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# A New Approach of Setting Machine-Tool Based on In-Situ Measurements of Manufacturing Dimensions

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**Abstract** The usual practice for machine operators in companies is to consider dimensions independently and set one tool per part. This leads to increased costs in terms of scrap parts and increased setup time, during which the machine is not producing. Now, the Copilot-Pro® and Multi-Criteria Inertial steering methodologies have been developed and introduced in production companies to alleviate the tedious task faced daily by machine operators. These methods consist of finding the direct link between the manufacturing dimensions of the part and the available corrections in the machine through an incidence matrix that takes into account the interdependencies between the manufacturing dimensions and the corrections. Both methods, using this matrix, allow the determination of the correction values that must be entered into the CNC (Computer Numerical Control) system to correct the deviations observed on the part. This allows for the simultaneous adjustment of a large number of tools (roughing and/or finishing tools) and avoids setup errors at the machine that could have undetectable short-term consequences on part quality. To determine manufacturing dimensions, the Copilot-Pro® method groups a manufacturing process into a minimal number of measurement and adjustment steps. Until now, the method has been developed with the objective of measuring the part off the machine to determine the necessary adjustments based on the measured deviations. In this article, we present an initial adjustment solution that uses the part's manufacturing dimensions measured in situ, without removing the part from the machine. The approach is presented using a simple example of a 2D part process, whose only role is to highlight situations that may be encountered in real-world applications. The proposed in-situ measurement method offers the advantage of measuring the part directly within the machine, without removing it or undergoing the measurement and adjustment steps that increase adjustment time. This should result in time savings and increased productivity.

***Keywords:*** *machine-tool, machine setting, manufacturing dimensions, tool-offset, in situ measurement*

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## 1. Introduction

In most machining companies, the activity of machine adjustment is entirely delegated to the machine operator at the foot of the machine. This operator relies on their professional experience and product knowledge, attempting by trial and error to bring manufacturing dimensions within tolerances. The objective of the Copilot-Pro® methodology, which has been the subject of several publications (Goldschmidt [1], Pairel et al. [2], Pairel et al. [3] and Abdelhakim [4]) and the Multi-Criteria Inertial steering (Abdelhakim [5], Abdelhakim et al. [6], Pillet al. [7] and Pillet et al. [8]), are therefore to reduce scrap rates and machine downtime to increase productivity.

Theses approaches consists of determining the manufacturing characteristics and calculating the adjustment parameters that operators must adjust in the numerical control (NC) system to correct deviations observed on the part. This helped to standardize practices among machine operators. Along the same lines, the author Pairel et al. [9] proposed to manually determine the adjustment ranges and manufacturing dimensions in order to facilitate the understanding and use of the method respectively by readers and users.

In the 1950s, A. Wade [10] proposed a method for dimensioning the finished part that provides an absolute definition of dimensions. All surfaces of the part will be positioned relative to a reference surface with a specification. This method has the advantage of allowing individual correction for each toleranced dimension. The correction of one dimension does not affect the others. Grubbs [11] proposes a machine setup rule based on a sequential setup approach.

Later, Bourdet [12,13] proposed a rating method called the ΔL method, which allows for consideration of the

dispersion on the dimensions to estimate manufacturing defects for the purpose of adjustment. It uses simulation to find the adjustment parameter that brings the dimension back within its tolerance. His method was used by Wolff [14] and Tichadou [15] in their study for evaluating machining dispersions in turning. Bourdet [16] also presented a setting approach that allows searching by simulation for the adjustment parameter to bring the dimension within its tolerance. The approach is situated in the case of a univariate context and assumes that the relationship between the adjustment parameter and the manufactured characteristic is bijective.

Lill et al. [17] proposed a setting rule for the first manufactured part. However, their rule became too rigid to adapt to serial steering. Due to the very approximate initial tool setting, Kibe et al. [18] developed a setting method to adjust the initial tool position using an in-situ measurement system. They implemented a measurement system to determine the tool position relative to the free surface of the workpiece.

Abdelhakim et al. [19] propose a comprehensive method that incorporates, in a single incidence matrix, the geometric parameters of the workpiece and the dynamic machining parameters to obtain the necessary setting for a good part.

The Copilot-Pro® methodology was designed to find and set machine tools based on off-machine manufacturing dimension measurements. In this article, based on the Copilot-Pro® methodology, we propose a new approach to tool setting through in-situ measurement of manufacturing dimensions.

## 2. Materials

### 2.1. Workpiece and Manufacturing Process

In practice, the design drawing (Figure 1) provided by the customer is not the one used in the workshop to control manufacturing. The methods department in charge of preparation must create a production drawing (Figure 2) showing the roughed and finished surfaces. They then calculate the manufacturing dimensions to be adjusted using the dimension transfer method [20], while optimizing their tolerances over the entire manufacturing process.

The adjustment range allows manufacturing operations to be performed in a different order than the process order. In some cases, this may lead to reordering the operations in the manufacturing process.

The example of the part in Figure 1, machined on the main spindle and then transferred to the sub-spindle to complete the operations, illustrates this problem and highlights the situations that may be encountered in reality.

The principle of the Copilot-pro® methodology consists of setting up the tools by carrying out the following three essential phases :

- The first phase, called "generation of setting/monitoring ranges," determines the setting and measurement steps that will be used subsequently to determine the manufacturing dimensions.
- The second phase, called “generation of manufacturing dimensions”, consists of determining, at the end of each measurement step, the manufacturing dimensions necessary and sufficient for control.
- Finally, the third phase, "pilot dimensions", determines the corrective tool dimensions or tool/program dimensions that allow the deviations observed on the manufacturing dimensions to be canceled.

The manufacturing process of the part is described in Figure 2 with the assumption that we are working with bar stock in screw machining. A bar feeder supplies the main spindle with bar where operations 10, 20 and 30 are carried out. Then the cutting (operation 30) and turning of face 2 (operation 50) operations are completed in the counter spindle (see figure 2).

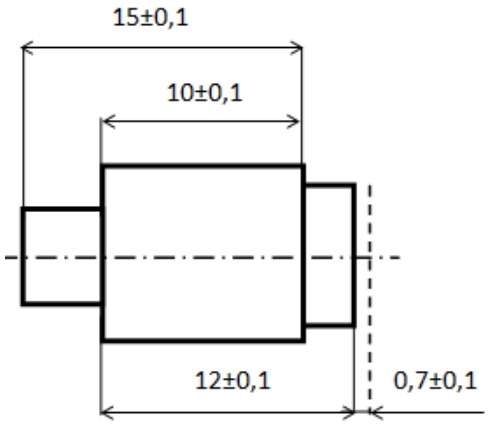



**Figure 1.** Design dimensions and method dimensions

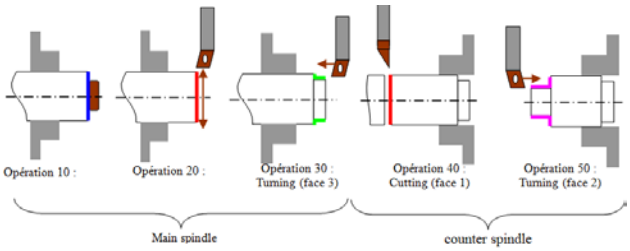



**Figure 2.** Manufacturing process of the workpiece

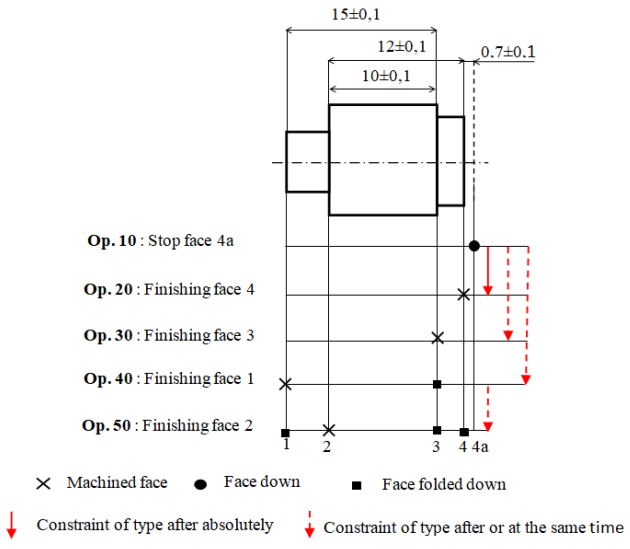



**Figure 3.** Process diagram

Through this manufacturing process, we establish the process diagram (figure 3) which allows us, on the one

hand, to represent all the manufacturing operations of the part and, on the other hand, to take into account both the time constraints and the technological constraints related to the manufacturing of the part.

## 2.2. Temporal Contraints

We distinguish two types of constraints regarding the grouping of manufacturing operations in the same measurement step: "absolutely after" constraints and "after or at the same time" constraints.

On the part, there is only one "absolutely after" constraint, located between operations 10 and 20, and symbolized in the process diagram of Figure 3 by a thick arrow pointing from the line of operation 10 to the line of operation 20.

This constraint means that the bar must be positioned against the stop on face (4a) before machining face (4), just as machining a finished face must be done immediately after its corresponding roughed face. The two faces cannot be in the same measurement step, as they cannot coexist. Conversely, for "after or at the same time" constraints, symbolized by a dashed line, the operations can be performed in the same measurement step because the faces can coexist.

# 3. Methods, Results and Discussion

## 3.1. Method 1: Machine Settings in the Case of Off-Machine Measurement

### 3.1.1. Generation of Adjustment Range

To generate the adjustment range, we allow the process to be stopped at any time to measure all faces (roughed and/or finished faces). We work with the complete process diagram (Figure 3).

We establish rules for constructing the adjustment range. These are listed below and allow us to set up the process in a minimum number of measurements, while taking into account the constraints of the process diagram.

- Rule 1: "Two manufacturing operations linked by a constraint of the type 'after' absolutely must not coexist on the same line of a measurement step." A manufacturing operation corresponds to the movement of the tool to machine one or more faces simultaneously and return to its initial position.
- Rule 2: "Two manufacturing operations linked by a constraint of the type 'after' or 'at the same time' can coexist on the same line of a measurement step."
- Rule 3: "A face existing in a measuring step (i) must be folded back in the measuring step (i+1)."
- Rule 4: "A measuring step should include as many manufacturing operations as possible, provided these are not dependent."

Thus, for the machining of this part, there will be two measurement steps as shown in figure 4.

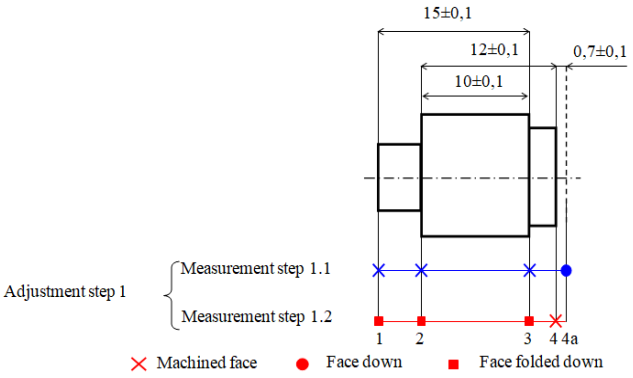



**Figure 4.** Adjustment diagram

### 3.1.2. Generation of Manufacturing Dimensions

We recommend determining manufacturing dimensions by first selecting those that directly correspond to the design dimensions. Then, determine the remaining dimensions using the minimum dimension path to obtain n-1 manufacturing dimensions for n faces of the part. A manufacturing dimension is defined as a dimension that connects two active faces from the same measurement step. It connects either:

- Two machined faces,
- A machined face and a fixed face,
- A machined face and a folded face.

**Tips and Strategies for Determining Manufacturing Dimensions**

Manufacturing dimensions must be determined for each measurement step. They are not necessarily equal to the design or method dimensions, but depend on them. We offer advice and strategies for determining the necessary and sufficient manufacturing dimensions for process control, aiming for a compromise between the "tolerance optimization" criterion and the "ease of measuring the part" criterion.

- **Tip 1**: Look for manufacturing dimensions that directly correspond to the design dimensions linking two faces in the same measurement step.
- **Tip 2**: Look for manufacturing dimensions that correspond to the design dimensions linking two faces between two measurement steps, with at least one face in common.
- **Tip 3**: Find manufacturing dimensions using the shortest path in the dimension chain. This doesn't necessarily mean measurement uncertainties, but rather the easiest to measure.

For the adjustment range, the manufacturing dimensions are :

Adjustment step 1
Measurement step 1.1
CE1-3 = CF1-3
CE2-3 = CF2-3
CM4-4a = CF2-4a – CF2-4
Measurement step 1.2
CE2-4 = CF2-4

By combining the equations of the two measurement

steps, we obtain relation (1) which links the design dimensions and method dimensions to the manufacturing dimensions.

$$[CE/CM]=[A]\cdot[CF] \tag{1}$$

With:

$[CE/CM]$ vector of design dimensions and method dimensions;

$[A]$: Matrix for converting design/method dimensions to manufacturing dimensions;

$[CF]$: vector of Manufacturing dimensions.

The matrix relation (1) can be expressed in the form below:

$$\begin{Bmatrix} CE1\text{–}3 \\ CE2\text{–}3 \\ CE2\text{–}4 \\ CM4\text{–}4a \end{Bmatrix} = \begin{Bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \end{Bmatrix} \begin{Bmatrix} CF1\text{–}3 \\ CF2\text{–}3 \\ CF2\text{–}4 \\ CF2\text{–}4a \end{Bmatrix}$$

### 3.1.3. Determination of Pilot Dimensions (Tool Corrections)

To determine the pilot dimensions necessary for process control, correction factors are chosen for each of the tools performing the manufacturing operations. The transition from relationship (2) to relationship (3), between the deviations of the pilot dimensions and the deviations of the manufacturing dimensions, allows the process to be controlled to maintain control over all manufacturing dimensions.

$$[E_0]=[X]\cdot[C] \tag{2}$$

and

$$[C]=[X]^{-1}\cdot[E] \tag{3}$$

Withc: $[E_0]$ : Matrix of deviations on manufacturing dimensions

$[C]$: Matrix of action variables (correctors)

$[X]$: Incidence Matrix of corrections on manufacturing dimensions

$[X]^{-1}$: Inverse Matrix of $[X]$, because it is a square matrix.

In the case where $[X]$ is not square, that is to say when we have fewer pilot dimensions than manufacturing dimensions, then we calculate the pseudo-inverse of Gauss by relation (4). Therefore, equation (3) becomes (4):

$$[C]=\left[X^T\cdot X\right]^{-1}\cdot\left[X^T\right]\cdot[E_0] \tag{4}$$

With: $[X]^*=\left[X^T\cdot X\right]^{-1}\cdot\left[X^T\right]$

### 3.1.4. Incidence Matrix

This is a matrix of the influence of the correctors on the dimensions. It links the measured deviations in the part's dimensions to the tool correctors. To determine the linear/matrix relationship between the deviations in the pilot dimensions and the deviations in the manufacturing dimensions, an exhaustive list of all the correctors/tool offsets acting on each face of the part must be drawn up. Then, one or part of the correctors can be fixed according to the desired control context (see equations 5 and 6).

$$\begin{cases} e_{CF1\text{–}3} = e_{CP_Z3} - e_{CP_Z1} \\ e_{CF2\text{–}3} = e_{CP_Z3} - e_{CP_Z2} \\ e_{CF2\text{–}4} = e_{CP_Z4} - e_{CP_Z2} \\ e_{CF2\text{–}4a} = e_{CP_Z4a} - e_{CP_Z2} \end{cases} \tag{5}$$

There are five pilot dimensions for the four manufacturing dimensions. In this case, we have an infinite number of solutions. In order to obtain an exact solution, therefore a square and invertible matrix, the position of the cutting tool (face 1) was fixed to avoid any possible collision of the tool with the machine. Hence, eCP_Z1 = 0 and equation (2) becomes :

$$\begin{Bmatrix} e_{CF1\text{–}3} \\ e_{CF2\text{–}3} \\ e_{CF2\text{–}4} \\ e_{CF2\text{–}4a} \end{Bmatrix} = \begin{Bmatrix} 0 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ -1 & 0 & 0 & 1 \end{Bmatrix} \begin{Bmatrix} e_{CP_Z2} \\ e_{CP_Z3} \\ e_{CP_Z4} \\ e_{CP_Z4a} \end{Bmatrix} \tag{6}$$

### 3.1.5. Steering Matrix

The steering matrix is a matrix for moving from the deviations to be compensated to the adjustments to be made. If the values of the deviations in the manufacturing dimensions are known, the values of the pilot dimensions (correctors/tool offsets) to be applied to bring all dimensions to their target value are calculated. By inverting the matrix system (equation 6), the steering matrix of the system is obtained, as given by equation 7.

$$\begin{Bmatrix} e_{CP_Z2} \\ e_{CP_Z3} \\ e_{CP_Z4} \\ e_{CP_Z4a} \end{Bmatrix} = \begin{Bmatrix} 1 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & -1 & 1 & 0 \\ 1 & -1 & 0 & 1 \end{Bmatrix} \begin{Bmatrix} e_{CF1\text{–}3} \\ e_{CF2\text{–}3} \\ e_{CF2\text{–}4} \\ e_{CF2\text{–}4a} \end{Bmatrix} \tag{7}$$

**Example of part adjustment**

Assuming that an initial adjustment has allowed the production of a first part with the following deviations:

$$\begin{Bmatrix} e_{CF1\text{–}3} \\ e_{CF2\text{–}3} \\ e_{CF2\text{–}4} \\ e_{CF2\text{–}4a} \end{Bmatrix}_0 = \begin{Bmatrix} 0.1 \\ 0.1 \\ -0.1 \\ 0.2 \end{Bmatrix}$$

Applying equation (7), we find the values of the corrections to be made below to correct the deviations observed on the manufactured part:

$$\begin{Bmatrix} e_{CP_Z2} \\ e_{CP_Z3} \\ e_{CP_Z4} \\ e_{CP_Z4a} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0.1 \\ -0.1 \\ 0.2 \end{Bmatrix}$$

These corrections will correct the deviations on the part. The second part produced will have residual deviations [E1] calculated using equation 8 below:

$$[E_1] = [E_0] - [X] \cdot [C] \tag{8}$$

$$\begin{Bmatrix} e_{CF1-3} \\ e_{CF2-3} \\ e_{CF2-4} \\ e_{CF2-4a} \end{Bmatrix}_1 = \begin{Bmatrix} 0.1 \\ 0.1 \\ -0.1 \\ 0.2 \end{Bmatrix} - \begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & -1 & 1 & 0 \\ 1 & -1 & 0 & 1 \end{bmatrix} * \begin{Bmatrix} 0 \\ 0.1 \\ -0.1 \\ 0.2 \end{Bmatrix}$$

This gives the values of the residual deviations measured on the second part after adjustment. We observe that the deviations on this second part are indeed zero on all three manufacturing dimensions, and only one manufacturing dimension shows a non-zero deviation of -0.1, which nevertheless remains within control, within the tolerance of 0.2.

$$\begin{Bmatrix} e_{CF1-3} \\ e_{CF2-3} \\ e_{CF2-4} \\ e_{CF2-4a} \end{Bmatrix}_1 = \begin{Bmatrix} -0.1 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Figure 5 below shows the deviations measured before and after machine adjustment.

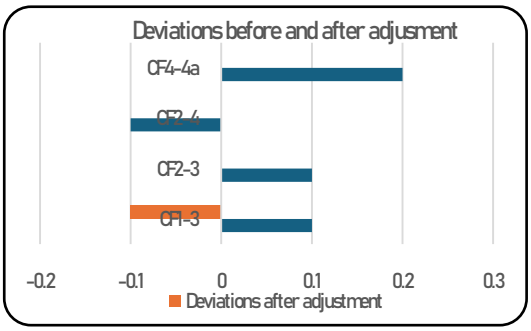



**Figure 5.** Deviations obtained before and after machine adjustment.

## 3.2. Method 2: Machine settings in the case of in-situ measurement

Through the manufacturing process of the part, a new process diagram is established in the case of in-situ measurement (see figure 6) which allows, on the one hand, to represent all the manufacturing operations of the part, on the other hand, to take into account both the time constraints and the technological constraints related to the manufacturing of the part.

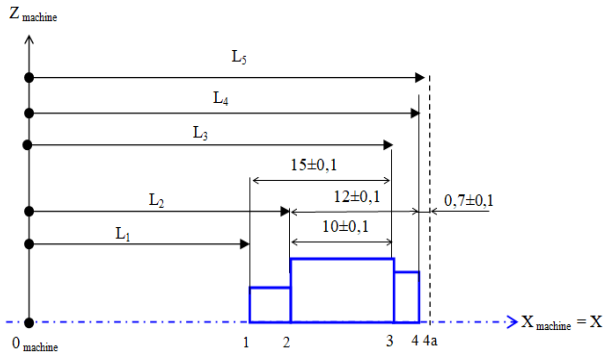



**Figure 6.** Process diagram for in-situ measurement

In the machine tool, the roughed dimensions must be measured beforehand, otherwise they would be lost. Dimension measurement is preferably performed in the machine tool, using a probe, for example. This allows for the direct measurement of surfaces relative to the machine origin (reference), specifically the distances L1, L2, L3, L4, and L5. The advantages of measuring in the machine tool are :

- no specific setup of the roughed workpiece is required;
- time savings in workpiece handling;
- the ability to directly measure method dimensions (e.g., allowances for finishing).

In this context, the incidence matrix of deviations on the dimensions in equation (6) becomes (9). In this case, the surface is measured directly. Each tool is associated with a compensator $e_{cPi}$.

$$\begin{Bmatrix} e_{L1} \\ e_{L2} \\ e_{L3} \\ e_{L4} \\ e_{L5} \end{Bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} e_{CP1} \\ e_{CP2} \\ e_{CP3} \\ e_{CP4} \\ e_{CP5} \end{Bmatrix} \tag{9}$$

With $e_{Li}$, the deviation on the surface *i* and $e_{Cpi}$, the deviation on the tool corrector *i*.

The advantage of this matrix is that it makes the measured characteristics completely independent in this process. The relationship between the deviations measured on the part and the tool corrections is bijective. Each surface is controlled by a single tool. By applying equation 3, the control matrix becomes (equation 10):

$$\begin{Bmatrix} e_{CP1} \\ e_{CP2} \\ e_{CP3} \\ e_{CP4} \\ e_{CP5} \end{Bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} e_{L1} \\ e_{L2} \\ e_{L3} \\ e_{L4} \\ e_{L5} \end{Bmatrix} \tag{10}$$

By analogy, considering the previously measured deviations on the part as initial deviations (E0) on the probed surfaces, we will have:

$$\{E_0\} = \begin{Bmatrix} e_{L1} \\ e_{L2} \\ e_{L3} \\ e_{L4} \\ e_{L5} \end{Bmatrix}_0 = \begin{Bmatrix} 0 \\ 0.1 \\ 0.1 \\ -0.1 \\ 0.2 \end{Bmatrix}$$

Similarly, if we apply equation (8), we obtain the residual deviations after adjustment given below.

$$\{E_1\} = \begin{Bmatrix} e_{L1} \\ e_{L2} \\ e_{L3} \\ e_{L4} \\ e_{L5} \end{Bmatrix}_1 = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

We observe a perfect adjustment due to the bijective relationship between the measured characteristics and the tool correctors.

## 4. Conclusion

To better control variations related to the measuring method and variations in part positioning within the machining fixture, mechanical parts manufacturing companies are increasingly adopting in-situ measurement systems using integrated machine measurement systems. In this context, a method for setting up machine tools based on in-situ measurements using probes is necessary.

In this article, using the existing methodology, we have demonstrated that it is possible to use an in-situ measurement system and determine the necessary adjustments to guarantee the quality of the produced part.

The method was developed using a simple part example; machining tests with deviations measured directly in the machine will definitively validate the approach.

The advantage of in-situ measurement is that it avoids the need for the Copilot-Pro® methodology, which entails measurement and adjustment steps that can be extremely burdensome for operators working at the machine. With the advent of coordinate measuring machines (CMMs), time savings can be achieved by measuring the part directly within the machine.

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