FABRICATING THE FUTURE

建筑数字化建造

Philip F. Yuan & Neil Leach
袁 烽　尼尔·里奇　编著

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INTRODUCTION
介绍

近年来，建设行业最重要的发展莫过于对数字化建造新技术的引进，从数控机床（CNC）到3D打印机、激光切割和各类机器人的使用。这些新技术对施工工艺有了更大程度的控制，并能保证其精确度，开创了一系列新施工方法的先河。这在中国——一个一度以手工业为主的国家中尤为明显，数字化建造技术正以前所未有的速度使建设行业发生巨大的转型。

本书旨在通过对该领域最新发展动态的纵览，来看出数字化建造技术对当代建筑实践的影响。本书的撰稿人涉及面甚广，从受数字化建造技术启发的商业公司，到对其不断研究的实验性工作室，再到材料商、工程师、学生以及各大院校的研究学者。但全书始终围绕着一条主线，那就是这些撰稿人对飞速发展的数字化建造领域所做出的巨大贡献。

本书是两本系列中英文版之一，另一本是关于编程脚本和计算设计的《建筑数字化编程》。这两本书是2011年在同济大学举办的“数字未来”展览的成果，这次展览是由同济大学建筑与城市规划学院和南加州大学中国学院共同主办。我们衷心地感谢：惠普、《建筑实录》杂志、《时代建筑》杂志、McNeel公司、盖里科技、Permasteelisa公司、同济大学建筑设计研究院、同济大学城市与规划设计研究院、南加州大学中国学院等赞助单位，你们的支持使这次活动能够成功举办。同时，我们衷心感谢本书的撰稿人和所有协助本书编撰工作的人，包括杨璇、戴拉莫 · 汉切克罗夫特在资料收集整理中所做的工作；袁佳麟在全书编辑过程中所做的协助工作；平面设计团队——4aTEAM，以及戴祥萍、黄韧玲、尹文所做的翻译工作。

袁烽 & 尼尔·里奇

One of the most important developments within the construction industry in recent years has been the introduction of new digital fabrication technologies from computer numerically controlled (CNC) milling to 3-D printing, laser cutting and the use of robots of various kinds. These new technologies have introduced a greater degree of control and precision in the construction process, and have opened up a range of new methods of construction. This is especially the case in China, a nation once dominated by manual construction, but where digital fabrication technologies on an unprecedented scale are beginning to transform the construction industry.

This volume seeks to offer an overview of the impact of digital fabrication technologies on contemporary architectural practice, by providing a snapshot of the latest developments in the field. Contributors to this volume range from inspired, commercial firms to progressive, experimental firms, and from fabricators and engineers to students and academic researchers. But the common thread throughout is an attempt to make a significant contribution to the rapidly developing field of digital fabrication.

This volume is part of a two volume bi-lingual edition that also includes a volume on scripting and advanced computational design, *Scripting the Future*. These volumes emerge out of the *DigitalFUTURE* conference and exhibition held at Tongji University in 2011 that were organized as a collaboration between the American Academy in China and the College of Architecture and Urban Planning of Tongji University. We are grateful to the sponsors who made these events possible: Hewlett Packard, *Architectural Record*, *Time+Architecture*, McNeel Associates, Gehry Technologies, Permasteelisa, Architectural Design and Research Institute of Tongji University, Shanghai Tongji Urban Planning and Design Institute, and the American Academy in China. We are also grateful to the contributors themselves as well as to all those who assisted in the production of this volume, including Sherry Yang, Deramore Hutchcroft, Crisie Yuan, the graphic design team — 4aTEAM, and the translators Xiangping Dai, Renling Huang and Wen Yin.

Philip F. Yuan & Neil Leach

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PREFACE
绪论

Digital Fabrication: A Paradigm Shift under the New Methodology

数字化建造：新方法论驱动下的范式转化

Philip F. Yuan / Digital Design Research Center, CAUP, Tongji University
袁烽 / 同济大学建筑与城市规划学院，高密度人居环境生态与节能教育部重点实验室数字设计研究中心

运用数字化方法设计，并就传统材料进行手工建造的方式，更近于在设计方法层面对传统建构思想的批判性延伸；而随着建造操作主体从“手工”向“机械”以及“数控机械”的转化，操作对象从“传统材料”向“多维材料”甚至“复合材料”的发展，已经不可避免地呼唤着新范式转化的到来。

讨论数字化建造问题必须建立合适的理论语境，当今理论界在希望用传统理论架构或体系来解释新的建筑实践时往往会首先找出文字上的关联，譬如说用“数字化建构”[1]来作为数字化设计方法与建构思想的联系。但“数字化建构”能否指代“数字化建造”呢？传统建构的诗意建造是否停留在狭义的层面呢？“数字化建造”究竟是“反建构”[2]还是一种“新建构”[3]呢？同时，“数字化建构”是否仅是一种半自主[4]的状态呢？本文试图从“设计方法的变革”，“建造工具对设计方法的实现”和“新兴材料与建造工具”的关系入手重新审视以上几个问题。

设计与建造工具变革所带来的范式转化

设计方法工具、建筑建造的过程和流程逻辑深刻地影响着新范式的产生。纵观建筑历史的发展，风格与思潮只是表象，其背后的设计方法与建造工具无不深刻地影响着建筑范式的革命：无论是透视法对于文艺复兴的影响，切石法对于巴洛克的推动，还是克林·罗的“透明性”概念所操作的轴侧画法对现代主义的作用。当我们重新

The use of traditional materials and craftsmanship to realize computational design offers us a practical critique of the traditional concept of ‘tectonics’ within contemporary design theory. Over time fabrication has evolved away from the craftsman to the CNC machine, and with this shift new materials have been developed that are far removed from traditional materials in that they are now designed not to be handled by man, creating a paradigm of multi-dimensional materials and composite materials that can only be worked by machines. With the implementation of digital design technologies in developing countries a new area of digital fabrication is emerging, where CNC craftsmen are leading the way.

This article sets out to establish a theoretical context for digital fabrication, by challenging contemporary theories that seek to understand new developments in architectural practice through the lens of conventional theories of progressive development. These theories form mental associations by using terms such as "digital tectonics" [1] that suggest a relationship between digital design and a tectonic methodology. But does the term "digital tectonics" represent "digital fabrication" ? Is there still poetry in tectonics when the craftsman is controlled by a digital model? Is "digital fabrication" an "anti-tectonics" [2] or is it a "new tectonics". [3] Or is "digital tectonics" only a quasi-autonomous solution to the fabrication problem? [4] The article attempts to rethink the above issues by uncovering the concepts

审视当代逐步出现的在多重系统理论推动下的图解理论时，图解的对象不仅在对象空间维度的描述上，同时也在建造逻辑上给出了全新的思维工具。建筑图解对于建筑的功能性、环境性、可建造性都进行了与现代主义和以前完全不同的描述与思考方式。对于图解思维的外化方式以及提升得益于设计计算技术，计算逻辑可以与图解逻辑打通联系，如程序编码（如MEL和RhinoScripting）和参数建模（采用Revit或DP等工具）均成为现实，以至于如果不掌握并精通这些工具的话，就很难在当代前卫建筑景观领域竞争。然而，技术推进应与更多目标及清晰的远景携手并行。

正如尼尔·里奇所说："计算机时代孕育的不仅是一种新风格，而是全新的设计手法，我们将新的计算技术应用于进化的和新兴系统中，建立并实施测试系统，使图解变成现实，现实变成图解。在这全新的领域里，形式变得毫不重要。我们应探索'算法技术'的潜在功能，并专注于更智能化和逻辑化的设计与建造流程。逻辑便是新的形式。"[5]

在建造逻辑上，从文艺复兴到现代主义，事实上对手工与材料的使用并没有太多实质性的革命。对手工与传统材料的使用积淀了建筑历史文化；大规模的机械化生产时代重新定义了现代主义的出现以及意义。如今，随着数控机械（CNC）以及机器人的产生与在其他学科领域的普及，3D打印技术的出现，打印材料的多元化和量产化，新的一种形式范式的产生事实上已经成为必然。

在实现工具层面上，从"手工"、"传统机械"到"数控机械"；在操作对象层面，从"传统材料"到新三维成型技术下的"多维材料"再到新材料技术影响下的"复合材料"。从以上要素的建造关系与逻辑，可以清晰地描述新范式产生的理由。当然，在以上建造操作的背景是参数化与算法设计方法的支持。

尤为重要的是，在此逻辑关系图解（见图1）中可以解读的是，"数字化建构"更加倾向于传统建造工具对传统材料的操作，可以视为运用数字化设计方法对传统建造的延续，如果用"半自主"状态来描述它的理论价值应该是比较客观的；而"数字化建造"则发展为数控工具对新材料的操作。这是一种全新的"自主性"设计与建造方法，其理论与建造思路与传统建构理论完全不同，无论从威廉·米歇尔的反建构理论[6]，还是格雷格·林恩的"合成物"建造理论[7]都彻底划清了"数字化建造"与"数字化建构"的关系。当然，二者对于"诗意建造"的理解体现了不同哲学与艺术意义层面的深意，但二者追求的都是一种"真实建造"。只不过这个真实一个来自对传统的垂青，一个源自对当下甚至未来的预判。

数字化建造实现方法与实践

相较于建构强调的是过程外隐含的意义，建造则更注重过程本身的逻辑性。在数字化建造中，数字化作为设计方法贯穿整个设计的始末，同时交织着建造方法和操作对象的作用流程。在运用过程中，3D打印技术、轮廓工艺、快速原型制作等先进技术的探索则重新定义了整个生产过程。这些并行的实践解读了从数字化建构到数字化建造的现实存在与范式转化的可能性。

that emerge from mixing supposedly opposite design methodologies, and attempting to understand the relevance that the development of new fabrication techniques and the emergence of new materials has on craftsmanship.

A Paradigm Shift: Updating Design and Fabrication Tools

Automated tooling processes and the formal logic of fabrication, such as fixings, have had a profound influence on the emergence of the new fabricating paradigm. Looking back at the development of architectural theory, styles and trends are merely presentational, underscored by the development of then new fabrication techniques that profoundly affect the transformation of architectural design. This might help us understand the relevance that representational techniques such as the development of perspective had on the architecture in the Renaissance, or the role that axonometric drawing based on Colin Rowe' s concept of 'transparency' plays in understanding modernism. By rethinking the contemporary diagram that is emerging through the promotion of multi-systems theory, the diagram' s new logic is both a description of spatial dimensions and the fabrication logic of the space. The digital diagram expresses the function, environment and fabrication of the building in a way totally different from Modernism and the past. Computational design technology created a leap in standards of graphic representation improving the concepts of externalization, and offering a clearer expression of fabrication techniques. Computational logic is connected to diagrammatic logic. For example, programming code (such as MEL and RhinoScripting) and parametric modeling (with tools like Revit or DP) are now commonly used in architectural design. As such, an architect who cannot use these tools proficiently will not be competitive in the contemporary avant-garde architectural design field. However, the progress of technology should have wider goals and clearer prospects than just competitiveness.

As Neil Leach writes, "Surely what the world of computation promises is not merely a new style, but a radically new way of approaching design, where we embed new computational techniques into evolutionary and emergent systems, and where we breed systems and test them out in real time, so that the diagram becomes the reality and reality is the diagram. Form should be seen as largely irrelevant within this new horizon. Instead we should be exploring the potential of algorithmic techniques, and focus on more intelligent and logical design processes. Logic should be the new form." [5]

With fabrication, the developments in craftsmanship and material use are not very obvious. From the Renaissance to Modernism, they followed the traditional notions of architectural history and culture, although the era of large-scale mechanical production redefined the appearance and significance of Modernism. However, with the invention and use of CNC milling machines and fabrication robots in

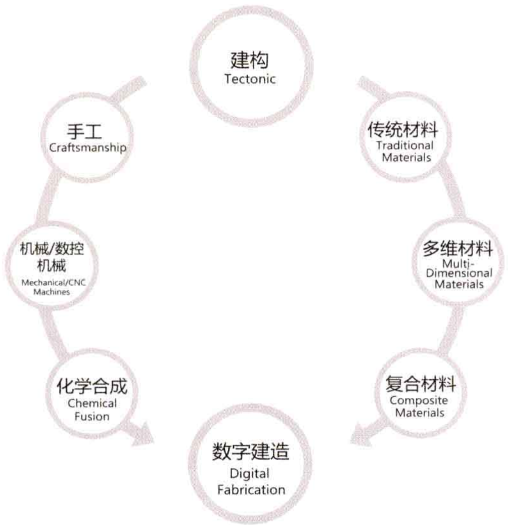

图1：新范式的建造关系逻辑
Figure 1: Fabricating Logic in the New Methodology

手工加工传统材料

自从弗兰普敦和艾森曼有趣的电梯对话故事发生后，数字化设计方法与传统建构理论似乎一直水火不容。但随着建筑实践的发展，值得质疑的似乎并不应该局限在弗兰普敦对建构意义理解的教条解释。同样是运用手工技术对于传统材料的操作，也可以通过运用数字化的设计方法来实现诗意的建造；而对于纸面数字建筑师而言，如何面对像中国这样的发展中国家，面对传统的施工技术并能在有限的投资状况下将复杂的数字化建筑设计付诸实践，是一个必须探讨的更深层次的问题。数字化建造可以创造性地运用低技术，这恰好是连接数字化与建构理论的一种特殊设计与建造方法，技术与传统将在这里找到一个新的契合点和谐共处。

机械操作传统材料

在生产实践中，对数字化建造手段的应用也促使了工作方式的变革。BIM和Revit等作为设计创想与成果间的桥梁，使得以传统材料实现建造的过程也发生了变化。多系统一体化的工作方式已经打破了传统的建筑师与工匠通过图纸沟通的模式。虽然很多实际项目运用的还是传统的机械与材料，但整个工作过程是在三维的状态下进行，建筑从生成到竣工的过程可以模拟预判，建筑师设计、传达、获得反馈的方式也相应变化，这种方式颠覆了我们对于通过平立剖来求解的诗性的领域。

数控机械操作传统材料

工业机器人在汽车生产制造等行业的使用已有较长的历史，但在建筑领域中，数控机械的运用才开始不久。瑞士苏黎世理工学院的法比奥格·拉马里奥与马提亚斯·科赫勒教授近期运用数控加工技术控制的飞行机器人操控传统的砌砖建筑，[8] 而他们在2008年威尼斯建筑双年展中的R-O-B项目，也是用数控机械手段（六轴机器人）来探索对传统材料（砖）的建造。[9] 新的自控工具在原材料性

other fields, such as car manufacturing, and current developments in materials for 3D printing technology, a wholly digital architectural paradigm is inevitably emerging.

With fabrication tooling, the range has expanded from "crafts" to "mechanical" and now to "CNC machines". With materials, the range has expanded from "traditional materials" to "multidimensional materials" and "composite materials". The relationship and logic of these developments stem from the distinction between man developing machines and machines creating machines, expressing the difference in thinking that has caused the new paradigm. These developments in mechanical fabrication have been further exaggerated by the contribution of parametric and algorithm design methodologies.

Most importantly, what can be derived from the diagram (Figure 1) is that "digital tectonics" is in principle coupled with traditional fabrication techniques for the operation of traditional materials. Therefore, it could be described as a "quasi-autonomous model" in the traditional fabrication tree, whereas digital fabrication employs the use of CNC machines to work on new and old materials. This is a distinct and relatively recent "autonomous" design and fabrication methodology, in that the theory and fabrication concepts greatly differ from traditional tectonic theory.

Moreover, the new, holistic understanding of the building as a process fuses construction with design. This shifting multi-disciplinary architectural paradigm calls for a change in the role of the engineer, which clearly becomes all the more important as his contribution throughout all the design phases is essential.

The "anti-tectonics" theory of William J. Mitchell [6] or the "composites" [7] fabrication theory by Greg Lynn highlight the difference between "digital fabrication" and "digital tectonics". The use of terms such as "poetic fabrication" in these theories reflects the similarities in their philosophical and artistic attitudes; they both pursue a kind of "realistic fabrication". However, concluding their theories, one advocates the traditional techniques and the other forecasts a purely digital future.

The Methodology and Practice of Digital Fabrication

In comparison to tectonic construction, fabrication places an emphasis on the logic of processing itself, whereas tectonic construction emphasizes a cognitive and skilled dependence. With digital fabrication, digitization plays a role as the main design concept during the whole design process. Fabrication methods include handcrafting, mechanical crafting, and CNC machining. The materials for fabrication are divided into traditional materials, multi-dimensional materials and composite materials. However, with the addition of 3D printing technologies such as Contour Crafting, rapid prototyping and other advanced technologies there is a new definition of fabrication that

能基础上定制非标准化构件的方法是在数字化建造中融合了传统经验与现代技术的手法。二者都需要在实验材料系统中加入以设计为导向的应用，以完成从现有物质到适应性结构和复杂几何的转换。而传统的材料与机械的结合方式在现阶段的情况下更便于将数字化建造应用于实际生产。

机械操作多维材料

运用机械手段来建造，在实际生产领域的实践程度更高。建筑师通过系统的逻辑思维和运用数字软件，协调多维复杂性与并不智能的单一实现方式的相互关系，完成数字化建造。麦克尔·汉斯迈耶的“第六柱式”就是用程序算法探索建筑形式，再将复杂形体进行单元和像素化，通过最小化的方式确认分析和分层进行，最终形成复杂的柱式作品。机械操作多维材料的方法打破了成本投入受限或数控机械在现实建造中条件应用的局限，要求建筑师具有对材料多角度、多维度的设计和美学敏感性，能够掌握先进数字技术但在现实的条件下不依赖技术实现建造的高度自主性。

数控机械操作多维性材料

利用计算机技术及数控加工技术，将建造材料进行多种手法的变化，增加其本身在空间中的维度，可以实现完整建筑形体的多维性营造。数控加工技术（CNC）铣削出传统轮廓的手段已普遍应用，然而从一整块建筑材料上打磨出复杂的几何体块进而搭建是与同种薄板材料但用不同的体积处理的方法是一样的。但是，对材料体积整体操作的形状费用（及时间）成本过高，如密歇根大学Matter设计工作室所运用的切石法，对材料性质就较为挑剔（多限于AAC、EPS和再生石等）。为了妥善地解决体积制作与材料多维性实现的问题，需要建筑师在将体积作为通用做法时对使用方法进行更多的研究。

化学合成操作复合性材料

3D打印技术操作的材料需要多种特性以满足成型的要求，从早期的树脂到ABS、不锈钢和复合了高纤维的混凝土材料，不同的复合型材料经开发应用于不同的工艺。现今进一步的探索仍在进行，建筑行业中摩菲西斯建筑设计事务所及福斯特建筑设计事务所是最初采用快速成型制作技术制作实体模型的先驱。而D-Shape打印机的发明，也使得大尺寸3D分层成型成为可能，建筑师研发出特定黏结剂与催化剂材料，使用施工机器人，采用CAD-CAE-CAM设计技术，建筑建造不再受施工者人力的限制。通过数控机械操作复合型材料的原理已远离传统意义上的建造理念，可以直接依靠三维模型建造实体，不需任何模板，应对复杂的几何体时体现出高度的自由度和精确度。

数字化建造作为一种设计与建造方法，驱动着建筑范式的革命性转化。数字化建造方法是实现传统建构思想走向未来的手段，作为新的实践方法，无论是通过“低技”参数化手段还是通过基于技术进步的全新方式来实现，都要求我们对包含“过程逻辑”与“形式意义”的建筑本体进行重新的思考。

now encompasses the whole production process, where elements are neither fabricated together nor constructed, but are created as a single whole. These practices embody the transition from digital tectonics to digital fabrication, and — with it — the possibility of a paradigm shift.

Craftsmanship and Traditional Materials

Since Kenneth Frampton's abrupt rejection of Peter Eiserman's ideas, digital design method has been seemingly incompatible with traditional tectonic theory. But within architectural practice, it seems that the dogmatic theories of Frampton on the sacredness of the 'tectonic' have been ignored. We witness daily the use of digital design methods to approach poetic fabrication by designing digital systems that allow the possible treatment of traditional materials. In China and other developing countries, new problems encountered are solved by implementing parametric systems into architectural design, which are programmed to deal with restricted investment and traditional construction technologies. This topic should be discussed in depth, especially by practical architects who are building here and encountering these very issues. Digital fabrication is equally applicable to the low-tech architectural arsenal, which redefines the roles of design and fabrication techniques connecting digitization with craftsmanship. Here we can find a new meeting point between technology and tradition.

Mechanical and Traditional Materials

Using digital fabrication methods in architectural production leads to the transformation of traditional working roles. The implementation of BIM software such as Revit streamlines the design concept into production information, changes the fabrication process and questions the usage of traditional materials. The development of integrated working methods between computer systems replaces the traditional communication mode between architects and craftsmen through drawings. Although traditional tools and materials are adopted in most projects, construction is conducted through a new set of diagrams removed from the traditional blueprint, where building becomes an algorithmic exercise. This new pattern overturns the architectural field where all messages were conveyed through plan, elevation and section.

CNC Machines and Traditional Materials

Although industrial robots have been used for a long time in the automobile and other high-end manufacturing industries, in the construction industry they have just started to be used. Prof. Fabio Gramazio and Prof. Matthias Kohler of ETH Zurich have recently programed CNC robots to do traditional bricklaying called Flight Assembled Architecture. [8] They have also explored the use of 6-axis robotic arms to stack traditional materials (brick) in their R-O-B project exhibited at the 2008 Venice Architecture Biennale. [9] Automatically controlled tools are customizing to produce non-standard components using algorithms based on the performance of the raw material. This is a combination of traditional expertise, modern technology and digital fabrication. The process relies on the properties of the material, in transforming it to the adapted structure with its complex geometry. The use of traditional materials in a mechanical process is more applicable for digital fabrication than for real construction at the present time.

Mechanical and Multi-dimensional Materials

Using mechanical methods for fabrication is more practical than using them for construction. Architects coordinate multi-dimensional complexities through systematic logical thinking, digital software and complete digital fabrication. For instance, in "The 6th Order" Michael Hansmeyer explores architectural patterns through programmed algorithms that modularize and pixelize complex tessellations. The algorithmic process analyses the layering process through minimizing and organizing system information to create multi-dimensional pillars, that would not have been possible for a craftsman to calculate or make on his own. Using craftsmen to operate multi-dimensional materials is a solution for tight budgets when there is limited use of CNC machines. It requires the architects to be endowed with aesthetic sensitivity and to be able to generate multi-dimensional and multi-perspectival designs, grasp advanced digital technologies and also actualize fabrication independently without relying on these fabricating technologies.

CNC Machines and Multi-Dimensional Materials

Using CNC machines to work on materials in various ways can increase the potential range of use of a material in space beyond the capabilities of a human worker, creating the opportunity for a multi-dimensional fabrication of a whole architectural form. Generally, CNC machines are used to mill out a shape for each piece or for an assembly that needs to be constructed later. However, the same principles can be used to remodel an entire section of the same material. Unfortunately working with a entire section in this way takes too much time and costs too much money for a realistic architectural budget. However, Matter Design Studio in University of Michigan have experimented with stereotomic robotics to model new materials. (The machine can work with AAC, EPS and reconstituted stone). Using these new design concepts requires architects to do more research into the operating methods of the machines and to take into account the volume being shaped.

Chemical Fusion and Composite Materials

Materials used in 3D printing need various features to meet tooling requirements. Different composite materials - from ABS, to stainless steel and high-fiber concrete — have been invented and used for different processes. Research into materials is still in progress, with new materials and CNC machines coming onto the market constantly. Architects such as Morphosis or Foster and Partners are pioneers in the use of rapid prototyping in fabrication, both having specific departments working solely in this field. The invention of the D-Shape printer makes large-scale 3D layered forming possible. Specific binders and catalysts have been developed by architectural technologists, along with construction robots using CAD-CAE-CAM technologies which are used in construction and fabrication, and are free from the constraints of labor. CNC machines operating with composite materials are going beyond traditional fabrication techniques to the extent that sophisticated material mockups have been developed directly from 3D models without referring to any other templates or fabricating methods. These processes of forming complex geometry and material connections are independent of human labor and produce elements that that far exceed the tolerances of traditional fabrication methods.

Digital fabrication is a new approach to design and fabrication that is promoting a revolutionary architectural paradigm. It enables traditional tectonic concepts to be continued to be pursued. As a practical method, whether it is realized by a "low-tech" parametric approach or is made possible by technological developments, it entails a rethinking of the architectural enterprise in terms of a "processing logic".

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