A REVERSE COMPENSATION FRAMEWORK FOR SHAPE DEFORMATION IN ADDITIVE MANUFACTURING

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ABSTRACT

Shape deformation is one of the important issues in additive manufacturing such as the projection Stereolithography process. Volumetric shrinkage combined with thermal cooling during the photopolymerization and other factors such as support-constrained layer building process, leads to complex part deformation that is hard to predict and control. In this paper, a general computation framework based on a reverse compensation approach is presented to reduce the shape deformation of fabricated parts. During the reverse compensation process, the shape deformation is first calculated by physical measurements. A novel method is presented with added markers for identifying the optimal correspondence between the deformed shape and the given nominal CAD model. Accordingly, a new CAD model based on the determined compensation can be constructed. The intelligently modified CAD model, when used in fabrication, can significantly reduce the part deformation when compared to the nominal CAD model. Two test cases have been designed to demonstrate the effectiveness of the presented computation framework. Future work is also discussed in the paper.

KEYWORDS
Additive manufacturing, Stereolithography, deformation, reverse compensation, cross parameterization.

1 INTRODUCTION

Mask-image-projection-based Stereolithography (MIP-SL) process is a novel Stereolithography process based on using digital devices such as Digital Micromirror Device (DMD). The DMD device consists of millions of micromirrors, the status of which can be switched at very high frequency (approximately 5000 Hz) [1]. As a result, it enables simultaneously and dynamically controlling the energy input of a whole area. The idea of the MIP-SL is to use mask images of 2D sliced layers to expose directly on liquid resin surface to selectively cure resin at desired regions [2, 3]. The building speed in this process can be greatly improved compared to laser based SLA process. For the MIP-SL process, several mask image planning methods have been developed [4, 5].

Although the MIP-SL process has advantages such as fabrication speed [6] and resolution [5], the parts it builds have deformation after they are removed from the platform or supporting structures. Figure 1 shows an example of such deformation, in which the physical object of a flat rectangular bar built by the MIP-SL process is shown. From the Figure, it can be seen that the left and right sides, denoted as A and B respectively, curl up. Hence the physically built object is no longer flat. In comparison, the original nominal model is shown in dashed line in Figure 1. This kind of curl distortion among other shape deformations are common in the parts built by the MIP-SL and other additive manufacturing (AM) processes. The goal of the paper is to develop a general computation framework to reduce shape deformations in AM processes.
reduce deformation from process planning aspects, specifically to explore different building styles that can reduce the internal stresses during building [15, 16]. However, these internal stresses still exist in the building process no matter how effective the process planning method is. Since liquid monomers converted to solid polymer during the polymerization, and parts are built in a layer-by-layer dynamic style. Some other researchers employed Design of Experiments (DOE) to study effects of key building parameters, and optimize them in order the reduce deformation of built parts [17, 18]. Still some researchers used either Finite Element Method (FEM) or other analytical methods to model the SLA process [8, 11, 19]. Recently we reported using exposure strategies can effectively reduce volumetric shrinkage as well as lowering down curing temperature during SLA photopolymerization process, thus can reduce part deformation [12, 13, 20]. However, as illustrated in the previous section, a lot of factors contribute to the final deformation, most of which are intrinsic in the unique additive manufacturing processes, and thus cannot be avoided. It would very difficult to incorporate all factors building an analytical models or a FEA simulation to get good predictions.

On the other hand, another problem is how to compensate the part to make it close to designed CAD model after fabrication. Some research have been conducted to reverse compensate the part geometry based on statistical measurement of deformation [21, 22]. In other manufacturing processes such as sheet metal forming, a reverse compensation method in springback compensation proved to be effective, which is called "displacement adjustment" (DA) method [23, 24]. The idea of DA method is to move the nodes of original STL surface in the opposite direction of deformation. The error between the deformed part and target is calculated first, which is then multiplied by a compensation factor, and added on the original STL model. This compensation strategy works when the compensated shape has same deformation as the original shape, i.e., the added compensation has no deformation. However, the compensated shape still has different deformation rate as original shape and the added compensation undergoes deformation at a rate that is unknown in reality. The relations between addition compensation and final deformation is complex and unknown (e.g. may not be simple linear relationship), which makes it difficult to calculate the actual compensation. Therefore, the relations need to be studied.

1.2 Contributions

Due to the fact that the shape deformation of a fabricated part comes from many different and complex factors, it is difficult to predict and compensate the factors one-by-one. Instead, our research proposes a reverse compensation to combine all the factors to a geometric design problem by assuming the parts are fabricated by the same manufacturing process. Specifically, we study the relationship between the shape and its deformation, and we modify the input geometry, such that fabricating the modified shape with the same building process will result in a built part that is close to the original nominal model. In this way, we preserve the "law" of shrinkage and stress in the
photopolmerization process and other deformation sources. Our contributions can be summarized as follows:
- We present a general framework for compensating the fabrication error by converting the complex sources of deformation to a sole geometry optimization.
- Our method captures the physical deformation for each point on the freeform models by establishing a continuous mapping based on cross-parameterization.
- We develop a compensation calibration to study the relationship of shape and deformation, and predict the compensation intelligently.

Our study is mainly based on the MIP-SL process. However, note that the presented computation framework is general, which can also be used to reduce part deformation in all other additive manufacturing processes.

The rest of paper is organized as follows. Section 2 presents the overview of proposed compensation framework. Section 3 explains the correspondence between two models and deformation calculations. Section 4 introduces the compensation calculation based on deformation study. Two test cases are demonstrated and analyzed in Section 5. Finally, conclusions are drawn and future work is outlined in Section 6.

2 OVERVIEW OF COMPENSATION FRAMEWORK

The computational framework to reduce deformation in the MIP-SL process is shown in Figure 3.

![Deformation control in SLA/AM processes](image)

Figure 3. Computational framework to reduce deformation.

Any built part that has deformation exceeding required tolerance can use the computational framework to reduce the deformation due to the fabrication process. In order to reduce the deformation, the first step is to calculate it. As deformation is difficult to predict accurately by analytical models or FEA simulation, we adopt the approach of measuring deformation based on physical measurement, by using tools such as CMM machines or 3D scanners. After scanning the fabricated model, correspondence between points on the nominal model and measured data needs to be established. There are different methods/principles to find correspondence, e.g., find the closest point. In this research, we use feature points or added artificial markers to find the correspondence between two models. Based on the correspondence, the two models can be aligned, and the deformation can be easily calculated by subtracting the coordinates of corresponding points on two models. After the deformation is calculated, reverse compensation method can be applied to compensate the nominal model, such that the built part is closer to the designed CAD model. The schematic of the simple bar test case is provided as an illustration to go through each step for the reverse compensation based on physical measurement in the computation framework. As shown in Figure 3, the original flat simple bar has deformation after built, such that the two tips curl up. We can use CMM or microscope to measure its deformed profile (shown in blue solid line in Figure 3). Alignment between the measured deformed profile and original nominal profile (shown in red solid line) is conducted. For each point on the nominal model, a corresponding point can be found on the deformed profile, as denoted by red and blue dash line. The nominal STL model can be modified by using the reverse compensated profile, and the final built part would be much closer to the desired shape.

Specifically, the compensation for each point can be calculated based on the deformation of offset models. Pick a random point $P$ on the original nominal model as an illustration. Let the added compensation to be $X$, and the deformation of the compensated point ($P+X$) in MIP-SL process is denoted as $f(P+X)$, which is a function of added compensation $X$. The objective of compensation is to find $X$ such that:

$$P + X + f(P+X) = P$$

(1)

It can be rewritten as:

$$X + f(P+X) = 0$$

(2)

To solve this equation, there are two main issues that have to be tackled.

1. First, given the nominal and the deformed models, how to capture the true deformation for every point on the models, such that $f$ can be computed for a particular $P$?

2. Second, for an AM process, the relation $f(P+X)$ is unknown and may be a non-linear equation. How to find the value of $X$ that can satisfy or approximate the equation?

These two questions will be answered in the following two sections. Before that, we define the following notions that will be used in the paper:

- $N$: The nominal model, which is the CAD model needs to be fabricated.
- $M$: The measured data of the fabricated physical model, which has undergone deformation.
- $C$: The compensated CAD model.
- $N_\text{off}$: The subscript + or ~ denotes the offset version of the model, outward or inward, respectively.

3 CORRESPONDENCE AND DEFORMATION

To capture the deformation for each point on the nominal model ($N$), such that the deformation function $f$ can be computed, we need to find its corresponding point in the physical deformed model ($M$). One way to find the corresponding points is using the closest points like in the ICP method [25]. Unfortunately, using closest points may lead to a many-to-one or one-to-many mapping that will result in
degenerated shapes, which violates the deformation in nature. Instead, these correspondences can be established by cross-parameterization, which will be described in this section.

### 3.1 Establish Correspondence between Models

In this research, we establish the correspondence between nominal model \((N)\) and deformed model (measured model, \(M\)) or between nominal model \((N)\) and offset models \((N_+, N_-)\) by using feature points that is known to have correspondence on two models, which can be either done by manual specification, or by some intelligent feature recognition algorithms [26]. If there is no salient feature point on the models, artificial markers are added on the surface of models to serve as the feature points. This is important especially for freeform shapes. An illustration of added markers is shown in Figure 4. Remarked that the designed markers on the nominal model as shown in Figure 4(a) need to have a suitable size in order to be successfully built and measured, as shown in Figure 4(b). After multiple testing, we design the markers as a set of cylinders with a diameter of 0.6mm and a height of 0.5mm in our study.

![Figure 4. Models with no salient feature points (a) Nominal CAD model (b) Physical model.](image)

The specified feature points define a sparse and discrete correspondence between different models. To establish a continuous mapping from the sparse one, we apply the cross-parameterization method [27, 28]. Specifically, the method partitions both of the models to a set of corresponding patches by linking the input feature points in a consistent way. Then, the cross-parameterization between the models is found by computing the mapping between all the corresponding patches. The mapping computed is bijective and optimized to have low distortion.

An example of cross-parameterization result is shown in Figure 5, in which 35 artificial markers have been added respectively on two models.

![Figure 5. Cross-parameterization of two models with 35 artificial markers.](image)

### 3.2 Capture the Deformation of Physical Model

Once the correspondence between the nominal model \((N)\) and the deformed physical model \((M)\) is established, the two models are firstly aligned, and the deformation for each point on the nominal profile can be easily calculated by subtracting its coordinate from that of its corresponding point on the measured profile.

For an illustration, a modified letter H model is used for the accuracy study in the SLA process. The schematics of the model used in this study are shown in Figure 6 (unit in mm). The part has length of 101.6mm, width of 20.32mm and height of 50.8mm. The model was built using a commercial MIP-SL machine (Ultra by EnvisionTec Inc. [3]). The built object is shown in Figure 7. It can be observed that plate A is curved, and points A and B have dents on the vertical surfaces.

![Figure 6. Schematic of Letter H part.](image)

![Figure 7. Built object of the Letter H model.](image)
As the modified letter H part is a 2.5D model, we can measure its 2D profile using a vision-based measurement tool. In this research, a high-precision microscope measurement machine – MicroVu [29] was used to measure the deformation of the built object. As can be seen from Figure 6, the 2D profile of letter H part is a regular shape consists of several rectangles. It would be intuitively to measure the corner points of these rectangles and their edges, and use these corner points to establish correspondence between nominal model (N) and measured deformed model (M).

The sample points in the nominal model (N), and their correspondences from the measurement of the physical model (M) are plotted in Figure 8, in which 10 points are sampled from each boundary curve, and more points are sampled around corner or position where large deformation gradients exist. User can control the number of sample points. The “+” points in blue denote nominal data, while “*” points in red denote measured data. From the magnified views of section (1) and (2), which are picked from the top horizontal plate and side surface, respectively, it is found that the measured data shows the top horizontal plate is curved, while the side surface have dents after built, which agrees with the deformation found on the physical built part. The deformation for each point on the nominal model can be easily calculated.

![Figure 8. Sample points of the nominal model and the corresponding points on the physical model.](image)

4 COMPENSATION CALIBRATION

The relations between the added compensation and the final deformation is a non-linear relationship, which makes it difficult to predict and compensate. Therefore, we investigated the relations of added compensation and deformation based on physical experiments in this research. In addition, we studied adding small compensation (or offsets) on the original nominal model in order to establish the relations between these small offsets and their related deformation using modified models, and, accordingly, to calculate the compensation based on them. Our method is based on the following assumptions and observations:

(1) Parts with the homogeneous shape will have the homogeneous deformation, i.e., deform in a similar trend and vary only in the amount. For example, bars with different thicknesses will all have curl distortion, although they may differ in the magnitudes.

(2) Models with small offsets will have the homogeneous shape as that of the original model.

(3) As the deformation of each point with or without compensation is in the same trend, it is assumed that there is no or very little compounded deformation caused by neighbors. Therefore, the deformation can be considered individually point-by-point.

Note that, the cross-parameterization presented in Section 3 is used to compute the correspondences among all the nominal model (N), measured physical model (M), offset CAD models (N+, N) and their measured physical models (M+, M). Therefore, for each point on any offset model or scan model, it would be straightforward to find its corresponding point on all the other models, and thus the deformation can be easily calculated and the comparisons of deformation using offset models can also be conducted.

4.1 Using Offset Models for Calibration

The method used in this study is explained as follows:

(1) First, building the original nominal model N, and for each point \( P_i, i \in [1, n] \), n is total number of vertices or sample points) on N, find the corresponding point \( Q_i \) on the measured model M, and calculate its deformation \( D_i \):

\[
D_i = Q_i - P_i
\]

(3) The physical experiments are to use several sets of compensation \( X \) (e.g. \( X_1, X_2 \), etc.) and their corresponding deformation (e.g. \( f(P+X_1), f(P+X_2) \), etc.) to approximate the deformation function \( f \), and find approximation to the root of equation (2).

As an illustration, two additional offset models for modified Letter H model are designed by offsetting every point along its normal direction outwardly and inwardly 0.5mm since the physical part has deformation around 0.5mm. The offset models (N+, N) and physical built parts (M+, M) of the modified Letter H model are shown in Figure 9. The red dotted lines show the offset profiles (N+, N), while the solid blue lines represent original nominal profile (N).
The offset models are built, measured and analyzed following the same procedures as the original nominal baseline model (N). After measurements, the same number of sampling points is picked on the offset profiles (N+, N-) corresponding to that of profile with no offset (N). Deformation for each point on the offset models (N+, N-) is calculated by using point in the deformed profiles (M+, M-) minus its corresponding point on the nominal profiles (N+, N). As illustrated earlier, the deformation for a point \( P_i \) on offset outwardly model (N+) is \( D_i^+ \), which is calculated by equation (4). Similarly, the deformation for a point \( P_i \) on the offset inward model (N) is represented as \( D_i^- \) and calculated by equation (5). The comparisons of measured deformed profiles (M, M+ and M-) and original nominal baseline (N) are shown in Figure 10.

In Figure 10, the blue "*" dots show the nominal baseline profile with no offset (N), while the red "+" dots show the deformed profile with no offset (M), the gray "x" dots show the deformed profile with offset inward 0.5mm (M_), and the pink "." dots show the deformed profile with offset outward 0.5mm (M+). From the magnified view of sections (1) and (2), it is found that nominal baseline profile (N) is within the range of deformed profiles with offsets (M+, and M-).

4.2 Compensated profile

Compensation for each point is calculated by using three pairs of offset and deformation. There are many ways to calculate the compensation based on these data, e.g. use polynomial functions with different orders to fit the data, and find the target compensation, etc. In our study, we used second-order polynomial to fit these data. The compensated profile is shown in Figure 11. The nominal baseline profile (N) and the original deformation profile with no offset (M) are also plotted in the figure for comparisons. The compensated profile shows in red dots, while blue dots show the nominal profile (N), and pink dots represent deformed profile (M). Magnified views of a point on the top surface of central plate, as well as a section on the region where dent occurs, denoted as (1) and (2), are drawn to better demonstrate the compensation result. From Figure 11, it can be seen that the compensated profile is in the reverse direction of deformed profile with respect to nominal profile, and every point has different values of compensation.

5 RESULTS

5.1 Test case 1 – 2.5D freeform shapes

The modified Letter H part has been selected as test case 1 for compensation study. The schematic of the model is shown in Figure 6. The correspondence between nominal models (N) and the measured physical models (M), as well as the calculation of compensated profile are explained in previous sections. Based on the compensation calculated, a modified nominal model is generated accordingly (denoted as C). The compensated STL model to be fabricated is shown in Figure 12.
5.1.2 Comparisons of deformation before and after compensation

The compensated STL is built and measured following the same procedure as other models. The measured deformed profile is aligned with nominal baseline profile, and the same number of sampling points is picked from the same positions of baseline nominal model and measured profile of compensated part. The comparisons of deformation using compensated STL model (C) and original model without compensation (N) are shown in Figure 13.

![Figure 13. Comparisons of deformation before and after compensation.](image)

Table 1. Deformation comparisons before and after compensation for test case 1 (unit: mm)

<table>
<thead>
<tr>
<th></th>
<th>Before compensation</th>
<th>After compensation</th>
<th>Improvement</th>
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<tbody>
<tr>
<td>$L^\alpha$-norm</td>
<td>0.768</td>
<td>0.270</td>
<td>65%</td>
</tr>
<tr>
<td>$L^2$-norm</td>
<td>0.276</td>
<td>0.090</td>
<td>67%</td>
</tr>
</tbody>
</table>

From the table, it is found that using the compensated model (C) can effectively reduce deformation when compared to using original model without any compensation (N), specifically, the deformation improvement is 65% and 67% in terms of $L^\alpha$-norm and $L^2$-norm, respectively.

5.2 Test case 2 – 3D freeform shapes

In order to further verify the effectiveness of our reverse compensation strategy, another test case, which is a freeform 3D shape as shown in Figure 15, has been selected to apply the presented computational framework.

![Figure 15. Testcase 2: (a) Isometric view; (b) Front view.](image)

The test case is built vertically, as shown in Figure 15(b). The physical built part has deformation with two legs spreading out. The deformation is mainly caused by the shrinkage of the top arch. The nominal dimension between the leftmost point and rightmost point is 51.92mm. However, in this test case, the surface of the test part is smooth with no sharp edge. Therefore, it would be difficult to use a microscope to measure the deformed profile. Instead, a 3D scanner is required to measure the built physical object. Similar measuring approach can be used for other 3D test parts.

In our study, a DAVID-SLS2 3D scanner [30] has been employed to measure the deformation of test case 2. The 3D scanner is calibrated before it is used for scanning. As it shows in Figure 15, test case 2 does not have many salient feature points which can be used for parameterizing the given model. Small artificial markers are added on selected positions to assist the parameterization by establishing correspondence between points on nominal model and deformed model.

5.2.3 Deformation calculations

The baseline nominal model with 35 artificial markers is built in Ultra machine. The nominal STL model (N) and physical built are shown in Figure 4. The physical built part is scanned using a 3D scanner followed the same procedures as those in test case 1. It should be noted that the top surface is scanned while the bottom is hollow, and the hole is filled during fusion process. The fusion result is shown in Figure 16(a), from which...
it can be seen that there are artificial markers on front and side surfaces.

The artificial markers on the scan model correspond to that on the nominal STL model. The positions of these markers on respective mesh model are recorded. To calculate the deformation of built part, these markers are smoothed and removed from both scan model and STL model since they are only designed to establish the correspondence of these two models and to assist mesh parameterization. The smoothed scan model with no marker is shown in Figure 16 (b). Consistent mesh parameterization of smoothed scan model (M) and nominal STL model (N) with no marker can be calculated based on the positions of these 35 corresponding markers, similar to that as shown in Figure 5. Every vertex in the scan model (with no marker) has a bijective mapping to a vertex in nominal STL model after parameterization.

The scan model is then transformed to align with nominal STL model, and plotted in Figure 17 (a). Magnified views of two sections selected from top and bottom are created for better illustration, shown in Figure 17 (b).

Figure 16. Scan model of baseline part: (a) Scan model with markers; (b) scan model with marker removed.

The scan model is then transformed to align with nominal STL model, and plotted in Figure 17 (a). Magnified views of two sections selected from top and bottom are created for better illustration, shown in Figure 17 (b).

Figure 17. Comparison of baseline nominal model and scan model compensation (a) Comparison of entire model (b) Magnified views of two sections

The blue dots represent the nominal STL model (N), while the red dots show the scan model (M). From which it can be clearly seen that the scan model has deformation with two legs splayed outward, and the part has shrinkage. Besides, by carefully examine the plot, it can be found that the deformation of left leg and right leg is not symmetric, which agrees with deformation of physical built part. This slightly non-symmetric deformation, which may be generated by hardware such as non-uniform light projection, demonstrates the effectiveness of using artificial markers and parameterization to find correspondence between scan model and nominal model.

5.2.4 Deformation of offset models and analysis
In order to investigate the relations of compensation and related deformation, two additional models (N+, N-) have been designed with offset outwardly 0.5mm and inwardly 0.5mm, respectively. The nominal offset models are shown in Figure 18.

Figure 18. Nominal offset models of test case 2

These two test parts are built and scanned with same parameter settings as the original baseline part. The physical built parts for offset models are shown in Figure 19. The physical built parts manifest deformation, which can be found by closely examine and compare Figure 18 and 19.

Figure 19. Physical built parts of offset models

Similar to the parameterization process in baseline model and its scan model, the nominal offset models (N+, N-) and scan models (M+, M-) are parameterized using the positions of 35 artificial markers on them. The comparisons of deformation using offset models with outward 0.5mm and inward 0.5mm are plotted in Figure 20(a) and 20(b), respectively. In both figures, the blue dots show the nominal model, while the red dots represent the deformed model (scan data).
As can be seen from Figure 17 and 20, all these three test parts \( M, M_{+}, \) and \( M_{-} \) follow the same deformation trend; with two legs splayed outward, and have dents in the center portion of legs. The parts are built on support structures. During the building process, two legs are built first. It can be found that the legs are built with a small angle upwards. The solidification of current building layer is restricted by the underlying layer, causing tensile stress on current layer and compressive stress on the underlying layer. Besides, the slightly mismatch of curing region between current layer and the layers below it will generate a bending moment, which has the tendency of bending the legs outwardly. The arch is built on top of two legs. Similarly, the shrinkage of arch layers are constrained by the two legs and the support structures, which leads to internal stress built up. The residual stress is released when the building process is finished and the part is removed from the support structures. The related bending moment will cause the legs splayed outwardly.

5.2.5 Reverse compensation

After mesh parameterization using artificial markers, all six models (nominal models \( N, N_{+}, N_{-} \) and scan models \( M, M_{+}, \) and \( M_{-} \)) have well-defined correspondence. Each vertex in one model has a unique bijective mapping to a vertex in another model. Therefore, the relations between deformation and offset for each vertex can be approximated by using the physical parts we built. Based on which the compensation can be calculated for each vertex (refer to Eq.(2) in Section 2). The calculated compensation and compensated STL model is shown in Figure 21 (a) and 21(b), respectively.

In Figure 21(a), the compensation profile is shown in red dots while the nominal model is shown in blue dots from which it can be found that the compensation is in the reverse direction as original deformation shown in Figure 17 and 20. Using the compensation profile, the nominal model can be easily modified with compensation added on it and exported as compensated STL model.

5.2.6 Deformation comparisons

The compensated STL model is built with 35 artificial markers added on it, and then measured using 3D scanner and compared with nominal model following the same procedure as before. The comparisons of physical part with and without compensation are shown in Figure 22.

![Figure 22. Physical parts comparisons: (a) without compensation; (b) with compensation.](image)

Unit: mm

![Figure 23. Deformation of built part with compensation: (a) Comparison of entire model; (b) Magnified views of two sections.](image)
The deformation of physical part with compensation is calculated by comparing nominal STL model and scan model, and shown in Figure 23. Magnified views of two select sections on the top and bottom are created for better illustration. Compare to Figure 17, it can be found that the part built with compensation has much less deformation than original designed shape.

Similar to test case 1, the deformation of physically built objects with and without compensation are quantitatively compared. $L^\infty$-norm (max distance) and $L^2$-norm (root mean squared distance) of points in nominal model to corresponding closest points in deformed model (x-z plane) is calculated for both parts, and shown in Table 2.

Table 2. Deformation comparisons before and after compensation for test case 2(unit: mm)

<table>
<thead>
<tr>
<th></th>
<th>Before compensation</th>
<th>After compensation</th>
<th>Improvement</th>
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<tbody>
<tr>
<td>$L^\infty$-norm</td>
<td>2.240</td>
<td>1.300</td>
<td>42%</td>
</tr>
<tr>
<td>$L^2$-norm</td>
<td>0.692</td>
<td>0.3111</td>
<td>55%</td>
</tr>
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The $L^\infty$-norm of deformation before and after using compensation is 2.24mm and 1.3mm, respectively, with deformation improvement around 42%. The $L^2$-norm of deformation without compensation is 0.692mm, while the $L^2$ Norm of deformation with compensation is 0.311mm, which shows that using compensation can have around 55% improvement on deformation.

6 CONCLUSIONS

In this paper, we presented a general computation framework based on reverse compensation to reduce the complex deformation that may happen in additive manufacturing processes. Corresponding points between nominal and deformed shapes are found by applying cross-parameterization using feature points. Such features points could be the existing salient features on the model, or any artificial markers added on 3D freeform shapes. By studying relations of offsets and deformation for each point, the reverse compensated models can be calculated. Two test cases have been selected to demonstrate the capability of the developed computation framework. The final compensated STL models are built and compared with original models. It is found that the compensated models can greatly reduce the shape deformation for both test cases.

Our reverse compensation requires the scanning of the fabricated models, however, there is measurement error that cannot be compensated by our method. In the future, we plan to generalize the framework to incorporate the non-manufacturing errors. We also plan to apply the computational framework to more general 3D test cases. We will study how to add artificial markers on the models to be more effective in registration and finding correspondence between measured and nominal models. More intelligent offsetting strategies for compensation calibration will also be investigated.

ACKNOWLEDGEMENT

The work is partially supported by Office of Naval Research with grant # N000141110671 and NSF grant number CMMI 1333550. We also acknowledge the help of Prof. Qiang Huang at USC and Mr. Leu-Yang Eric Huang, a high-school summer intern, on 3D scanning study.

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