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Multi-operation blank localization with hybrid point cloud and feature-based representation

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Abstract

Sustainability objectives, including the endeavor to reduce waste, energy consumption and machining effort gave rise to the near net shape (NNS) machining concept, which requires the initial rough blank to be as close to the final machined product as possible. Nevertheless, the opportunity of savings in material, energy and effort come with a risk of manufacturing scrap even in case of a very small geometrical error of the blank. This issue is addressed by blank localization, i.e., the act of placing the final machined product in the geometry of the rough blank. Multi-operation blank localization was proposed recently to exploit tolerances in the product design to compensate potential geometrical errors of the blank. It places each feature group, machined together in the same operation, separately in the blank. When tolerances connecting different feature groups allow, these feature groups can be moved slightly according to the measured actual blank geometry. This paper proposes a novel multi-operation blank localization approach that models the rough blank as a free-form geometry, capturing all possible geometrical errors, whereas represents the final product using a feature-based model. The problem of blank localization for minimizing tolerance errors while leaving sufficient allowance is formulated and solved as a convex quadratically constrained quadratic program (QCQP). In a case study from the automotive industry, it is shown that the proposed multi-operation approach outperforms earlier methods that handle the product as a single solid geometry.

Keywords: blank localization; free-form machining; point clouds; quadratic programming; optimization

1. Introduction

This research was motivated by the concept of *near net shape machining*, which aims to improve the sustainability and cost efficiency of subtractive manufacturing techniques by pre-shaping the blank as close to the final product geometry as possible. This reduces material use and machining effort, and therefore, energy consumption and manufacturing costs. Yet, it also implies that upon even a minor, within-tolerance deviation of the blank, the machining process parameters may have to be adjusted to the actual blank geometry to receive a final product that complies with the design specifications.

Workpiece localization (or workpiece referencing) has always been an engineering problem to be solved as part of subtractive machining processes; it involves locating the to-be-machined workpiece in the workspace of the machine. In the early days of machining, contact-based solutions were the only available methods and those are still a popular choice, even in combination with modern production technologies like additive manufacturing [6]. Non-contact methods based on vision systems [7] or 3D measurements [2, 13, 16] are popular because of their versatility, speed and high accuracy.

The problem of reconstructing the product geometry from point cloud data is a classical field of reverse engineering [8]. The overall procedure is typically subdivided into four basic phases: (1) *data capture* using contact or non-contact measurement methods, (2) *pre-processing* including noise filtering and registration, (3) *segmentation and fitting* of surface models by finding the parameters that match the measurements the best, and when required, (4) the *creation of the CAD model* (e.g., stitching the fitted surfaces together using appropriate blending surfaces). Current challenges in feature recognition include identifying the underlying part or surface function in addition to mere geometry [11], as well as the recognition and classification of potential geometrical defects [10].

Blank localization is a special case of workpiece localization that focuses on ensuring sufficient *machining allowance* for the subtractive process. It can be described as placing the nominal geometry of the machined part or its features entirely inside the actual blank geometry. To ensure that allowance is uniformly distributed along the surface of products with complex shapes, [15] proposes an iterative workpiece localization process that utilizes rotational and translational registration matrices. Other objectives for maximizing allowance include least squares, minimax and maximin criteria [5, 9, 14].

All the above papers place the entire final product in the blank as a single solid geometry. The idea of placing individual machining features separately, while considering the dimensional tolerances between them, was originally proposed in [3], and elaborated further in [4]. This approach, called *multi-operation blank localization* can achieve more robust manufacturing processes by achieving a higher machining allowance. In [4], the authors focused on applications where the challenge was compensating the deviation of the feature positions on the blank, and accordingly, actual blank geometry could be described using perfectly shaped features. Compared to that, the main novelty of the current approach is applying a point cloud characterization of the blank geometry, which allows compensating local geometrical errors of the individual features as well.

This paper is structured as follows. In Section 2, the optimal blank localization problem is defined formally. The proposed solution approach, including geometrical models and computations, as well as the mathematical model for finding the optimal placement of the machined features are presented in detail in Section 3. First experimental results for a sample automotive component (see Figure 1) are presented and discussed in Section 4, whereas conclusions are drawn and directions for future research are proposed in Section 5.

2. Problem statement

The objective of the blank localization problem is placing the final product, characterized via its machined features, in the the actual blank geometry. This must be performed by considering the precise shape of the blank, the allowance between the machined features and the blank, all dimensional tolerances between machined features or rough surfaces, as well as the structure of the NC code used during machining.

The actual geometry of the *blank* is captured by a point cloud, which can be partitioned according to machined features: each measured point of the blank surface must be either assigned to the machined feature that removes the given surface area from the blank, or classified as unmachined surface.

The final product is created from the blank by establishing a set of *machined features*. Face and hole features, and correspondingly drilling and face milling are considered in this study. The final product conforms to the design specifications if the placement of every feature satisfies the following two criteria. First, every machined feature must be placed entirely inside the blank, leaving sufficient *machining allowance* between the rough surface of the blank and the final machined feature surface to ensure proper surface finishing even in case of potential errors during measurement and machining. The allowance

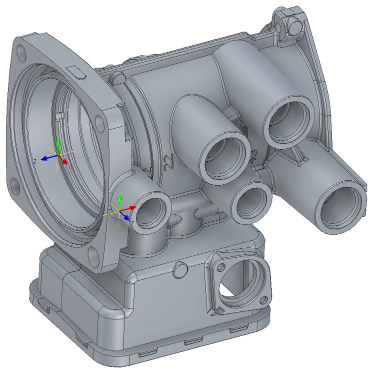

Fig. 1. Sample workpiece machined on four sides by four operations, with 10 drilled holes and 10 machined face (2 of 4 part zeros are shown).

for a given feature is defined as the smallest distance between the machined feature surface and a measured point assigned to that feature. Second, all *dimensional tolerances* must be satisfied. In addition to dimensional accuracy, these tolerances are also important because they ensure the desired fit with other products. Each dimensional tolerance defines a minimum and a maximum distance between two notable points, both of which can be either a feature point of a machined feature (placed during blank localization) or a point on the rough surface of the blank (given in the input). Tolerances between two points on the rough surface can be disregarded, since the solution of the blank localization problem has no impact on the satisfaction of those tolerances.

Machined features are created using a given CNC code. The code consists of two major sections: (1) the definition of the machined features w.r.t. a local reference frame, and (2) the location of those reference frames called *part zeros* in the workspace of the machine. Any modification of the first section is possible only with the permission of the customer after extensive quality assurance procedures. At the same time, the adjustment of the part zeros is regarded as a safe modification of the CNC code, which can be performed whenever needed for achieving a final product that conforms to design specifications. In this paper, an *operation* is defined as machining the group of features assigned to the same part zero.

Hence, formally, solving the blank localization problem consists in computing the position of the part zeros in the CNC code in such a way that the given lower bound on the machining allowance, as well as all dimensional tolerances are satisfied. The objective is minimizing the *average tolerance error* over all dimensional tolerances, where an error of 0% corresponds to the center, and 100% to the limits of the tolerance interval. The following assumptions are made:

- A product defined by machined face and hole features, as well as unmachined blank surfaces is considered.
- The nominal geometries of the rough and machined features are available.
- Actual blank geometry is characterized by a measured point cloud, where each point can be assigned to a feature or classified as unmachined rough surface.

- Each machined feature is assigned to a part zero in the CNC code.
- The rotation of each part zero is fixed w.r.t. the workpiece datum frame. The axes of the machined holes, as well as the surface normals of the machined faces are parallel to the z axis of the corresponding part zero.
- All tolerance requirements can be encoded into the form of dimensional tolerances that prescribe a minimum and a maximum distance between the feature points of two machined features, or the feature point of a machined feature and a measured point on the blank.
- The only allowed modification of the CNC code is the adjustment of the part zeros.

A further assumption is that a calibrated machine model is available, thus the geometric transformation between the local workpiece coordinates and machine workspace coordinates is available. Consequently, the optimization problem can be solved independently of the machine in the coordinate frame of the *workpiece datum*, which is defined as a physically or virtually measurable point on the workpiece where the workpiece and its fixture make contact.

3. Solution approach

This paper proposes an approach whose application takes place in two different stages of the product life cycle. In the *preparation* stage, once for each new product, a machining cell model is built and calibrated, involving the machine, the fixture, and the fixture-workpiece relation. The feature-based product model is constructed, including machined features (Section 3.1) and tolerances (Section 3.3). Finally, the process of blank measurements up to the segmented point cloud representation is planned (Section 3.2).

In the *production* stage, once for each lot of blanks or each individual workpiece, the blank is measured and the resulting point cloud is processed. The mathematical model of optimal blank localization is constructed automatically from the measured data and solved (Sections 3.4 and 3.5). Finally, the computed part zeros are applied on the machine and the workpiece is machined.

3.1. Feature-based representation of nominal geometry

A *feature-based model* for the nominal blank and the final product geometries is employed. The current implementation supports two types of machining features: holes and faces. The machined hole feature refers to the cylindrical surface of the hole. If the front face of the hole needs to be machined as well, then it is represented by a separate face feature. In order to reflect the characteristics of 3D and 4D machining centers, it is assumed that the surface normals of the faces, as well as the axes of machined holes are parallel to the z axis of the corresponding part zero, and the positive z direction points outwards from the product geometry.

Each feature can have two states, a *rough* and a *machined* state. The rough state on the blank is produced with a non-subtractive shaping process (e.g., casting, forging, or 3D printing), and it is characterized by a *nominal geometry* (e.g., drawing or CAD model) that describes its ideal shape. After the production of the blank, the *actual geometry* of the rough feature can be reconstructed by appropriate measurement techniques, resulting in a point cloud representation. The *machined state* of the feature describes the desired geometry on the final product, which is specified by the CAD model and the CNC code used for machining.

Regarding the states actually taken by each feature, the following three cases are possible: (1) the feature has a pre-shaped surface on the blank and it must be machined, i.e., it takes both a rough and a machined state; (2) the feature does not have a pre-shaped surface, but it must be machined, i.e., it takes only the machined state; or (3) the feature is shaped on the blank directly to its final geometry, i.e., it does not have to be machined and it takes only a rough state.

3.2. Point cloud representation of actual rough geometry

While the *nominal geometry* of rough features can be described by the feature-based model with perfect geometrical shapes, their *actual geometry* can deviate from this ideal model. The actual geometry is captured by a point cloud representation. In order to assign individual points to the given rough features, the point cloud is filtered and segmented by exploiting the known nominal geometry. The nominal geometry of the rough blank may differ from the machined geometry, as in the case of casting, when cast holes are cones, while the drilled holes are cylinders. As the nominal rough geometry is only used for the point cloud segmentation, this difference does not impact later stages of the process. For each feature, points around the surface of the nominal geometry are searched for. For hole features, points that are within a $\pm\epsilon$ band of the cylindrical or conical surface are assigned to the rough geometry of the feature. For face features, a bounding box is considered around the

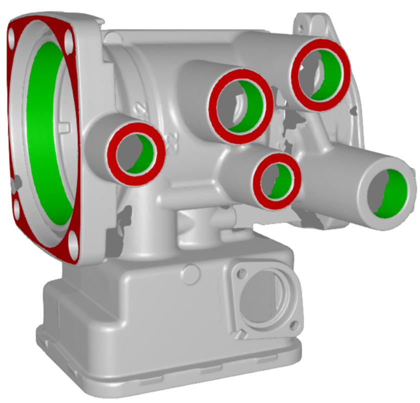

Fig. 2. Measured point cloud segmented by features. Points associated with holes (respectively, faces) are displayed in green (red). Two operations on two different sides of the workpiece are shown: the first involves one face and one hole, while the other includes five holes and four face features.

plane with well-chosen edge lengths. The edge lengths and the value of ϵ need to be specified manually.

Commercially available measurement systems often readily provide a processed, triangulated mesh representation of the blank. This mesh can be exploited for refining the assignment of points further by comparing the surface normals of the triangles to the nominal geometry. A given point on the mesh is included in the partition if the surface normal of the mesh and the nominal geometry are within an α angle band. This method is inspired by the compatibility measures used in the Efficient RANSAC algorithm [12]. The results of assignment for the sample product are shown in Figure 2, where the segments of the mesh corresponding to individual features provided by the measurement system are displayed.

3.3. Dimensional tolerances

Dimensional tolerances are defined on the 3D distance between the so-called *feature points* of two features. They are usually defined between two machined features, while occasionally between a machined and a rough feature.

For machined features, the location of the feature point is determined during the solution of the blank localization problem. The feature point for a machined hole is the intersection of its axis and front face, whereas for a face, it is an arbitrary point in the plane of the face.

In contrast, the location of the feature point of a rough feature is fixed on the blank. The method for computing the location from the actual geometry is defined by industrial standards according to the type of the feature and the tolerance. In the case study presented in this paper, the feature point of rough faces is computed as the center of gravity of the corresponding point cloud segment.

3.4. Machining allowance

Machining allowance, δ, is the smallest distance between the points of a rough feature and the corresponding (nominal) machined feature surface. Accordingly, allowance is defined only for features that take both a rough and a machined state. To lighten the computational burden on the solver, it is sufficient to consider points of the rough surface that, for some values of the part zeros, may become the closest points, and therefore, define an active constraint in the optimization model.

For face features, by the convention on the direction of the z axis and the surface normal, the single relevant point is the one with the lowest z coordinate. Since the direction of the z axis is known in advance, the point can be chosen during preprocessing.

For hole features, the allowance equals the distance between an assigned point and the cylindrical surface, which is always perpendicular to the axis of the hole. This axis is parallel to the z axis of the part zero. Consequently, the allowance can be calculated in the xy plane of the part zero. Moreover, it is easy to see that only the points located on the convex hull in the xy plane can define active constraints. Accordingly, the set of points can be reduced to those on the convex hull in xy. This procedure is visualized in Fig. 3. These filtering steps are performed before solving the optimal blank localization problem.

3.5. Optimal blank localization

With a given segmented and filtered point cloud for describing the actual blank geometry and a given feature-based model of the final product, the optimal blank localization problem can be formulated as a convex *quadratically constrained quadratic program* (QCQP) as displayed in Fig. 4. The notation is defined in Table 1, where vectors and matrices are highlighted with bold font, and abbreviation *hv* denotes a homogeneous vector.

The objective (1) is to minimize the average tolerance error, relative to the center of the tolerance field for each dimensional tolerance. Constraint (2) computes the distance between the two feature points connected by the dimensional tolerances. Depending on the feature states, either the position of the machined feature point (defined w.r.t. the corresponding part zero in the CNC code, and then transformed into the workpiece datum frame) or the rough feature point (given directly in the workpiece datum) is considered. The objective function in itself does not guarantee that all tolerances respect their lower and upper bounds; hence constraint (3). Allowance is calculated for each point in the segment assigned to a rough feature. Therefore, in equation (4), the distance of a point and the corresponding machined feature point is calculated. The distance vector is computed in the part zero coordinate frame of the feature, because then the radial and axial distance, and subsequently the allowance can be calculated easily. For hole features, the radial distance is calculated from the xy distance by constraint (5), and then the machined radius is subtracted to ensure appropriate allowance (6). For face features, the axial distance must be greater than the allowance (7).

All constraints of the above model are linear, except for equality (5), which is a convex quadratic constraint. This is thanks to the known rotation matrix $\mathbf{R}_p$ of the part zeros. Accordingly, the proposed optimization model is a convex QCQP, which can be solved efficiently with existing solvers in the problem size relevant in industrial applications. Although this QCQP is structurally similar to the model presented in [4], a

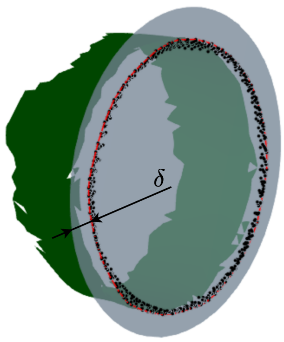

Fig. 3. Filtering the points assigned to a hole feature. The green surface contains the points originally assigned to the rough hole feature. Black dots are the projection of those points into the xy plane. The red polygon is their convex hull. The gray disk is the projection of the machined hole.

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

$$\text{subject to} \quad \mathbf{e}_t = \begin{cases} \mathbf{T}_{p(f_1)} \cdot \mathbf{v}^M_{f_1} & \text{if } s_1 = 1 \\ \mathbf{v}^R_{f_1} & \text{if } s_1 = 0 \end{cases} - \begin{cases} \mathbf{T}_{p(f_2)} \cdot \mathbf{v}^M_{f_2} & \text{if } s_2 = 1 \\ \mathbf{v}^R_{f_2} & \text{if } s_2 = 0 \end{cases} \qquad \forall t = (f_1, f_2, s_1, s_2) \tag{2}$$

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

$$\mathbf{v}^M_f - \mathbf{T}^{-1}_{p(f)} \cdot \mathbf{v}^Q_q = \mathbf{d}_q = \begin{bmatrix} x^d_q \\ y^d_q \\ z^d_q \\ 1 \end{bmatrix} \qquad \forall f \in H \cup F,\ q \in PC_f \tag{4}$$

$$(x^d_q)^2 + (y^d_q)^2 = (d^{xy}_q)^2 \qquad \forall f \in H,\ q \in PC_f \tag{5}$$

$$d^{xy}_q - r^M_f \ge \delta_{min} \qquad \forall f \in H,\ q \in PC_f \tag{6}$$

$$-z^d_q \ge \delta_{min} \qquad \forall f \in F,\ q \in PC_f \tag{7}$$

Fig. 4. QCQP model of the blank localization problem.

Table 1. Notation.

Indices, sets and functions	
f	Feature index
t	Tolerance index
q	Point 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)
PC_f	Set of points from the point cloud assigned to feature f
N	Number of tolerances
Parameters	
δ_{min}	Minimum machining allowance [mm]
$\mathbf{v}^R_f$	Feature point coordinates of rough feature f w.r.t. the workpiece datum [hv, mm]
$\mathbf{v}^M_f$	Feature point coordinates of machined feature f w.r.t. the corresponding part zero [hv, mm]
$\mathbf{v}^Q_q$	Coordinates of point q of the point cloud w.r.t. the workpiece datum [hv, mm]
r^M_f	Radius of hole feature f in the machined state [mm]
b_t^-, b_t^+	Lower and upper bounds of tolerance t [mm]
Variables	
$\mathbf{T}_p = \begin{bmatrix} & \mathbf{R}_p & & x_p \\ & & & y_p \\ & & & z_p \\ 0 & 0 & 0 & 1 \end{bmatrix}$	Homogeneous transformation matrix of part zero p w.r.t. the workpiece datum. Rotation matrix $\mathbf{R}_p$ is fixed, whereas translation values x_p, y_p, z_p are decision variables [mm]
$\mathbf{d}_q$	Distance between a point q and the feature point of its corresponding machined feature [hv, mm]
d^{xy}_q	Projected length of $\mathbf{d}_q$ in the xy plane [mm]
$\mathbf{e}_t$	Distance of two feature points connected by tolerance t [hv, mm]

substantial difference is that here, allowance is computed for individual points of the cloud, rather than for features.

4. Experimental evaluation

The proposed approach was validated in an industrial case study involving the machining of the automotive part displayed in Fig. 1. Departing from a near net shape cast blank, 10 hole and 10 face features must be machined on a four-axis CNC machine in 4 operations. The features are connected with 3 rough-machined and 18 machined-machined tolerances. Most of the tolerances are defined between the axes of two machined holes and a typical value is 60 ± 0.2 mm.

Point cloud measurements were taken using a Scantech 3D laser scanner with resolution up to 0.025 mm. The scanner produced a point cloud with 964630 points. The diameter of the point cloud was 150.47 mm. Parameters $\epsilon = 0.1$ mm and $\alpha = 10°$ were used for classification, which resulted in 390-14478 points per feature, whereas the remaining 895244 points belong to unmachined surfaces, irrelevant for blank localization. Filtering for the relevant points led to 43-239 points for each hole feature, and a single point for each face feature. The involved optimization problem had to be solved for these altogether 946 relevant points for the 20 features.

The blank localization approach was implemented in Julia [1], using FICO Xpress 9.0 as a QCQP solver. Solving this problem to proven optimality required 0.14 seconds of computation time on a laptop computer with Intel i7-1165G7 2.80 GHz CPU and 16 GB RAM under Windows 11.

Experiments investigated the performance of three different approaches to solve the blank localization problem. The conventional *solid* approach places the final product in the blank as a single geometry. The *sequential multi-operation* method determines the applicable part zero for each operation one by

Table 2. Experimental results.

	Average tolerance error		
Min. allowance	Solid	Sequential multi-op	Integrated multi-op
0.025 mm	3.4%	12.5%	2.1%
0.050 mm	4.6%	-	2.3%
0.068 mm	5.7%	-	2.5%
0.100 mm	-	-	16.1%
0.120 mm	-	-	35.3%

one, considering the tolerances that connect the actual group of features to previously placed features. Finally, the proposed *integrated multi-operation* approach computes the optimal part zero for every operation in one computational step.

The results are presented in Table 2, where different rows correspond to different minimum allowance values, while columns display the tolerance error achieved by the given approach. A dash '-' indicates that the approach could not find a feasible solution for the given bound on the allowance. The classical solid approach could solve the problem with at most 0.068 mm allowance, and led to a tolerance error of 3.4-5.7%. The heuristic, sequential multi-operation method achieved rather poor results, with at most 0.025 mm allowance and a high, 12.5% tolerance error; this was due to fixing the first part zeros without a proper, holistic view of the consequences on later operations. Finally, the proposed integrated multi-operation approach could not only improve the tolerance error for each value of the allowance (2.1-2.5% for values feasible with other approaches), but it could also warrant a significantly higher allowance of 0.120 mm. The latter is particularly important, as an allowance of at least 0.1 mm is desired by the industrial partner. Obviously, better allowance comes with worse tolerance error, which is consistent with the underlying idea of trading tolerance for machining allowance.

5. Conclusions and future work

The paper introduced a new blank localization technique for compensating the inevitable small geometrical deviations of blanks. The novelty of the proposed approach lies in (1) capturing the actual geometry of the blank via a point cloud representation, (2) describing the desired final product geometry by using a feature-based model, and (3) applying different part zero correction values for groups of features machined in different operations. It was demonstrated that the proposed approach can be applied to real industrial problems in an automated and computationally efficient way. In experiments, it resulted in 76% higher machining allowance compared to classical approaches that place the entire final product in the blank as a single solid geometry. Moreover, for a given minimum allowance, the proposed approach achieved 38–56% lower average tolerance error than classical approaches.

The next step towards practical application is physical verification via machining multiple lots of the product at the industrial partner. Verification will focus on establishing performance guarantees by quantifying potential errors introduced during the different stages of the procedure, including measurement, computations, and actual machining. An important research question is assessing the practical applicability of the two alternative techniques for modeling blank geometry: the feature-based model that is less sensitive to certain measurement errors but fails to capture local geometrical errors of individual features, versus the point cloud representation that captures all fine details of the blank surfaces but can be more sensitive to noisy measurement data.

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