A Hybrid Geometric Modeling Method for Large Scale Conformal Cellular Structures

Hongqing Wang [a]
Senior Research Engineer

Yong Chen [b]
Assistant Professor

David W. Rosen [c*]
Professor

[a] 3D Systems, 26081 Avenue Hall, Valencia, CA 91354
[b] Department of Industrial and Systems Engineering, University of Southern California
Los Angeles CA 90089
[c] The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology
Atlanta, GA 30332

* Corresponding Author: 404-894-9668, david.rosen@me.gatech.edu

ABSTRACT

This paper presents a hybrid geometric modeling method to create CAD models of large-scale conformal cellular structures effectively and efficiently. Cellular material structures can be engineered at the mesoscopic scale for high performance and multi-functional capabilities. One type of cellular structure is conformal lightweight truss. A simple method of constructing models of uniform trusses is to pattern unit cells linearly within a CAD system. However, by orienting strut directions and adjusting strut sizes, such trusses can be optimized to achieve superior strength, stiffness, and weight characteristics. For large truss structures, computational and storage complexities cause difficulties in CAD system modeling. In this paper, a new hybrid geometric modeling method by using both solid modeling and surface modeling techniques is developed to directly create tessellated models and automate the geometric modeling process of conformal truss structures efficiently. This hybrid modeling method is intended to support the design, analysis, optimization, and manufacture of conformal truss structures. Examples are presented and the computational efficiency of the hybrid method is compared with the approach of creating the complete solid model of cellular structures. The hybrid geometric modeling method can be generalized to various types of cellular structures as well as other periodic structures.

KEY WORDS

Geometric Modeling, Cellular Structure, Truss Structures, Conformal Structures, Additive Manufacturing, STL

1 INTRODUCTION

Cellular material structures can be designed and manufactured for high performance and multi-functionality. The performance of these engineered cellular materials corresponds to certain geometric configurations of their microstructures. Lightweight truss structure is one type of engineered mesoscopic cellular structure and an example is shown in Figure 1. A truss can be used as the internal structure of a part to achieve material distributions that result in improved strength and/or stiffness and reduced inertia [1-4]. These truss lattice materials can be utilized as an alternative to metallic foam in lightweight structures, but with more configurable material distributions than stochastic metal foams [5]. With the development of additive manufacturing processes (also known as rapid prototyping), the manufacture of mesoscopic truss structures becomes feasible for mesoscale sizes and is more cost-effective than casting for macro-sizes [6, 7]. These developments may enable new applications in industries such as aerospace, automotive, manufacturing, and bioengineering [6, 8, 9]. The manufacturing of mesoscopic truss structures utilizes the unique capability of additive manufacturing processes, which can fabricate parts with virtually any geometry. The STL file format is the de facto CAD model for additive manufacturing processes [7].

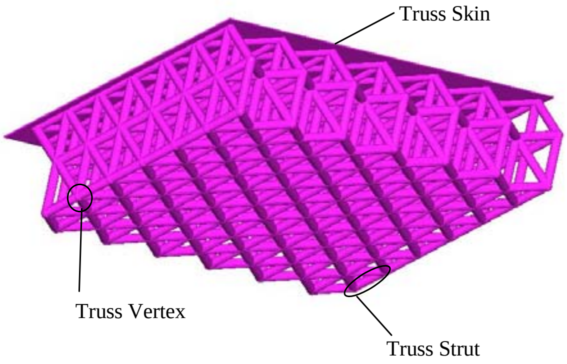


Figure 1 An Example of Uniform Truss

The mechanical performance of a mesoscopic cellular structure is highly dependent on its underlying microstructure (strut topology and pattern). A conformal mesoscopic cellular structure resulting from the optimization of individual microstructures can enhance the structure's performance and be adaptive to the design requirements. In the research of multifunctional cellular structures, Gibson, Ashby, Hutchinson and Evans designed and manufactured uniform octet-truss for the core of flat sandwich panels [2, 4, 8]. The uniform truss is a pattern of unit cells (microstructure) repeated in every direction as shown in Figure 1. However, a conformal truss shown in Figure 2 with variable strut sizes and strut orientations can achieve significantly better performance than the uniform truss [1, 10, 11]. The individual strut sizes in the conformal truss can be adaptively configured through structural optimization. Moreover, a conformal truss topology with struts oriented toward external loads can better distribute loads and help the structure become stretching-dominated, particularly for a one-layer truss structure. Topology means the pattern of connectivity or spatial sequence of members or elements in a structure. It defines the positions of truss nodes (coordinates) and the strut connectivity between truss nodes (start and end).

Figure 3 shows a typical design process for synthesizing conformal cellular structures. It starts with the specifications of design domain and design requirements. The topology and the size specifications result from a design synthesis process, e.g., a multiple objective optimization process for high strength, high stiffness, low material volume, or high heat dissipation rate [1, 11, 12]. Currently, the program implemented by the authors can create topology consisting of octet truss and Kelvin foam truss. The resulting topology and size specifications are used to create the CAD model of the conformal cellular structure through geometric modeling. The obtained CAD model is used for visualization and manufacturing. This paper mainly discusses the issues related to geometric modeling of conformal cellular structures and presents a hybrid geometric modeling method to resolve these issues.

Figure 2 An Example of Conformal Truss

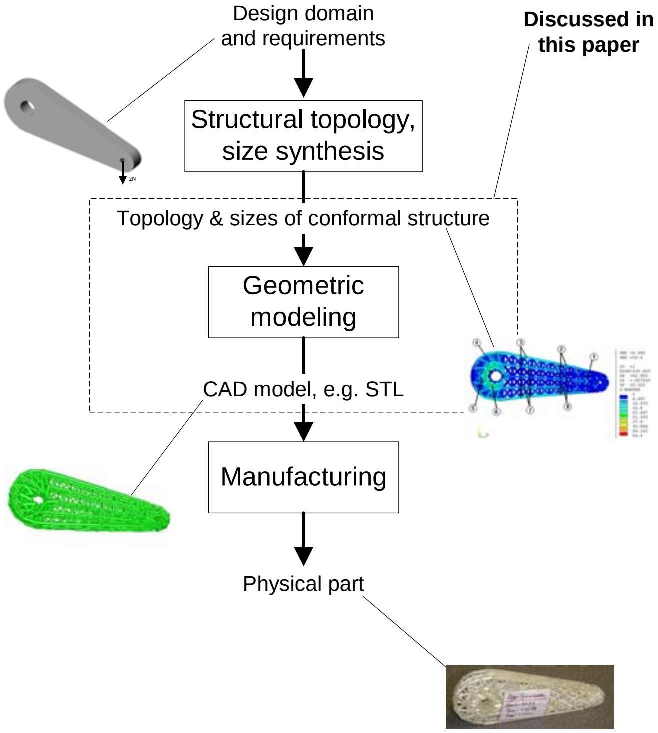


Figure 3 A Typical Design Process of Conformal Cellular Structures Adaptive to Design Requirements

A simple patterning operation with unit cells to create a uniform truss in a commercial geometric modeling package (e.g. Unigraphics, SolidWorks) has significant limitations. First, uniform trusses are not as strong or stiff per unit mass as conformal trusses. Trusses that conform to external shapes and enable synthesis are needed. Second, the construction of solid models of truss structures is limited by the computational demands of many Boolean operations and by memory limitations of computers. We are interested in designing structures with thousands of struts, but such structures are not possible to create using conventional solid modeling technology. In addition, manual construction of truss structures is not feasible due to the overwhelming number of struts in a typical truss structure. Therefore, an automatic design approach should be developed to facilitate geometric modeling of conformal truss structures. The geometric modeling method should support the design, analysis, optimization, and manufacture of conformal truss structures.

This paper discusses and compares two possible approaches that could be utilized to create geometric models of conformal trusses. The first approach is by solid modeling, which creates the complete solid models of truss structures based on a geometric modeling kernel, such as ACIS [13], and then generates their STL models [7] for manufacturing. This approach takes significant computational resources to generate the solid models since Boolean operations are required to add every single strut onto the existing truss part. The second approach is a hybrid geometric modeling method, which creates the STL model for the truss structure directly, without creating a complete solid model of the entire structure. The hybrid method creates an STL model of each unit truss (a selected microstructure of truss structure) using both solid modeling and surface modeling techniques, and then simply stacks all the unit truss tessellated surface (STL) models together without complex Boolean operations to generate the STL model of the entire structure. An STL model is a tessellation of the part surface. Hybrid geometric modeling is superior to solid modeling for this application since it takes significantly fewer computation resources. In this paper, ACIS [13] is used as the geometric modeling kernel. Section 2 discusses the topologies of truss structures and chooses the right microstructure for solid modeling. Section 3 presents the hybrid geometric modeling approach to directly create STL model for conformal truss. Section 4 compares the efficiencies of the solid modeling and hybrid approaches.

2 TRUSS TOPOLOGY AND UNIT TRUSS

Due to the complex geometries of truss structures, truss topologies are used to define the truss node positions and the strut connections [1, 14]. Sample topologies of the octet and Kelvin foam trusses are given in Figures 4 and 5, respectively. The geometries of truss structures are far more complex than those of typical CAD models. However, the individual elements (struts) are described by simple shape primitives. Truss primitives are the basic elements composing the truss structure. They are repeated in certain directions as shown in Figures 4 and 5 and may differ from one another in terms of their size, position, and orientation. The tetrahedron (tetra) is the microstructure (unit cells) of Octet trusses [15]. The truncated octahedron is the microstructure of Kelvin foam trusses [15]. The truss structures can be generated through repeating the primitives in several directions as a pattern of the truss primitives. The geometries of the joints where neighboring microstructures are connected are relatively complicated for a conformal truss due to the struts' sizes and orientation changes. Figure 6 shows that the resulting intersection curves between the solid struts (represented as cylinders) are different from one to other. It is infeasible to simply stack the microstructures together into the entire truss without Boolean operations.

Rather than using tetrahedral, truncated octahedral, or other polyhedral primitives, we have developed a more general primitive with which to construct truss structures. Our primitive, unit truss, consists of a central node and half-struts connected to the central node as shown in Figure 6. Each strut is divided into two half-struts by its middle. In

Figure 7, three connected unit trusses are shown. With this unit truss, we can construct models with octet, Kelvin foam, or other truss structures. The number of half-struts in a unit truss depends on the truss type and the location of the central node. A unit truss with a central node in the middle of an octet truss has 12 half-struts, while a unit cell with a central node at the boundary has 9 half-struts. Another advantage is that the topology of our unit truss is parameterizable and patternable. As shown in Figure 7, unit trusses are connected at the ends of their half-struts with no overlap of their geometry. Therefore, geometric models of unit trusses can be simply stacked after positioned at the desired coordinates. There is no overlap between any two unit trusses. The stacking process does not require any Boolean operations, which demands high computational resources. In the synthesis stage of the design process shown in Figure 3, the topology of a truss structure can be generated by using a parametric modeling method [14], and unit trusses can be patterned parametrically. However, it is very difficult and has no computational advantage to parameterize the solid geometries of the truss structure and the unit trusses due to the geometry variations of the joints shown in Figure 6.

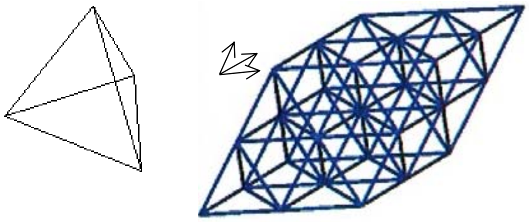


Figure 4 Octet Truss and Tetrahedron Microstructure

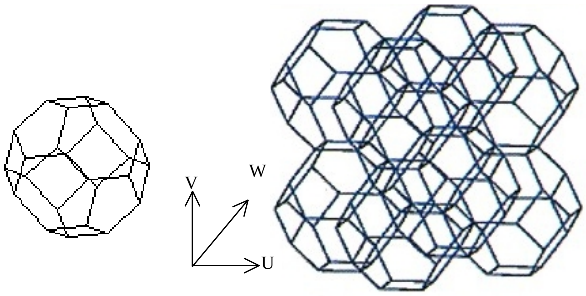


Figure 5 Kelvin Foam Truss and Truncated Octahedron Microstructure

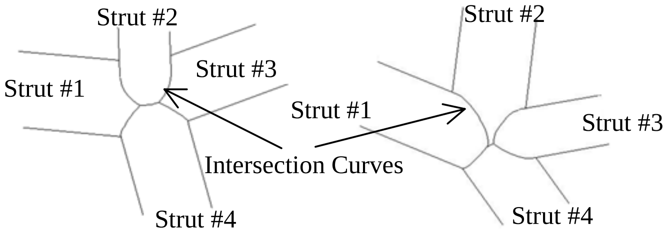


Figure 6 Geometry Variations at Strut Joints Due to Strut Size and Orientation Changes

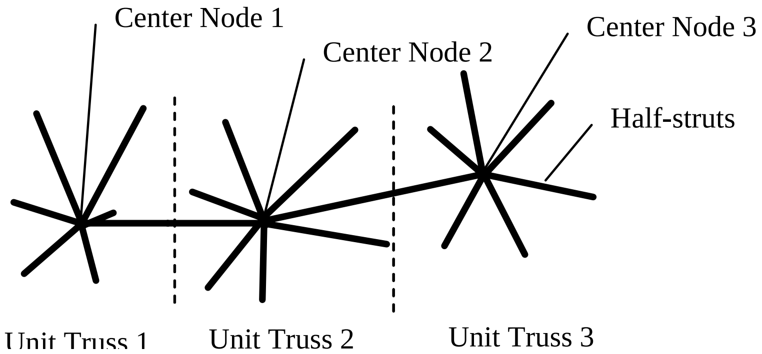


Figure 7 Unit Truss

The proposed hybrid geometric modeling method for constructing STL models of cellular structures is presented here. Inputs to the method are the truss topology and size specifications. The output is the STL model of the entire conformal truss. ACIS is used as the geometric modeling kernel. The overall method of the hybrid geometric modeling approach for a truss structure with N nodes and M elements follows:

Repeat Steps I-IV for all nodes ($i = 0,1,2,\ldots,N-1$) and start with an empty STL model ($STL_{all} = null$) for the structure.

I. Formulate the i^{th} unit truss: find all the struts connected to the i^{th} node among all the M elements; let the half-struts connected to the i^{th} node be $E_{i,j}$ and the struts' diameters be $d_{i,j}$; a total of NE_i struts are found; $j = 0,1,\ldots,NE_i - 1$

II. Create the solid model $ACIS_i$ of the i^{th} unit truss in the form of boundary representation (B-rep).

III. Remove all the NE_i struts' end faces $FACE_{i,j}$ ($j = 0,1,\ldots,NE_i - 1$) from the B-rep model $ACIS_i$ and obtain its STL (faceted) model STL_i using surface faceting.

IV. Simply stack the STL model STL_i of the i^{th} unit truss into the existing STL model $STL_{all} = STL_{all} \oplus STL_i$.

Steps I and IV are straightforward and easy to understand. Steps II and III will be presented in detail in Section 3.

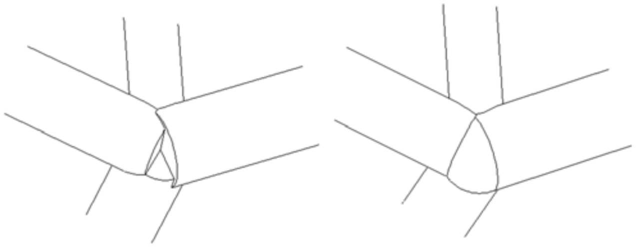
3 DIRECTLY CREATING STL MODELS WITH HYBRID GEOMETRIC MODELING

The presentation of the hybrid geometric modeling method starts with solid modeling of unit trusses, and then geometric modeling of the entire truss structure is discussed.

3.1 Create Solid Model of Unit Truss

During solid modeling of each unit truss in Step II, a sphere is added to its central node to smoothen the joint geometry and avoid non-manifold geometry. It is fairly obvious that the added sphere can smoothen the geometry of the joint where the connected struts meet together. Figure 8 shows how the sharp corners at the joint are removed. The smoothening process not only remove the sharp corners resulting between intersected struts, but also improves the joint's mechanical properties by reducing stress concentrations.

The second purpose of adding a sphere to each central node is to avoid non-manifold entities. Some non-manifold entities may result from solid modeling of unit trusses due to coincident lines or faces. An example is shown in Figure 9, where three cylindrical struts with equal diameters meet together at a common joint, Node A. The intersection edge, Curve E, between Strut 1 and Strut 2 is indicated as a bold line. The curve E is on the end faces of both Strut 1 and Strut 2. If a new cylinder, Strut 3, is united with the existing union model of Strut 1 and Strut 2, the curve E would be on the end face of Strut 3. So three faces would share the edge, Curve E, and the resulting union geometry is non-manifold [16]. Non-manifold geometry also appears when two collinear struts with the same diameters are united by a Boolean operation. This 2-manifold joint model and the boundary are not topologically equivalent. According to the topology of edges and faces, one edge can only belong to two faces at the same time in the physically realizable entities. Edges belonging to more than two faces cannot be realized in ACIS R7 [17]. Although the recent ACIS releases, such as R13 and R14, can support this kind of non-manifold solids, we still prefer to avoid non-manifold edges since they do not provide any advantages in representing or manufacturing truss structures.



a) Joint Before Smoothening b) Joint After Smoothening

Figure 8 Smoothening Joint by Adding Sphere to Central Node

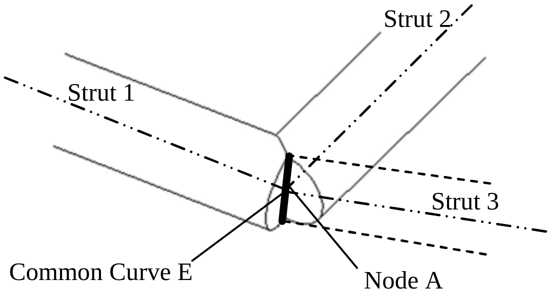


Figure 9 Non-manifold Entities in Truss Structures

Adding spheres to the joints avoids non-manifold entities and the result is shown in Figure 10. The diameter of the sphere should be larger than that of any cylindrical strut incident to the joint's central node. Otherwise, the sphere would not smooth the joint geometry and Boolean operations may result in non-manifold topology. To avoid non-manifold entities, we increase the sphere diameter to be 0.001 percent larger than the largest strut diameter among the cylindrical struts connected to the joint.

3.2 Remove End Faces and Obtain STL Model of Unit Truss

After the solid models (ACIS) of unit trusses are created, the struts' end faces are removed in Step III. All the struts' end faces are planar, not curved, so they are easy to find and remove from the B-rep topology of the entire solid model. The resulting unit trusses are surface models. Figure 11 shows an example of removing end faces of unit truss. All remaining geometry is tessellated using the ACIS faceting tool and converted into STL format.

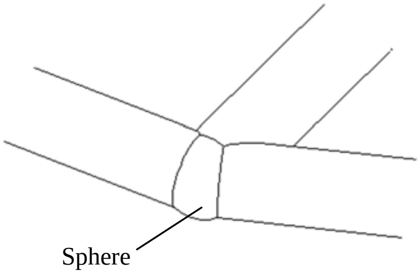


Figure 10 Add Sphere to Avoid Non-manifold geometry

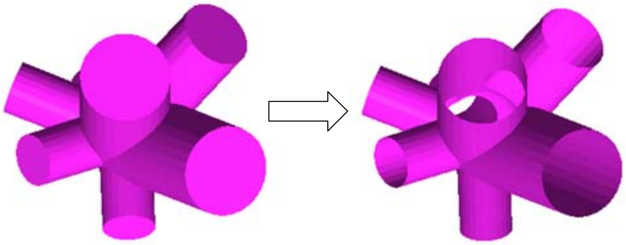


Figure 11 Removing End Faces from Unit Truss

3.3 Stacking Unit Trusses into the Entire Truss

After generating STL models for all unit trusses, these STL models are stacked into the STL model of the entire truss without expensive computations as in Step IV. An example combination of two unit trusses is shown in Figure 12. However, it must be ensured that the vertices of STL models meet up exactly with each other, without gaps or overlaps. Figure 13 shows the connection between two neighboring unit trusses sharing a common strut. The ACIS faceting tool must be configured to ensure the STL vertices along the coincident circular edge are coincident. Therefore, no Boolean operation is required during stacking the STL models of all the unit trusses. The solid modeling process was implemented with C++ and ACIS. The input is the truss topology and the output is the STL model of the entire truss structure.

4 EXAMPLES

A few examples are tested to evaluate the effectiveness and the efficiency of the hybrid geometric modeling method for conformal truss structures. The test platform is a Dell Dimension XPS machine with Intel 700 MHz CPU, and 512 MB RAM, running on a Window 2000 Operating System. Figure 14 shows a half-cylinder truss covered by a thin skin. The entire geometric modeling process is automated with no human interaction. No non-manifold entity is created and the resulting STL model is free of error. The half-cylinder truss was built on an SLA 3500 system [18].

Compared with the approach of creating the complete solid model, the hybrid geometric modeling method significantly reduces computational resources for geometric modeling of large-scale truss structures. Table 1 shows the time and RAM usage by the approach of creating complete solid model (labeled as ACIS) and the hybrid geometric modeling method (labeled as STL).

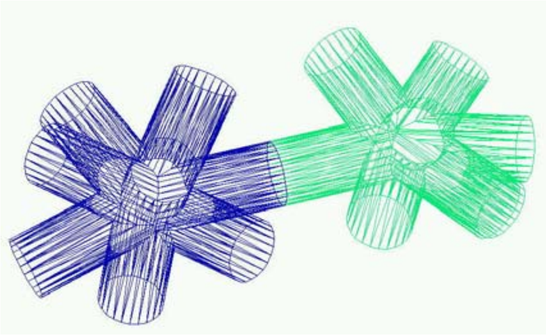


Figure 12 Stacking Unit Trusses into Entire Truss

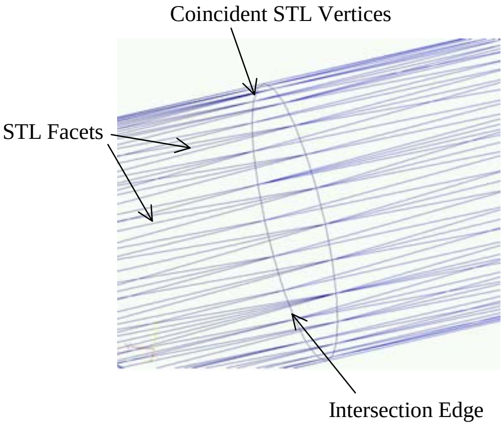
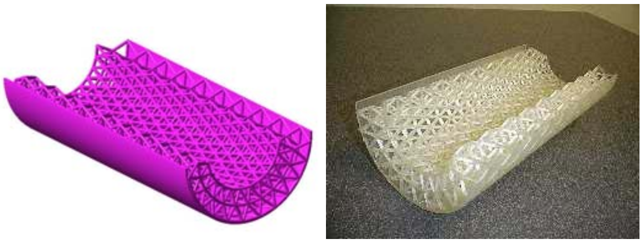


Figure 13 Connection between Two Neighboring Unit Trusses



a) STL Model b) SLA Part

Figure 14 Test Samples

Figure 15 shows the running time versus the number of struts in the truss structure. When the number of struts is fewer than 1200, it takes less time to create the complete solid (ACIS) model than to directly create STL model using the hybrid geometric modeling method. This is because the hybrid geometric modeling method needs to initialize and terminate the required ACIS tools every time when the program creates a single unit truss. The program for creating the complete ACIS model only initializes and terminates the ACIS tools once and it can significantly save time. In fact, a large portion of time is used to initialize and terminate the ACIS tools for the hybrid geometric modeling method. As shown by the tests on a program implemented by the authors, when the strut number is more than 2400, the running time for creating the complete ACIS model tends toward infinity (represented as dashed line) since the available RAM (512 MB) is used up. When a single program uses up the available RAM, the computer resorts to the virtual memory on the hard drive, but this process takes significantly longer time to exchange data between the RAM and the hard drive for a single program. So the running time becomes extremely long to build the complete ACIS model for the large-scale truss structures. When the strut number is over 2000, the running time for creating STL model using the hybrid geometric modeling method is almost linear, which means that its running time is directly proportional to the number of struts. The hybrid geometric modeling method could run more efficiently if the ACIS tool was only initialized and terminated once. However, we implemented the method in this manner since ACIS models are unloaded from RAM only after the ACIS tools are terminated and we would encounter memory limitations.

Figure 16 shows the RAM usage versus the number of truss struts from the tests performed with the programs implemented by the authors. Low RAM is demanded for the hybrid geometric modeling method. The RAM is primarily used to store the STL model. Even if the number reaches 4662, the RAM usage is only about 150 MB, of which around 120 MB RAM is used to store the STL model. There are about 1200 triangular facets on one vertex group, and each facet requires 96 bytes to store it. So one vertex group requires about 115 KB of RAM to store its STL model. There are 1044 vertex groups in the largest truss listed in Table 1, so the total required RAM to store the STL model is about 120 MB. The ACIS components require around 30 MB RAM, and the total required RAM to create the STL model is about 150 MB, which matches with the test result very well. The curve of the RAM usage by the hybrid geometric modeling method is almost linear, which shows that the RAM usage is approximately proportional to the number of struts in a truss structure.

Table 1 Time and RAM Consumption of Geometric Modeling for Truss Structures

	Element#	225	480	1074	1999	3547	4662
Time (second)	ACIS	37	107	370	2400	N/A	N/A
	STL	80	222	539	991	1256	1361
Memory (MB)	ACIS	52.6	95.68	321.5	450	N/A	N/A
	STL	32	37.5	49.316	68.04	84.9	99

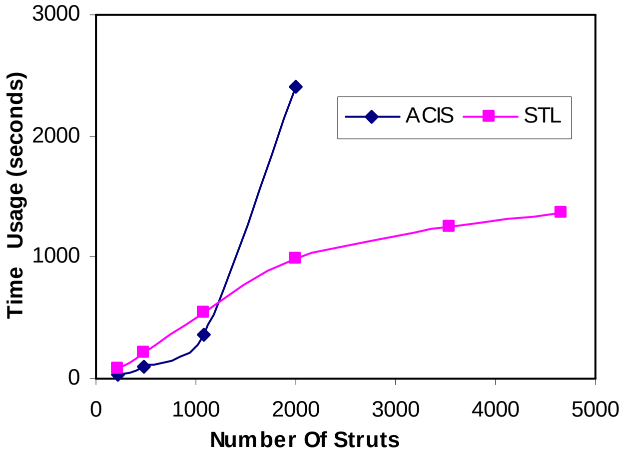


Figure 15 Test Result: Time vs. Strut Number

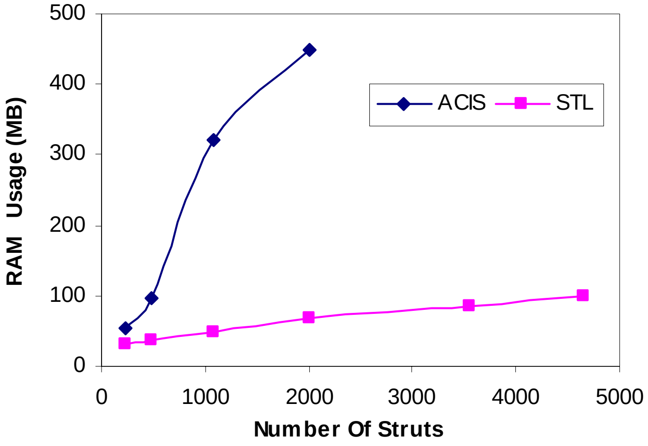


Figure 16 Test Result: Used RAM vs. Strut Number

The hybrid geometric modeling method can be extended to other cellular structures composed of various microstructures and even some special structures with periodic topology. For such an application, choosing an appropriate microstructure is the most important step. For example, Figure 17 shows a chainmail and its suggested microstructure for the hybrid geometric modeling approach. No intersection or overlap between the neighboring microstructures exists, and it is possible to stack the microstructures together without Boolean operations. The hybrid geometric modeling method can significantly save computational resources for geometric modeling.

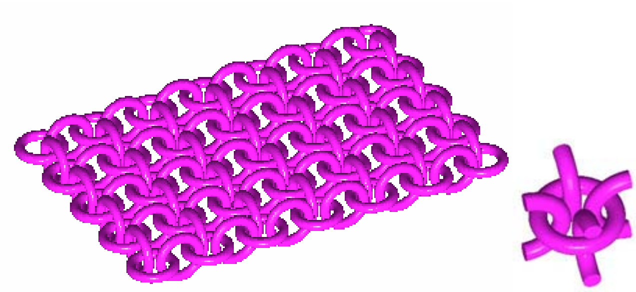


Figure 17 Chainmail and Its Suggested Microstructure for Geometric Modeling

5 CONCLUSIONS

The hybrid geometric modeling method effectively and efficiently generates tessellated geometric models of large-scale conformal cellular structures. This method facilitates the design, analysis, optimization, and manufacture of cellular structures. In this paper, conformal, mesoscale truss structures are used as an example. An automated process is developed for constructing geometric models of truss structures by using unit trusses as the microstructures. The structures' joint geometries are smoothened and non-manifold geometries are avoided. The computational efficiency of the hybrid geometric modeling method is evaluated by comparing to the approach of generating complete solid models.

It is shown that the hybrid geometric modeling method is far more computationally efficient and just as effective as the solid modeling approach for the geometric modeling of large-scale conformal cellular structures. The unit truss approach works for any truss lattice structure with cylindrical or conical struts. In fact, any parameterizable, repeatable shapes can be used as illustrated in the chain-mail example in Figure 17. We have constructed truss models much larger than those reported in Figures 15 and 16, including models with 20,000, 40,000, and 100,000 struts. The model with about 20,000 struts took approximately 45 minutes to generate, which corresponds well with the trend reported in Figure 15. The unit truss approach is limited to parameterizable, repeatable shapes. More general unit cells with complex blended geometries are desirable to model, for example for tissue scaffolds, and will be pursued in the future.

ACKNOWLEDGEMENTS

We gratefully acknowledge the U.S. National Science Foundation, through grants IIS-0120663 and DMI-0522382, and the support of the Georgia Tech Rapid Prototyping and Manufacturing Institute member companies for sponsoring this work.

REFERENCES

[1] H. Wang, "*Computer-aided design methods for the additive fabrication of truss structure*," Master Thesis, School of Mechanical Engineering, Georgia Institute Of Technology, Atlanta, GA, 2001.

[2] V. S. Deshpande, N. A. Fleck, and M. F. Ashby, "Effective properties of the octet-truss lattice material," *Journal of the Mechanics and Physics of Solids,* vol. 49, pp. 1747 – 1769, 2001.

[3] C. C. Seepersad, J. K. Allen, D. L. McDowell, and F. Mistree, "Robust topological design of cellular materials," ASME Design Automation Conference, Chicago, IL, September 29-October 2, 2003, Paper Number: DAC-48772

[4] J. C. Wallach and L. J. Gibson, "Mechanical behavior of a three-dimensional truss material," *International Journal of Solids and Structures,* vol. 38, pp. 7181-7196, 2001.

[5] A. G. Evans, J. W. Hutchinson, N. A. Fleck, M. F. Ashby, and H. N. G. Wadley, "The topological design of multifunctional cellular metals," *Progress in Materials Science,* vol. 46, pp. 309-327, 2002.

[6] D. Dutta, F. B. Prinz, D. Rosen, and L. Weiss, "Layered manufacturing: current status and future trends," *ASME Journal of Computing and Information Science in Engineering*, vol. 1, pp. 60-71, 2001.

[7] P. Jacobs, *Rapid prototyping & manufacturing: fundamentals of stereolithography*, 1st ed, SME, Dearborn, MI, 1992.

[8] S. Chiras, D. R. Mumm, A. G. Evans, N. Wicks, J. W. Hutchinson, K. Dharmasena, H. N. G. Wadley, and S. Fichter, "The structural performance of near-optimized truss core panels," *International Journal of Solids and Structures*, vol. 39, pp. 4093-4115, 2002.

[9] Y.-L. Cheng, J. Stamp, R. Leitge, and F. B. Prinz, "Additive/Subtractive Material Processing for Mesoscopic Parts," Solid Freeform Fabrication Symposium, Austin, Texas, 1999

[10] A.-J. Wang and D. L. McDowell, "Optimization of a metal honeycomb sandwich beam-bar subjected to torsion and bending," *International Journal of Solids and Structures*, vol. 40, pp. 2041-2320, 2003.

[11] S. A. Burns, *Recent advances in optimal structural design*: American Society of Civil Engineers, 2002.

[12] G. I. Rozvany, *Topology Optimization in Structural Mechanics*: Springer Verlag, 1997.

[13] "*ACIS technical overview*," Spatial Technology, Boulder, CO, 2000.

[14] H. Wang and D. W. Rosen, "Parametric modeling method for truss structures," ASME Computers and Information in Engineering Conference, Montreal, Canada, September 29-October 2, 2002, Paper Number: DETC02/CIE-34495

[15] R. B. Fuller, *Synergetics, explorations in the geometry of thinking*, Macmillan Publishing, 1975.

[16] M. E. Mortenson, *Geometric modeling*, John Wiley & Sons, Inc., New York, 1997.

[17] J. Corney and T. Lim, *3D modeling with ACIS*, Saxe-Coburg Publications, 2001.

[18] "SLA 3500 System," 3D Systems, Inc. http://www.3dsystems.com, May 05, 2005