).

With the parameters presented in Table 1, it is possible to obtain the errors associated with the part. It is determined that the systematic error is constant in the process and is present in the same way in each of the measurements made on the feature. The leading cause of systematic errors in the process is attributed to defects in the manufacturing machine. Eq. (20) is used to calculate a systematic error value. The result obtained for the systematic error is presented in Table 2.

$$Error_{Sis} = V_i - \bar{X}_i \tag{20}$$

where V_i: Desired value $\bar{X}_i$: Mean

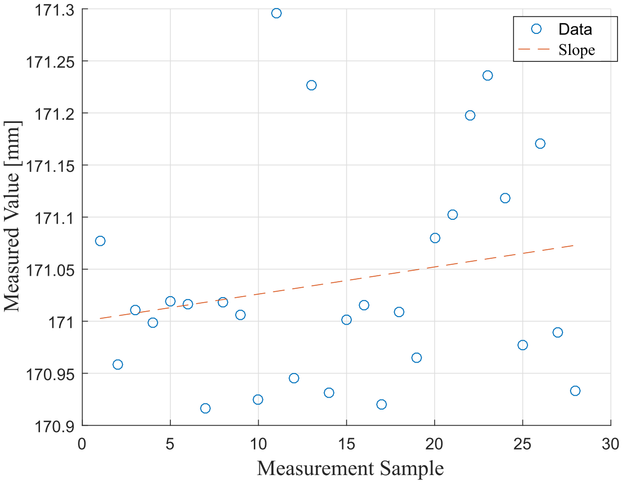


FIGURE 10. **Linear regression relation between valor & measurement sample.**

The value for the manufacturing error is obtained using the root mean square error definition with the variability values of the natural process (6σ).To characterize the error, we determine the angle associated with the displacement of each actuator or axis of the machine using the vestigial data found in part. The offset angle is calculated by performing a linear regression on the standard distribution data to obtain a line correlating with the measurement result values. The equation obtained for each feature will describe a slight incline calculated to determine the offset angle. The data used in this procedure is the output data generated by the Mitutoyo Measurlink software.

Fig. 9 shows the graphical result thrown for the *Dx* feature. The information on each feature that was manufactured in

TABLE 3. Parameters of the errors in position and orientation of the actuators.

Test	m_x	m_y	O_{XY}	O_{yr}	i_r	j_r	*X − Axis joint error*	*Y − Axis joint error*
1	17.41	8.31	[10,10]	[-5,15]	[0.985,0.174]	[0.259,0.966]	10°	-15°
2	13.25	7.56	[10,10]	[-5,15]	[0.985,0.174]	[-0.259,0.966]	10°	15°
3	-12.94	10.61	[10,10]	[20,2]	[0.985,0.174]	[0.259,0.966]	10°	-15°
4	-8.37	-6.78	[10,10]	[20,2]	[0.985,-0.174]	[-0.259,0.966]	-10°	15°

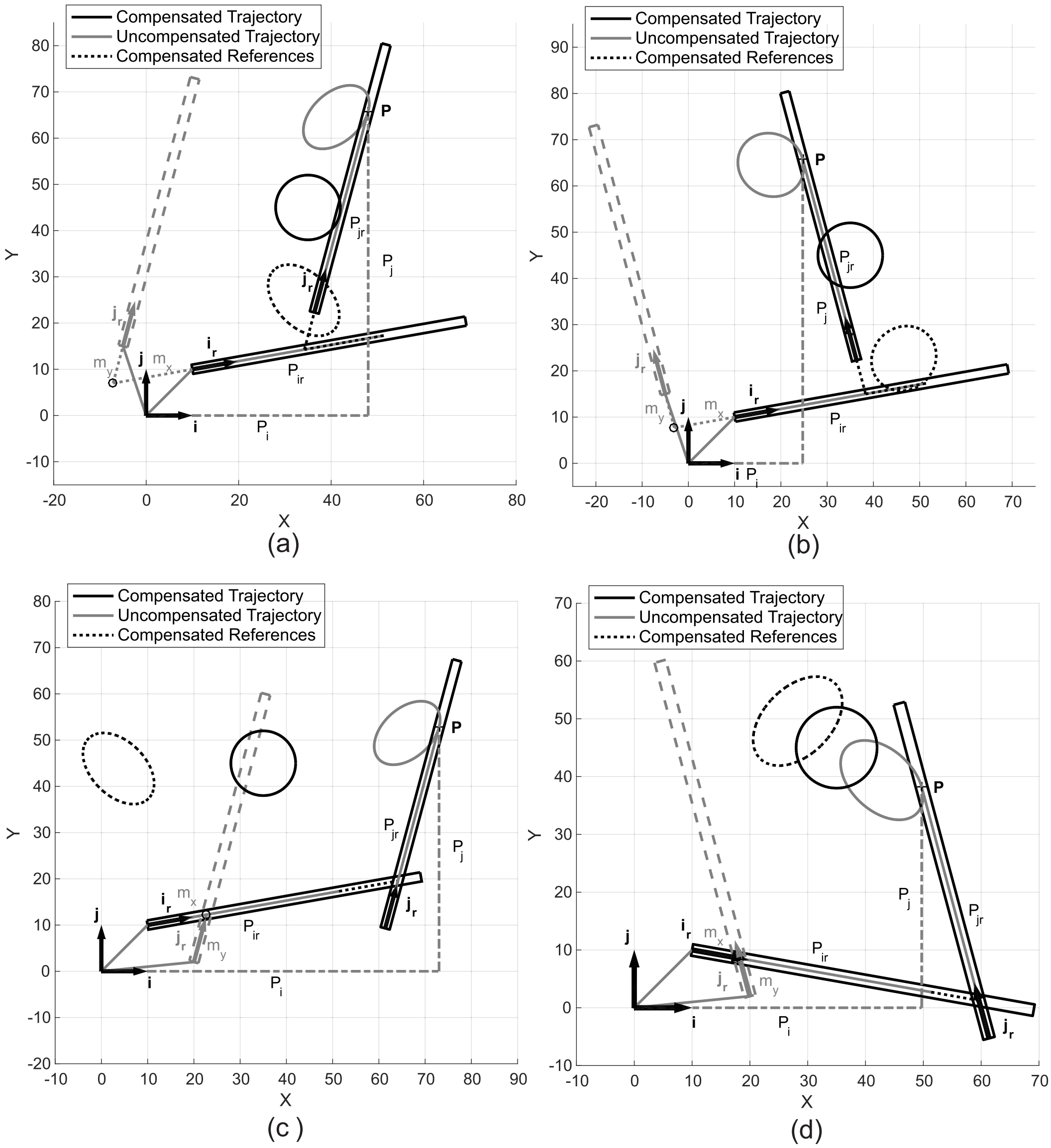


FIGURE 11. Analysis of the trajectories generated by applying and without applying the kinematic compensation algorithm.

the disposition of a machine tool axis is extracted. Fig. 10 shows the result of the linear regression procedure for Feature Dx. Table 2 summarizes the result for each feature analyzed; it presents the deduced equation and the displacement angle concerning an axis of the machine. The results obtained allow for making corrective maintenance decisions that improve the part's quality.

The presented procedure shows a dominant error, and it is possible to estimate its deviation. The processed data sample contains traces of systematic errors due to machine problems.

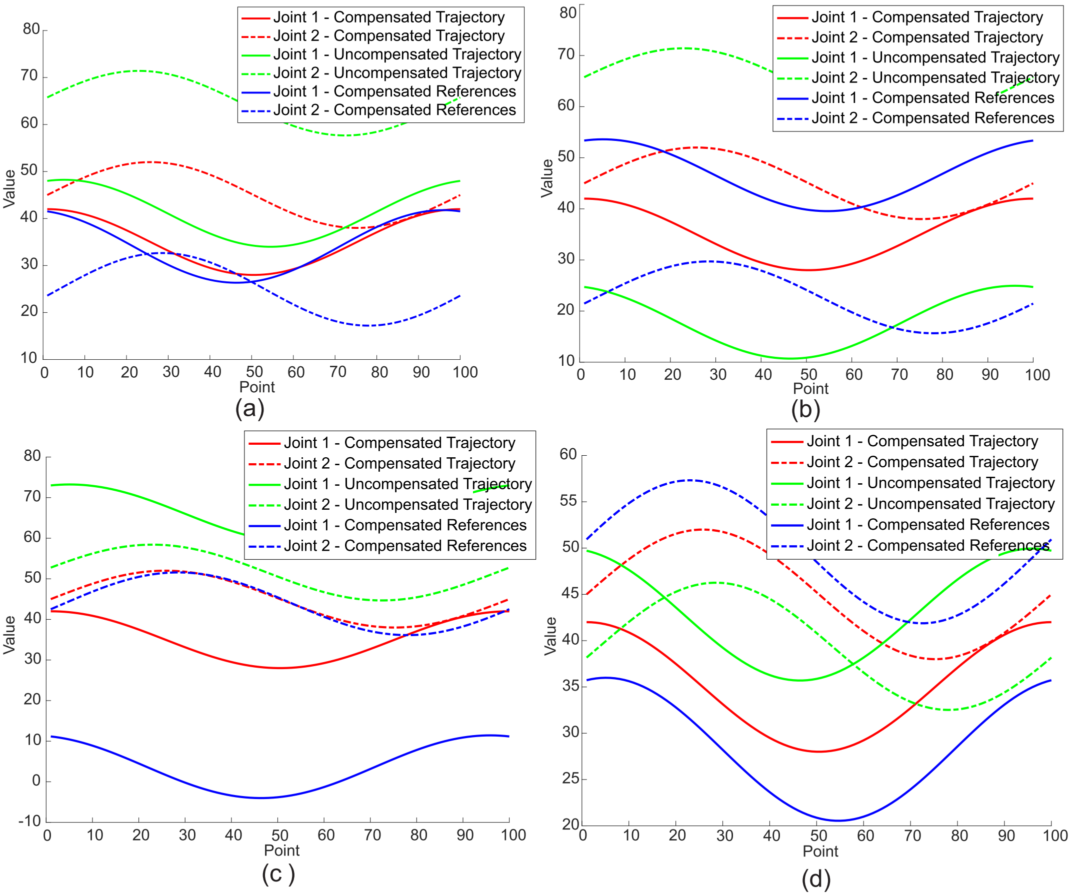


FIGURE 12. **Quantitative analysis of the trajectories generated by the CNC applying and without applying the kinematic compensation algorithm.**

The scenario introduces an error compensation algorithm that allows building pieces to reduce the variability detected. The objective is to obtain dimensional conformity that favors the balance between productivity and quality. This strategy controls the process and algorithmically compensates for identified errors.

V. TYPICAL CASE: CIRCULARITY ERROR COMPENSATION

The proposed algorithm is verified by constructing a CNC machine model with two degrees of freedom in a simulation environment. The experiment introduces significant errors in both position and orientation in the two actuators that define the trajectory on the X-axis and the Y-axis. After causing errors in the machine's configuration assembly, a circular operating path is created. Subsequently, the simulations were carried out using traditional kinematic calculations to generate the CNC's trajectory. Finally, the new references were generated using inverse kinematics with the compensation algorithm. Fig. 11 shows some of the tests performed; in these tests, it can be seen how the orientation errors of the actuators were varied (see parameters in Table 3, which is why a considerable error of perpendicularity is generated).

In Fig. 11 (a), a schematic of a Cartesian configuration is illustrated whose actuator that defines the path on the X-axis has an orientation error of 10°, and the actuator that defines the path on the Y-axis has an error of 15° (measured clockwise). Note that the two actuators have a significant phase shift concerning the initial position; These high-magnitude fictitious errors were defined to identify traces of the manufacturing process. By defining a circular path and observing the results obtained, the effectiveness of the error compensation strategy can be corroborated using the proposed algorithm. Fig. 11 shows the trajectories obtained by following a sequence with references provided by the computerized numerical control; the result obtained is an elliptical path when projecting a circular path (see gray ellipse). It is observed that there is a considerable phase shift in the resulting position concerning the projected one; note that it is further to the right of the projected point on the X-axis and has a greater magnitude in the position on the Y-axis. Fig. 12 (a) shows the numerical values of the trajectories of the two actuators with and without compensation and the trajectories with compensated references.

The kinematic compensation algorithm to correct the error generates new references (Ellipse of black color in interrupted line, Fig. 11). The offset references generated by the algorithm are characterized by being located in the opposite direction to the initial offset, seeking to prevent manufacturing error. Similarly, the proposed algorithm generates eccentric references where the ellipse's central axis corresponds to the ellipse's minor axis resulting from the traditional method, allowing for suppressing the eccentricity errors derived from the location errors of the actuators.

Fig. 11 (b) shows the result obtained for an error variation of 15° (measured clockwise) on the actuator that defines the trajectory on the Y-axis. Fig. 12 (b) shows the numerical values of the trajectories of the two actuators with and without compensation, and the trajectories with compensated references. Fig. 11 (c) presents the result for position errors in the actuators concerning the origin. Orientation errors provide an environment for experimentation of the actuators, causing variations more or less than 90Â°, which is the ideal condition. In all the tests, it is observed that the algorithm generates and modifies the path references to compensate for the machine error. Fig. 12 (c) shows the numerical values of the trajectories of the two actuators with and without compensation, and the trajectories with compensated references.

In Fig. 12, it is possible to graphically observe the behavior of the actuators with the numerical values adopted in each of the trajectories. The graphic results of both compensated trajectories and those produced by assembly errors are shown to analyze the strategy and compare. It can be seen how the compensated trajectory references are acting in the opposite direction to the original trajectory, with assembly errors in all cases.

The proposed kinematic compensation algorithm is essential to the manufacturing error correction strategy. It demonstrates that with closed-loop manufacturing control, it is possible to reduce manufacturing uncertainties caused by assembly problems and machine structure errors. The algorithm generates new references for the trajectory in proportion to the acting error, which allows manufacturing uncertainties to be drastically reduced without the machine's need for intervention or manual recalibration. The proposed algorithm can be used to prepare the machine tool as a form of recalibration via software, enabling the possibility of making changes online during system operation, increasing production times, reducing machine stops, and maintaining geometric and dimensional control of the manufactured parts.

VI. CONCLUSION

The flow of information in the architecture presented is supported by the neutral STEP exchange files that meet the communication requirements between the measurement and manufacturing processes, meeting the demands for integration and interoperability with technologies adhering to the perspective of Industry 4.0.

The concepts of error control documented and studied in statistical processes have applications within closed-loop manufacturing. The architecture is validated within a case study that begins with determining the machine tool's geometric error, directly influencing geometric errors when manufacturing the feature.

The article presents the error compensation strategy through an algorithm that modifies the joint positions of the machine to correct the error without performing a mechanical intervention on the machine. This strategy can compensate for systematic and progressive errors in machine tools and is projected to be used in real-time control by enabling digital twin definitions.

This research promotes technological solutions based on exchange-neutral files that guarantee integration and interoperability. A computational implementation method adhering to the STEP standard was developed. The solution obtained is specific and applied within the manufacturing context, but it allows knowing and interpreting the standard to develop new solutions that increase functionalities.

The dimensional and geometric inspection processes become relevant within the digital context, especially in collecting and constructing knowledge; Technological advances in measurement systems seek to automate the process, reduce human involvement and minimize errors produced in the measurement phase. The closed-loop inspection strategy requires solutions promoting integration, maintaining interoperability, interpreting results, associating manufacturing errors with process causes, establishing automatic error compensation strategies, and optimizing the measurement process.

In future work, the Closed Loop Machining methodology should be validated using a machining center with several years of use, exhibiting an adequate level of wear in the actuators/joints, to validate the proposed method by identifying potential gains through the reduction of positioning errors and improvement in the quality of the machined part, thus comparing the results without compensation and with error compensation on an industrial machine. In these experiments, the effect of different actuator speeds should be considered to observe the behavior of the error and its compensation.

Automatic feature recognition, generation of optimal paths, kinematic control, and configuration of process variables can be controlled algorithmically to improve process efficiency. Hybrid fabrication structures, including real-time inspection within fabrication, can make error control more flexible.

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