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Multi-operation optimal blank localization for near net shape machining

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The paper proposes multi-operation blank localization to fit final product geometries into near net shape blanks. Groups of machining features are located subject to tolerance intervals on their relative positions and a lower bound on the machining allowance which accommodates for uncertainties of measurement and machining. The tolerance error, i.e., the deviation of the resulting dimensions from the center of the tolerance intervals is minimized. The blank localization problem is formulated as a convex quadratically constrained quadratic program that can be solved efficiently for parts with real-life complexity, as demonstrated by a case study from the automotive industry.

Measurement; Machining; Optimization

1. Introduction

The essence of *near net shape* (NNS) manufacturing is to create blanks with complex functions and geometries by non-subtractive processes as close to their required final geometric shape, surface and material properties as possible. Hence, the product with its functional features can be extracted in the finishing step with minimal material removal. The final shape is typically given by *machining*, but other finishing processes can also be applied. Beyond directly reducing material and energy demand, and consequently, costs, this approach can contribute also to the economical use of production resources and the reduction of lead times, along with improvement of quality. Overall, NNS manufacturing has the potential to align two, often conflicting key objectives: *competitiveness* and *sustainability.*

The basic idea has been prevailing for decades in production engineering [1] which continuously investigated more and more sophisticated processes and technologies from casting, forging, forming, welding [2], up to additive manufacturing and powder technologies [3] for producing NNS parts. The range of materials was extended from metals to ceramics and composites [1]. This approach gave an impetus to the tight integration of design and manufacturing [4], and less obviously, also to making metrology [5] and quality control [6] "productive". Thanks to these developments, NNS manufacturing has become a viable approach to producing both large-scaled parts (like gears and wings for wind turbines) [7][8] and micro-sized components.

The direct motivation of this work came from the *automotive industry* and the production of complex, high-quality mechanical components where the machining of parts from metal blocks would be extremely wasteful in terms of material, time, and energy. Hence, semi-finished (or blank) parts are cast with tight allowance to NNS and subsequently finished by machining. Functional features are linked by tight tolerances and have fine surface finish, hence, all these features need to be machined. This happens on machining centers using CNC code approved by the customer. Casting does not produce blanks with the required precise geometric shape, hence, these are subject of measurement.

The key question investigated in this paper is how to adapt the machining code based on the measurement data so that one can (1) satisfy all design specifications expressed in terms of dimensional tolerances, and (2) compensate the inherent uncertainties of the casting, measurement, and machining technologies. *Tolerances* give some margin for allocating the to-be-machined part in its NNS blank geometry, whereas the *machining allowance* can accommodate for all the uncertainties. Automating this process and finding the best possible machining code which minimizes chances of producing scrap against all uncertainties and functional requirements are basic needs of the industry, also far beyond the scope of this specific application.

In machining, *workpiece referencing* or *part localization* is the process of establishing a reference frame on the workpiece before machining it. Conventionally, this is carried out by an operator based on the measured position of appropriately selected geometric features, surfaces, edges, or points on the workpiece. This conventional process is automated, e.g., in [9] using stereo vision and image processing techniques. [10] presents a camera-based approach using a self-calibrating on-machine vision system. In [8], laser triangulation is applied to locate large free-form composite parts. [11] proposes a novel approach based on sample consensus and iterative closest point algorithms for sensor calibration and for transforming the measured workpiece position from the scanner to the CNC coordinate system.

In case of machining operations, workpiece referencing also involves the optimal placement of the final product in the actual blank geometry; this optimization problem is called *blank localization*. Almost all blank localization approaches in the literature look for one transformation that places the entire to-be-machined product in the blank as a single solid geometry. These include a combination of entropy optimization and quasi-Newton methods to maximize the minimum allowance between the measured points of the blank and the corresponding points on the nominal product geometry [12]. A similar technique uses sequential quadratic programming with maximin objective in the first, and then least squares criterion subject to a suitable lower bound on the allowance in the second round of optimization [13]. [14] proposes photogrammetry on non-coded markers, and computes the best placement by minimizing a least squares criterion. The authors are aware of a single approach that looks for different transformations for different features [15], considering the dimensional tolerances specified between those features. While that paper introduces a generic nomenclature and a highlevel approach, it does not arrive at a well-defined formulation of the optimization problem or an algorithm for solving it.

Hence, this paper is the first to provide a mathematical formulation of the multi-operation blank localization problem. It proposes a convex quadratically constrained quadratic programming model that can be solved efficiently using commercial solvers. The approach is illustrated and compared to earlier approaches in an industrial case study. It is a follow-up of the conference paper [16] that focused on the optimal placement of the features machined in a single operation.

2. Problem statement

Blank localization is the act of placing the finished product in the blank geometry. This paper captures blank and product geometries using a *feature-based* model, where each feature may have a *rough* (on the blank) and a *machined* (on the final product) state. Yet, features that remain in the rough state (surfaces left unmachined), or created directly in the machined state (e.g., small-diameter drilled holes without a corresponding precast hole) are also allowed. *Machining allowance* is the smallest distance between the rough and the machined geometries of a feature.

Geometrical information in *CNC codes* is structured into two main sections: (1) the characterization of machined features relative to a local reference frame; and (2) the poses of those reference frames for each operation in the workspace of the machining center. These reference frames are called *part zeros*. The former section of the CNC code can only be changed with the permission of the customer backed by very strong reasons, while the latter section may be changed whenever required.

The freedom in choosing each part zero separately gives rise to additional flexibility compared to approaches that place the entire product as a single solid in the blank. Henceforth, in *multi-operation blank localization*, a *feature group* is defined as the ensemble of features machined in the same *operation*, using a *common part zero*. The global reference frame for blank localization is the *workpiece datum* frame, defined based on the fixturing of the workpiece.

Formally, the blank localization problem involves finding part zero coordinates for each operation in such a way that the finished product complies with the design specifications, i.e., (1) the product geometry must be located entirely inside the blank, leaving sufficient allowance to compensate any error stemming from the measurements and machining, and (2) the *inter-operation dimensional tolerances* must be respected. Satisfaction of the *intra-operation tolerances* is guaranteed by the CNC code. It is noted that each dimensional tolerance connects two features, either in the rough (only for features left unmachined) or in the machined state. To compensate potential errors during machining, tolerance intervals in the product specification are decreased by the machining precision, which can be estimated based on shopfloor experience about the given machine and operation.

Part zeros that minimize the *average tolerance error* are sought. For this purpose, actual dimensions are compared to the specified dimensional tolerances: an error of 0% means that the actual dimension matches the tolerance center, whereas 100% that it falls on the upper or lower limit of the tolerance interval. The average is taken over all dimensional tolerances. The following assumptions are made:

- A prismatic part defined by face and hole features is assumed.
- Blank geometry is described by rough features with regular shape but potentially imperfect position and dimensions. There is no need for a free-form representation of the blank because (1) the most relevant areas are the inner surfaces of the holes that can hardly be measured precisely, and (2) local geometrical errors of the features are managed by standard quality control procedures.
- The rotation of the part zeros w.r.t. the workpiece datum is known and fixed. The axes of holes and surface normals of faces are parallel to the z-axis of the corresponding part zero.
- The only allowed modification of the CNC code is the position adjustment of the part zeros.
- Dimensional tolerances can be encoded into minimal and maximal distance between notable points (feature points) of two (unmachined) rough or machined features.

3. Industrial case study

The approach is illustrated on the automotive component shown in Fig. 1. Four sides of the cast blank must be machined in four operations, which involves drilling 10 holes and milling one face. All other surfaces, including the complete top and bottom of the blank, remain unmachined. The localization problems corresponding to the different sides of the part are connected by 19 inter-operation dimensional tolerances, typically, between the axis of a drilled hole and a rough or machined face. The entire machining process takes place on a four-axis machining center (XYZB) without re-grasping the part.

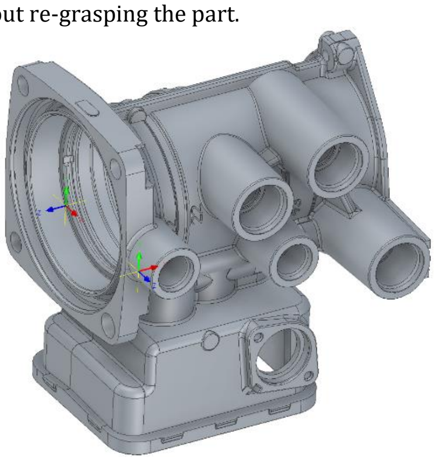

Fig. 1. Sample workpiece machined on four sides by four operations, with 10 drilled holes and 1 machined face (2 of 4 part zeros are shown).

In current industrial practice, blank localization is performed lot by lot as an iterative trial-and-error process. The first part of each lot is machined with heuristically selected part zeros (typically, with values used for the previous lot), and in case of any error (e.g., feature surface left unmachined), experienced human operators adjust the part zeros. This procedure is iterated until a correct product is achieved. Obviously, this is a tedious task that relies strongly on the skill of the operators, and often leads to producing scrap. An automated computation method that helps avoid unnecessary iterations and scrap is highly desired.

In order to generate the required inputs of the proposed blank localization approach, a *Digital Twin* (DT) of the machining cell is built. It contains the calibrated geometrical models of the machine, fixture, as well as the final product and the measured blank. Measurements can be taken by any applicable instrument and processing software, e.g., a laser scanner or a coordinate measuring machine. The DT is updated whenever changes happen in geometry; typically, upon the arrival of a new lot of blanks. With fully calibrated objects in the DT, the part zeros computed in the workpiece datum can be transformed into machine coordinates.

For capturing blank and final product geometry, feature-based models are applied, built from hole and face features. Hole features include the cylindrical surface and the front face of the hole. Feature locations are characterized via *feature points*. The feature point of a hole is the intersection point of its axis and front face. In reality, precast holes on the blank are conical, but only the outer, larger diameter defines tight constraints in the optimization model, and therefore, cylindrical features can be used. The feature point of a face is an arbitrary point in the corresponding plane. Machined feature points are defined relative to their part zeros in the CNC code, whereas rough feature points are measured in the workpiece datum.

The application of the method to a new machining cell or new product requires building the calibrated DT of the cell, and composing the feature-based product model from the CNC code, drawings and Product Data Management system (PDM). Upon the arrival of a new lot of blanks, new measurements must be taken, whereas the generation of input for the optimization model and the computation of new part zeros for the lot are performed in a fully automated way. The method can be applied on any machine whose kinematics allow implementing the translation of the part zeros defined in the CNC code.

4. Solution approach

The multi-operation blank localization problem can be formulated as a quadratically constrained quadratic program (QCQP) model as follows. The notation is summarized in Table 1, where vectors and matrices are highlighted with bold font, and abbreviation *hv* denotes a homogeneous vector.

Table 1. Notation.

Indices and functions	
f	Feature index
t	Tolerance index
s	Feature state: rough ($s = 0$) or machined ($s = 1$)
$p(f)$	Part zero index of feature f
$A_t(.)$	Projected length of a vector along the direction of tolerance t [mm]
H	Set of hole features that are present on the blank (rough state) and must be machined (machined state)
F	Set of face features that are present on the blank (rough state) and must be machined (machined state)
N	Number of tolerances
Parameters	
δ	Minimum machining allowance [mm]
$\boldsymbol{v}_f^R$	Feature point coordinates of rough feature f w.r.t. the workpiece datum [hv, mm]
$\boldsymbol{v}_f^M$	Feature point coordinates of machined feature f w.r.t. the corresponding part zero [hv, mm]
r_f^R, r_f^M	Radii of hole feature f in the rough and machined states [mm]
b_t^-, b_t^+	Lower and upper bounds of tolerance t [mm]. $b_t^- < b_t^+$
Variables	
$\boldsymbol{T}_p = \begin{bmatrix} & \boldsymbol{R}_p & & x_p \\ & & & y_p \\ & & & z_p \\ 0 & 0 & 0 & 1 \end{bmatrix}$	Homogeneous transformation matrix of part zero p w.r.t. the workpiece datum. Rotation matrix $\boldsymbol{R}_p$ is fixed, whereas translation values x_p, y_p, z_p are decision variables [mm]
$\boldsymbol{d}_f$	Distance between rough and machined feature points of feature f [hv, mm]
d_f^{xy}	Projected length of $\boldsymbol{d}_f$ in the xy plane of the part zero of feature f [mm]
$\boldsymbol{e}_t$	Distance of the two feature points connected by tolerance t [hv, mm]

The objective (1) is to minimize the average tolerance error compared to the center of the tolerance intervals. Constraint (2) calculates the distance vector of the two relevant feature points for each toleranced dimension. During this, the coordinates specified in the CNC code w.r.t. the corresponding part zero must be transformed into the workpiece datum for machined features ($s = 1$), whereas raw coordinates measured directly in the workpiece datum can be used for rough features ($s = 0$). The projected length of this distance vector must be in the defined interval (3). For ensuring a proper machining allowance, the distance vector of the rough and machined feature points must be calculated for each feature that exists both in the rough and the machined states (4). This is performed in the part zero frame of the feature. The Euclidean norm of the projection onto the xy plane of the part zero is computed in (5), which determines the machining allowance on the cylindrical surface of hole features (6). The same is ensured for face features and the front faces of hole features by constraint (7).

Since the rotation components of transformation matrices $\boldsymbol{T}_p$ are fixed, all the above expressions are linear, with the exception of equality (5), which is a convex quadratic constraint. Therefore, the proposed mathematical model is a convex QCQP, which can be solved efficiently using off-the-shelf solvers.

Minimize

$$\sum_t \frac{2}{N} \left| \frac{A_t(\boldsymbol{e}_t) - \frac{b_t^+ + b_t^-}{2}}{b_t^+ - b_t^-} \right| \tag{1}$$

Subject to

$$\boldsymbol{e}_t = \begin{Bmatrix} \boldsymbol{T}_{p(f_1)} \cdot \boldsymbol{v}_{f_1}^M & \text{if } s_1 = 1 \\ \boldsymbol{v}_{f_1}^R & \text{if } s_1 = 0 \end{Bmatrix} - \begin{Bmatrix} \boldsymbol{T}_{p(f_2)} \cdot \boldsymbol{v}_{f_2}^M & \text{if } s_2 = 1 \\ \boldsymbol{v}_{f_2}^R & \text{if } s_2 = 0 \end{Bmatrix} \qquad \forall t = (f_1, f_2, s_1, s_2) \tag{2}$$

$$b_t^- \le A_t(\boldsymbol{e}_t) \le b_t^+ \qquad \forall t \tag{3}$$

$$\boldsymbol{v}_f^M - \boldsymbol{T}_{p(f)}^{-1} \cdot \boldsymbol{v}_f^R = \boldsymbol{d}_f = \begin{bmatrix} x_f^d \\ y_f^d \\ z_f^d \\ 1 \end{bmatrix} \qquad \forall f \in H \cup F \tag{4}$$

$$(x_f^d)^2 + (y_f^d)^2 = (d_f^{xy})^2 \qquad \forall f \in H \tag{5}$$

$$r_f^M - r_f^R - d_f^{xy} \ge \delta \qquad \forall f \in H \tag{6}$$

$$-z_f^d \ge \delta \qquad \forall f \in H \cup F \tag{7}$$

The approach is illustrated in Fig. 2, which shows two out of the four feature groups of the industrial case study in orange (one hole feature belonging to part zero *p1*) and purple (five hole features belonging to part zero *p2*). All machined features within a group must be moved together due to the common part zero. The two feature groups are connected by 15 tolerances (10 are shown in the figure, each referring to the distance of two feature points projected onto the axis of a hole). Two further feature groups and their tolerances are not displayed for the sake of transparency. Moreover, machining allowances coming from the geometrical distance of the machined features and their rough counterparts in the blank must be considered.

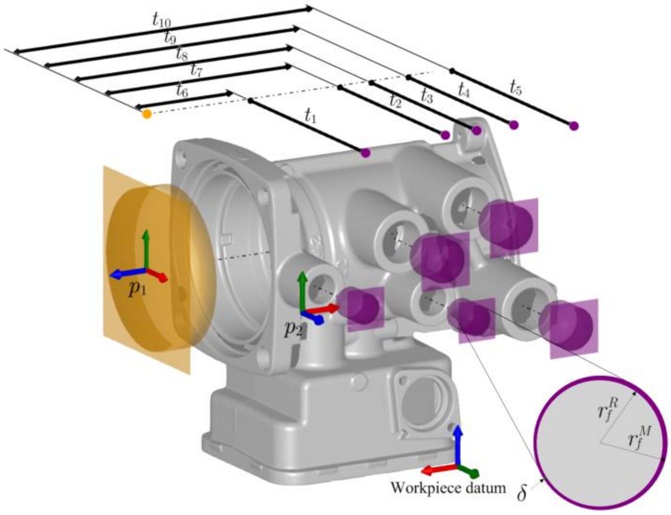

Fig. 2. Measured NNS blank with two out of the four machined feature groups in orange and purple, and 10 tolerances connecting them.

5. Experimental evaluation

The proposed approach was implemented in Wolfram Mathematica and its LinkageDesigner package for DT modelling, Julia for data processing [17], and FICO Xpress for solving the QCQP model. Setting up the model for the sample product presented in Section 3 required mapping the product model from the drawings and the CNC code into the DT. Blank measurements were performed using a Scantech 3D digital measurement system, which includes a laser scanner and software for extracting rough features from the measured point cloud.

In experiments, the proposed approach was compared to a conventional blank localization method using a single solid, as well as to the sequential multi-operation approach which localizes feature groups one by one, considering in each step the tolerances connecting the current group to previously fixed feature groups [16]. Solving the convex QCQP took less than 0.1 s, which shows that computational complexity is not a bottleneck for realistic problem sizes.

The results are presented in Fig. 3, which displays the average tolerance error as a function of the minimum allowance for each of the investigated approaches. The conventional solid and the sequential multi-operation approaches computed feasible localizations with at most 0.148-0.156 mm allowance, while the proposed integrated multi-operation approach ensured up to 2.22 times higher, 0.330 mm allowance values. Although these values conform to the current industrial practice (0.1-0.15 mm allowance), the higher allowance of the proposed approach gives significant additional robustness to the machining process by compensating greater errors of the blank. Obviously, higher allowance comes with higher tolerance errors.

Moreover, for any given allowance, the proposed approach resulted in considerably lower tolerance error than its competitors. For example, for an allowance of 0.140 mm, it achieved an average tolerance error of 3.4%, as opposed to the errors of 14.7% and 19.8% of the other approaches. For the solid approach, high tolerance error comes partly from the asymmetric tolerances, i.e., nominal dimensions deviating from tolerance centers. For both the solid and the integrated multi-operation approaches, the mild increase of the curves in the low, 0-0.148 mm allowance range comes from trading the single tolerance that connects a machined and a rough surface for a better allowance value. The integrated approach can improve the allowance further by sacrificing other tolerances as well, which is depicted by the steeper increase in the right side of the diagram. The sequential approach achieved poorer allowance and tolerance error due to setting the first part zero without due consideration of the subsequent machining operations.

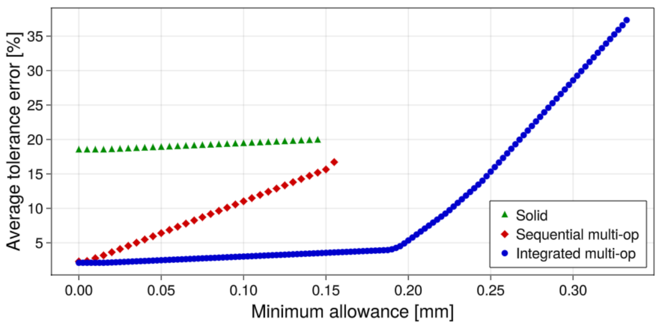

Fig. 3. Average tolerance error as a function of minimum allowance for each of the evaluated approaches.

The solution computed by the proposed approach has been submitted to the industrial partner, where systematic machining and subsequent measurement tests are in progress, while the overall approach met with a clearly positive reception. The partner plans to introduce the approach into daily use on the shopfloor.

6. Conclusions

This paper presented a novel multi-operation blank localization approach that places each feature group, machined in the same operation, separately in the blank, considering inter-operation tolerances. This gives rise to additional flexibility compared to conventional approaches that handle product geometry as a single solid. The new model can be exploited to compensate larger errors of the blank, resulting in the reduction of scrap, or to make the blank with lower allowance, which helps save material, energy, and machining time. New part zeros computed result in a sufficient allowance and very low tolerance errors that together guarantee a product that conforms to the design requirements even in case of blank errors that may lead to producing scrap with conventional blank localization techniques.

Future work will address extension to the rotation of the part zeros. Furthermore, a variant that captures blank geometry as a free-form surface using a point cloud can be of interest in applications where accessibility for high-precision measurements is not an issue and local geometrical errors occur that cannot be captured properly by the current feature-based representation. The method can be used in a broad range of NNS processes in manufacturing applications.

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