# CHALLENGES IN TOLERANCE TRANSFER FOR ADDITIVE MANUFACTURING

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**Abstract:** From the design point of view, datum features are used to imply design intent of particular function of the part or sequence of assembly of components in a product. Each feature in a part could potentially have different datum reference based on the design intent. In traditional manufacturing, datum references are used to identify positions of machining features. In order to save time and cost, the number of datum references used in creating features are reduced in manufacturing. As the datum references are changed, validity of the tolerance specification and design intent is verified through a process called tolerance transfer or conversion. In additive manufacturing, parts and assemblies are built layer by layer, implying that all the features in the process will have common a datum reference. Different datum references could still be specified for post processing steps.

This paper identifies issues related to tolerance transfer in AM processes. In AM, layer by layer manufacturing of part may lead to features being completed before the feature's design datum reference is completed. Furthermore, based on the build direction, variations in feature and datum references can occur. When performing tolerance transfer, a process planner needs to consider (a) design intent, (b) build direction (c) process variation and (d) datum references.

## 1. INTRODUCTION

To ensure proper functioning of a product after manufacturing, the designer must arrive at satisfactory specifications of geometry, material, tolerances, surface finish and any other additional requirements for the product. The specifications necessary for such communication have well established standards, for example, the ISO 10303 [1-3] series of standards govern geometry specification while the ISO 1101 [4] and ASME Y14.5 [5] series of standards govern tolerance specification. Proper functioning of an "as designed" product relies on manufacturing the product within the specification, including allowable variations (tolerances).

Tolerance specification is the specification of the type and value of tolerances based on available Geometric Dimensioning and Tolerancing (GD&T) standards (e.g., ASME Y14.5 [5] or ISO 1101 [4]. GD&T is a language to communicate acceptable 3D variations of geometric elements in a part from design to manufacturing and inspection. GD&T is based on mathematical representations of the variation of geometric elements and manufacturing knowledgebases [6,7]. Different tolerancing activities that are part of the production process are covered in this paper and shown in Figure *1*1 (adopted from [8]).

### 1.1. Tolerancing activities

Different tolerancing activities are undertaken at different stages of the production process to ensure that (i) appropriate tolerances are specified by the designer and (ii) the specifications are followed by the manufacturer. These activities include tolerance analysis, tolerance synthesis, tolerance specification, tolerance transfer, and tolerance evaluation.

To ensure functionality of a product after manufacturing, the designer must arrive at a satisfactory set of tolerances that will preserve the design intent to match manufacturing capabilities. A designer can arrive at a satisfactory set of tolerances by using one of two approaches: tolerance analysis or tolerance synthesis [8-12]. With *tolerance analysis*, the designer estimates values for individual part tolerances and then uses a software analysis tool to determine the resultant range of variations for a critical dimension or function of

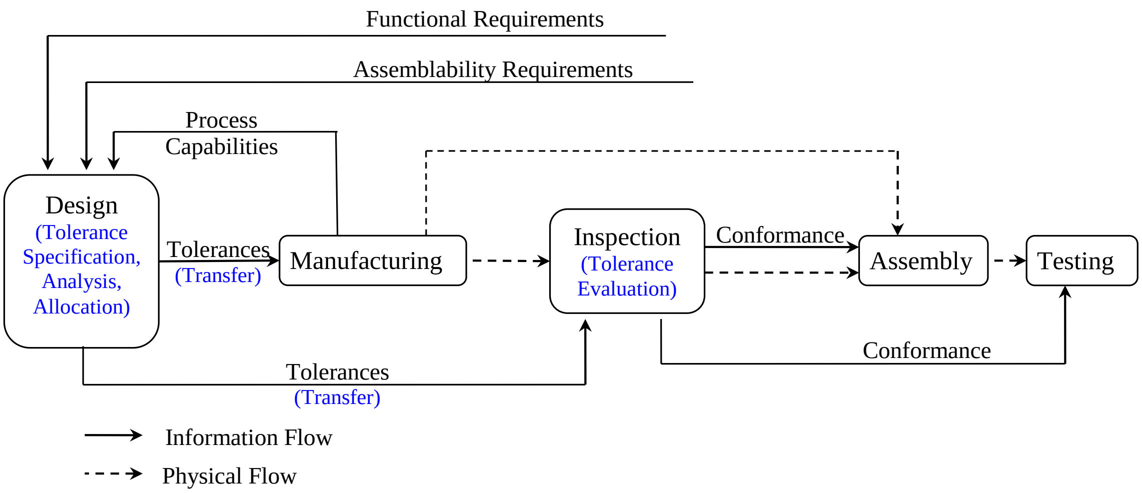



*Figure 1: Modified figure from* [7]*, showing different tolerancing activities in product life cycle.*

the assembly. With *tolerance synthesis*, often called tolerance allocation, the desired control at target features (e.g., a maximum clearance to ensure proper lubrication or control of noise) is chosen. Then, the tolerances are generated from a mathematically based tolerance model, also in an automated way, to meet that choice.

The final *tolerance specification* to each feature is a tradeoff between tight tolerances, which usually result in better performance of the assembly, and loose tolerances, which result in lower cost to manufacture the individual parts but also in a lower probability of proper assembly and/or function. Arriving at a satisfactory set of tolerances using tolerance analysis is an iterative process. With tolerance synthesis, often optimization techniques are applied using functionality-related heuristics.

The manufacturing and inspection stages of the product life cycle very often use different datum features than those desirable for design and function. Therefore, tolerances suitable for design function must be transferred, i.e., related, to tolerances on different dimensions with different datum features in such a manner that the product's desired function is not compromised. This transformation of tolerances is called ***tolerance transfer*** [10-14].

*Tolerance evaluation* deals with the analysis of the data obtained from dimensional measurements and conformance of the part with the specified design tolerances. As is evident from the discussion presented. Each tolerance activity is conducted in a particular phase of the production process. Tolerance analysis or synthesis leading to tolerance specification occurs in the design stage. Tolerance transfer and subsequent analysis is conducted at the beginning of the manufacturing stage. Tolerance evaluation (if needed tolerance transfer too) is conducted in the inspection stage. The focus of this paper is tolerance transfer that is conducted at the beginning of the manufacturing stage and will be detailed in the next section.

### 1.2. Tolerance transfer

From the design point of view, datum features are used to imply design intent of particular function of the part or sequence of assembly of components in a product. Each feature in a part could potentially have a different datum reference based on the design intent. In traditional manufacturing, datum references are used to identify positions of machining features. To save time and cost, the number of datum references used in creating features are reduced in manufacturing. As the datum references are changed, validity of the tolerance specification and design intent has to be verified. As these datum features are changed, manufacturer might conduct tolerance analysis to verify the design intent and validity of the transferred tolerances.

A simple example is presented in Figure 2 to illustrate tolerance transfer. Figure 2(a) indicates designer's intent, which is to control the location of surfaces C and B with respect to the surface A. The dimensions $l_1$ and $l_2$ have tolerances $t_1$ and $t_2$, respectively.

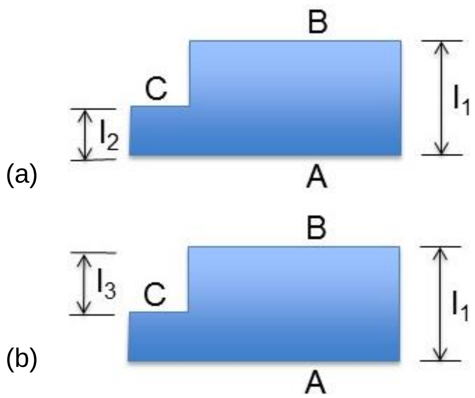



*Figure 2: Simple part with linear dimension showing different dimensioning schemes*

As the manufacturer changes the datum features from surface A to surface B, the location of surface C is now accomplished using dimension $l_3$. The tolerance $t_3$ on $l_3$ has to be computed to maintain the tolerance on $l_2$ that the designer required. From the simple chain of dimension in Figure 2(b), it is evident that $l_2 = l_1 - l_3$ and therefore $t_2 = t_1 + t_3$. This will lead to the computation of $t_3 = t_2 - t_1$. The result of changing the datum reference is that the manufacturer has to control the dimension with much tighter tolerance.

The above example demonstrates simple tolerance transfer. The purpose of this paper is to highlight the challenges in applying tolerance transfer to additive manufacturing (AM). The next section will present AM and tolerance related developments.

## 2. ADDITIVE MANUFACTURING

Additive Manufacturing (AM) produces parts by joining materials in layer-by-layer fashion. There are many different types of AM processes. These are well classified and studied in the literature [15-17]. AM processes are capable of producing complex free-form surfaces and many different kinds of structural lattices using a large variety of materials, including plastics, metals, ceramics and biomaterials.

As in traditional manufacturing processes, tolerance analysis or synthesis leading to tolerance specification will be utilized in AM too. Tolerance transfer will be needed to economically produce parts with less setups and less post processing. Tolerance evaluation is needed to ensure that parts produced meet the designer's requirements.

Although, all the tolerancing activities will be useful in AM, they need to be adopted to the novelties that AM technology presents. For e.g. in tolerance specification, current GD&T standards do not have the right set of mechanisms to control the variations in geometric features that are feasible with AM. The need for new specification tools in tolerancing standards have been presented in [17] [16]. These can be classified as (a) AM-driven specification needs and (b) specification needs highlighted by the versatility of AM processes. AM-driven specification needs include build direction, layer thickness, support structure related specification, and scan/track direction. Specification needs highlighted by the versatility of AM processes include, region-based tolerances for complex free-form surfaces, tolerancing internal functional features, tolerancing lattice and infills.

AM not only creates additional tolerance specification needs but also impacts how tolerance transfer is conducted. The purpose of this paper is to highlight these challenges in tolerances transfer. The next section will demonstrate a comparison of tolerance transfer activities between traditional and additive manufacturing.

## 3. TOLERANCE TRANSFER COMPARISON

To demonstrate tolerance transfer, the specification shown in *Figure 3* will be utilized. The specification shows a part with planar datum feature A, hole datum feature B, a pattern hole datum feature C and a side profile of the part. The datum feature B is toleranced with

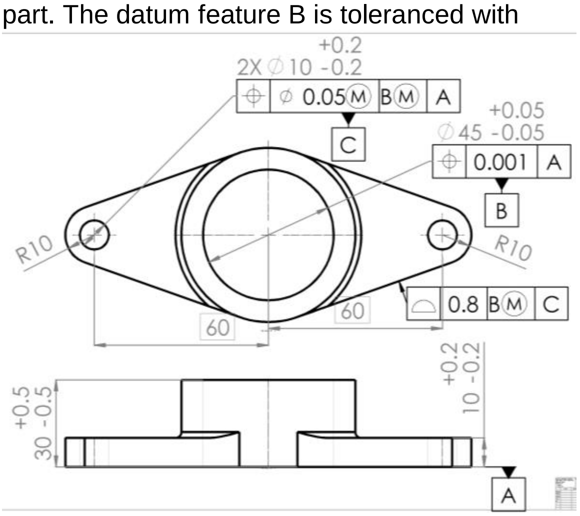


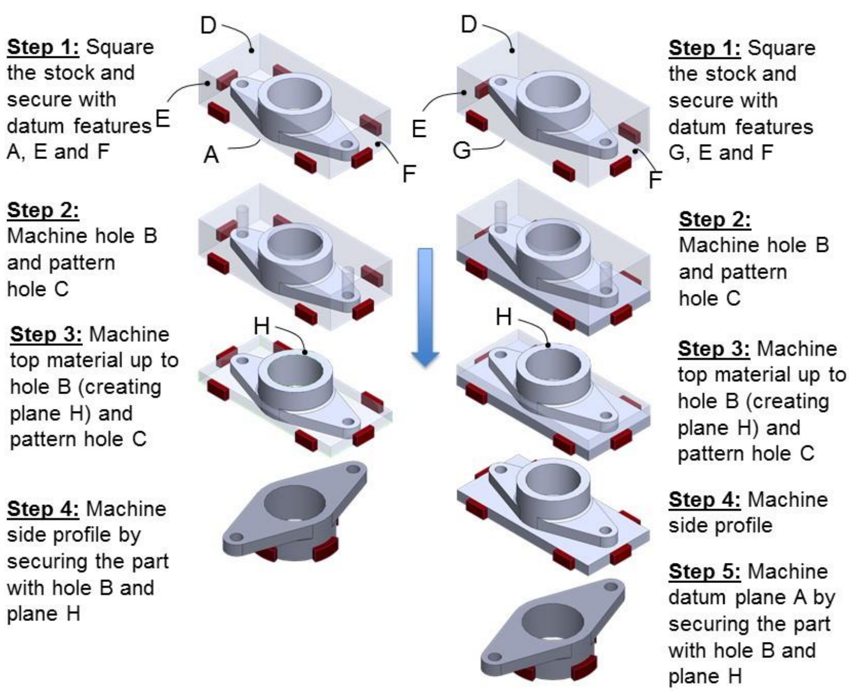

*Figure 3: Part with GD&T specification to demonstrate the tolerance transfer.*

respect to datum feature A. The datum feature C is toleranced with respect to datum features A and B. The side profile is toleranced with respect to datum feature C. Specification to datum feature B and C also includes size tolerances besides position tolerances.

## 3.1 Tolerance transfer in traditional manufacturing

Figure 4 and Table 1 show two potential process plan to machine the part from Figure 3. In order to avoid incurring additional costs of setups and related time loss in machining the part with datum feature A and center hole B, new and convenient datum features are generated in the two process plans shown in Figure 4. As is evident, both these plans do not conform to the design intent of controlling the side holes C with respect to the center hole B.

A rectangular stock larger than the dimensions of the part will be chosen to produce the part shown in Figure 3. Figure 4(a), step 1 shows the rectangular block machined close to the maximum dimensions of the part. Step 1 creates additional datum features labelled D, E and F that will be utilized in the subsequent steps. In process plan 1(Figure 4(a)), datum plane A will be created in Step 1. In the process plan 2 (Figure 4(b)), additional datum plane G is created in Step 1. The datum plane G provides for additional material to hold the part in the machine. This additional material will aid in machining the side profile in a later step 4. Figure 4(a) step 2 shows the rectangular block with machined holes, either from datum plane A or G (Figure 4(b) step 2). Figure 4(a), step 3 shows the machined top plane for holes B and C with respect to datum A or G (Figure 4(b)). In Figure 4(a), process plan 1, the part is currently secured with planes E and F that will be machined out as the side profile is created. Therefore, the part needs to be secured with another datum feature in order to create the side profile. Therefore, to create the side profile in process plan 1, the part needs to be mounted upside down with respect to hole B and the top plane of hole B (labelled as datum plane H). In process plan 2, the side profile can be machined as is and then the part is inverted to create datum plane A (step 5, Figure 4(b)). As this process plan is created with modified datum features, new tolerances will be computed than the ones specified in *Figure 3*. The computation of tolerance values is similar to the example shown in section 1.2. These operations with corresponding tolerances are also shown in *Table 1*.




(a) Process Plan 1 (b) Process Plan 2

*Figure 4: Steps and additional datum feature in a Process plan for machining the part shown in Figure 3.*

*Table 1: Process plan options showing different datum features and tolerances than those specified in Figure 3.*

| Feature | Datum feature | Tolerance (mm) |
|---|---|---|
| **Process Plan 1** | | |
| Datum plane A | D | 0.0001 |
| Center Hole B | A,E,F | 0.025 |
| Side Holes C | A,E,F | 0.025 |
| Top Plane of B | A, E, F | +/- 0.5 |
| Top Plane of Side holes C | A, E, F | +/- 0.2 |
| Side Profile | B, C | 0.8 |
| **Process Plan 2** | | |
| Plane G | D | 0.0001 |
| Center Hole B | G, E, F | 0.025 |
| Side Holes C | G, E, F | 0.025 |
| Top Plane of B | G, E, F | +/- 0.25 |
| Top Plane of Side holes C | G, E, F | +/- 0.1 |
| Side Profile | G | 0.8 |
| Datum A | Top Plane of B | +/- 0.25 |

Both process plans still require two setups to create the datum plane A and the side profile C. The tolerance values are modified so that the final variations in the worst-case would still meet the tolerance specified by the designer. For example, center hole B and side holes C are created with tolerances 0.025mm from datum features A, E and F. This is done so that in the worst case, the tolerance between center hole B and sides holes C remains 0.05mm as specified.

## 3.2 Tolerance transfer in AM

When the part shown in *Figure 3* is to be manufactured using additive manufacturing, first of all a build direction will be chosen. This build direction will then determine the primary datum. In this case because of the planar nature and lateral size of datum plane A, build direction is chosen perpendicular to datum plane A. This choice of build direction and datum plane A leads the plan shown in *Figure 5*. At step 0, an origin and a coordinate system is established with respect to the motion controller in the AM process. Steps 1 through N will build part in a layer-by-layer fashion. In the end, the part is removed from the build platform and inspected to further processing. In certain situations, there might be support structures that needs to be removed followed by machining or abrasive process to finish the part.

In the build direction, the tolerances in *Figure 3* are 1mm for the height of datum hole B and 0.4 mm for the height of datum holes C. In the AM

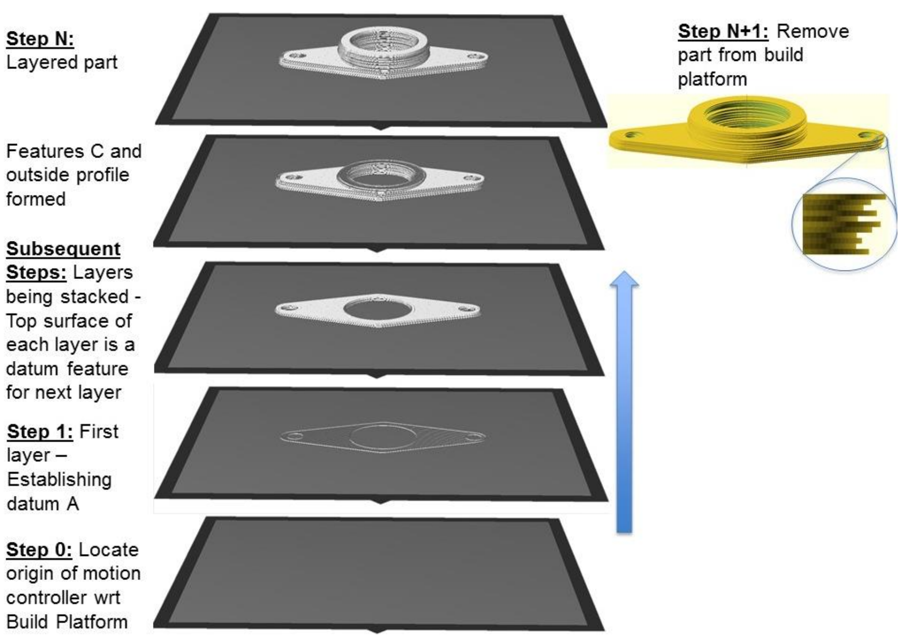



*Figure 5: Process plan for producing part shown in Figure 3 in AM*

process, the number of layers to the top plane of datum hole B, are 81. Then, the required tolerance on the height of each layer can be computed as 1/81 = 0.01234mm (assuming all the layers have same thickness).

In the lateral direction, in each layer, location of holes will be independently controlled with respect to the coordinate system established with the motion controller. Assuming that the motion controller's accuracy for a particular AM process is given as 0.03 mm in the lateral direction. The location error for a layer of datum hole B will be 0.03mm. The location error for a layer of hole C will be 0.03mm. In the worst-case scenario, the variation between datum hole B hole C can be 0.03+0.03 = 0.06mm. This variation will be greater than the specified tolerance (0.05) between holes C and datum hole B, when the size of holes C and datum hole B are 9.8mm and 44.95mm, respectively.

Furthermore, as each layer can be produced offset with respect to the previous layer, the variation in form, orientation and position of the holes will be much greater. This can be rectified in sub-processing by enlarging the datum hole B and datum hole C. This is because the material modifier specified allows for greater tolerances (upto 1.4mm) when the holes are made larger (datum hole B at 45.05mm and holes C at 10.02mm).

## 4. CHALLENGES IN TOLERANCE TRANSFER FOR AM

Tolerance transfer related challenges for AM will be presented in three categories. They are challenges related to producing (a) single parts, (b) as-built assemblies and (c) multiple parts in single build. These challenges will be highlighted based on the fact that the parts may require further post-processing to meet the required tolerances.

### 4.1 Challenges related to Producing Single Parts

As is evident from the example in section 3.2, the selection of the *build direction* also effects the selection of the primary datum feature for the process plan. The first layer created to produce a part in effect creates the primary datum feature. Primary datum feature is a datum feature which constraints the location of another feature as much as possible. Therefore, selection of the *build direction* also effects the selection of the primary datum feature for the process plan.

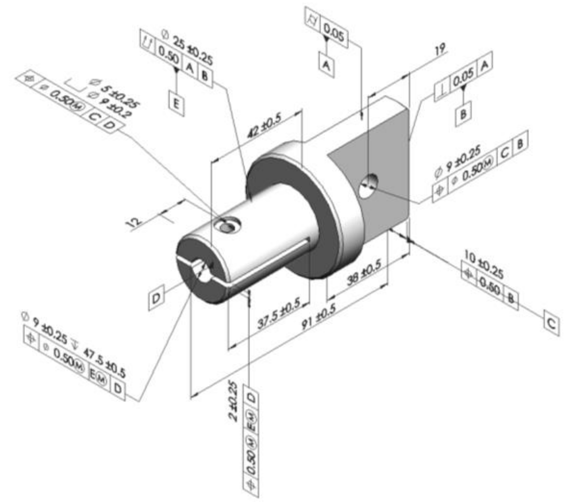
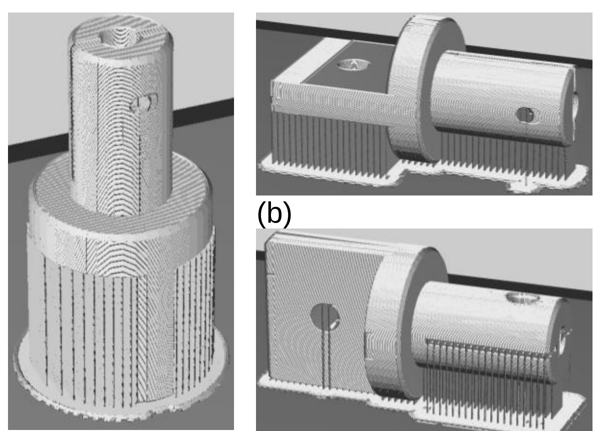


*Figure 6: A mill/turn part with GD&T specification.*

For parts with large flat surface (*Figure 3*), it is usually easy to choose a build direction and primary datum feature (datum plan A for *Figure 3*). For parts as shown in *Figure 6* or parts with non-planar surfaces, it is usually difficult to select a build direction or primary datum feature.

Furthermore, based on the geometry, material and the AM process, special structures are built, (called *support structures*) to be able to produce the part layer by layer. Many researchers have built methodologies for optimizing build orientation [19-23], none of which includes tolerancing requirements. Three different build direction and associated support structures for the part shown in *Figure 6* are shown in *Figure 7*. These support structures would require additional post-processing to remove them and to finish the surface to the specification.



(a) (b) (c)

*Figure 7: Three different build direction and related support structures for the part in Figure 6*

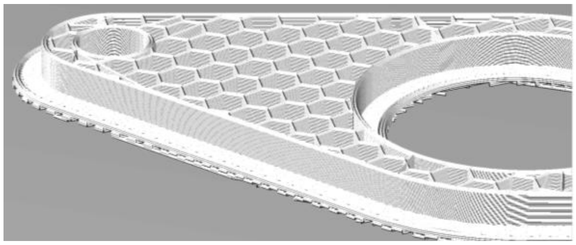


*Figure 8 Part from Figure 3 being built. Smaller hole will be completed before the larger hole (a datum for smaller hole).*

The post-processing steps, if abrasive in nature, would require attention when choosing layer thickness and number of shells in the AM processes. In AM processes, in order to save material, parts can be created with less material on the inside (infill) and have multiple layers (shells) close to the outside surfaces. When abrasive processes are used, material will be removed from the surfaces of the AM part. In planning for this material removal, number of shells and layer thickness needs to be considered. Otherwise, too much material removal will lead to inaccurate geometry.

In AM, parts are built layer by layer, implying that all the features in the process will have common a datum reference. Different datum references could still be specified for post processing steps. Figure 8 shows the part from Figure 3 being built. The larger hole in Figure 3 is specified as the datum for the smaller hole. As is evident in Figure 8, the smaller hole will be finished before the larger hole (datum reference for smaller hole) will be completed.

### 4.2 Challenges related to Producing As-Built Assemblies

As-built assemblies in AM will have a single datum reference for all the parts in the assembly. This would require tolerance transfer to change datum features and ensure that the AM system capability will meet the computed and required tolerances.

Furthermore, as-built assemblies are made with AM processes for assemblies that are in motion. Usually these assemblies have large clearances between moving components. These are typically in the range of 0.15mm or more. In these assemblies, due to large clearances, greater rattle, wear, fatigue leading to early part failure might be possible.

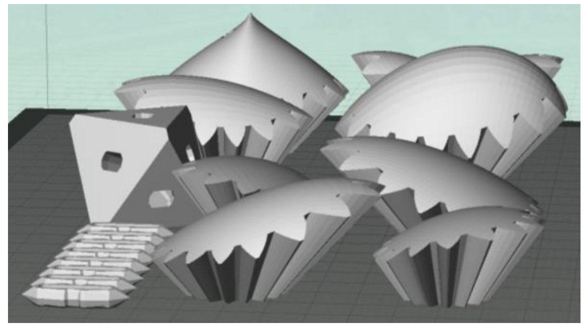


*Figure 9: Multiple parts with overlap along the projection on build platform.*

### 4.3 Challenges related to Producing Multiple Parts in Single Build

In AM processes, to reduce cost of each part, multiple parts are produced in a single build. In relation to this notion, many algorithms have been proposed to maximize the utilization of build volume [24]. *Figure 9* shows multiple parts located on build platform (model from http://www.thingiverse.com/thing:12208). A few of the parts have their geometries under other parts in the build direction. This can severely effect geometry in AM processes, as the geometry of one part may impact geometry of other. Furthermore, AM process parameters from one layer will impact another, suggesting the need for careful attention from a process planner in manufacturing critical parts.

## 4. SUMMARY

This paper introduced the notion of tolerance transfer in process planning. A comparison of tolerance transfer for a part produced using traditional and additive manufacturing was presented. The comparison highlighted several challenges related to tolerance transfer in AM processes. When performing tolerance transfer, a process planner needs to consider (a) design intent, (b) build direction (c) process variation and (d) datum references.



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