Title:
**Recursive Segmentation: An Approach to Produce Large and Complex Designs**

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Introduction:
Additive manufacturing and computational modeling approaches have enabled the production of complex and intricate parts. Yet, there has been relatively lesser exploration of how these emerging technologies can support the production of very large parts and assemblies. This paper will explore an approach to segmentation using recursion. *Segmentation* is the division of a large model into smaller modules using a set of design rules [1, 6, 7]. In *recursion*, a process is called within a sub-step of the process itself. In this case, a model is segmented, then those initial modules are re-segmented to meet a design criterion through a recursive process.

A typical challenge is that printers often have fixed volume print beds. While larger (e.g. >1m$^3$) printing systems have been developed [3] or those which are extensible in a single dimension [4] there are opportunities to explore how alternative approaches, such as modular segmentation may support large scale part production with additive manufacture. Previous work has introduced one mechanism for segmentation of large parts via computational algorithm to support large scale prints [2, 10–12].

In parallel, one proposed advantage of additive manufacturing, in early rapid prototyping literature, was the concept of adaptive fidelity or optimal layer slicing [9, 14]. This is the theoretical notion of refining part granularity in regions of interest where higher precision is required [8, 14]. However, in practice, there has been relatively little pursuit of adaptive granularity. This is likely due to the practical limitation that it is non-implementable in most machines. Common processes (FDM, SLM, SLS) typically operate with a fixed beam or filament diameter. In some processes the vertical height layer precision can be tunable within a small tolerance [13]. These approaches are still limited to refinement only in a single dimension. This would not cover many cases where adaptive granularity is desired, e.g. a high-quality surface layer. Thus, an alternative is to explore how new design processes might support adaptive precision in other ways.

Recursive Segmentation:
In this study an approach is presented that supports the production of arbitrarily large models and/or adaptive tolerancing through a process of recursive segmentation. This approach enables parallel printing, such as is possible with a printer farm [5]. For a single extruder, print time scales with the characteristic dimension cubed, e.g. $\Re^3$. Conversely, a segmented assembly can be of arbitrarily large scale, yet the print time is equivalent to that of one module. This requires parallel extruders.

The process-concept consists of two primary steps. The first step is a segmentation algorithm that slices an initial three-dimensional part into an array of spatially distributed, approximately equal volume smaller modules. The second step is to evaluate each of these smaller segments against a convergence criterion, whether it be dimensional accuracy, target volume, or other criteria such as mold slice segmentation (detailed in a case study later). If a module does not meet the convergence criteria, it is fed back into the segmentation algorithm and recursively sliced. That is a module produced in the first round is further segmented into smaller modules. Once the criteria are satisfied all the parts are exported for production. They may be printed in parallel. This segmentation process is outlined by the following pseudocode algorithmic description:

1) Import BASE_MODEL (the original part)
2) Append BASE_MODEL to SEGMENT_LIST
3) k = 1
4) FOR each part in SEGMENT_LIST
    a. Segment part into k segmented modules
    b. Append each module to SEGMENT_LIST
5) FOR each part in SEGMENT_LIST
    a. IF part fails criteria, move to next part,
    b. ELSE store part in PRINT_LIST, remove from SEGMENT_LIST, move to next part
    c. IF no part meets criteria, increase k by 1
    d. RETURN to segment (above)
6) Export PRINT_LIST

For the case studies below, segmentation is executed in a software co-developed by two of the authors, called LuBan (www.luban3d.com). The standard convergence criteria for LuBan is volume. With LuBan, a model of any arbitrary size can be segmented into parts that will fit inside a user-specified volume. The algorithm firstly examines the size of the object in orthogonal directions, i.e. x, y, and z, and compares it with a build volume threshold for each these axes. Whichever direction exceeds the build size by highest factor is set as the one that requires plane cutting. Then LuBan performs an intersection calculation between a new cutting plane (or series of evenly spaced cutting planes) and the object, in the form of a triangular mesh. The intersections of the plane and all meshed-triangles are calculated. New triangles are generated on the cutting section to close the open mesh on each segment. As a result, two or more new closed mesh objects are produced. LuBan will perform a size check on the new mesh objects and apply another cutting plane if needed. This process is repeated until all new segmented mesh objects are within the user-specified build volume for the first axis. It will then move on and repeat the process for each axis.

<u>Exemplar Case Study 1, Complex Casting Mold:</u>
One potential application is to support the production of complex molds for re-usable casting. A traditional mold is often either destroyed by use or limited to several segments, often only split in a single plane. It can be complicated to produce a mold that splits in multiple planes as more planning and CAD work is required. As a result, is it often difficult to develop a mold with no overhangs for complex shapes. Recursive segmentation can be used to solve this issue if the convergence criteria is to ensure that any segmented module can be separated from the model once the molding material is cast (i.e. 'no overhangs'). In the example, silicone is used to cast a complex shape that could not be generated using a two-piece mold due to several complex overhangs.

To produce this casting, there are several steps involved. These steps are derived from the algorithm shown above. Starting from the target part to be cast, a surface thickening function is used. In this case, one of the LuBan features supports expanding the model's thickness by a predefined value. This thick outer shell, with the original part subtracted, forms an initial single part mold for the complex model. The original model (Figure 1.a) and expanded surface (Figure 1.b) are shown below.

After an initial segmentation, each part is then inspected to see whether it meets the necessary criteria for production. In this case, the intention for these parts is to be used as a casting mold. Therefore, there should be no overhangs on any part that will form the inner surface of the mold. An overhang will mean that part would not be easily removable from the mold once the filler material hardens. As a demonstration of the need for recursion, a simple segmentation (with no recursion) is performed on the model. Even with a very fine segmentation, resulting in 216 unique parts (Figure 1.c) there are still parts that fail to meet the design criteria of no overhangs. Thus, recursion is applied.

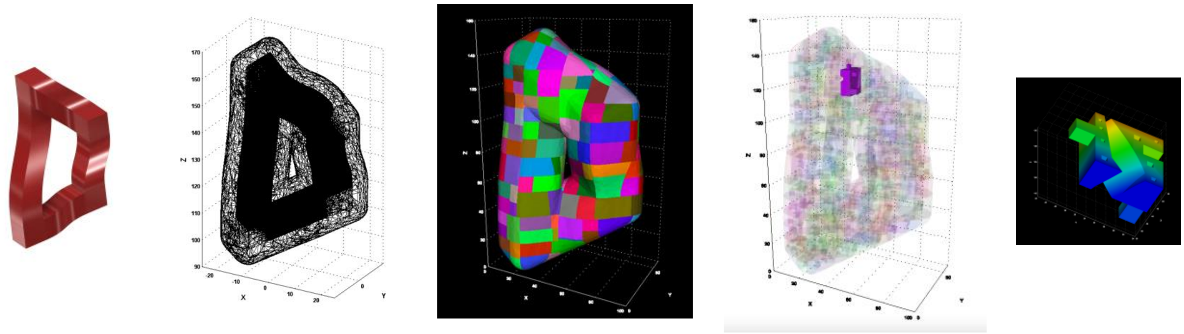

Fig. 1: (a) Original CAD part, sculpture that depicts one possible realization of Penrose' impossible square formed to resemble the letter 'D', which is also the IDC logo. This is the form to be cast; b) the expanded surface which forms a single part, initially unsplit, mold form; (c) results of initial, naïve segmentation (216 parts); (d) highlight of location of example failed component, this initial segmentation fails, there are still overhangs; (e) closeup view of module with overhang.

In recursive segmentation, the large model is initially split into four parts. This is the coarsest segmentation that allows for some parts that meet the criteria. Then, only those parts which did not meet the criteria (they still have overhangs) are recursively segmented until overhangs are gone. This process is visually outlined in detail in Figure 2 and results in 17 unique parts.

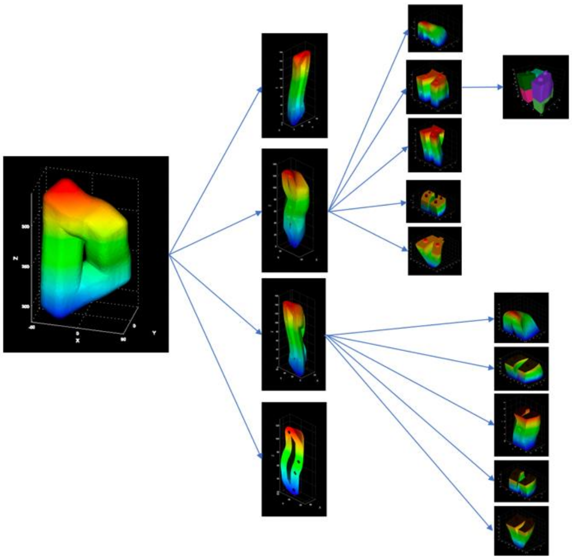

Fig. 2: Depiction of a recursive segmentation case study for complex mold generation. Three levels of iteration were required to meet the convergence criteria of 'no inner surface overhangs', resulting in 17 unique components.

In the recursion step, parts that did not meet the criteria are re-segmented (See Figure 2). They are imported in to LuBan as new designs and re-segmented, in the same manner that the initial complete part was segmented. The results of this segmentation are a new set of 7 smaller modules (See Figure 2). Each of these re-segmented modules satisfied the criteria of no overhangs with respect to the mold surface. After this procedure, the entire model now consists of 17 parts. The final step is to print all the components, assemble the array and create a silicone casting. The cast model is shown in Figure 4.

Fig. 3: Case study of an applied casting process. This type of complex casting could have applications such as customized medical implants. The figures above are the: (a) printed modules, (b) integrated model with silicone injected, (c) cast model.

To empirically evaluate the effectiveness of this recursion process, a cost analysis is undertaken. In many machining processes, cost is proportional to surface area. In a case where this CAD process was used to produce a precision mold to cast a part for actual use, such as medical-grade prosthetic for example, cost would be proportional to surface area (assuming a medical grade mold was produced by CNC machining metal modules). This is because any precise surface requires machining. Subtractive machining cost is generally proportional to total part surface area. Industrial mold making also typically indicates higher cost in proportion to the number of parts in a mold for the same reason. A comparison of cost using a one-step segmentation versus a recursive process follows in Table 1.

Such a mold would generally not be manufacturable (except as a sacrificial mold) without segmentation. Further, recursion could equate to a substantial cost reduction in the production of this complex mold. Notice that the production surface area for the single step segmentation process of the same mold is substantially greater, by approximately a factor of 5 times.

| ***Approach*** | ***Surface Area*** |
|---|---|
| Single step segmentation | ~ 0.4 $m^2$ |
| Recursive segmentation | ~ 0.09 $m^2$ |

Tab. 1: Comparison of surface area (as a proxy for cost) by two methods

<u>Exemplar Case Study 2, Large Scale Print:</u>
A second case is provided in which a large and complex model is produced using segmentation with build volume as the convergence criteria. The model is too large to be printed on the target machine as a single piece. This case demonstrates reduction of print time and the ability to produce parts outside the build volume of the target machine. This process can add value if parts are produced in parallel (to reduce time) and in smaller segments (to produce a large model), See Figure 4 on the next page.

<u>Discussion and Conclusions:</u>
This study presented a high-level process for recursive segmentation that can enable the production of large or complex molds for casting as well as the production large complex models using a fixed bed size volumetric production method such as fused deposition modelling, or FDM printing.

The first case study demonstrates that recursive segmentation can reduce model cost for when producing complex molds for casting. The requirement for segmentation is that “no part shall have an overhang on the part surface”. Recursive segmentation of the base model results in a set of 17 smaller modules that were without overhangs. This approach enables the automated generation of a

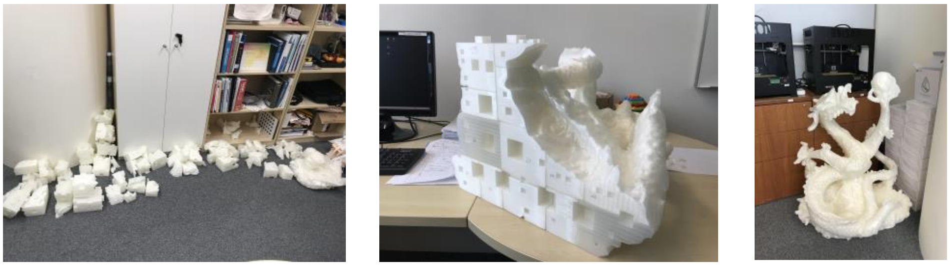

Fig. 4: Chinese dragon sculpture composed of 129 components, with 1000mm by 800mm by 600mm bounding dimensions. (a) Printed components, (b) partial integration, (c) final integration.

complex mold. The second case demonstrates production of a large scale, complex model, directly using a single segmentation phase followed by subsequent parallel FDM printing and assembly.

Recursive segmentation could be applied to other metrics such as maintaining a surface feature tolerance and allowing smaller parts to be printed on a high-resolution machine and larger parts to be printed on a lower resolution machine. This could enable targeted precision in production. For this study, the module segmentation for fixed volume was executed automatically, while the mold segmentation was executed manually, both were executed within the LuBan software.

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