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Towards early estimation of part accuracy in additive manufacturing

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Abstract

Additive manufacturing (AM) is becoming more diffused. In spite of its advantages: capability to manufacture complex internal feature and material efficiency, AM has inherent drawback from its layer-by-layer nature. ”Staircase effect” is observed due to the slicing process of the computer model in which a rough surface from a theoretically smooth surface will be obtained. Hence, there will be a deviation of the produced part from its nominal model. A methodology to predict the deviation of computer model of an additive manufactured part after fabrication process is presented. A case study is proposed using cylindrical features due to its common real case application. Cylinder is a representation of pin-hole geometry. This geometry is an assembly feature which is very important to guarantee the parts can be assembled with their pair. The dimensional and geometric deviation of the cylindrical feature after fabrication is estimated and could be a useful information for the designer.

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Keywords: Additive manufacturing;Tolerance verification;Dimensional and geometric deviation;STL;Least-square; Minimum-zone

1. Introduction

Additive manufacturing (AM) becomes a more and more diffused method to realize a product. The ability of AM to manufactured a very complex part (complex cavity), which is impossible to be produced by conventional subtractive method, in layer-by-layer way has promoted the development of new and innovative products [1]. Nowadays, AM technologies become mature and are used to produce a final working part and tooling for manufacturing [2].

Since AM technology work based on adding material layer-by-layer from the sliced computer model, there will be deviation in the manufactured product. There are two main reasons for this deviation. Firstly, AM does not work on the original CAD representation, instead, based on Stereolithography (STL) file in which the nominal surface of the part is approximated into a triangular mesh representation. Secondly, a ”stair-case” effect occurs due to the slicing of the STL file in building the part layer-by-layer. The deviation can affect the manufactured part features by which the assembability and functionality depend on them.

In this article, a methodology to predict the deviation of an additive manufactured part is presented. The prediction can be applied to the STL file before sending the file to the AM machine so that the designers can have an estimation of how their part will become after the fabrication. By this, they can revise their design, re-adjust building parameters, or estimate the ability of the process to meet the given tolerance, to have a desired result before starting the process. Examples of improvement can be redesigning the part, re-arranging the build orientation and position, relaxing the tolerance, or change with another feasible process. A cylindrical feature will be considered as a case study due to its important and common functionality. Cylinder is an assembly feature involved in the ”pin-hole” relation that enable the parts to be assembled together to construct the functioning product assembly. Cylinder orientation and diameter (dimensional properties) and cylindricity (geometric deviation) are the characteristics that will be predicted.

2. Additive Manufacturing Technology

Additive manufacturing is relatively a new technology compared to the conventional substractive manufacturing e.g. metal cutting. This is the enabling technology to free the designer in realizing their innovative idea as well as significantly reducing cost of customized product [3]. The steps of AM from a design until fabrication process is illustrated in Fig.1. The steps start from a 3D computer model. Then, this file is converted into the

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so-called STL format represented by a mesh of triangles and is imported to an AM machine specific software for slicing procedure. Finally, from the sliced file, the AM machine builds the part layer-by-layer until the complete part is obtained. There are a wide range of material types available for these machines, such as polymer, ceramic and metal. Following the wide range of material types, various AM mechanism are also available in the market [2]. AM applications are spanned from mechanical, automotive, aerospace fields until medical application [4][5], as well as new emerging applications (bio-engineering).

Nomenclature

- F The distance function of points to the fitted geometry
- $\mathbf{x}$ A generic point in 2D (x, y) or 3D (x, y, z)
- $\mathbf{x}_0$ A point on a line/axis
- $\mathbf{x}_i$ The i-th point of the point cloud
- d_i The distance of point $\mathbf{x}_i$ to the fitted geometry
- $\mathbf{M}$ A $nx3$ matrix of all the data points, defined as: $[x_1 y_1 z_1; \cdots\cdots\cdots; x_n y_n z_n]$
- $\mathbf{n}$ The direction cosine (orientation) of a line or axis
- $||\cdot||$ L_2-norm of a vector: $||x|| = \sqrt{x^2 + y^2 + z^2}$
- $||r||$ L_2-norm of sum of squared residual
- ∇ Scalar function gradient: $\nabla J = (\partial J/\partial x, \partial J/\partial y, \partial J/\partial z)$
- t The geometric deviation of the inspected feature.
- $\mathbf{T}$ Error perturbation matrix. The matrix is defined as: $\begin{bmatrix} 1 & -\epsilon_{\theta z} & \epsilon_{\theta y} & \epsilon_x \\ \epsilon_{\theta z} & 1 & -\epsilon_{\theta x} & \epsilon_y \\ -\epsilon_{\theta z} & \epsilon_{\theta x} & 1 & \epsilon_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- $\mathbf{x}'_i$ The perturbed i-th point of the point cloud
- $\mathbf{v}_i$ The i-th vertex of the triangulation whose components are $[v_i x\ v_i y\ v_i z]$
- $\mathbf{I}_p$ The intersection point between the slicing plane and a triangle whose components are $[I_p x\ I_p y\ I_p z]$
- $Corr_{ij}$ Correlation between i-th and j-th scale of an axis

3. Tolerance Verification

Tolerance verification is an important process in manufacturing cycle. It is one of the major contributors for the total production cost of a part [6]. Two kind of tolerance can be verified: dimensional and geometrical tolerance. Both of them are

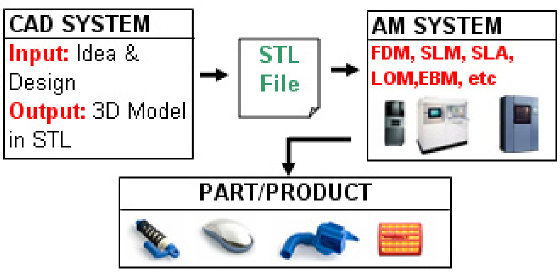

Fig. 1. Steps in AM from design to manufacturing.

important and do not substitute each other. To evaluate the related dimensional and geometric erros, a geometry of feature has to be fitted (associated) accordingly.

3.1. Dimensional tolerance verification

Dimensional tolerance verification usually involves Least-Square (LSQ) fitting procedure. In this verification, a LSQ substitute geometry from points $\mathbf{x}$ is derived and its dimension, such as diameter and axis orientation will be calculated. The fundamental of this fitting is reconstructing a substitute geometry which has the minimum square distance to the points $\mathbf{x}$, represented as a matrix $\mathbf{M}$, obtained from the inspection process. The mathematical formulation of the fitting objective is:

$$\arg\min_{\mathbf{x_0},\mathbf{n},r} \quad F = \sum_{i=1}^{n} d_i^2 \tag{1}$$

Since the feature is a cylinder, $d_i = d_{i(3dp2Axis)} - r$. Definition of $d_{i(3dp2Axis)}$ is:

$$d_{i(3dp2Axis)} = ||(\mathbf{x_i} - \mathbf{x_0}) \times \mathbf{n}|| \tag{2}$$

The results of the minimization are the estimated parameters of the substitute cylinder, which are the direction vector of the axis $\mathbf{n}$, a point $\mathbf{x_0}$ belonging to the axis, an the estimated radius r. The method used to solve the minimization problem is Levenberg-Marquardt (LM) algorithm based on [7] combined with chaos optimization [8] to improve the overall performance [8].

3.2. Geometric tolerance verification

Geometric tolerancing differs from the dimensional one. It aims at guaranteing that the geometric deviation are not so large to compromise the assembly of the part under inspection with the other mating parts [9]. The general definition of geometric deviation is a minimum distance of two separating nominal feature which contain all the measurement points of the interest feature and the fitting recomendation is Minimum-Zone (MZ) fitting [10]. Hence, for cylindricity, the two separating nominal feature are cylinders. To find MZ tolerance zone, it is necessary to solve the following optimization problem:

$$t = \arg\min_{\mathbf{x_0},\mathbf{n}} {}_j\ (\max r_i - \min r_i) \tag{3}$$

r_{ij} is the distance from $i - th$ point to the $j - th$ solution. Graphical illustration of dimensional and geometric fitting of a cylinder is presented in Fig. 2.

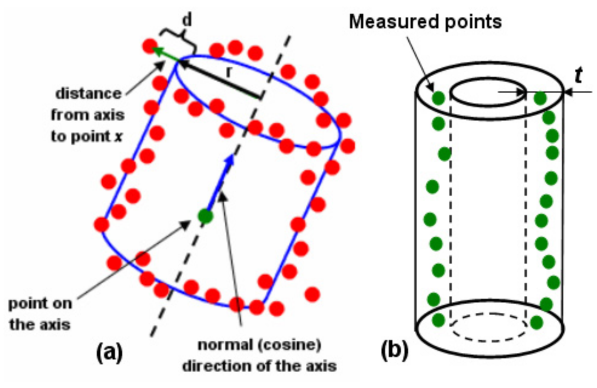

Fig. 2. (a) Dimensional LSQ fitting (b) Geometric MZ fitting.

4. Methodology for Estimation of Dimensional and Geometric Deviation from a STL Design File

Design is the key of success of AM technologies [11][12]. An innovative design of a product exploits the ability of these technologies to yield those geometries which the conventional machining methods are not able to manufacture. Hence, analysis of design for additive manufactured part is very important. Researchers have reported results in analyzing STL file for machining planning such as planning of 5-axis free-form surface machining [13] and drilling operation [14]. Compensation of AM machine systematic error has been proposed [15]. In their work, systematic error of the machine is taken into account. For high-level AM machine, this systematic error should be compensated by the manufacturer and what remains are random error of the machine and other errors (e.g. material flow, material shrinkage, etc). Hence, prediction of deviation of an additive-manufactured part from its nominal geometries from the STL design file is useful for part design improvement. In this article, a methodology to estimate this deviation from an STL file is presented. Deviation related to cylindrical feature will be estimated. In general, the methodology consists of three main steps (Fig. 3): identification of points-trajectory in AM process for cylindrical feature in all orientations, perturbation of the identified points-trajectory by incorporating AM volumetric and other errors, and estimation of cylindrical feature deviation by means of simulation.

4.1. Points-trajectory identification of cylindrical feature

STEP 1: Slicing of STL file. This is the initial step of cylindrical feature recognition. The STL file is sliced by slicing plane z_i based on the desired thickness and part orientation. For the efficiency, in each slice z_i, only the relevant triangle of faces are considered which are those whose vertices are neither all above nor all below the slice height. For each intersecting triangle, its three vertices v are arranged such that $v_1 \leq v_2 \leq v_3$ sorted by their z values. When slicing plane intersects a triangle, there are five possible conditions as explained in Fig. 4a. In each triangle intersection, there will be two intersecting points. For these two points, *head* and *tail* status will be given depending on whether the triangle is an external or internal contour. If it is an external contour, then the assignment of *head* and *tail* will be anti-clockwise and vise versa (Fig. 4b). Subsequently, each pair of intersection point will be recorded in a data structure along with their normal vector (the face normal vector) $\mathbf{n_i}$ and their face id f_i for the use in feature grouping later on. Intersection point I_p is obtained utilizing the parametric equation of a line. The components of I_p are:

$$
\begin{aligned}
I_p x &= v_i x + p\,(v_j x - v_i x)\\
I_p y &= v_i y + p\,(v_j y - v_i y)\\
I_p z &= v_i z + p\,(v_j z - v_i z)\\
\textit{where} &: v_i z < I_p z < v_j z
\end{aligned}
\tag{4}
$$

where p is a parametric constant obtained at slice z_i. To get the intersection point, p is calculated at first by equating the z_i and $I_p z$ in which the component of $v_i z$ and $v_j z$ are known. After obtaining p, x and y coordinate of the intersection point ($I_p x$ and $I_p y$) at z_i can be calculated. Since the recorded pairs are not arranged (Fig. 4c), sequencing procedure to build the countours is done by connecting each pairs by matching their *head* and *tail* among all recorded pairs. All detected contours are grouped.

STEP 2: Identifying the circle/elipse contour for each slice z_i. After slicing, each close contour will be grouped. Then, the next step is the identification of which ones among the close contours are the circle contours. The way to do this is by checking the normal vector of the intersection points for each obtained closed contours. In general, an estimation of normal vector of a point in triangulation field are $\mathbf{n_1}= \sum_{k=1}^{6}\mathbf{nf_k}/k$ and $\mathbf{n_2}= (d_1\mathbf{n_1}+d_2\mathbf{n_3})/(d_1+d_2)$ (illustrated in Fig. 5a). For cylindrical feature, the estimation of point's normal vector is simplified as (see Fig. 5b):

$$\mathbf{n_p} = \frac{\mathbf{nf_{left}} + \mathbf{nf_{right}}}{\mathbf{2}} = \frac{\mathbf{nf_1} + \mathbf{nf_2}}{\mathbf{2}} \tag{5}$$

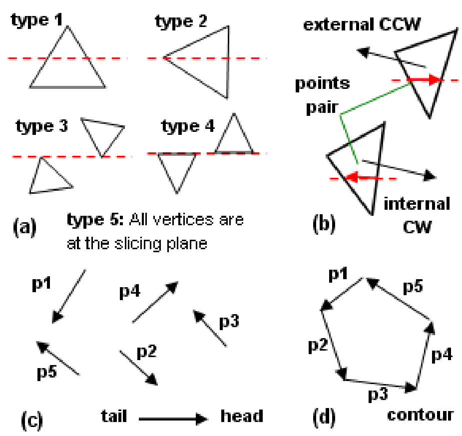

Fig. 4. Illustration of slicing procedures.

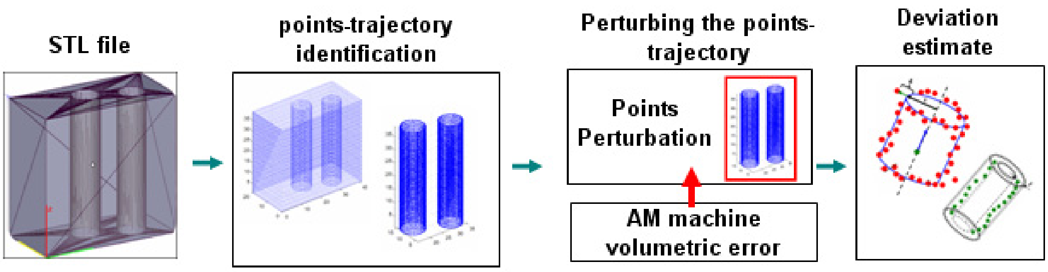

Fig. 3. Steps of the methodology to estimate part deviation from STL file.

These normal vectors for each points are calculated when connecting all the point's pairs to form a closed contour. Circle contour determination is done by sequentially checking all the pair of angles α_{ij} formed by two consecutive normal vectors n_i and n_j of points for each closed contour. If $\forall\{\alpha_{12}, \alpha_{23}, \alpha_{34}, \cdots, \alpha_{(n-1)n}\}$, α 0.8 $\leq \cos\alpha \leq$ 0.99999, then it is idetified as "circle/elipse contour".

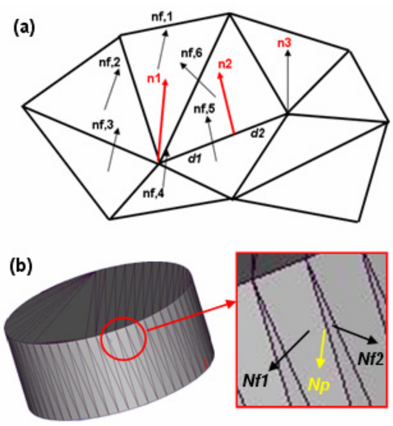

Fig. 5. Normal vector calculation for each intersection points.

STEP 3: Grouping the circle/elipse contours belonging to the same cylindrical feature. Each identified circle closed contours are stored in a data structure along with their involved triangles. These triangles are used as the linker for the circle contours in different slicing planes but belong to the identical cylindrical feature. Thus, if the triangles of the circle contour are identical with the one on the different layer, they belong to identical feature. On the first layer of slicing plane, all detecetd circle contours form new groups of cylindrical feature. Subsequently for the second to the rest of the layer slicing, each detected circle contours are linked to already exist cylindrical group based on the lingking triangles, otherwise, a new cylindrical group is created.

STEP 4: Identifying other cylindrical feature which are not in vertical orientation. Since the algorithm detects the cylindrical features from their set of "circle (or elipse) cross-section" along z-axis , STEP 1-STEP 3 are initially carried out in vertical orientation (Fig. 6-left). Hence, cylindrical features which are not in vertical orientation will not have a circle (or elipse) contour on the slicing plane as such, the feature can not be detected. In this step, the part will be rotated 90^0 both around

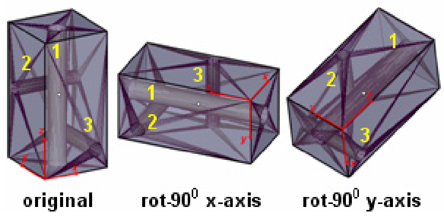

Fig. 6. Rotation of 90^0 along x- and y-axis in cylindrical feature identification.

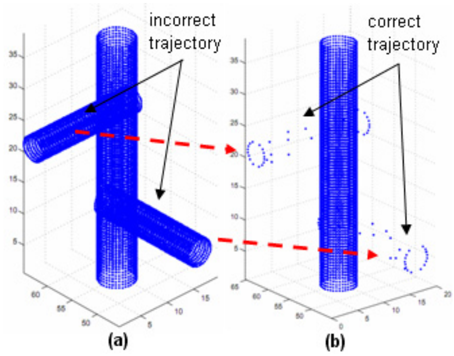

Fig. 7. (a) incorect-trajectory identification and (b) the correct identification.

x- and y-axis (Fig. 6) such that any horisontal cylinder feature will have orientation not extreemely far from 90^0 orientation. Subsequently, STEP 1-STEP 3 are repeated for each rotation. And then, the part is re-rotated to its original position after the cylindrical features have been detected and their correspond triangles have been stored.

STEP 5: Re-slicing the identified horizontal cylindrical features. The detected cylindrical feature and the related points from the previous step do not represent the actual trajectory during the building process (Fig. 7a). As such, re-slicing is carried out only for those triangles representing the horisontal cylindrical features. Subsequently, the correct trajectory points during material addition process can be obtained as illustrated in Fig. 7b.

4.2. *Perturbation of identified Points-trajectory*

STEP 6: Perturbation of identified trajectory points. The purpose is to simulate the position error of each trajectory points (e.g. nozle location) during material addition. The perturbation is carried out by considering main error contributors: machine volumetric error, material flow and material shringkage. In this study, FDM machine was simulated. Hence, the volumetric error of this FDM has to be estimated as well as the other source of errors. The perturbation of a point is applied by multiplying the nominal point time a perturbation variance matrix $\mathbf{T}$, which is $\mathbf{x_i'} = \mathbf{Tx_i}$.

In the matrix $\mathbf{T}$, it consists of six type of errors, which are translation error along x, y and z-axis as well as rotation error around x, y and z-axis (Roll, pitch, yaw). Generation of these axis errors uses a spatial statistic technique [16] in which the errors are corelated each other depends on their spatial distance with respect to each other. The errors should represent volumetric error of the machine, material flow, material shringkage, and other relevan error depend on the AM process. A variagrom model is used to model the error behaviour [16]. They are generated from a multivariate distribution. This distribution can be gaussian, exponential, and other type which fit best to the selected AM used. The variance-covariance matrix elements are specified by the variogram model considering "nugget" to take into account process-related random errors such as machine vibration. The variogram function is defined as:

$$\gamma(i, j) = f(corr(i, j), s, n, r) \quad (6)$$

s, n and r are the variogram parameters which are sill, "nuget" and range respectively. Errors are generated along each conisdered axis within certain range (the working range) and step width. After that, a krigging technique [18] is used to fit a function from these generated points to have an estimate of errors at any position of the axis.

4.3. Deviation estimate from the STL design file

STEP 7: Estimation of dimensional and geometric deviation. In this final step, all the perturbed points of the trajectory of all the cylindrical fetures found in the part are numerically fitted according to the types of deviation. Cylinder diameter and orientation are estimated by LSQ fitting according to section 3.1, while for cylindricity is estimated according to MZ fitting explained in section 3.2.

5. Case study

A study case is presented to give evidence of the effectiveness of the proposed methodology. Fig. 8 shows the steps of the implementation as well as the part design. The nominal design consists of three cylinders: one tilted-horizontal cylinder (c1) and two vertical cylinders (c2,c3). In our case, we only consider 2.5-axis machine, as such only translation error in x(dx) and y(dy) are considered and the rotation axis errors have been considered negligible. Estimation of combined machine errors of the FDM is based on [17]. In their report, the deviation of the machine with regard to the nominal dimension is about 0.07 mm. This deviation is considered as the confound error of the machine volumetric error as well as material flow and shringkage as it was obtained from the accuracy analysis of the built part. Subsequently, this deviation is used as input for the gaussian porcess model to simulate errors. The nugget value is set much smaller than the sigma with consideration of the error of the machine vibration is small compared to the main errors. In the simulation, the layer thickness of the building process is set to 0.25 mm as the FDM specification to be simulated.

A Gaussian Process (GP) is used to generate the error along x and y as well as z-axis. The Gaussian variogram is defined as:

$$\gamma(i, j) = s - [n + (s - n)e^{\frac{-3h(i,j)^2}{r^2}}]; \quad h = \sqrt{axis_i - axis_j} \quad (7)$$

s, n and r are the variogram parameters. s is set to 0.07 since it is represent the confounded error [17], n is 0.000125 and r is 30. Errors are generated along the axes range with 1 mm scale interval. Subsequently, a curve function is fitted for each axis errors by using ordinary kriging method [18]. The estimated function is formulated as:

$$\hat{y}(\mathbf{x}) = \hat{\mu} + \mathbf{r}'\mathbf{R}^{-1}(\mathbf{y} - \mathbf{1}\mu) \quad (8)$$

Correlation between two scale on an axis $Corr[axis_i, axis_j]$ is $exp[-d(axis_i, axis_j)]$. Meanwhile, $d(axis_i, axis_j)$ is defined as $\theta|axis_i - axis_j|^p \quad \theta \geq 0, p \in [1, 2]$. $\mathbf{r}$ is A $1 \times n$ vector whose element i-th is $r_i(axis^*) = Corr[axis_i, axis_j]$. $\mathbf{R}$ is A $n{\times}n$ matrix whose elements are $Corr[axis_i, axis_j]$. $\mathbf{y}$ is A $1 \times n$ vector of error in an axis (x or y). $\hat{y}(\mathbf{x})$ is An estimate value of error with respect to scale position of an axis. $\hat{\mu}$ is An average of an error in axis (x or y).

In table 1, the feature characteristics to be predicted are radius, angle of the cylinder axis with regard to the horisontal plane, and cylindricity. The first two are dimensional characteristics while the last one is the geometric characteristic. The results of the predicted value in this table were obtained from simulation of 50 runs. For the predicted values, they are shown with the format of mean values and their interval within 95% confidence level (2σ). From the simulation results, the devia-

Table 1. Deviation estimate from the simulation results.

Feature characteristic	Cylinder 1	Cylinder 2	Cylinder 3
Nominal			
Radius [mm]	5.00	6.00	6.00
Axis Angle [deg]	10	90	90
Cylindricity [mm]	0.00	0.00	0.00
Predicted			
Radius [mm]	5.0006 ± 0.0969	6.0119 ±0.0845	6.0129 ± 0.0889
Axis Angle [deg]	10.3874 ± 0.6736	89.667 ± 0.4145	89.7262 ± 0.3802
Cylindricity [mm]	0.3447 ± 0.2642	0.3553 ± 0.1514	0.3325 ± 0.1235

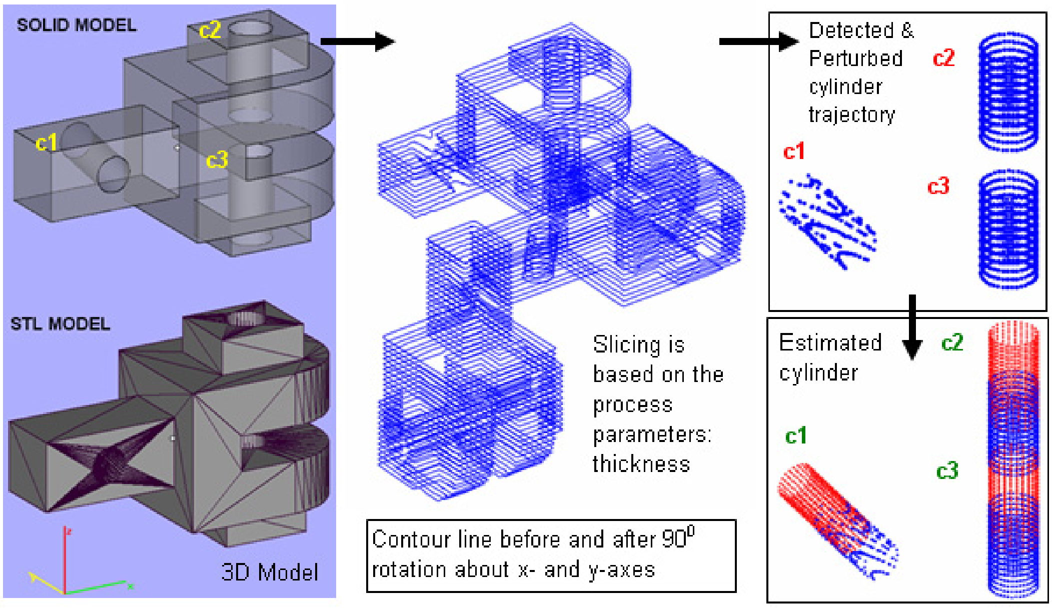

Fig. 8. Implementation steps of the case study.

tion of the radius < 0.013 mm which is coherent with the report by [17]. They stated that the machine is capable in producing part for length tolerance > 0.13 mm. Attention should be given for the other two prediction results: axis angle and cylindricity. From the results, they are considered as large error in the case of precision parts product.

6. Summary and Outlook

In this article, we proposed a methodology to estimate dimensional and geometric deviation of features of a part from its STL format by simulating the additive manufacturing process incorporating confounding errors from volumetric and material-related errors, such as material flow and shringkage. For the future, these errors should be considered and treated separately to have a better estimate of the errors contributors. The feature selected in this study is a cylindrical feature (physically, it is in the form of pin-hole or shaft-hole relations) due to their fundamental functionality in mechanical components. The case study considers FDM machine by considering its growing popularity and accuracy improvement. The results show that it is reasonable to estimate feature's deviation of a part from its STL file before fabrication. This information is important for the designer such that a design improvement can be carried out from the feedback of predicted deviation values.

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