Towards Fabrication Information Modeling (FIM):
Four Case Models to Derive Designs informed by Multi-Scale Trans-Disciplinary Data

Jorge Duro-Royo[1,3] and Neri Oxman[1,2]
[1]*Massachusetts Institute of Technology, Dept. of Architecture and Urban Panning, Media Lab, Mediated Matter Group, 75 Amherst St., Room E14-433b, Cambridge, MA, 02142 U.S.A.*
[2]*Corresponding author: neri@mit.edu,* [3]*j_duro@mit.edu*

ABSTRACT

Despite recent advancements in digital fabrication and manufacturing, limitations associated with computational tools are preventing further progress in the design of non-standard architectures. This paper sets the stage for a new theoretical framework and an applied approach for the design and fabrication of geometrically and materially complex functional designs coined *Fabrication Information Modeling* (FIM). We demonstrate systems designed to integrate form generation, digital fabrication, and material computation starting from the physical and arriving at the virtual environment. The paper reviews four computational strategies for the design of custom systems through multi-scale trans-disciplinary data, which are classified and ordered by the level of overlap between the modeling media and the fabrication media: (1) the first model takes as input biological data and outputs 3D printed digital materials organized according to functional constraints; (2) the second model takes as input geometry and environmental data and outputs robotically wound fibers organized according to functional constraints; (3) the third model takes as input material and environmental data and outputs CNC deposited pastes organized according to functional constraints; (4) the forth model takes as input biological, material and environmental data and outputs robotically deposited polymers organized according to functional constraints. The analysis of these models will demonstrate the FIM approach and point towards its value to designers who seek to inform their work through multi-scale trans-disciplinary data, a capability that is currently missing from standard design-to-fabrication workflows.

INTRODUCTION

Bridging the gap between virtual geometric-based design platforms and physical material-based fabrication tools presents interesting possibilities for digital design and fabrication [2, 11]. This gap was formed partly due to the fact that virtual design tools are generally based on geometrical representation and lack robust means to integrate material properties and fabrication constraints in the design workflow [2, 3, 31, 34]. Academic and industrial bodies are advancing hardware platforms that demand rapid growth of computational tools to interface with them [7, 8, 9]. It is expected that overlap among and across media will result in more efficient design protocols and will achieve better functionality across length and time scales [3, 4]. The main goal of the FIM approach is to integrate form generation, digital fabrication, and material computation starting from the physical and arriving at the virtual environment. Such shape-to-material integration can be observed in biology such as butterfly wings, silk cocoons, termite mounds or shark scales [1, 5, 14].

This research lies at the intersection of advanced manufacturing, digital design, and material computation. More specifically, our work draws from concepts and addresses issues in the following: file-to-fabrication (F2F) and direct digital manufacturing (DDM) approaches [14, 30-36] as well as generic digital fabrication platforms [38]; parametric and generative computation [39]; building information modeling (BIM); multi-scale and heterogeneous materials modeling [17 – 28]; computer-aided biological design (BioCAD, GenoCAD) [41]; integrated computational materials engineering (ICME); and computational materials science. Within the field of product and architectural design *Fabrication Information Modeling (FIM)* explores issues currently addressed by pioneers in the fields of Material Science, Civil Engineering, and Biology.

EXPERIMENTAL DETAILS

Methods presented herein are written in C++ and Java, using the Eclipse IDE environment (2014, The Eclipse Foundation, Canada), and C#, using the RhinoCommon geometrical kernel [39]. Exemplary designs are fabricated with advanced additive manufacturing technologies, employing both commercial and customized machines (Objet Connex 500 and Kuka KR AGILUS robotic arm KR 10 R1100 SIXX WP).

DISCUSSION

We present *Fabrication Information Modeling (FIM)*, a methodology designed to bridge the gap between virtual design tools and advanced digital fabrication tools. Today, designers have proficient complex geometry control that has advanced the field of design towards new territories [2, 35]. Our goal with FIM is to push these advancements even further by devising virtual tools that operate with non-geometric design parameters. By ways of metaphor, FIM is to design fabrication what a microscope is to design analysis. We envision FIM as a methodology not by which to view the world but rather by which to make it across scales and across disciplines. Such designs, we believe, can be informed not only by shape, but also by, for example, material properties and machine mechanics. More specifically, three main requisites for future design software platforms that encode the FIM methodology are the integration of: (1) multi-scale geometric representations; (2) fabrication and material properties, and; (3) trans-disciplinary data sets.

Traditional digital design workflows in the domains of architecture and engineering separate between the various phases of a typical design process [31, 34, 35]. Generally, these phases include ideation through sketching (DES); virtual tracing with computer-aided design tools (CAD); analysis of designs through computer-aided engineering (CAE), transmission of designs to digital fabrication machines via computer-aided manufacturing tools (CAM), fabrication (FAB), and final product processing (PRD). In contrast, Fabrication Information Modeling (FIM) attempts firstly to explore design processes that establish feedback loops between these sequential phases (DES-CAD-CAE-CAM-FAB-PRD); secondly, FIM attempts to progressively blur the lines between design phases, fusing them with their sequential neighboring processes in the design pipeline; and thirdly, FIM attempts to expand the design process so that parameters given by each phase are integrated in a multi-level and multi-disciplinary computational design methodology. The FIM design methodology seeks to combine interrelated subsets of constraints, definitions, and properties that are present in the four models presented in this section. These subsets include: (1) multi-scale geometry; (2) material properties; (3) fabrication constraints, and; (4) trans-disciplinary data.

Model 1: A multi-function unit-based surface encoding multi-scale geometry and trans-disciplinary data.

The first model translates the design rules related to a prehistoric fish armor into a biomimetic exoskeleton. The workflow applies to any geometrically complex surface. The work was executed in collaboration with Prof. Christine Ortiz (Ortiz Laboratory of Nano-mechanics of Structural Biological Materials, MIT Material Science Dept.) and Prof. Mary C. Boyce (MIT Mechanical Engineering Dept.). The organism combines flexible and stiff armor patches for movement and protection functions achieved through material and geometry gradation. The computational model that we developed incorporates three levels of hierarchy for the translation onto a human armor. Firstly, it incorporates morphometric data into the local geometry of each fish scale. Secondly, it implements a mesh directionality strategy to absorb the special features of the human body and allow new scale types to emerge. Thirdly, it embeds optimization data maps that inform the entire scale system with bio-mechanic constraints [5] (**Figure 1**).

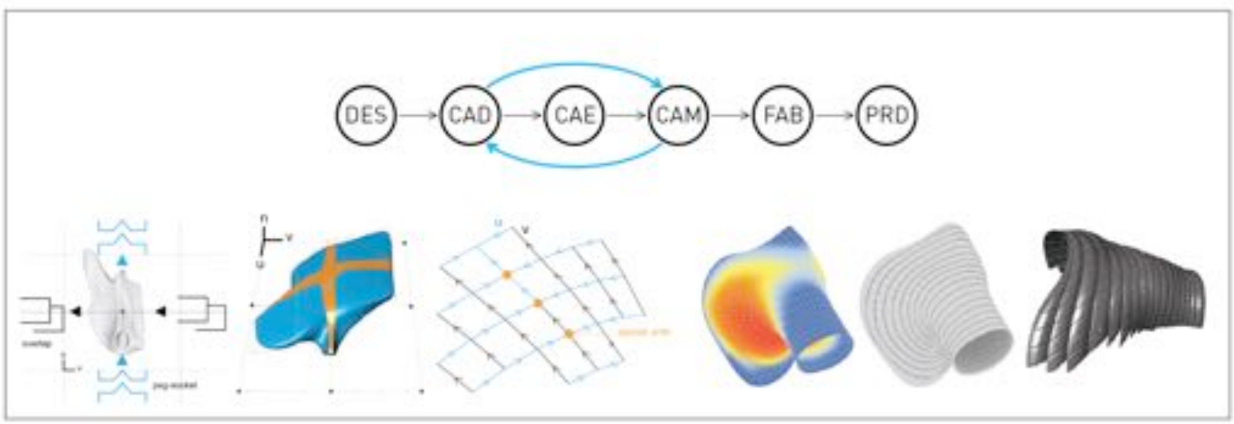

Figure 1: A multi-functional unit-based surface for a *Bio-mimetic Armor* encoding multi-scale geometry and trans-disciplinary data. Inspired by a prehistoric fish scale system, we built a multi scale algorithm with representation metadata operating at three levels of resolution: unit adaptation, mesh directionality and connection, and biomechanics optimization.

Model 2: A multi-constraint algorithm encoding fabrication processes and trans-disciplinary data.

The second model investigates a multi constraint algorithm for the computation of the *Silk Pavilion* project (Mediated Matter, Media Lab Lobby 2013). The installation combined computer-controlled and biological fiber composite fabrication. We contributed to the project with a computational algorithm taking into account three types of constraints across scales. The first set of parameters is related to the biological constraints of the silk worm's spinning motion; the second parameter set is related to scaffold fabrication parameters such as machine gantry or the number of thread hooks; and the third type integrates overall environmental maps, such as heat and light, to design silkworm movement guiding apertures on the structure [29] (**Figure 2**).

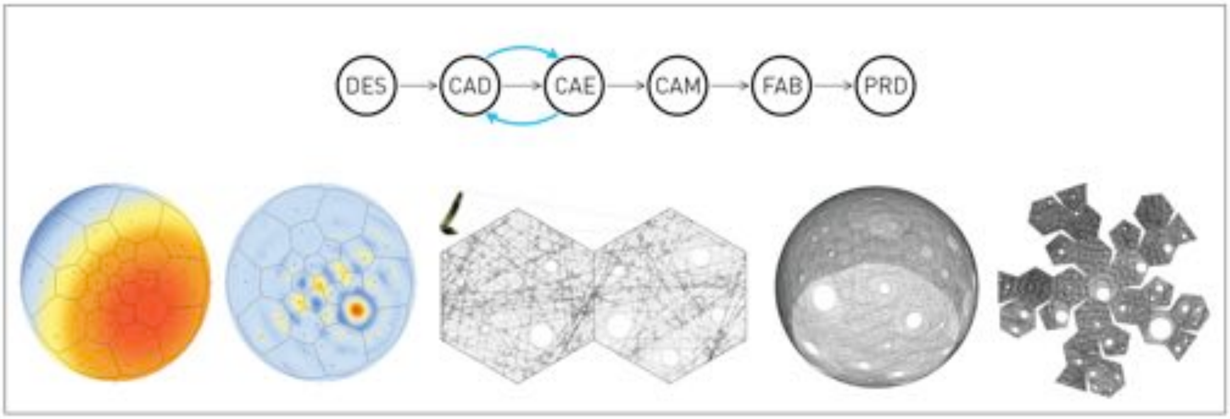

Figure 2: A multi-constraint algorithm was developed for the *Silk Pavilion*, which encodes fabrication processes and trans-disciplinary data. We developed an environment to design a large-scale fiber structure for silkworm spinning that could take into account biological, environmental, and fabrication constraint data. Specifically, the environment computes parameters relating to the biomechanics of the worms, environmental light and heat maps, and fabrication limitations of the CNC fabrication platform.

Model 3: A decentralized construction system encoding fabrication constraints and temporal material curing scales.

The third model is an environmentally-driven decentralized construction system called *Bots of Babel* (Mediated Matter, Lisbon Architecture Triennial, 2013). We designed a behavioral protocol for a set of suspended cable robots equipped with extrusion nozzles carrying material. The system operates across three levels of complexity. First, it controls discrete drop placement and curing-time data. It also governs the behavioral rules of the "agent fabricator" entities. Finally, it implements the designer's input as rule sets for bottom-up, or top-down shape formation [30] (**Figure 3**).

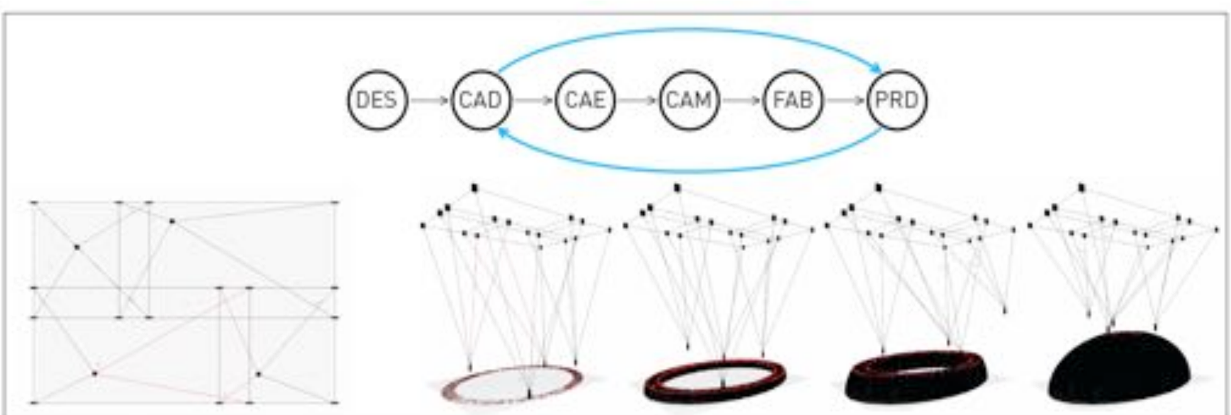

Figure 3: A decentralized construction algorithm encoding fabrication constraints and temporal material curing scales for a decentralized cable robot system. The algorithm rules inform mechanical, material, geometrical and time-based meta-information. Specifically, the platform is

designed to identify and solve for awareness behavior of the agents, plaster drop-curing times, and geometric rules for constructing the target product.

Model 4: A water-based hierarchical fabrication platform that encodes material representation and trans-disciplinary data.

The forth model investigates a hierarchical fabrication platform for the *Ocean Pavilion* project (Mediated Matter, Media Lab Lobby 2014). The platform implements direct digital manufacturing of structured objects and parts using biomaterials. For this project, we generated a seamless workflow to synchronize a portable and customized multi-nozzle deposition tool with an industrial robotic arm. The workflow operates at three levels of hierarchy. First, it determines material distribution and material concentration in geometrical primitives. It then transforms the primitives into extrusion geometries by pressure fine-tuning. Finally, it defines geometric and material property maps for the overall shape of the printed structures [15] (**Figure 4**).

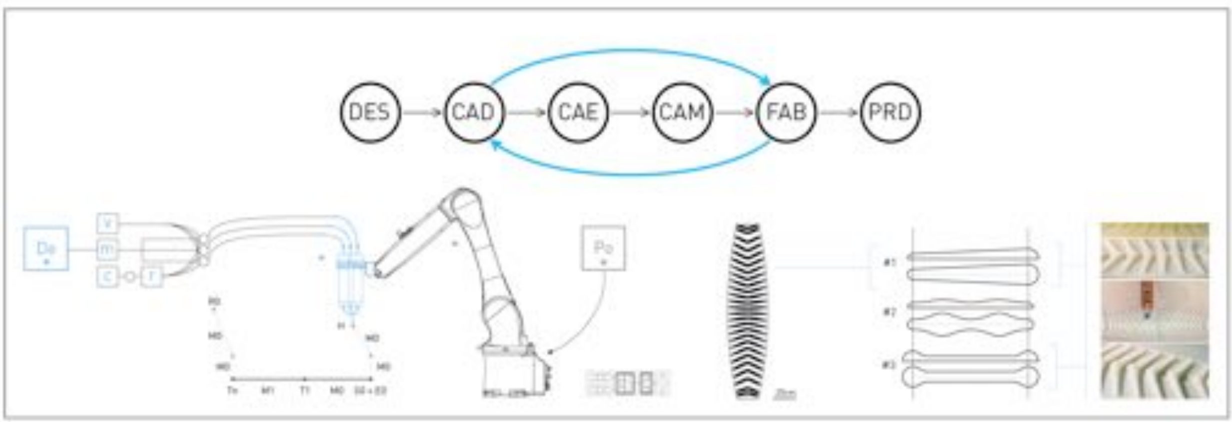

Figure 4: A hierarchical fabrication platform encoding material representation and trans-disciplinary data. We implemented a hierarchical fabrication workflow that encodes geometry, material and mechanics meta-data in the form of geometric mesh-free 2d primitives that encode material pressure maps for the emergence of structure.

CONCLUSIONS

This research serves to demonstrate a new design workflow for designers who seek to inform their work with multi disciplinary data, and operate between virtual and physical domains. It is our hope that products designed implementing the FIM methodology will successfully integrate form generation, digital fabrication, and material computation; exhibiting functional integration, multi scale performance and aesthetic qualities.

Future work will compare the design process enabled by FIM to other CAD-CAM design processes from a modeling, file-generation and fabrication perspectives. The exercise will replicate FIM products designed with commercial CAD platforms with different geometric solver kernels such as Maya (Autodesk), CATIA (Dassault Systems) and Rhinoceros3D (McNeel). In this context we plan to pose a design problem to proficient users in the mentioned platforms and register problems and limitations that they may encounter when designing and fabricating the products with off-the-shelf CAD and CAM software.

ACKNOWLEDGMENTS

Ideas, concepts and methods reported herein have been developed to support ongoing projects at the MIT Mediated Matter Group. Some work was supported in part by the US Army through the MIT Institute for Soldier Nanotechnologies (Contract No. W911NF-13-D-0001), the Institute for Collaborative Biotechnologies (Grant No. W911NF-09-0001 from the US Army Research Office), the National Security Science and Engineering Faculty Fellowship Program (Grant No. N00244-09-1-0064)), and the TBA-21 Academy (Thyssen-Bornemisza Art Contemporary). We would like to thank our colleagues at the Mediated Matter Group, Prof. Christine Ortiz (MIT DEMS), Prof. Mary C. Boyce (MIT MechE), Dr. James Weaver and Dr. Javier G. Fernandez (Harvard Wyss Institute), and Dr. Fiorenzo Omedetto (Tufts University).

REFERENCES

[1] Vincent J., Bogatyreva O. A., et al. Biomimetics: its practice and theory. Journal of the Royal Society Interface 2006; 3:471-482.

[2] Oxman N. Material-Based Design Computation. Massachusetts Institute of Technology 2010.

[3] Oxman N. Structuring materiality: design fabrication of heterogeneous materials. Architectural Design 2010; 80:78-85.

[4] Oxman N. Variable property rapid prototyping. Virtual and Physical Prototyping 2011; 6:3-31.

[5] Duro-Royo J., Zolotovsky K., Mogas-Soldevila L., Varshney S., Oxman N., Boyce M.C., Ortiz C. MetaMesh: A hierarchical computational model for design and fabrication of biomimetic armor surfaces. Computer-Aided Design Elsevier 2014; in press.

[6] Biswas A., Fenves J.S., Shapiro V. Representation of heterogeneous material properties in the Core Product Model. Engineering with Computers 2008; 24:43-58.

[7] Shapiro V., Tsukanov I., et al. Modeling and analysis of objects having heterogeneous material properties. Google Patents 2004.

[8] Shapiro, V., Tsukanov I., et al. Geometric issues in computer aided de- sign/computer aided engineering integration. Journal of Computing and Information Science in Engineering 2011; 11:021005.

[9] Chiu W. and Yu K. Direct digital manufacturing of three-dimensional functionally graded material objects. Computer-Aided Design 2008; 40:1080-1093.

[10] Biswas A., Shapiro V. Heterogeneous material modeling with distance fields. Computer Aided Geometric Design 2004; 21:215-242.

[11] Vidimce K., Wang S., Ragan-Kelley J., Matusik W. OpenFab: A Programmable Pipeline for Multi-Material Fabrication. SIGGRAPH Conference Proceedings 2013; 32:1-12.

[12] Kou, X.Y., Tan S. T. Heterogeneous Object Modeling: A review. Computer-Aided Design 2013; 39:284-301.

[13] Hon K.K.B. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Springer 2010.

[14] Gibson I., Rosen D. W., et al. Direct digital manufacturing. Additive manufacturing technologies Springer 2010; 363-384.

[15] Duro-Royo J., Mogas-Soldevila L., Oxman N. Flow-Based Fabrication: An Integrated Computational Workflow for Digital Design and Additive Manufacturing of Multifunctional Heterogeneously Structured Objects. Computer-Aided Design Journal 2015 (in revision).

[16] Mogas-Soldevila L., Duro-Royo J., Oxman N. Water-based Robotic Fabrication: Large-Scale Additive Manufacturing of Functionally-Graded Hydrogel Composites via Multi-Chamber Extrusion. 3D Printing and Ad- ditive Manufacturing 2014; 1:1-11.

[17] Kieback B., Neubrand A., Riedel H. Processing techniques for functionally graded materials. Materials Science and Engineering 2003; 362:81- 106.

[18] Malone E. and Lipson H. Multi-material freeform fabrication of active systems. ASME 2008 9th Biennial Conference on Engineering Systems Design and Analysis American Society of Mechanical Engineers 2008.

[19] Hiller J. and Lipson H. Design and analysis of digital materials for physical 3D voxel printing. Rapid Prototyping Journal 2009; 15:137-149.

[20] Hiller J. and Lipson H. Tunable digital material properties for 3D voxel printers. Rapid Prototyping Journal 2010; 16:241-247.

[21] Weiss L., Merz R., et al. Shape deposition manufacturing of heterogeneous structures. Journal of Manufacturing Systems 1997; 16:239-248.

[22] Kumar V. and Dutta D. An approach to modeling and representation of
heterogeneous objects. Journal of Mechanical Design 1998; 120:659-667.

[23] Samanta K. and Koc B. Feature-based design and material blending for free-form heterogeneous object modeling. Computer-Aided Design2005; 37:287-305.

[24] Siu Y.K. and Tan S.T. Modeling the material grading and structures of heterogeneous objects for layered manufacturing. Computer-Aided Design 2002; 34:705-716.

[25] Kou X. and Tan S. A hierarchical representation for heterogeneous object modeling. Computer-Aided Design 2005; 37:307-319.

[26] Biswas A., Shapiro V., et al. Heterogeneous material modeling with distance fields. Computer Aided Geometric Design 2004; 21:215-242.

[27] Chen J. and Shapiro V. Optimization of continuous heterogeneous models. Heterogeneous objects modeling and applications Springer 2008;193- 213.

[28] Pratt M.J. Modeling of Material Property Variation for Layered Manufacturing. In: Cipolla R. and Martin R., editors. The Mathematics of Surfaces IX Springer 2000;486-500.

[29] Oxman N., Laucks J., Kayser M., Duro-Royo J., Gonzales-Uribe C. Silk Pavilion: A Case Study in Fiber-based Digital Fabrication. FABRICATE Conference Proceedings 2013; 248-255.

[30] Oxman N., Duro-Royo J., Keating S., Peters B., Tsai E. Towards Swarm Printing. Made by Robots: Challenging Architecture at a Larger Scale. Architectural Design Special Issue 2014; 84:3:108-115.

[31] Oosterhuis K. File to Factory and Real Time Behavior in Architecture.

Fabrication: Examining the Digital Practice of Architecture. Proceedings of Conference of the AIA Technology in Architectural Practice Knowledge Community Cambridge/Ontario 2004.

[32] Afify H. M. and Elghaffar Z. A. A. Advanced Digital Manufacturing Techniques (CAM) in Architecture Authors. Proceedings of the 3rd International ASCAAD Conference 2007.

[33] Scheurer F. Materializing complexity. Architectural Design 2010; 80:86- 93.

[34] Oosterhuis K., Bier H., Aalbers C., Boer S. File-to-Factory and Real- Time Behavior in ONL-Architecture. AIA/ACADIA Fabrication: Examining the Digital Practice of Architecture, University of Waterloo School of Architecture Press 2007;.294-305.

[35] Sheil B. De-Fabricating Protoarchitecture. In: Stacey M., editor. Proto- typing Architecture Conference Building Centre Trust London 2013;372- 390.

[36] Sass L. and Oxman R. Materializing design: the implications of rapid prototyping in digital design. Design Studies 2006; 27:325-355.

[37] Chang, C. Direct slicing and G-code contour for rapid prototyping machine of UV resin spray using PowerSOLUTION macro commands. The International Journal of Advanced Manufacturing Technology 2004; 23:358-365.

[38] Farouki R. T., Manjunathaiah J., et al. G codes for the specification of Pythagorean-hodograph tool paths and associated feed rate functions on open-architecture CNC machines. International Journal of Machine Tools and Manufacture 1999; 39:123-142.

[39] McNeel R. Grasshopper generative modeling for Rhino, Computer soft- ware (2011b), http://www. grasshopper3d. com 2010.

[40] Duro Royo J., Mogas Soldevila L. and Oxman N. Methods and Apparatus for Integrated Large Scale Robotic Fabrication of Functionally Graded Materials and Structures. US provisional patent pending (M.I.T. Case No. 17388T) 2014.

[41] Sun W., Starly B., Nam J., Darling A. Bio-CAD modeling and its applications in computer-aided tissue engineering. Computer-Aided Design 2005; 37:1097-1114.