Simplified Production of Large Prototypes using Visible Slicing

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ABSTRACT

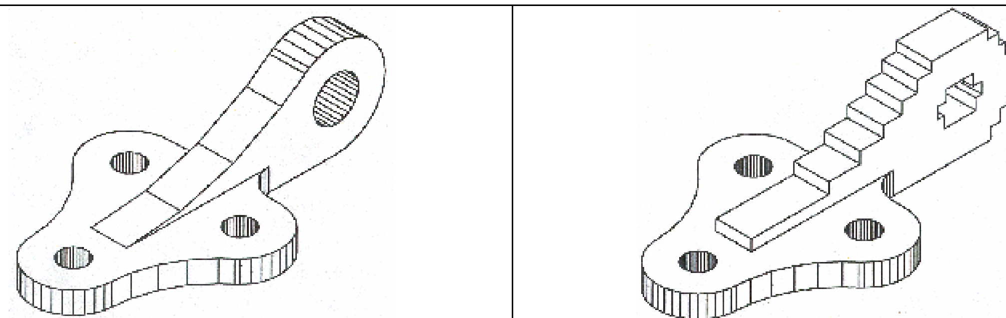
Rapid Prototyping (RP) is a totally automatic generative manufacturing technique based on a "divide-and-conquer" strategy called 'slicing'. Simple slicing used on 2.5-axis kinematics of the existing RP machines is responsible for the staircase error. Although thinner slices will have less error, the slice thickness has practical limits. Visible Slicing overcomes these limitations. A few visible slices exactly represent the object. Each visible slice can be realized using a 3-axis kinematics machine from two opposite directions. Visible slicing is implemented on Segmented Object Manufacturing (SOM) machine under development. SOM can produce soft large prototypes faster and cheaper with accuracy comparable to that of CNC machining.

Keywords: Rapid Prototyping, CNC machining, Visibility.

1. Introduction

CNC machining, a *subtractive* manufacturing method, is the most accurate process capable of producing objects out of any material. However, it requires human intervention for generating the cutter paths. The difficulty in developing foolproof CAPP systems for subtractive manufacturing led to the development of *additive* or *generative* manufacturing methods popularly known as *Rapid prototyping (RP)*. Essentially RP is a CNC machine with an embedded CAPP system for generative manufacturing. Total automation in RP is achieved through a "divide and conquer" strategy called *slicing*. While slicing simplifies a 3D manufacturing problem into several 2D manufacturing problems that could be automated, it is the slicing that also introduces a staircase effect; the resulting stair step errors limit severely the accuracy of the rapid prototypes (Figure 1). In other words, to achieve total automation by limiting the motions to 2.5-axis kinematics, existing RP processes compromise on accuracy. The accuracy can be improved by choosing very thin slices but that would increase the time for producing the prototype thereby enhancing the cost prohibitively. Furthermore, the surface finish of the rapid prototypes can hardly match that of the CNC machined parts as the minimum layer thickness has practical limits. Therefore, ways and means to increase the slice thickness without sacrificing accuracy have been explored by many researchers.

The slices of all commercially available RP machines are of uniform thickness and have their edge surfaces vertical, i.e., both the bottom and top contours of the slice are the same. This type of slicing is called *uniform slicing of 0^{th} order edge surface* [1]. As the number of slices is very high in these RP machines, researchers have been exploring various ways to reduce it. This led to the proposals for *adaptive slicing* by several researchers. Adaptive slicing results in less number of slices than uniform slicing for the same accuracy. In adaptive slicing, the slice thickness at any location depends on the local geometry, particularly, normal and curvature. Furthermore, in addition to 0^{th} order edge surfaces, researchers have considered the use of 1^{st} order, 2^{nd} order or even higher order edge surfaces as illustrated in Figure 2; the 1^{st} order edge will be a ruled surface, the 2^{nd} order edge will be a quadratic surface and so on. The prismatic surfaces of the slices with 0^{th} order edge can be realized with 2.5 axis kinematics; Single axis in conjunction with a mask will also do as in the case of *Solid Ground Curing (SGC)* and micro photolithography machines [2, 3]. The ruled surfaces can be realized using end milling, wire EDM or laser machining which may require upto 5 axes. For a given accuracy required, higher the order of edge surface, less is the number of slices. *Hybrid Layered Manufacturing (HLM)*, *Solvent Welding Freeform Fabrication Technique (SWIFT)* and *Thick-Layered Manufacturing (TLM)* are some efforts in these directions [1, 4, 5]. However, these methods use the traditional "generative or additive approach" of RP and hence (i) they inherently produce only approximations of the objects, (ii) the reduction in the number of slices is not substantial and (iii) they suffer from severe implementation difficulties in realizing the higher order slices. Therefore, manufacturing objects in thicker slices without sacrificing accuracy on simple machines has been the dream of researchers for quite sometime.



(a) CAD model

(e) Physical prototype with stair steps

Figure 1 Staircase Effect in RP

The first attempt towards this goal was in SDM process [6]. SDM makes use of two deposition heads, one each for depositing model material and a suitable support material. The slices of the object are obtained by splitting it wherever its normal just becomes horizontal, i.e., wherever its Z component changes its sign. To that extent, SDM also uses visibility considerations for slicing. In any slice, the normals of the object may be upward or downward. In all regions of the slice where the normals are downward, support is required there and hence the support head deposits material filling those regions. Since any such deposition is only near-net, machining is used to finish it. This is followed by the deposition of model material and again finishing it using machining. Thus each slice is built by deposition and machining of support and model materials alternately until the entire slab of the slice is complete. Essentially, the previous region(s) deposited and machined act as mold cavities to hold the subsequent depositions. In SDM, slicing and the subsequent process planning to determine (i) the various regions for any layer, (ii) the order in which these regions are to be deposited and (iii) the tool path for deposition and machining of each of these regions, are all too involved.

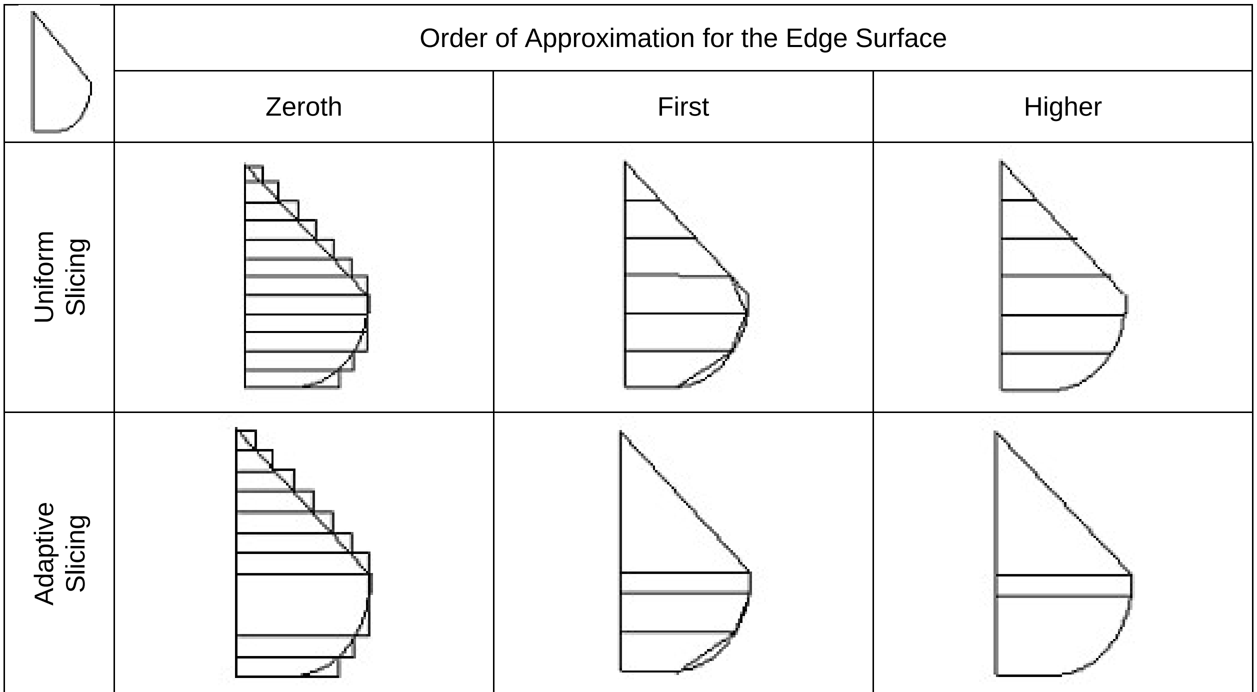


Figure 2 Various Slicing Methods

The research group of K. Lee has proposed a *Hybrid RP (HRP)* process which also aims at building objects with minimum number of slices [7]. They first identify and separate machinable features and suppress them. The resulting geometry is only sliced for HRP. Each slice which is quite thick is built through the near-net material deposition and net-shape machining. Although this process claims to produce objects with minimum number of slices, it requires fair amount of user input to determine the machinable features and the levels at which slicing is to be done.

Similar segmentation approaches can be observed in a few other applications. “100 day engine project” carried out by Ford is one such example [8]. In order to reduce the engine development time, they split the engine casting into slices of appropriate thicknesses manually; these slices were machined and then joined by brazing. Another example is *Space Puzzle Molding* process from Protoform of Germany which can automatically design the injection molding dies of very complex objects in pieces that constitute the die halves and inserts [9, 10]. These pieces fit together in a special frame like a 3D jigsaw puzzle. Molds are manually assembled and disassembled during each shot. Chen and Rosen also have proposed a method of automatically obtaining the injection mold in pieces from the CAD model of the plastic object [11, 12]. Karunakaran et al. have developed a software program called OptiLOM which eliminates grid cutting and decubing operations in LOM-RP [13]. In order to extract the LOM prototype from inside a box, OptiLOM splits the material inside and surrounding the object into the minimum number of extractable pieces; when the combined STL file of all these pieces and the object are made in LOM machine, there will be no grid cutting and decubing. The stock halves and the plugs calculated by OptiLOM essentially are the mold halves and inserts. While the above three works, viz., the work of Chen and Rosen, Space Puzzle Molding and OptiLOM, aim at obtaining the molds of an object, albeit in pieces, visible slicing proposed here aims at splitting the object itself into segments each of which satisfy certain manufacturability criteria, viz., cutter access to the entire surface of the segment either from top or bottom. Interestingly, Dongwoo and K. Lee too have addressed the problem of splitting an object such as a stamping die into pieces machinable from two opposite directions [14]. However, they aim at splitting the object into a minimum number of such machinable pieces so that they can be machined individually and then glued together; the pair of machining directions corresponding to each piece could be different in their method.

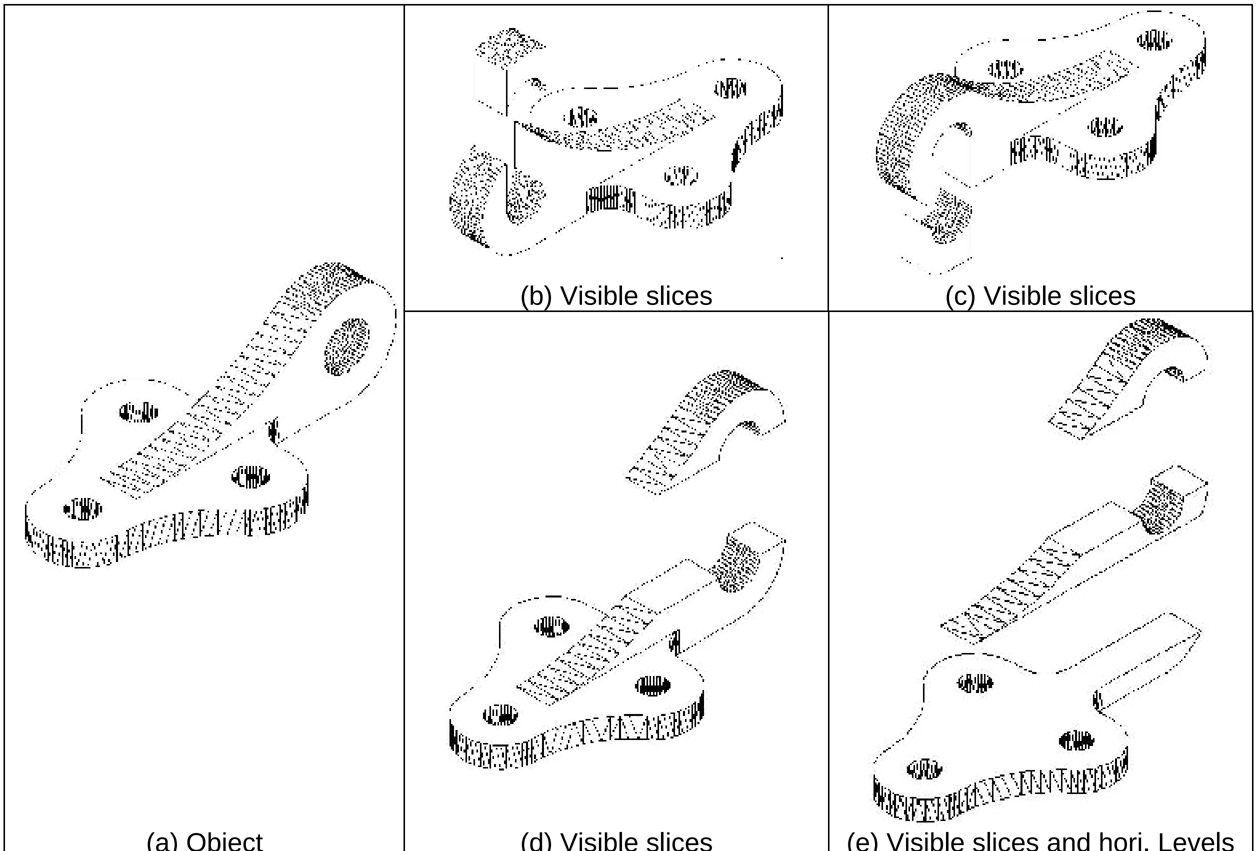
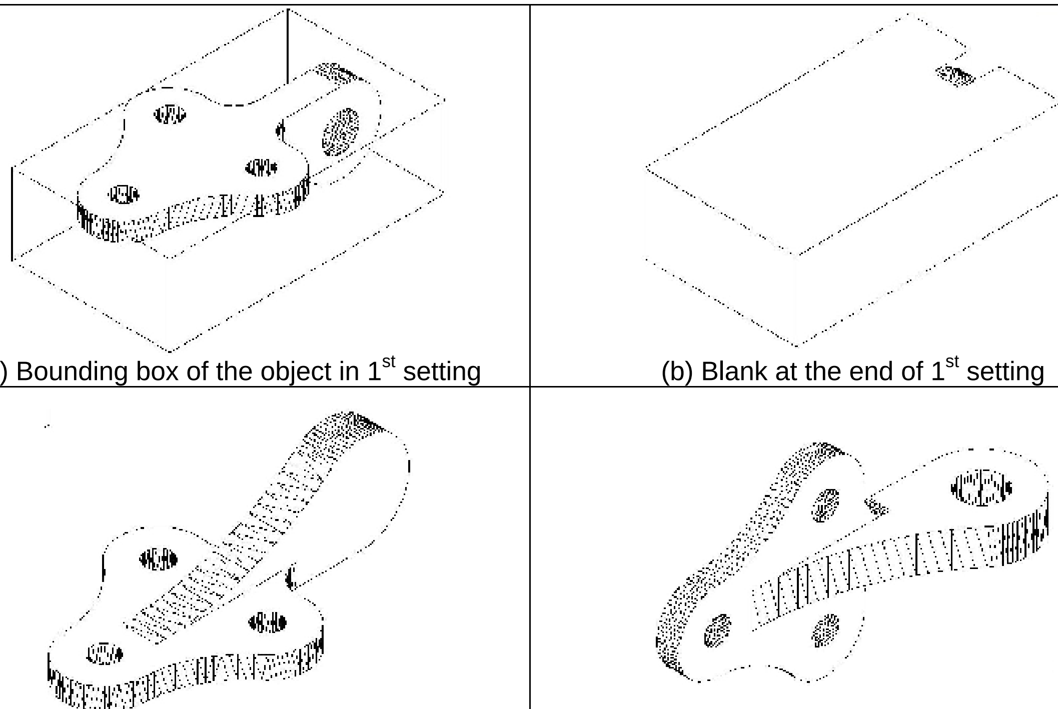


Figure 3 Illustration of Visible Slicing

The literature review in slicing reveals several technology gaps. The existing slicing method, viz., *uniform slicing of 0th order edge*, used in popular RP machines gives rise to staircase effect which in turn is responsible for approximation in the prototype geometry, poor surface finish, large number slices and high cost. Emerging RP machines that make use of *higher order adaptive slicing* continue to follow the traditional generative approach. Hence the prototypes are still approximate albeit better than their predecessors. They use higher axis kinematics which is too expensive and fool proof CAPP for subtractive manufacturing required for these systems is still not available. Emerging RP machines that make use of *hybrid approaches*, viz., combination of additive and subtractive processes, suffer from severe implementation difficulties in realizing the slices. There has been a longstanding need to develop a process that will use thick slices that conform exactly to the object. These need not have parallel top and bottom planes. In other words, what is required is splitting the object into segments wherein the segmentation is based on manufacturing considerations without sacrificing accuracy. These slices can be realized using a 3-axis kinematics. The final implementation of Visible Slicing may be a hybrid machine.

2. Visible Slicing

In the conventional slicing strategies, the slice thickness and the part accuracy are closely related. As against this, visibility is used as the criteria for determining the slice thickness in the proposed *Visible Slicing*. The object is split into *visible slices*, also known as *segments*. The intersection of any vertical ray with the visible slice will be always a pair of points. When the faces encountered by the ray happen to be vertical, one gets a line segment as intersection in which case the end points of this line segment can be treated as the pair of intersection points. This characteristic of visible slice ensures its machinability by a vertical cutter from two opposite directions. Figure 3 illustrates the concept of visible slicing for an object shown in Figure 3a.



(a) Bounding box of the object in 1st setting

(b) Blank at the end of 1st setting

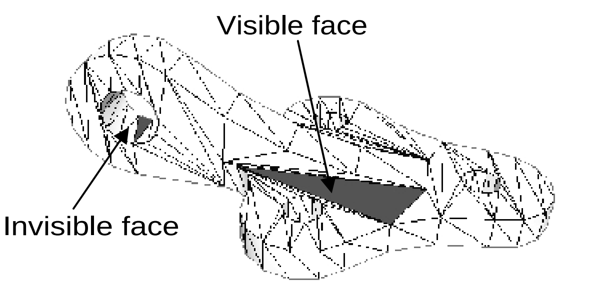
(c) Blank at the end of 2nd setting

(d) Blank at the end of 3rd setting

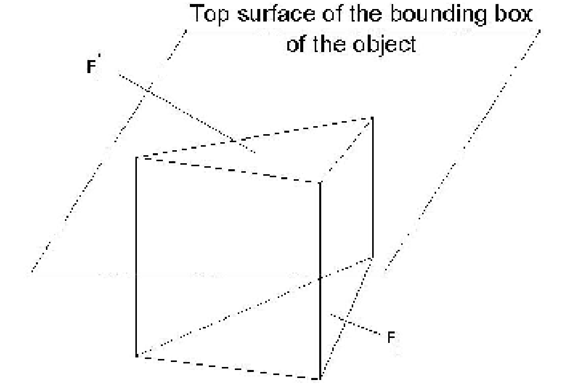
Figure 4 Settings Required in CNC Machining for the Same Object

An object need not have a unique set of visible slices and hence some more variants are possible as shown in Figures 3b-e. Figures 3b & c are the two possible sets of visible slices. The raw material used for realizing these visible slices will be equal but Figure 3d will require the least amount of raw material. Therefore, after obtaining the visible slices, a post-processing is done to transfer materials among these visible slices so as to minimize the total raw material requirement.

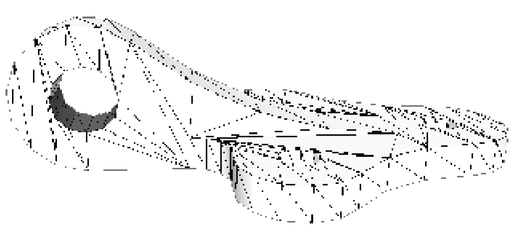
The number of visible slices can be correlated with the number of setups required in CNC machining to produce the object. Figure 4a shows the blank of this object in 1st setting. Figure 4b shows the blank at the end of 1st setting. After reversing the object, the remaining surfaces are machined except the eye-end hole (Figure 4c). Machining this hole requires a separate setting as shown in Figure 4d. It is also possible to machine it in just two settings shown in Figures 4c & d. Therefore, CNC machining, which is purely a subtractive process, requires two to three settings to make this piece from a blank. The same object can be made in just two visible slices (Figure 4d), each requiring machining from top as well as bottom.



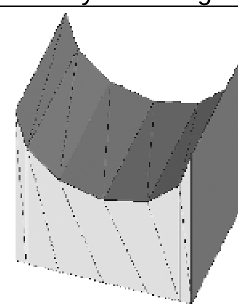
(a) Examples of visible and invisible faces



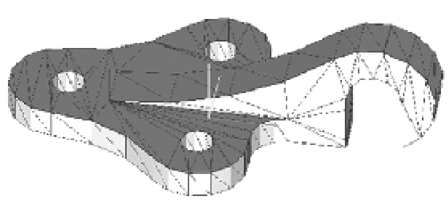
(b) Prism obtained by extruding the face upward



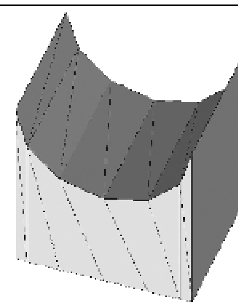
(c) Invisible patch I_p obtained by recursively collecting the invisible faces



(d) Solid S_1 obtained by extruding the invisible patch I_p till the bottom of the bounding box of the manifold solid S_{org}



(e) Segment resulting from ($S_{org} - S_1$)



(f) Segment resulting from ($S_{org} \cap S_1$)

Figure 5 Algorithm for Visible Slicing

If the slicing is accurate enough, the horizontal surfaces of the object can be obtained during the slicing operation itself whereas the non-horizontal surfaces will require machining in scan milling. Therefore, after obtaining the set of visible slices that have the least heights, the authors prefer to split them further if any of the slices have large horizontal surfaces. Accordingly, the preferred set of slices for this object will be the one shown in Figure 3e. This is obtained from Figure 3d by splitting the bottom slice at its horizontal surface.

Algorithm for Visible Slicing

A face of the solid will be called *invisible face* if (i) its normal is upward and (ii) it is shadowed by its other faces; otherwise, it will be called a *visible face*. These are illustrated in Figure 5a. A contiguous set of invisible faces is called *invisible patch*. The segments of the object will be identified in a top-down manner in this algorithm. Let S be the set of visible slices or segments. Algorithm 1 converts the object O into the set of visible slices S. It produces visible slices but they could be more in number with the possibility of combining some of the segments into one segment without affecting the visibility. This post-processing is done by Algorithm 2.

Algorithm 1 Algorithm for Determining the Visible Slices

```
Initialize S with O.

For each member of S, say S_i,
{
   status = Segment(S_i, S_segments);
   If status = true, then continue as S_i is already a visible slice;
   Else remove S_i from S and add its segments S_segments at the end of S;
}
```

Algorithm 2 Algorithm for Post-Processing to Combine Visible Slices Wherever Possible

```
For each member of S, say S_i,
{
   For each member of S, say S_j,
   {
      Continue if i = j;
      Continue if S_i and S_j do not overlap along Z direction;
      S_new = S_i ∪ S_j;
      status = Segment(S_new, S_segments);
      If status = true, // This means that S_new is a visible slice
      {
         Replace S_i by S_new;`
         Remove S_j from S;
      }
}
```

Function 1, viz., `Segment` takes a manifold solid S_{org} as input. If S_{org} is already a visible slice, it returns "`status = true`"; otherwise, it returns "`status = false`" and also calculates the segments $S_{segments}$ of the original solid S_{org}. Note that $S_{segments}$ will be an array of manifold solids but these may or may not be visible slices.

Function 1 Function to Split the Given Solid S_{org} into Its Segments $S_{segments}$

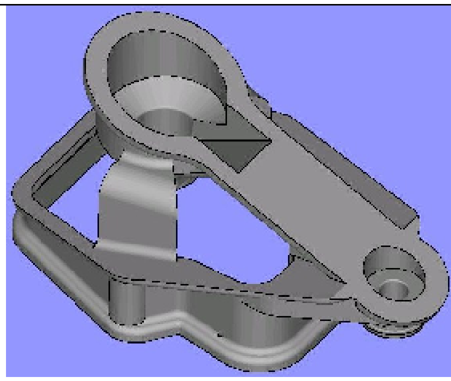
```
status Segment ( S_org , S_segments )
{
   Status = false; // Initially assume that S_org is not a visible slice.

   Step 1: Identifying the first invisible face:
   ---------------------------------------------
   For every face F_i of the input manifold solid S_org ,
   {
      Let F_i' be the projection of F_i on the top of the bounding box of S_org .
      Make an extruded solid P between F_i and F_i' (see Figure 5b).

      For every face F_j of S_org ,
      {
         If (i==j), Continue;
         If ( F_j is below F_i ), continue;
         If F_j intersects P ,
         {
            status = true; // F_j is the first invisible face. So break.
            break;
         }
      }

      if (j > number of faces of S_org ),
      {
         status = true; // Declare that the input solid as a visible slice.
         Return; // The object is already a visible slice.
      }

      If (status = true) break;
   }

   Step 2: Recursively growing the first invisible face F_j into an
   invisible patch I_p :
   ----------------------------------------------------------------
   Initialize the invisible patch I_p with F_j ;
   while (true)
   {
      For each of the three neighboring faces of F_j , say F_i ,
      {
         For every face F_k of S_org ,
         {
            If F_k is not same as F_i , continue;
            If F_k lies outside the X and Y extents of F_i , continue;
```

```
            If F_k is below F_i, continue;
            If the projections of F_i and F_k in XY plane intersect
            {
               add face F_i to the invisible patch, I_p;
               Set F_j = F_i;
            }
         }
      }
      If none of the three F_i is added to I_p, break the while loop as
      construction of the invisible patch I_p is complete; // see Figure 5c
   }

   Step 3: Obtaining the segments S_segments from the invisible patch:
   ---------------------------------------------------------------
   Make a solid S_1 by extruding I_p till the bottom of the bounding box of
   S_org (see Figure 5d).

   Calculate (S_org - S_1) and (S_org n S_1). These are shown in Figures 5e and
   5f. These two solids are two segments of S_org.

   If these are non-manifold solids, split them into manifold solids. All
   these manifold solids will be returned as S_segments. Note that all the
   elements of S need not be visible slices. Note also that S_1 and (S_org n
   S_1) are same in the illustration of Figure 5 (d and f); however, this may
   not be the case always.
```

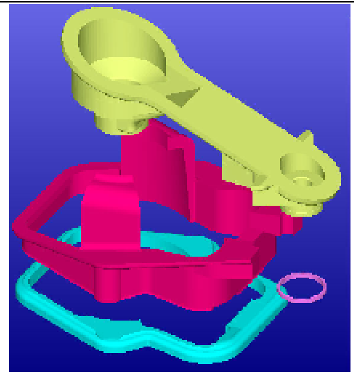
3. Illustrative Example

Gear lever housing, a fairly complex object shown in Figure 6a, was taken for illustrating the principle of visible slicing. The visible slicing program of the authors was able to split this object into 4 visible slices or segments. These segments are shown in exploded view in Figure 6b. These visible slices were built using FDM 1650 RP machine; they could have been made using a 3-axis CNC machine as well. These four physical segments are shown in Figures 6c-f. The final physical object shown in Figure 6g was obtained by gluing these segments.

The machine being built by the authors called *Segmented Object Manufacturing (SOM)* will be able to produce this object automatically as explained in the previous section [15]. The authors have developed the software for automatically generating the cutter path for machining the visible slices using a single ball nose end mill. However, it is desirable to develop software that would make use of ball, bull and flat end mills of different diameters intelligently. Furthermore, more fine-tuning of the post-processing part of visible slicing algorithm is desirable to transfer material among layers to minimize height.

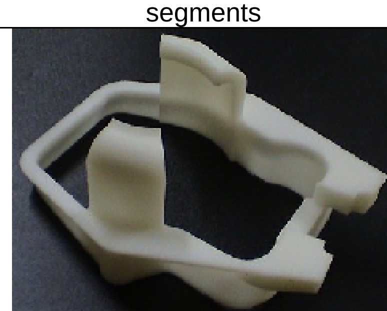


(a) Gear lever housing to be built



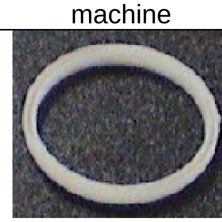
(b) Exploded view of the visible slices or segments

(c) 1st visible slice made on FDM 1650 RP machine

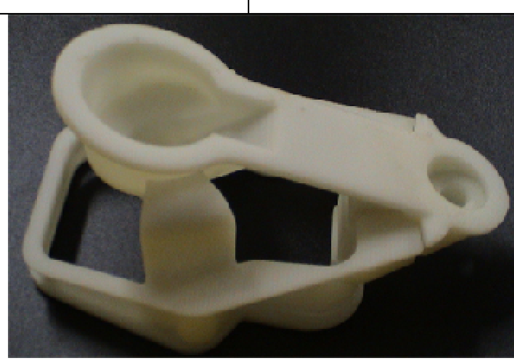


(d) 2nd visible slice made on FDM 1650 RP machine

(e) 3rd visible slice made on FDM 1650 RP machine



(f) 4th visible slice made on FDM 1650 RP machine



(g) Visible slice assembled into gear lever housing

Figure 6 Illustration of the Manufacture of a Gear Lever Housing Using SOM Principle

6. Conclusions

Existing RP machines produce 3D objects by assembling their 2D approximations called slices. Hundreds of thin slices constitute the object so as to make it reasonably accurate. On the contrary, visible Slicing splits the object into a few exact chunks called visible slices or segments which are automatically machinable from two opposite directions on a 3-axis machine. This novel slicing method is implemented in a new RP process under development called Segmented Object manufacturing (SOM). SOM will be useful for making soft large prototypes automatically, accurately, quickly and economically. Particularly it will be useful for manufacturing patterns of Evaporative Pattern Casting (EPC). The principle of SOM can be used for manufacturing even hard objects using CNC milling semi-automatically; blocks of the required thickness can be machined on two opposite faces to get the visible slices which can be joined using fastening, adhesive bonding or brazing depending on the application requirements. It is interesting to note that SOM and a few other RP processes (like SDM, HLM and TLM) that aim at manufacturing objects in thick layers heavily depend on machining. In other words, the conventional wisdom of RP being an additive or generative process may no longer hold good.

References

1. Karunakaran, K.P., Shanmuganathan, P.V., Jadhav, S.J., Bhadauria, P. and Pandey, A. (2000): “Rapid Prototyping of Metallic Parts and Moulds”, J. of Materials Processing Technology, Vol. 105, pp. 371-381.
2. Chua Chee Kai and Leong Kah Fai (1997): *Rapid Prototyping: Principles and Applications in Manufacturing*, John Wiley & Sons.
3. M.Farsari & others (2000): “A novel high-accuracy microstereolithography method employing an adaptive electro-optic mask”, *Journal of Materials Processing Technology*, 107, 167-172.
4. Taylor, J.B., Cormier, D.R., Joshi, S. and Venkataraman, V. (2001): “Contoured Edge Slice Generation in Rapid Prototyping via 5-Axis Machining “, Robotics & CIM, Vol. 17, pp. 13-18.
5. Broek, J.J., Horváth, I., Smit, B., Lennings, A.F., Rusák, Z. and Vergeest, J.S.M. (2002): “Freeform Thick Layer Object Manufacturing Technology for Large-Sized Physical Models”, Automation in Construction, Vol. 11, pp. 335-347.
6. Krishnan Ramaswamy (1997): ”Process Planning for Shape Deposition Manufacturing”, Ph.D. Dissertation, Department of Mechanical Engineering, Stanford University.
7. Junghoon Hur, Kunwoo Lee, Zhu-hu, Jongwon Kim (2002,): “Hybrid Rapid Prototyping System Using Machining and Deposition”, Computer Aided Design, Vol 34, pp. 741-754.
8. http://rapid.lpt.fi/archives/rp-ml-1997/0366.html (2004): Email Communication of Prof. Ian Gibson to RPML group.
9. www.protoform.com (2004): Web site of Protoform, Germany.
10. http://www.enimco.com/puzzle.html (2004).
11. Chen, Y., Rosen, D.W. (2003): “A Reverse Glue Approach to Automated Construction of Multi-Piece Molds”, Journal of Computing and Information Science in Engineering, Vol. 3, No. 3, pp. 219-230.
12. Chen, Y., Rosen, D.W. (2001): “A Region Based Approach to Automate Design of Multi-Piece Molds with Applications to Rapid Tooling”, Proceedings of ASME Design Engineering Technical Conference, September 9-12, Pittsburgh, Pennsylvania.
13. Karunakaran, K.P., Shivmurthy Dibbi, P. Vivekananda Shanmuganathan, Srinivasarao Kakaraparti and D.Sathyanarayana Raju (2002): "Efficient Stock Cutting in Laminated Manufacturing", Computer-Aided Design, Vol 34, No. 4, pp. 281-298.
14. Dongwoo Ki and Kunwoo Lee (2002): “Part Decomposition for Die Pattern Making”, Journal Material processing Technology, Vol. 130-131, pp. 599-607.
15. K.P. Karunakaran, Saurabh Agrawal, Pankaj D. Vengurlekar, Onkar S. Sahasrabudhe, Vishal Pushpa and Ronald H. Ely (2005): “Segmented Object Manufacturing”, *IIE Journal of Design and Manufacture*, Vol. 37, No. 4, pp. 291-302.