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

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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).

**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.

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