Implicit modeling for additive manufacturing

Contact : Sylvain Lefebvre (sylvain.lefebvre@inria.fr) and Cédric Zanni (cedric.zanni@loria.fr)

Team : Alice, LORIA (Laboratoire Lorrain de Recherche en Informatique et ses Applications)

Context

Additive Manufacturing (AM) technology distinguishes itself from more traditional fabrication processes by several significant factors. It allows the creation of objects with complex geometry that would not be possible by subtractive manufacturing or molding. Additionally, 3d printers are of much simpler use than other tools. Finally, since the cost per objects does not change depending on the size of the production run, it allows for per object customization. These reasons, combined with the relatively low cost of some existing 3d printers, explain the interest taken in this technology by the general public. While *fabrication* of a given object is simplified by AM, it is not the case of the *modeling* of the geometric model that represents an object.

Existing geometric modelers tend to remain of complex use: the creation of 3d objects often requires as much technical skills as creativity. In the context of object personalization, this is accentuated by the fact that a potential user would need as much expertise as the original designer in order to simply modify the object, e.g. through deformations. Indeed, deformation techniques generally consider only the geometry and not the functionality of the objects. In the context of fabrication, this problem is accentuated by the most commonly used object representations: meshes and b-reps. In order to represent volumes, the latter should verify some properties: defining a 2-variety, being watertight and not presenting self-intersections. In addition, meshes do not intrinsically define smooth surfaces; their resolution should be adapted to the scale of the print, adding an additional parameter which the user should choose carefully.

On the other hand, implicit surfaces, due to their volume definition ($\{P|f(P) \geq 0\}$), do not face these problems **[HWC13]**. For instance, for a given slice of a model it is straightforward to extract an image representing the inside/outside property of each pixel by simply computing the sign of f for each pixels. One of their main advantages is the facility to create complex shapes by combination of simpler ones thanks to the combination of smooth blending **[Blinn82]** and sharp CSG **[Ric73]** operations. This property notably allows the representation of shapes of arbitrary topology. Recently, the two main drawbacks - cost of visualization **[GPP*10,RLD*12]** and precise control of blending **[BBCW10,GBC*13,ZBC15]** - limiting their use in practice have started to be overcome.

Objectives

However, implicit surfaces did not receive as much attention as meshes and a number of **fundamental challenges remain** in order to use them **efficiently** for **modeling and personalization** of both artistic and technical shapes in an **Additive Manufacturing context**.

1. *How to provide precise control over the shape generated by implicit surfaces while allowing efficient analysis and processing of the defined volume ?*

Being able to control precisely some properties of the object during modeling is essential when targeting fabrication. For instance, minimal thickness of the shape is important in order to guarantee fabricability: thin features which thickness are around machine precision might not be printed correctly, the limit thickness might also depend whether a wall or a spike is printed. Topology is also important as it can be part of the functionality of an object (a tube used to transport a fluid). Depending on the AM technology used, other properties such as angles with respect to the printing direction are also important. We should not only be able to control these properties but also be able to measure them easily for shape processing. By robustness, we mean that the sliced object properties (topology, thickness) should be preserved, and the process optimally used, especially if it can accurately reproduce curves.

2. *How to obtain a fast and reliable slicing (and visualization) of implicit volumes ?*

Contrary to B-rep and meshes, implicit surfaces do not provide an explicit representation of the surface which is problematic for their visualization. In order for implicit surfaces to be accepted as a modeling tool, their rendering should be performed in real time (even for large models) to provide an acceptable user experience. Furthermore, when it comes to slicing (required in order to generate the code driving the fabrication tool), robustness is paramount if the fabricated object are to be used in sensitive domains (such as medical engineering).

3. How can we simplify the modeling and personalization of volume models ?

In order for implicit surfaces to be usable in practice, it also requires that objects can be modeled rapidly: this requires non destructive deformations. Furthermore, allowing parametrization of object limits the amount of work needed to create new ones (as it simplify re-use of subparts of objects) and allows to adapt an object to a new context of use (e.g. a new patient for medical application). To allow such type of modeling, it is very important to model points on the surface either to serve as handle to drive deformations or to define constraints such as contacts. However, it is very difficult to define such points on an implicit surface and track them through its evolutions. Finally, parametrization of an object should not only depend on its geometrical properties but also on its functionality.

4. How can we described gradient of properties inside the volume ?

Additive manufacturing allows to fabricate complex objects containing several materials or micro-structures. A major interest of those structures is to enable the fabrications of an object with a precise control over its properties such as controlling a trade-off between lightness and resilience. While there is a lot of work describing the micro-structures themselves, only few study the problem of describing their variations in space (e.g. by defining gradients of properties and sharp transitions). Such descriptions with traditional representations (meshes) is not manageable due to their surface nature and the sheer amount of data that would be required.

The proposed research is regrouped in three main axes with an additional transversal study. First, implicit surfaces representations,should be revisited. Contrary to previous works, we intend not only to improve blending behavior but also to design a mathematical model such that the processing of the resulting volume is simplified. Secondly, the development of visualization and processing algorithms that are both fast and robust will be targeted. We will notably investigate the use of direct rendering methods for slicing implicit surface as well as filtering for the case where the shape is too detailed for the printing resolution. Developed algorithms should use both the mathematical properties of the field function and be well adapted to the massive parallelism of the GPU. Then, the next goal is to develop dedicated modeling techniques that are well adapted to the creation of objects that can be parametrized. In order to do so, constraints between different elements that are not explicitly defined should be introduced: it is necessary to be able to apply position and contact constraints between points on implicit surfaces and relate those to the implicit surface parameters. Finally, those works should be extended to the control of gradient of properties. Indeed, the same problematics arise with multi-materials: guaranteeing the topology of each group of materials in presence of sharp transitions, efficient visualization and slicing.

One important aspect of this proposal is the restriction to a subset of implicit surfaces which should allow more optimizations of the rendering algorithms and of the scalar field evaluations. Indeed, efficiency of computation have always been a major concern when using implicit surfaces, however, a large part of previous work do not make any assumption on the representation and assume very generic function definition for the field f which limit the range of optimizations that can be applied. Since we are targeting fabrication of objects with complex geometry (to prove usability in real applications), we will strive to assess robustness and efficiency of the developed methods on such objects. We will only use primitives that have either a compact support or for which a bounding volume can be computed given a limit scalar value (e.g. such that a given primitive only has a local influence on the surface). Therefore, challenges will mainly be targeted for a subset of implicit representation verifying such property, namely in the context of skeleton-based implicit surfaces and basic geometric primitives (spheres, cubes, cylinders, cones). The reasons are that those representations are compact and expressive (helping for direct manipulation of shape and modeling **[JLW10]**) while still allowing to represent a large range of shapes.

References

[Bli82] J. F. Blinn : "A generalization of algebraic surface drawing". *ACM Trans. Graph. 1*, 3 (July 1982), 235–256.

[BBCW10] A. Bernhardt, L. Barthe, M.-P. Cani, B. Wyvill : "Implicit blending revisited". *Proc of Eurographics, Computer Graphics Forum. 29*, 2 (2010), 367 :76.

[GBC*13] O. Gourmel, L. Barthe, M.-P. Cani, B. Wyvill, A. Bernhardt, M. Paulin, H. Grasberger : "A gradient-based implicit blend". *ACM Trans. Graph. 32*, 2 (Apr. 2013), 12 :1–12 :12.

[GPP*10] O. Gourmel, A. Pajot, M. Paulin, L. Barthe, P. Poulin : "Fitted BVH for Fast Raytracing of Metaballs". *Proc of Eurographics, Computer Graphics Forum. 29*, 2 (2010), 281 :288.

[HWC13] P. Huang, C.L. Wang, Y. Chen : "Intersection-Free and Topologically Faithful Slicing of Implicit Solid", *ASME J. Comput. Inf. Sci. Eng,* 13(2), (2013)

[JLW10] Z. Ji, L. Liu, Y. Wang : "B−Mesh: A Modeling System for Base Meshes of 3D Articulated Shapes". *Computer Graphics Forum* (2010), pp. 469–476.

[Ric73] A. Ricci : "A Constructive Geometry for Computer Graphics". *Computer Journal* 16,2, (1973), 157–60.

[RLD*12] T. Reiner, S. Lefebvre, L. Diener, I. García, B. Jobard, C. Dachsbacher : "A Runtime Cache for Interactive Procedural Modeling". *Computer & Graphics 36,5, Proc of Shape Modeling International* (2012).