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# Digital twin assisted workpiece referencing for compensating the stock deviation of casted parts

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**Abstract**

Stock deviation of casted parts needs to be handled by adapting the CNC machining code to every new batch. Usually, human experts deal with this workpiece referencing task, but the demand for automation is expressed by the industry. This paper introduces a Digital Twin (DT) supported workpiece referencing method, implemented in the following steps: building the DT of the CNC machining cell, loading measurements of the casted part into the DT, solving the workpiece referencing problem as a convex optimization problem, and generating the compensated CNC code. The proposed approach is illustrated in a case study from the automotive industry.



*Keywords:* Machining; Workpiece referencing; Digital Twin; Convex optimization

## 1. Introduction

As industrial digitalization moves forward, more and more tasks are automated that were previously done by human workers. These changes are motivated by numerous factors, for example labor shortage, pursuing cost effectiveness or zero-defect manufacturing [1]. These factors motivate the research topic of this paper: compensating the lot-to-lot variation of the workpiece during the machining of cast aluminum parts. Different batches of a cast workpiece might have small—within tolerance—variations in various dimensions, because of mould wear for example. Manufacturing processes must implement a reaction to these variations to mitigate the risk of manufacturing scrap.

Locating a part or its features in the workspace of a machine is called the *workpiece referencing* or *part localization* problem. Numerous solutions have been proposed by scholars, however, this task is still often performed by human workers. Similar task also arises in the field of *blank localization* (also called *raw part alignment*) when the transformation that brings the designed model into the blank part must be found. In both cases, finding the appropriate transformation (position and rotation) is formulated as an optimization problem.

Both workpiece referencing and blank localization require appropriate measurement technology and efficient algorithms for processing the measured data and solving the resulting optimization problem.

One approach to apply vision-based calibration techniques is to mount camera(s) to the machine [2,3]. Authors of [2] mount a stereo camera to the spindle of a machine and locate a known template part in the image that is attached to the workpiece's reference point. In [3], the authors mount a camera to the machine tool spindle and use photogrammetry techniques to calibrate the system. Both approaches locate the part's position in three degrees-of-freedom (DoF).


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Laser scanners are also utilized as on-machine measurement devices [4,5], though, these devices are physically mounted outside of the workspace of the machine tools. In [4], the authors use a laser scanner to locate free-form FRPC (fiber-reinforced polymer composite) parts. Their system handles one rotational and two translational dimensions and a simple iterative algorithm is used for computing the part location referenced to its nominal counterpart. In [5], the authors propose a system that can transform the mounted workpiece's position to the CNC machine coordinate system. For sensor calibration, sample consensus (ICP – Iterative Closest Point) and least squares algorithms are used, and ICP is used for locating the nominal workpiece (CAD data) in the measured point cloud.

Typical approaches to *blank localization* address finding a common transformation for placing the entire to-be-machined part inside the blank, represented by point cloud measurements. Finding the best placement is cast as an optimization problem, where common criteria include maximin (i.e., maximizing the minimum machining allowance at the measured points), minimax, or some least-squares-type criterion [6–8]. Optionally, a minimum allowance constraint can be set. Furthermore, approaches differ in allowing or prohibiting negative allowances that can be repaired by rework (e.g., adding extra material by welding) in some applications. The authors are aware of a single contribution [9] where the part surface is decomposed into features, and different features can be machined with different transformations. This comes with the additional requirement of handling the dimensional and geometrical tolerances between different features in the blank localization model. Most methods assume six DoF transformations involving translation and rotation, but some are limited to positional alignment.

## 2. Problem statement

CNC programs are written in a reusable way and *part zeros* are essential part of this feature. The machining positions are not programmed in an absolute coordinate frame, e.g., in the *machine zero*, but relative to the workpiece, so the programs are universal and can be moved across fixtures, machines and even factories. The *part zero*—also called *part zero point* in industry—is the frame that moves the machining positions to a workpiece in a specific fixture on a specific machine. To ensure quality control requirements, machining companies are not allowed to modify the machining positions, they can only change the *part zeros* to customize the production to their machines and processes.

One issue that companies may need to address is the stock deviation of the raw cast parts. Cast parts may vary from batch-to-batch, and to mitigate the risk of surfaces left unmachined or manufacturing out-of-tolerance products, companies need to compensate the stock deviation. As the machining itself can only be influenced through the *part zeros*, their precise value must be found. To find the correct *part zero*, one needs to locate the part in the machine's workspace, thus solve the *blank localization* problem.

In this paper, a specific subproblem is addressed. In a drilling scenario, the holes on one side of a cast workpiece may have considerable (geometrical) deviation relative to each other, but the reference positions are not changed. Therefore, an optimal *part zero* needs to be found that ensures that the whole surface of every hole is machined, and the tolerance criteria of the machined holes are also met.

There are several requirements that the correction method must fulfill:

- Only the *part zero*s can be modified in the CNC code.
- The nominal values and tolerances of the holes must be respected.
- The entire feature surface must be machined.
- Machining centers with multiple nests within multiple fixtures must be handled.

## 3. Solution approach

In this paper, a novel approach is presented that solves the *blank localization* task by locating the to-be-machined features and finding the optimal *part zero* that satisfies the above listed requirements.

The authors make the following assumptions regarding the approach presented in this paper:

- The current approach addresses hole features only and models them as cylinders.
- The methodology is currently implemented to only handle one side of a workpiece that has multiple holes.
- The solution is aimed at setups where the feature cylinders' axes in the fixtures are parallel with the machine's axes.

The proposed methodology unfolds in the following five steps:

1. Building and calibrating a Digital Twin (Sec. 3.1)
2. Loading measurements into the Digital Twin (Sec. 3.2)
3. Formulating the *blank localization* problem as a planar convex optimization problem (Sec. 3.3)
4. Solving the convex optimization problem (Sec. 3.4)
5. Generating the CNC code with the newly calculated *part zeros* (Sec. 3.5)

In this paper—because of nondisclosure agreement restrictions—original CAD models and images are not shown, only simplified versions, where the machined hole features are preserved, but unrelated geometries have been changed.

### 3.1. Digital Twin

The Digital Twin consists of two major components: the kinematic description of the machining center and a database containing the parameters of different machines, as well as workpiece measurements. The kinematic description uses a graph representation (kinematic graph), where the nodes of the graph are the various links (or bodies) building up a linkage, while the edges between two nodes are joints, connecting the bodies corresponding to the given nodes. This approach is widespread in mechanism and robot modeling, and suits perfectly this case as well. With this approach, it is possible to model the machining center, fixtures and workpieces; together

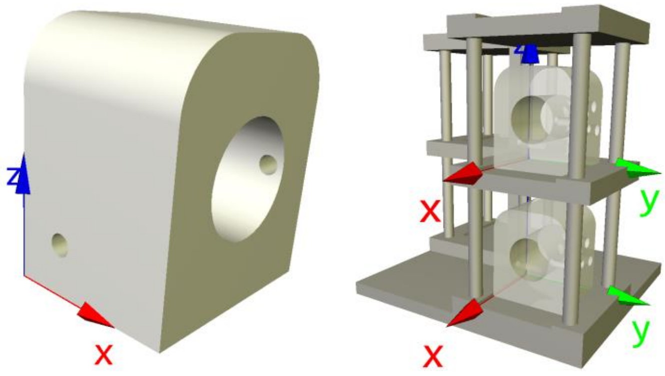


Fig. 1. (a) *Workpiece datum* on the back of a workpiece; (b) *Nest datums* of two nests of a fixture (with the workpiece being transparent).

it will be referenced as work cell. The database stores every parameter of the kinematic graph including geometries, dimensions, and calibration data as well as all the measurements (Sec. 3.2).

There are certain nodes that do not represent a link in the kinematic graph, but key coordinate frames that have an important role in assembling and handling the work cell. The two foremost important key frames are the *nest datum* and the *workpiece datum*. They are presented in Fig. 1.

The workpieces are fixed to the nests' back, bottom, and left face with clamps from the right and top sides. These three faces (planes) define a coordinate frame, called *nest datum*. The corresponding faces can be defined on the workpiece as well, resulting in the *workpiece datum*. The workpieces are inserted into the model via joining one instance of the same *workpiece datum* to each *nest datum* in the kinematic graph. This is important because with these datum frames, the physical connection between the fixture and the workpieces are exactly modeled.

An important point is that the *nest datums* of the Digital Twin must be calibrated to the physical work cell. This calibration must be precise for every *nest datum*, as their relative position may show some variance compared to the designed state. Calibration of the Digital Twin is basically a kinematic modeling task during the creation of the work cell model. As plenty of references are available in the literature, e.g. [10], the calibration methodology is not addressed in this paper.

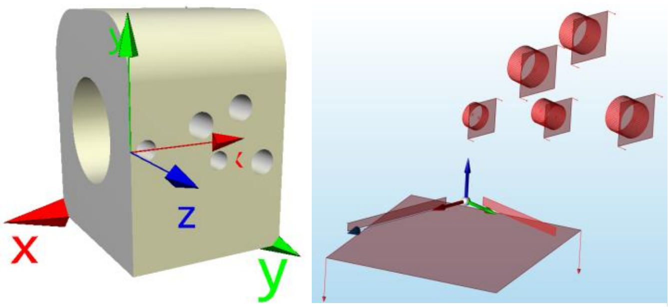


Fig. 2. Measured side of the workpiece: (a) CAD model with *a reference frame* (front) and *workpiece datum* (back); (b) *Measured cylinders* with the *workpiece datum*.

### *3.2. Measurement processing*

As the correction process is based on the cylinder features, the positions and radii of those cylinders must be collected. Two cylinders are defined for each feature: a *reference cylinder* and a *measured cylinder*.

The *reference cylinder* is the nominal value of a feature represented with a cylinder. The position values are usually given in a *reference frame* with tolerances. The *reference frame* is usually attached to a feature, e.g., a planar face of the workpiece, and is given in the *workpiece datum*. Features on one side of a workpiece usually share the same *reference frame*, while different sides of a workpiece may have different *reference frames*. The *reference frames* and the position and radius of the *reference cylinders* can be derived from the part's drawing or the part's CAD model.

The *measured cylinder* is a cylinder feature on the raw cast part. The positions are defined relatively to the workpiece datum. If possible, the feature that defines the *reference frame* is also measured. It is referred to as *measured reference frame*. The measurement values can be acquired via a measurement instrument, e.g., coordinate measuring machine (CMM), or 3D scanner. A processing method is needed to segment and fit cylinders to the acquired point clouds. One such method is the RANSAC algorithm [11]. For each feature, the *reference cylinders* and *measured cylinders* are collected and stored in the database, (see examples for a measurement in Fig. 2).

### *3.3. Problem formulation*

Fixtures can have multiple nests, each holding a workpiece. Multiple sides of a workpiece can be machined. The reusability of the CNC program is ensured by defining *part zeros* for each *reference frame* of a workpiece for each nest. For example, a CNC program for a fixture that has six nests with a workpiece having four of its sides machined—assuming that each side has its own *reference frame*—will have twenty-four *part zeros*. The goal is to locate all *part zeros* so that the machined holes fully include the *measured cylinders* and respect the tolerances. The approach presented in this paper only locates the positions of *part zeros*. It is assumed that the orientation values, if present for example in case of a 4D or 5D machining center, can be determined intuitively, e.g., by setting the angles of a *part zero* so that the *z* axis of the machine is parallel with the *reference cylinders'* axes. Each of the *part zeros* can be deduced with the following procedure, part of that is visualized in Fig. 3. Both *reference* and *measurement cylinders* are given in the *workpiece datum*—the *reference cylinders* being in the *reference frames,* that are themselves given in the *workpiece datum*—they can be inserted into the DT through a *nest datum*, which means that positions and distances can be measured relative to the *machine zero*. As mentioned previously, for every *reference frame* and every nest, a *part zero* is defined. Therefore, every *reference cylinder* is collected that is given in a specific *reference frame* and the measured counterpart of those cylinders as well.

The *part zero's* position constitutes of three coordinates, one that is parallel to the *z* axis of the machine (*z* coordinate) and two which are perpendicular to it (*x, y* coordinates). The *z* value

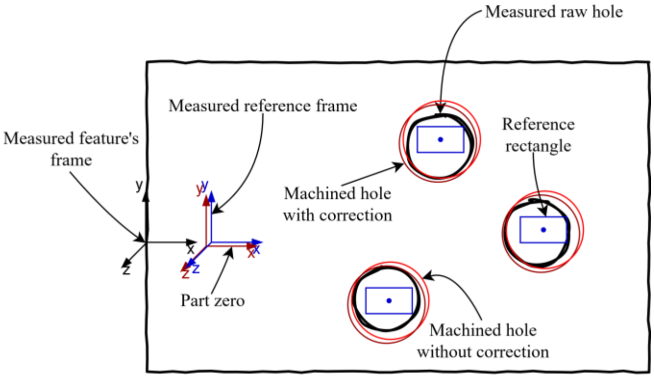


Fig. 3. Locating one *part zero* (visualized on the side of the workpiece). The *initial part zero* is covered by the *measured reference frame*.

can be determined by calculating the *measured reference frame's z* value.

To define the *part zero's x-y* value, a planar problem is considered, see the drawing in Fig. 3. The *reference cylinders'* positions with their tolerances are recorded relative to the *measured reference frame*. As the tolerances form a rectangle around the nominal positions, they will be called the *reference rectangles*. The position of the *measured cylinders* and their radii are also defined relative to the *measured reference frame*, they will be named the *measured raw holes*.

An *initial part zero* is considered that will be shifted to its final position in the optimization step. Its rotational coordinates—if there is any—are determined intuitively, e.g., the to-be-machined side of the workpiece should be turned in front of the machine's main spindle. The *z* coordinate of the *initial part zero* is already found as described above. The *x* and *y* coordinates of the *initial part zero* can be chosen arbitrarily—as they will be shifted relatively to the initial position—but a good setting is the *x* and *y* coordinates of the *measured reference frame*. The positions and radii of the *reference cylinders* are also noted relative to the *initial part zero*, as if it was the *reference frame*. They are referred to as *machined holes,* (see Fig. 3). The *initial part zero* and the *machined holes* model the actual machining. By shifting the *initial part zero*, the *machined holes* are also moved as they would be in the actual machining center. To find the optimal shift of the *initial part zero*, two criteria must be fulfilled. First, the *machined holes'* center-point must be inside of the corresponding *reference rectangle* and secondly the *machined holes* must cover the corresponding *measured raw holes*. This can be modeled as a convex optimization problem and is described in the following section.

It is possible that the *reference frame* cannot be measured on the raw cast part, for example when a milling operation will create the feature that defines the *reference frame*. In this case the *measured reference frame* must be derived from a measurable feature on the workpiece—marked as *measured feature's frame* in Fig. 3.

### *3.4. Convex optimization*

The problem of finding the optimal shift for the *initial part zero* has been encoded into a convex quadratically constrained quadratic program (QCQP) model [12] as follows, using the notation displayed in Table 1.

Table 1. Notation.

| Parameters | |
|---|---|
| $(x_i, y_i)$ | Measured center-point of raw hole $i$ [mm] |
| $r_i$ | Measured radius of raw hole $i$ [mm] |
| $(X_i, Y_i)$ | Center-point of machined hole $i$ [mm] |
| $R_i$ | Radius of machined hole $i$ [mm] |
| $(x_i^{\min}, y_i^{\min}), (x_i^{\max}, y_i^{\max})$ | Corners of reference rectangle $i$ [mm] |
| **Decision variables** | |
| $\tilde{x}$ | Correction along the $x$ axis [mm] |
| $\tilde{y}$ | Correction along the $y$ axis [mm] |
| $d_i$ | Distance between the center-points of the raw and the machined hole $i$ [mm] |
| $\delta$ | Machining allowance [mm] |

Maximize

$$\delta \tag{1}$$

subject to

$$x_i^{\min} \le X_i + \tilde{x} \le x_i^{\max} \quad \forall i \tag{2}$$

$$y_i^{\min} \le Y_i + \tilde{y} \le y_i^{\max} \quad \forall i \tag{3}$$

$$d_i^2 \le (X_i + \tilde{x} - x_i)^2 + (Y_i + \tilde{y} - y_i)^2 \quad \forall i \tag{4}$$

$$\delta \le R_i - r_i - d_i \quad \forall i \tag{5}$$

$$\delta, d_i \ge 0 \quad \forall i \tag{6}$$

The objective (1) is finding correction values $(\tilde{x}, \tilde{y})$ in such a way that the minimal machining allowance is maximized. The corrected center point coordinates must be in the reference rectangles (2), (3). The distance between the raw and the machined center-points of each hole, taking into account the applied correction, is expressed by constraint (4). This distance, and the difference of the measured and reference radii define an upper bound on the machining allowance (5). The machining allowance $\delta$ and the distances $d_i$ are positive (6), whereas the correction values $\tilde{x}$ and $\tilde{y}$ are free, i.e., they can take either positive or negative values. It is emphasized that the above QCQP is convex, which means that it can be solved efficiently to global optimality in the problem size relevant for the industrial application.

*3.5. CNC code generation*

The optimal *part zeros* can be calculated by applying the correction values to the *initial part zero*s. Then, they are stored in the database, and they can be compiled to CNC code for a given machine and program.

## 4. Case study

To comply with the confidentiality of the parts and machines used to validate this work, a “dummy” part has been generated, where the positions of the holes are taken from an existing workpiece, but other—unrelated—geometries have been altered. The workpiece is shown in Fig. 2 (a). Its right side, where five holes must be machined, is chosen to validate the algorithm. The machine that is used in this paper is a 4-axis (XYZB) high performance machining center.

The algorithm for processing the measured data and the DT was implemented in Wolfram Mathematica with the LinkageDesigner plugin. The convex QCQP solution approach was implemented in FICO Xpress version 8.8, using the Mosel programming language. The measurements have been taken with a FaroArm Quantum$^{E}$ measuring arm. The Faro CAM2 software was used to process the measurements and output the requested cylinder positions and radii.

As this work describes ongoing research, the proposed approach is validated with a currently running machining setup. The DT was built and calibrated with on-machine measurements. Then, the right side of a raw part was measured, where there are five holes. An image from the measurement software is shown in Fig. 2 (b).

On this side of this workpiece, the *reference frame* is attached to a planar surface that is milled in the same step, as the hole drilling happens, thus this frame cannot be measured directly. Therefore, the plane on the front of the workpiece was measured and used as *measured feature’s frame* and the *measured reference frame* was derived by moving it 0.3 *mm* inwards to the workpiece to model the milling operation.

This *measured reference frame* was chosen as *initial part zero*. The *machined holes* and *measured raw holes* were recorded as described in Sec. 3.3. The input values for the optimization step, as well as the calculated allowance is shown in Table 2. The resulted correction value is [0.199, -0.099] relative to the *initial part zero*.

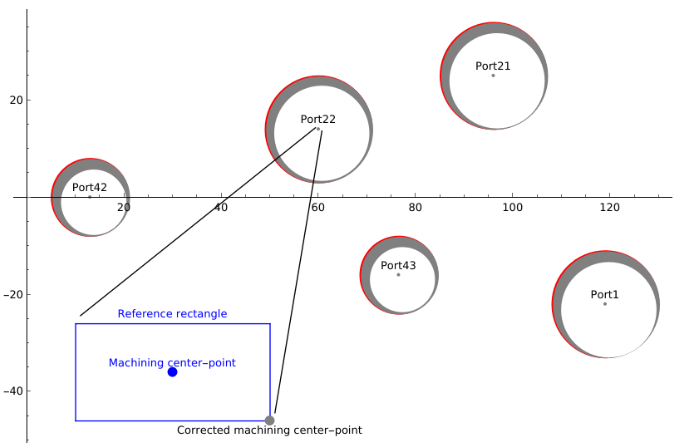


Fig. 4. Visualization of the holes with the correction offset.

Table 2. Center-points and radii of the machining and measured raw holes (in millimeters).

| ID | Port1 | Port21 | Port22 | Port42 | Port43 |
|---|---|---|---|---|---|
| Machining center-point (x-y) | 119 | 96 | 60 | 13 | 76.5 |
| | -22 | -25 | 14 | 0 | -16 |
| Machining radius | 11 | 11 | 11 | 8 | 8 |
| Tolerances (x-y) | ± 0.2 | ± 0.2 | ± 0.2 | ± 0.2 | ± 0.2 |
| | ± 0.1 | ± 0.1 | ± 0.1 | ± 0.1 | ± 0.1 |
| Measurement center-point (x-y) | 119.392 | 96.399 | 60.341 | 13.426 | 76.937 |
| | -23.127 | 23.994 | 13.187 | -1.004 | -16.924 |
| Measurement radius | 9.82 | 9.80 | 9.797 | 6.735 | 6.701 |
| Corrected machining center-point (x-y) | 119.2 | 96.199 | 60.199 | 13.199 | 76.699 |
| | -22.099 | 24.900 | 13.900 | -0.099 | -16.099 |
| Calculated allowance | 0.731 | 0.626 | 0.433 | 0.606 | 0.532 |

In Fig. 4, the *measured raw holes* are marked with white disks. The *machined holes* are denoted by red disks and the *corrected machined holes* are shown as gray disks. As can be seen, the gray disks completely cover the white disks, which means that no surface will be left unmachined. *Reference rectangles* are not shown, because they are very small, however, one of them is shown enlarged. The correction can be seen, as the *corrected machining center-point* is moved to the corner of the *reference rectangle* which means that the result respects the tolerance values.

Reading Table 2 the same conclusions can be drawn. The *corrected machining center-points* are within tolerance, and the calculated allowances are all positive. At the same time, the allowances are relatively small, which is possibly the result of the poor selection of the *measured reference frame*. Future development could enhance the result by choosing the *measured reference frame* algorithmically and not by hand.

## 5. Conclusion and future work

In this paper, a novel method has been presented that solves the problem of workpiece referencing. First, the raw parts are measured, then the measurements are loaded into a calibrated Digital Twin, along with the reference positions of the to-be-machined features. Then, the optimal part zero correction is computed, and the updated CNC code is generated, thus solving the workpiece referencing problem.

Our approach has the following properties: 1) only the to-be-machined features are used for the correction calculation and not the whole workpiece geometry, 2) the tolerances of the features’ positions are respected.

As our research progresses, validation is planned in production with a new batch of cast parts and machining them with the calculated part zero correction. As showcased in Sec. 4, a coordinate measuring arm has been used and a human worker is needed for this part of the process. As 3D scanners are widely available, the automation of the measurement process using a 3D scanner and a robotic arm is a task to be explored. Since it is planned to implement this methodology in production, the automation step will be part of the future work. The current research only focuses on "hole features"—drilling and tapping. It is an interesting further direction to extend the methodology to handle milling and turning operations as well.

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