沙盒
——基于计算机辅助建造和增强现实技术的风景园林规划设计操作平台

SANDBOX — AN OPERATION PLATFORM FOR LANDSCAPE ARCHITECTURE PLANNING AND DESIGN BASED ON COMPUTER AIDED MANUFACTURING AND AUGMENTED REALITY TECHNOLOGY

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摘要

在规划设计过程中，用以表达基地原始信息、承载规划设计行为的操作界面，就是规划设计操作平台。随着数字化技术的进步，一种基于计算机辅助建造技术（CAM）和增强现实技术（AR）的操作平台逐渐发展起来，这就是“沙盒”。本文阐述了“沙盒”平台的技术背景，简要回顾了平台的发展历程。作者以北京林业大学风景园林规划设计研究院数字景观研究中心制作的沙盒为例，介绍了“沙盒”平台的架构，并着重展示了其数字信息分析模块的功能及运作原理。“沙盒”是一种能够精确还原现场、直观承载手工设计操作，并进行实时人机互动的四维操作平台。

关键词
规划设计；操作平台；沙盒；计算机辅助建造；增强现实

ABSTRACT

A planning and design operating platform is an operational interface which is used in the process of planning and design to demonstrate the base information of an existing site, and to facilitate planning and design activities. With the improvement of digital technology, an operating platform called Sandbox has been developed, based on Computer Aided Manufacturing and Augmented Reality technology. This paper introduces the technical background of the Sandbox platform, and briefly reviews its development. The author takes the sandbox produced by Digital Landscape Research Center of the Landscape Architecture Planning and Design Institute of Beijing Forestry University as an example, to explain the framework of the Sandbox platform, and to emphatically show the functions and operational principles of its digital information analysis module. The Sandbox is a four-dimensional operation platform that precisely represents the site, directly carries out manual design and operation, and realizes real-time human-computer interaction.

KEY WORDS
Planning and Design; Operating Platform; Sandbox; Computer Aided Manufacturing; Augmented Reality

1 前言

在规划设计过程中，用以表达基地原始信息、承载规划设计行为的操作界面，就是规划设计操作平台。任何规划设计都需要通过操作平台来实现，在计算机技术尚未普及的手工设计时代，景观规划设计操作平台往往为手工草图（如在按比例打印的原始地形图上覆盖半透明草图纸来制图）、手工沙盘模型等。随着计算机辅助设计技术（CAD）的普及，设计师逐渐熟悉了AutoCAD、3D-max、Sketch-up、Rhino、Revit等设计软件。

从手工时代一直到现在，设计师最习惯在二维图纸上进行设计草案的推敲。二维图纸虽然能够给设计方案提供一个最基础的操作平台，却严重缺乏竖向的直观推演能力。景观是建立在地表之上的，竖向设计是景观规划设计的基础，其重要性不言而喻，而将三维的地貌用二维等高线表达出来，再通过二维等高线推敲竖向设计的方式极为抽象晦涩。

手工沙盘即能解决三维竖向信息直观表达的问题，一些拥有良好操作性能的沙盘材料，如黏土、石膏等，还能够方便设计师在原始地形的表面进行手工塑形，实现在三维操作平台上进行规划设计。然而，传统的手工沙盘在生成原始地形的环节上存在较大的技术难度：黏土、石膏等软质沙盘材料很难通过手工技术精确还原场地地貌；而纸板、泡沫等硬质沙盘材料加工出的精度较高的模型又无法进行设计塑形。

当代的计算机软件，已经能够在数字世界里精确地还原场地信息，并且通过数字化工具实现场地规划设计。然而，这种平台仍然存在两个重要的问题。首先，数字三维模型依然要靠二维屏幕来呈现，三维空间感因此大打折扣。其次，数字三维模型无法进行直观的手工操作，需要依靠相对晦涩的软件工具来实现规划设计动作，这种平台提供给设计师的操作方式依然犹如隔靴搔痒。

1 Introduction

A planning and design operating platform is an operational interface which is used in the process of planning and design to demonstrate the base information of an existing site, and to facilitate planning and design activities. Some kind of operating platform is required to achieve planning and design. In the manual design era, before computer technology was popularized, landscape planning and design was often conducted through the platform of hand drafting (for example, making sketches on semitransparent trace paper over a base map printed to scale) and handmade sand table models. With the popularization of computer aided design (CAD) technology, landscape architects have become familiar with design software such as Auto CAD, 3D-max, Sketch-up, Rhino, and Revit.

From the manual design age to the present, landscape architects have been accustomed to cultivating their designs through two-dimensional drawings. Although, without a doubt, two-dimensional drawings do provide a most basic operating platform for designing, they seriously lack the ability to visualize vertical elements. As landscapes are mostly built on the earth's surface, vertical design plays a significant role in landscape planning and design. But the method of designing vertical elements by demonstrating three-dimensional (3D) topography using two-dimensional contours may seem rather abstract and obscure.

Handmade sand tables are a good way to solve the problem of 3D expression of vertical information. Those with good operating performance, made of clay or gypsum, even allow designers to conduct planning and design on the operating platform of the original terrain through hand shaping. However, the traditional handmade sand table has difficulties in generating existing topography: one can hardly accurately restore site topography by hand using soft materials such as clay and gypsum. Although it is possible to achieve high precision using hard materials, such as cardboard or foam, these materials are unable to be easily shaped.

Contemporary computer software is already able to accurately represent site information in the digital world, and achieve site planning and design through digital tools. There are, however, two important problems with these platforms. First, the digital 3D model still depends on a two-dimensional screen to be displayed, which results in a great reduction of the 3D sense of space. Second, the digital 3D model cannot be hand-operated in a visual way, instead, it relies on relatively complex software to do planning and design. Thus, this kind of operation method is not efficient either.

2 技术背景

随着数字化技术的发展，计算机辅助建造技术（CAM）和增强现实技术（AR）的普及，一种新型操作平台逐渐发展起来。

2.1 计算机辅助建造技术

CAM在建筑学界常被称作数字化建造，是利用计算机技术和三维成型技术辅助设计和建造的一系列技术的统称。

这种早先主要应用在工业和制造业领域的技术，其运作的原理如下：首先，将建造目标的三维数字模型转化、编译成三维成型工具的动作路线和工序内容代码（如CNC数控机床的输出信息是刀具加工时的运动轨迹工序）。接下来，由数控三维成型设备（如激光雕刻机、CNC数控机床、三维打印机、工业机器人等）依据工序代码将物理材料加工或装配成实体。通过CAM技术，能够快速将虚拟数字模型转化成为物理实体。（图1）

2.2 增强现实技术

增强现实技术是一种将真实世界信息和虚拟世界信息"无缝"集成的技术，这种技术的目标是把虚拟数字信息嵌套在现实世界里并进行实时互动。

2 Technological Contexts

With the improvement of digital technology, as well as the popularization of Computer Aided Manufacturing (CAM) and Augmented Reality (AR) technology, a new type of operating platform gradually developed.

2.1 Computer Aided Manufacturing

CAM, often called Digital Fabrication in the field of architecture, is a combination of computer technology and physical 3D molding to assist design and construction.

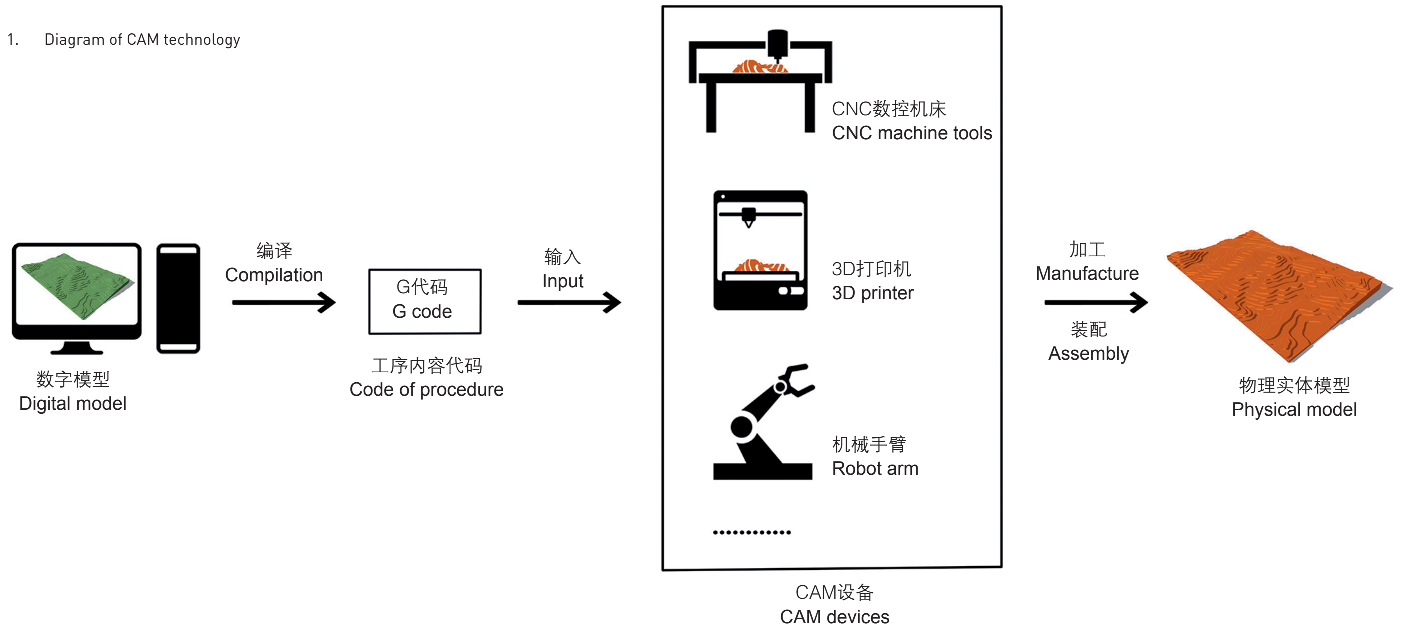
Mainly used in industrial and manufacturing sectors in the past, this technology works as follows: First, the 3D digital model of the construction target is converted and compiled into action lines and process code for the 3D molding tools (for example, the output information of CNC machine tools is the movement trail of the cutting tool). Next, the physical material is machined or assembled into an entity by a numerically controlled 3D-shaping apparatus (for example, laser engravers, CNC machine tools, 3D printers, industrial robots, etc.). Through CAM technology, virtual digital models can be quickly transformed into physical entities (Fig. 1).

2.2 Augmented Reality

AR is the technology that "seamlessly" integrates real-world information with virtual world information. The goal of this technology is to embed virtual digital information in the real world for real-time interaction.

1. CAM技术图解

1. Diagram of CAM technology



AR技术最早应用在军事领域（如战斗机飞行员的头盔显示系统），其运作的基本原理是通过感应设备（如战斗机的雷达、摄像头、红外探测器等）识别现实世界中的信息（如敌机位置、海拔高度、相对速度等），经过数字化运算处理后，这些信息被转化为字符或图像的形式，经显示设备（如头戴式显示器，投影器等）投射到真实世界，再被人类感官所感知，实现了真实物理世界与虚拟数字世界的实时互动。（图2）

2.3 沙盒平台的发展回顾

早在2002年，麻省理工大学的数字媒体实验室就曾基于AR技术发展出一套名为"照亮的黏土"的系统。这套系统由一个可旋转的黏土工作台、一个激光三维扫描仪、一个投影仪和一部装有分析软件的电脑组成。悬吊在黏土工作台上方的激光三维扫描仪能够实时采集黏土的形态改变，将数字信息输入电脑。接下来，一套专门为系统开发的软件能够对黏土的数字信息进行分析，包括高程、坡度、光照、径流和土壤侵蚀等。最后，分析的结果将以可视化图像的形式，由投影仪投射在黏土表面。这套系统初步实现了人与实体物理模型、虚拟数字模型之间的互动。[1]（图3）

瑞士苏黎世联邦理工学院建筑系的LVML实验室也发展出一套类似的名为"沙盒"的操作平台。与"照亮的黏土"系统相比，这套平台

AR technology was first used in the military field, in the display systems of fighter pilots' helmets. Its purpose is to identify real-world information, including enemy aircraft position, altitude, relative speed, etc. through sensing devices (radar, camera, infrared detector which set in the fighter), digitally process that information, and then project it in the form of characters or images via display devices (head-mounted displays, projectors, etc.) into the real world. The information is then perceived by human senses, thereby realizing real-time interaction between the real physical world and the virtual digital world (Fig. 2).

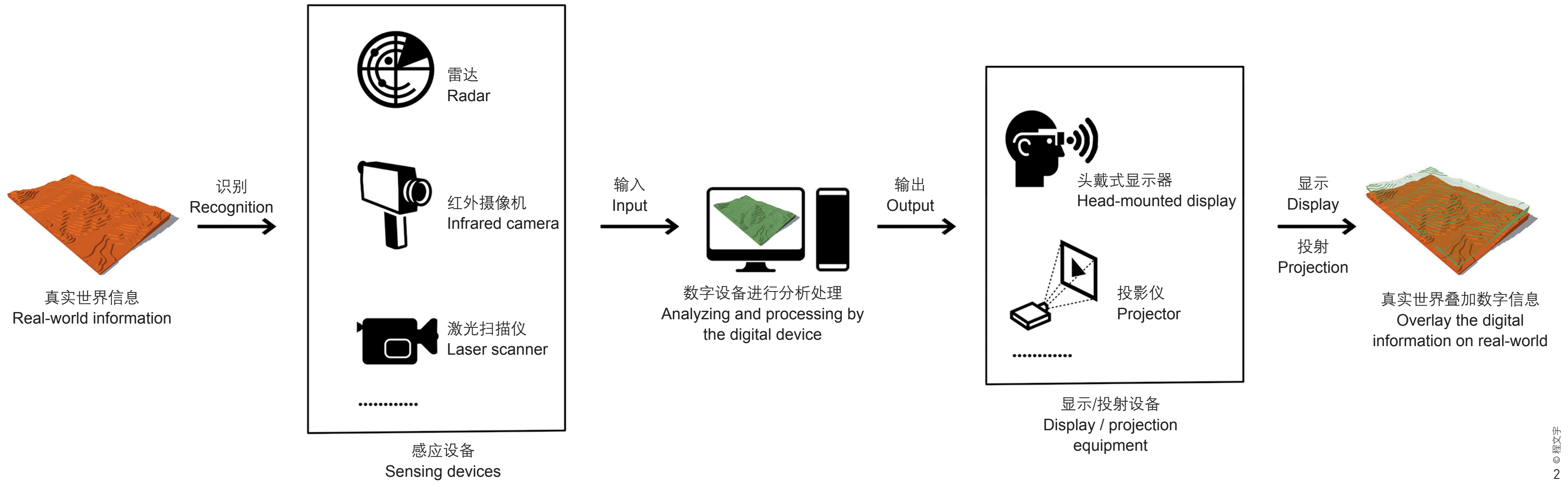
2.3 A Review of Sandbox's Development

As early as in 2002, based on AR technology, The Media Laboratory at Massachusetts Institute of Technology developed a system called "Illuminating Clay." The system consisted of a rotatable clay table, a 3D laser scanner, a projector, and a computer equipped with analysis software. Hanging above the clay table, the 3D laser scanner was able to capture real-time shape changes in the clay, and input digital information to the computer. Next, a set of software specifically developed for the system analyzed the digital information gathered from the clay model, including elevation, slope, sun shadow, runoff and soil erosion. Finally, the analysis results were projected onto the surface of the clay by the projector in the form of a visualized image. This system was the first to realize the interaction between human perception, a physical model, and a virtual digital model.[1] (Fig. 3)

The LVML Lab at the School of Architecture, Swiss Federal Institute of Technology Zurich (ETH Zurich), also developed

2. AR技术图解

2. Diagram of AR technology



在系统中加入了CAM技术。为更加精确地再现原始地形，研究人员将设计基址的地形生成数字三维模型（DTM），再导出其负模并用CNC数控机床雕刻成形。接下来，负模被倒扣在一个盛满粘性沙子的模型工作台上，压实再揭开负模后，就形成了由沙子塑造的设计基址的正向三维模型。设计师可以在这个三维模型的基础上用雕刀和小铲之类的工具反复推敲，以形成理想的设计方案。沙盒上装有小型激光三维扫描仪，可以将沙子模型随时转化成为数字模型并进行实时分析。[2]（图4）

由美国南加州大学建筑学院景观系的景观形态实验室在2010年开发的“快速景观原型设计机（RLPM）”，则在CAM技术上又突进了一步。RLPM采用机器人手臂来生成原始地形，与瑞士苏黎世联邦理工学院的“沙盒”相比，这种方式比CNC机床雕刻负模更为快速直接。[3]（图5）

3 平台架构

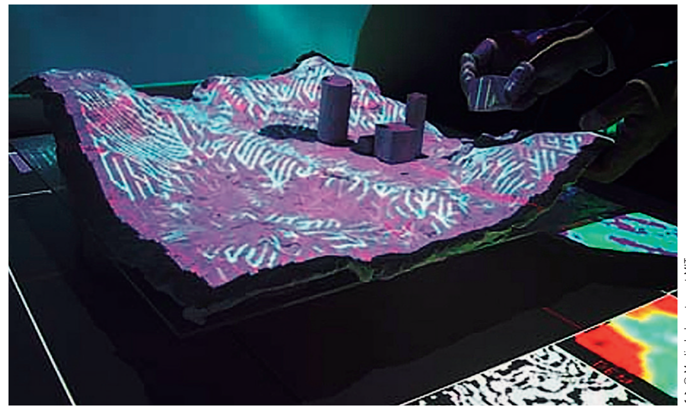
从上述各种版本的系统中可以发现，“沙盒”平台主要由以下4部分组成：基于CAM技术的地形实物再现及设计操作模块、基于AR技术的数字信息识别模块、数字信息分析模块和数字信息投射模块。下面

a similar operating platform called the “Sandbox.” Unlike the “Illuminating Clay” system, this platform applies CAM technology. In order to more accurately reproduce the original terrain, researchers would generate a Digital Terrain Model (DTM), transform it into a negative mold, and then use the CNC machine tools to engrave the shape. Next, the negative mold was inverted on a model table filled with viscous sand. After compaction, the sand formed a positive 3D model of the base topography. Designers could then work on the 3D model repeatedly, using tools such as knives and small shovels, until they formed the ideal design. The sandbox is equipped with a small 3D laser scanner, which can at any time convert the sand model into a digital model and conduct real-time analysis. [2] (Fig. 4)

The Rapid Landscape Prototyping Machine (RLPM), developed in 2010 by the Landscape Morphologies Lab in the Department of Landscape, School of Architecture at the University of Southern California, made another step forward in CAM technology. Compared with the Sandbox of the ETH Zurich, the RLPM uses a robot arm to create the original terrain, which is much faster and more direct than the CNC machine tool. [3] (Fig. 5)

3 The Platform Structure

From various versions of the system, we can see that the Sandbox platform is mainly composed of four parts: a CAM-based physical terrain reproduction and design operation module, an AR-based digital information recognition module, a digital information analysis module, and a digital information projection



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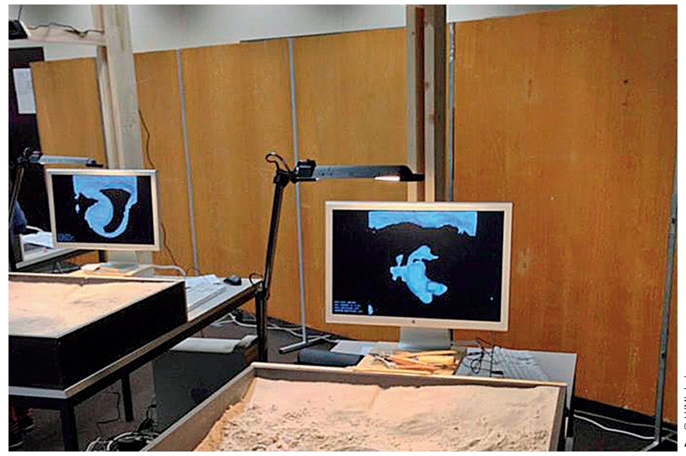

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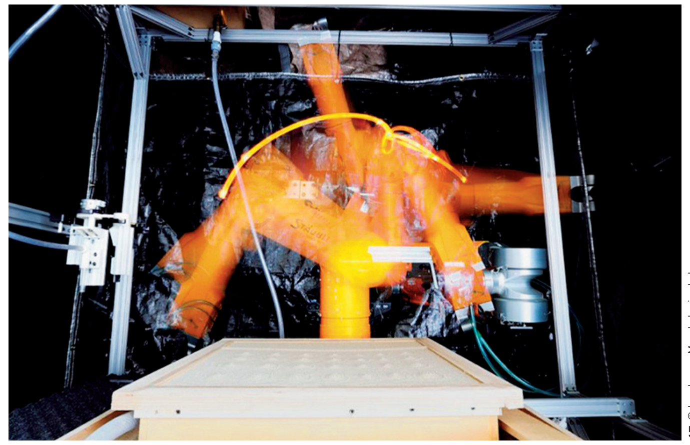

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3. “照亮的黏土”系统
4. LVML实验室研发的“沙盒”系统
5. “快速景观原型设计机”系统

3. Illuminating Clay
4. Sandbox developed by the LVML Lab
5. The Rapid Landscape Prototyping Machine

6. 北京林业大学风景园林规划设计研究院设计的“沙盒”系统图解

6. Diagram of Sandbox developed by the Landscape Architecture Planning and Design Institute, Beijing Forestry University

以北京林业大学风景园林规划设计研究院制作的“沙盒”为例，来阐释整个系统的架构。（图6）

3.1 地形实物再现及设计操作模块

这个模块需要提供一个基础的物理操作界面，以再现场地地形信息。场地的三维数字模型需要通过CAM设备加工制作成物理模型，物理模型应选用易塑形的材料来承载随后的设计操作。

3.1.1 模块硬件组成

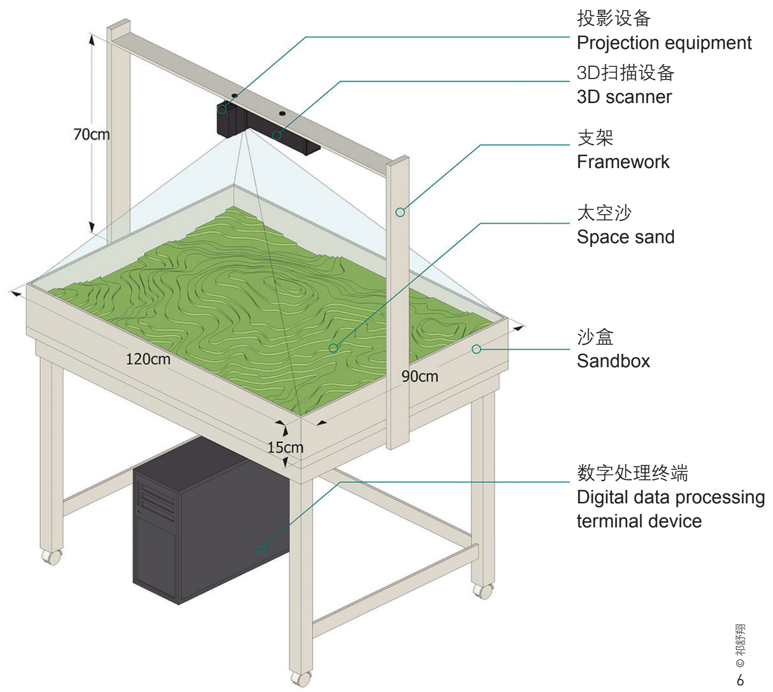
我们选择了一种名为“太空沙”的儿童玩具沙作为物理塑形的材料，“太空沙”是将深海细沙与蜡、胶水、保湿剂等按照一定比例糅合而成的混合物，这种沙子具有良好的粘性，能够反复塑形并且长时间保持形状。为了在后期投影时呈现出更好的效果，我们选择了浅米色的太空沙。

沙子被盛放在一个长120cm、宽90cm、高15cm的盒子里，这个盒子由松木板以燕尾榫的方式拼接而成。盒子的尺寸经综合考虑CAM工具的加工范围、三维扫描仪的识别精度及微型投影仪的投射尺寸等因素而确定。盒子上方设立支架，用于挂载三维扫描设备和微型投影仪。

3.1.2 模块运作方式

依托“沙盒”平台，目前有两种方式能够达成地形实物再现：负向成型方式和正向成型方式。

负向成型方式即运用CAM设备加工地形负模，再将负模按压在沙子表面形成正向模型的方式。首先，场地的三维数字模型需要被适度



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module. Next, we take the Sandbox produced by The Landscape Architecture Planning and Design Institute of Beijing Forestry University as an example, to explain the structure of the whole system. (Fig. 6)

3.1 Terrain Reproduction and Design Operation Module

This module requires a basic physical operating interface in which to reproduce the site terrain information. The 3D digital model of the site will be processed into a physical model by the CAM equipment, and the physical model should be made of easily-shapeable materials to facilitate the subsequent design operation.

3.1.1 Module Hardware

We chose “space sand,” a type of toy sand made for children, as our physical shaping material. A mixture of deep sea sand, wax, glue, and humectant in precise proportions, this type of sand has good viscosity, can be repeatedly molded, and maintains its shape for a long time. In order to display better results in the later projection stage, we used light beige colored space sand.

The sand is contained in a box 120 cm in length, 90 cm in width and 15 cm in height, and spliced with pine boards in a dovetailed manner. The size of the box was determined with full consideration of the processing range of the CAM tool, the recognition accuracy of the 3D scanner, and the projection size of the micro projector. A bracket was set up above the box for mounting the 3D scanner and the micro projector.

3.1.2 Module Operation Mode

With the Sandbox platform, there are two methods to achieve terrain representation: negative molding and positive molding.

The negative molding method uses CAM equipment to process a negative of the desired terrain, then inverts and presses the negative mold onto the sand surface to form a positive model.

简化并缩放到合适的比例（模型尺度往往取决于CNC数控机床的加工范围）。随后，三维数字模型被导入Rhino软件生成负向数字模型，再导入PowerMill①软件中设置雕刻的各项策略，生成雕刻的刀路，并根据刀路导出CNC数控机床的动作指令代码（G代码）②。接下来，CNC数控机床将依据G代码雕刻出负模，负模的材料可以是松木或代木树脂③，这些材料的硬度适中，既容易雕刻，又具备一定的强度，可以挤压沙子以形成最终的模型。最后，将负模按压在事先耙松过的沙子表面，就生成了地形正向模型。（图7）

正向成型方式即运用CAM设备直接生成地形正向模型的方式。目前能够在沙子上塑形的CAM设备主要是机械手臂。机械手臂是模仿人手臂运动方式的CAM设备，由舵机或步进电机配合谐波传动减速装置提供动力，可遥控控制或编程控制，理论上满足7自由度的机械手臂就可以模拟人手臂做出的任何运动。将机械手臂前端的抓手替换成旋转刀头、扒犁或铲刀，就可实现在沙盒中塑形的目标。但相比CNC数控机床，大型机械手臂成本高、编程难度高、使用危险性高等特点限制了其普及。另外，用机械手臂在软性的沙子上塑形的难度极大，一方面

First, the 3D digital model of the site needs to be simplified and zoomed in to an appropriate scale (the scale of the model often depends on the processing range of the CNC machine tools). Second, the 3D digital model is imported into the software Rhino to generate the negative digital model, and then imported into PowerMill① to set the engraving strategies, generate the engraving tool path and derive the operation instruction code (G code)② for the CNC machine tool. Next, the CNC machine tool engraves the negative mold based on G code, using pine or resin wood③. Due to their moderate hardness, these materials are both easy to engrave, and intense enough to extrude the sand to form the final model. Finally, the positive model is generated by pressing the negative mold against a raked sand surface. (Fig. 7)

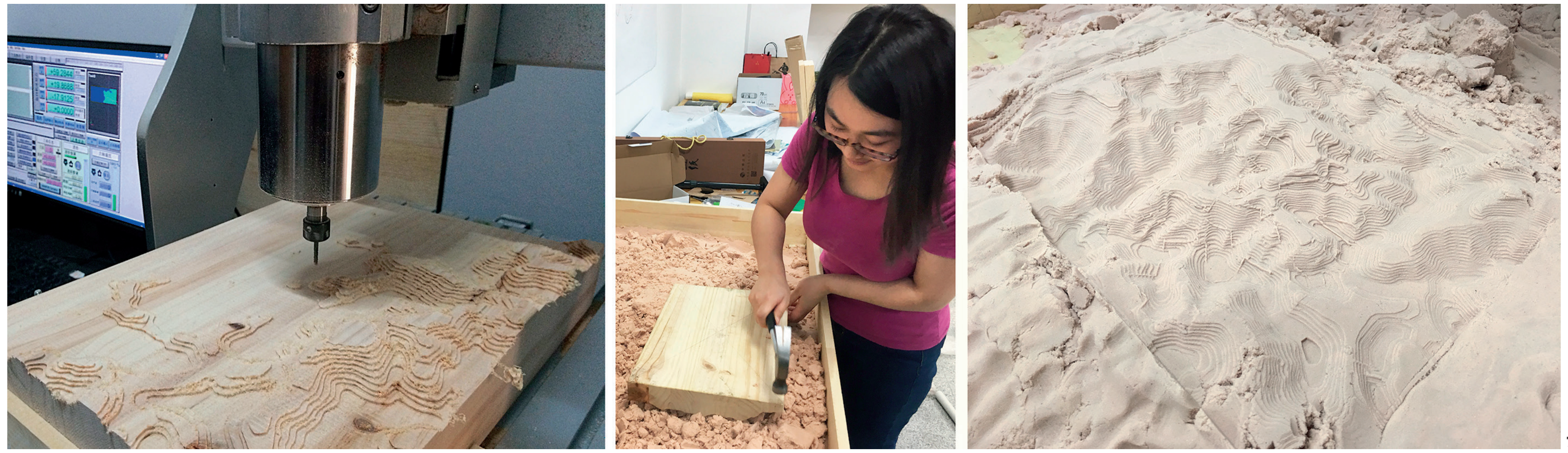
The positive molding method directly generates the positive model of the topography using CAM equipment. Currently, the mechanical arm is the primary CAM equipment capable of shaping sand. The mechanical arm imitates the movement of a human arm, and is powered by a steering engine or stepper motor, combined with a harmonic drive; it can be remote controlled or programmed. In theory, a mechanical arm that meets seven degrees of freedom is able to imitate any movement of human arms. By replacing the gripper at the front of the mechanical arm with a rotating cutting head, a plow, or a blade, we can make it able to shape material in the sandbox. However, compared to CNC machine tools, large-scale mechanical arms carry a high cost, high programming difficulty, and high risk of application, which makes them difficult to popularize. In addition, due to its insufficiency in intensity, soft sand is very difficult to shape with a mechanical arm, and the sand shape often collapses. Furthermore, the waste generated by molding operations cannot be effectively

① PowerMill是英国Delcam公司出品的数控加工编程软件系统。
② G代码是一种数字化控制程序语言，常用于对CAM自动化机床的控制中。
③ 代木树脂是一种物理特征接近木头的树脂，又称可机加工树脂板材。

① PowerMill is a CAM solution for CNC programming by Delcam.
② G code is the most widely used numerical control (NC) programming language. It is used mainly in CAM to control automated machine tools.
③ Resin wood's physical characteristics is similar with wood, which can also be called machinable resin plate.

7. CNC负模雕刻及挤压沙子形成最终的模型
8. Kinect生成的点云

7. CNC machine tool engraves the negative mold and extrude the sand to form the final model
8. Point cloud generated by Kinect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④ Kinect 2.0是微软Xbox one游戏机的感应器，包括一个250万像素的红外线深度感应器和720p摄像头。
⑤ Processing是麻省理工学院媒体实验室开发的开源程序语言。

④ Kinect 2.0 is a line of motion sensing input devices for Xbox one, with built-in 2.5 million pixels infrared depth sensor and a webcam that can stream video in 720p.
⑤ Processing is an open source programming language developed by Media Lab of MIT.

由于沙子的强度不够，极易塌陷，另一方面塑形操作后产生的废料也无法得到有效清理，难以形成平滑的表面。但相比于负向成型方式，若能使用机械手臂实现正向塑形，则可极大简化流程。

3.2 数字信息获取模块

本模块的核心目标是分析设计操作影响下的沙盒模型信息，并将其转译为三维点云信息后输入至下一个模块。

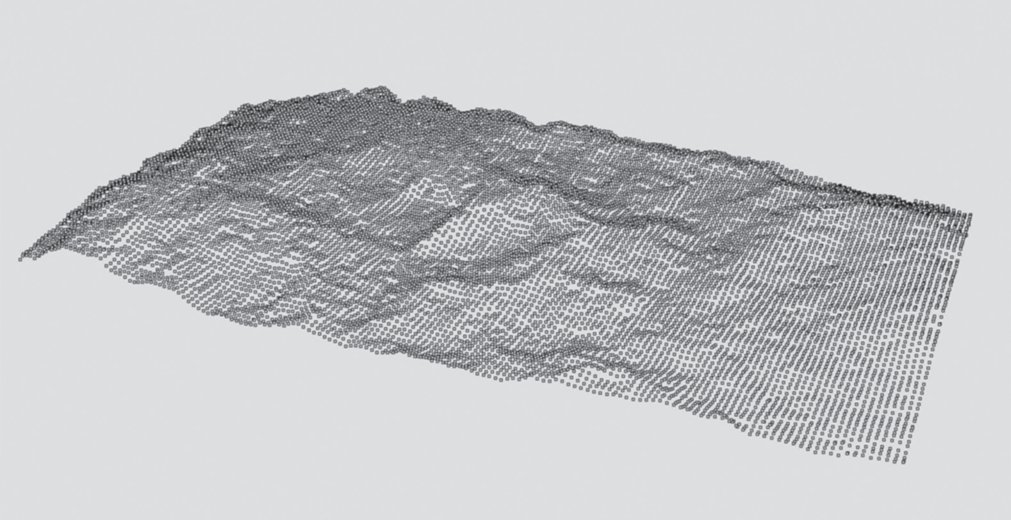
3.2.1 模块软硬件组成

模块的核心硬件是一台三维扫描仪，经过对市面上各种三维扫描设备的比选，我们选择了微软Kinect 2.0④。相比于其他三维扫描设备，Kinect简单易用，价格便宜，扫描精度也较高。更重要的是，微软为Kinect推出了windows环境下的开发套件（电脑转接器）及软件开发工具包（SDK）开发平台，使得Kinect能够脱离Xbox游戏机独立运行。通过SDK开放的应用程序接口，开发者可通过调用丰富的内建函数直接控制Kinect。

由于SDK开放端口无法与三维建模软件（Rhino）直接通信，我们使用了一种名为Processing⑤的程序设计语言编写了一个小程序，该程序能够调用Kinect SDK内建函数来控制Kinect，并对其返送的数据进行转码，成为Kinect与Rhino之间的信使。

3.2.2 模块运作方式

通过运用Processing编写的程序，我们可以对Kinect发射器发送工作指令，由Kinect发射的红外射线经由沙盒地形反射后被Kinect红外接收装置接收，经Kinect内建算法计算，就获得了被扫描地形的空间点云信息。接下来，这些点云信息被返送至Processing程序，程序将通过局域网协议对点云信息进行转码，以输出Rhino软件能够识别的数据格式。（图8）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cleaned to form a smooth surface. Nevertheless, compared to the negative molding method, if the mechanical arm can achieve positive shaping, it would greatly simplify the process.

3.2 Digital Information Obtaining Module

The core goal of this module is to analyze the sandbox model developed in design operations, compile it into 3D point cloud information, and input it into the next module.

3.2.1 Software and Hardware Components of the Module

For the 3D scanner, the core hardware of this module, we chose the Microsoft Kinect 2.0④ after considering a variety of 3D scanning equipments on the market. Compared to other three-dimensional scanners, Kinect features advantages including ease of use, reasonable price and high scanning accuracy. More importantly, Microsoft has launched computer adapters and a Software Development Kit (SDK) for Kinect, making it able to run independently without Xbox. Through the application programming interface provided through the SDK, software developers can directly control Kinect by invoking a rich variety of built-in functions.

As the SDK open port cannot directly communicate with the 3D modeling software (Rhino), we use a programming design language named Processing⑤ to write a small program that invokes Kinect SDK built-in functions to control Kinect. The program also could transcode the returned data which functions as a messenger between Kinect and Rhino.

3.2.2 Operating Method of the Module

Through the use of the program written by Processing, we can send work instructions to the Kinect transmitter. Infrared rays transmitted by Kinect are reflected by the sandbox terrain and received by the Kinect infrared receiver. After computing by the Kinect built-in algorithm, a spatial point cloud of the scanned terrain is generated and sent back to the Processing program, which will transcode the information through Local Area Network protocol, in order to output data in the format that Rhino can recognize. (Fig. 8)

3.3 数字信息分析模块

空间点云信息被输入本模块后，通过预设的软件，对数字模型进行针对性的分析，并且以可视化图像的模式输出分析成果信息。

3.3.1 模块软硬件组成

数字分析模块主要由一台电脑和数据处理软件构成，我们选择了Rhino与Grasshopper组合作为数据处理软件。Rhino是一款功能强大的三维建模软件，拥有强大的兼容性。Grasshopper是一款在Rhino环境下运行的采用程序算法生成模型的插件，根据不同的建模、分析及表现需求，我们可以按照算法逻辑组合"电池"构建目标程序，通过调整输入"电池"的参数来控制最终模型的形态或界定分析及表现过程。Grasshopper的这种可视化的编程方法，使得设计师不需要有编程功底即可完成比较复杂的参数化模型建造及参数化分析和表现工作。

3.3.2 模块运作方式

我们利用Grasshopper编写了基于点云信息的地形高程、坡度坡向、填挖方、径流模拟、日照辐射等一系列分析程序。这一系列分析模块在Rhino接收到Processing发来的点云数据后自动运行。分析的结果与三维地形实时联动，地形修改后，坡度、坡向、汇水等分析结果也会实时更新，这种联动反馈可为设计师提供更加直观的视觉界面，为理性的设计操作提供参考。

3.4 数字信息投射模块

本模块是一个与物理模型坐标精准对位的投射系统，能够将上一模块输出的可视化图像信息精准投射在模型表面，从而实现虚拟数字信息与真实物理模型的叠加。

3.4.1 模块硬件组成

模块的核心硬件是一个投影仪，由于投影仪需要吊装在沙盒正上方，并能随沙盒移动，因而要求其体积小、重量轻。另外，投影仪需要在尽可能短的垂直距离上投出尽可能大的画面，因此我们选择了

3.3 Digital Information Analysis Module

After the spatial point cloud information is input to this module, it conducts targeted analysis of the digital model through preset software, and outputs the analysis results in the form of visual images.

3.3.1 Software and Hardware Components of the Module

The digital analysis module mainly consists of a computer running a combination of data processing software: Rhino, a powerful 3D modeling software with strong compatibility, and Grasshopper, a plug-in that runs in the Rhino environment and generates models from programmed algorithms. According to different types of modeling, analysis, and performance requirements, we can combine different components, or commands, based on the algorithm logic to build the desired program. By adjusting parameters of the input components, we control the shape of the final model, or define the analysis and presentation processes. Grasshopper's visual programming approach allows designers to perform complex parametric modeling and parametric analysis and presentation without programming skills.

3.3.2 Operating Method of the Module

Based on point cloud information, we use Grasshopper to write a series of programs analyzing elevation, slope gradient and aspect, cut and fill, runoff simulation, sunshine radiation, etc. This series of analytic modules run automatically after Rhino receives the point cloud data sent by Processing. The results of the analysis are linked with the 3D terrain in real time. After terrain modification, the results of slope gradient, slope aspect, and water catchment analysis update in real time. This feedback loop provides a clearer visual interface to help designers achieve rational design operations.

3.4 Digital Information Projection Module

This module is a projection system precisely aligned with the physical model coordinates. It can precisely project the visual information outputted by the previous module onto the surface of the model, superimposing the virtual digital information and the real physical model.

3.4.1 Hardware Components of the Module

The core hardware of the module is a projector. Since the projector has to be mounted above the sandbox and move with the sandbox, it should be of small size and light weight. In addition, to cast the largest possible image in the shortest possible vertical distance, we chose a portable short focus

便携式短焦投影仪，具体型号为华硕S1投影仪，其投影比为1.1:1，分辨率为854×480，亮度200流明。投影仪吊装在沙盒平台上的高度为70cm，投射影像尺寸为64cm×48cm。

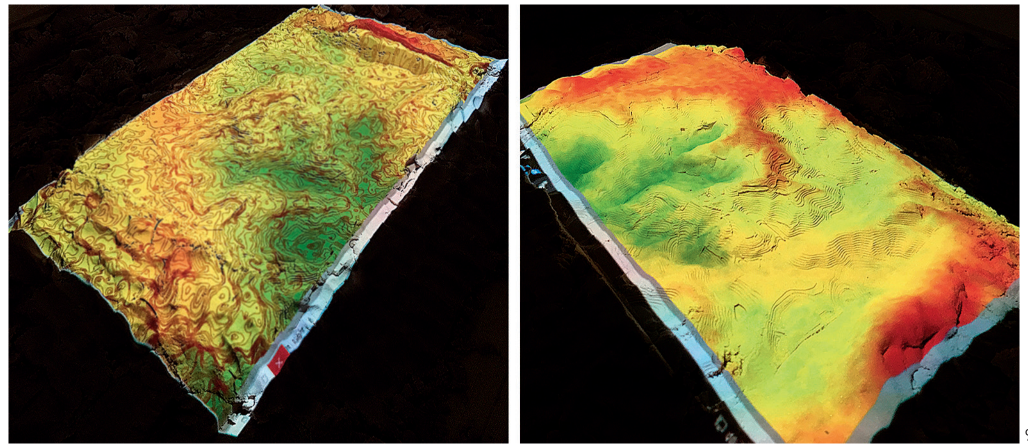
3.4.2 模块运作方式

首先要对投射系统与沙盒模型进行坐标校准：我们可以用小木棍在沙盒中设立三个物理参照点，通过调整三个参照点的投射影像，能够让影像与沙盒地形之间建立起正确的对位关系。接下来，景观设计师可以根据设计需要，调用地形高程、坡度坡向、填挖方、径流模拟、日照辐射等数字信息分析模块，投影仪将通过正投的方式将分析模块输出的图像信息投射到沙盒地形表面，实时辅助设计操作。

4 数字信息分析模块功能及运作原理

4.1 高程可视化

对场地高程的解读分析是设计的基础，我们能够利用Grasshopper编写的程序自动连接数字地形相同的高程点以生成等高线。通过输入绝对或相对高程、设定等高距，即可生成目标等高线，在此基础上，通过增加筛选条件，还可以区分首曲线和计曲线。程序的另一种模式是通过自定义色阶来表达高程，参照地理学惯用的竖向色阶，即可直观表达高程信息。最后，程序也能够以数字形式显示任意点高程。（图9）



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9\. 高程可视化

9\. Elevation Visualization

projector, ASUS S1, with a projection ratio of 1.1:1, resolution of 854 × 480 pixels, and brightness of 200 lumens. The projector is mounted 70 cm above the sandbox platform, with a projected image size of 64 cm × 48 cm.

3.4.2 Operating Method of the Module

First, we need to calibrate the coordinates of the projection system and the sandbox model by using small wooden sticks to set up three physical reference points in the sandbox. By adjusting projection images of these three reference points, we can establish the correct corresponding relationship between the image and the sandbox terrain. Next, landscape architects can invoke the digital information analysis modules such as terrain elevation, slope gradient and aspect, fill and cut, runoff simulation, and sunshine radiation, according to the design requirements. The projector will project the image information outputted by the analysis module to the sandbox terrain surface as a positive projection, providing real-time assistance to the design operation.

4 Functions and Operation Principles of the Digital Information Analysis Module

4.1 Elevation Visualization

The interpretation of site elevation is the basis of the design. Programs written in Grasshopper can automatically connect elevation points in the digital terrain to generate contours. By entering absolute or relative elevations and setting contour intervals, we can create target contours. On this basis, by adding screening conditions, we can even distinguish intermediate contours and index contours. Another mode of the program expresses elevation through customized color gradation. Referring to the vertical color gradation commonly used in geography, we can clearly express the elevation information. Finally, the program can also display any point elevation in numerical form. (Fig. 9)

4.2 坡度、坡向和开发适宜性分析

地形坡度与坡向是影响场地设计策略的重要因素。与高程分析类似，我们能够利用Grasshopper编写的程序自动识别数字地形的坡度与坡向，并以色阶显示预设的分级。在此基础上，我们也可以选择单独显示地形的有利或不利特征（如单独显示坡度大于25度的不宜建设的区域），来评价地块的开发适宜性，以进一步指导设计（图10）。

4.3 获取剖面

剖面是解读场地竖向信息的直观工具，我们可以使用Rhino自带的命令直接输出任意位置的场地剖面，以直观考量场地的关键竖向信息。

4.4 土方平衡

用传统的网格法计算填挖方，过程繁琐且误差较大。而我们所编写的程序则能够通过计算原地形表面与设计地形表面间的体积变化量，得到更加精准的土方变化数值。该计算结果以方格网的形式实时显示，网格交点处显示原标高、设计标高、高程变化量等数据，方格中心显示对应区域的填挖方数值。程序还可以以不同色彩区分显示填方、挖方区域，以直观表达土方平衡的情况。（图11）

4.2 Analyses of the Slope Gradient and Aspect and Development Suitability

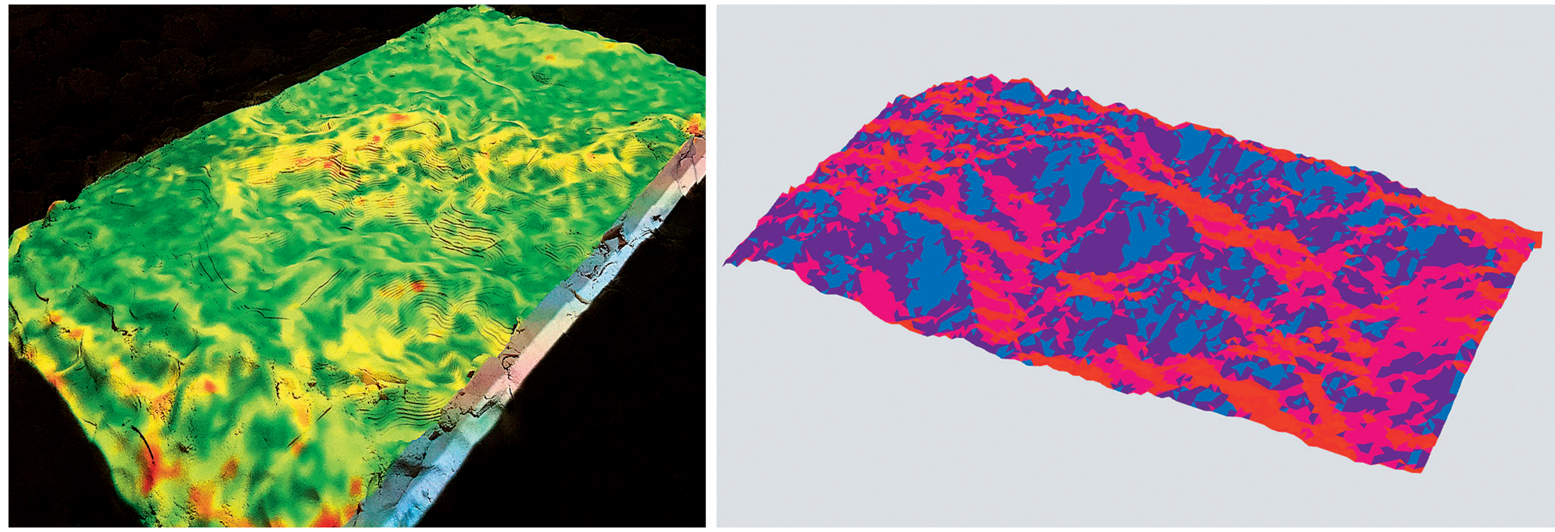
Slope gradient and slope aspect are important factors which affect site design strategies. Similar to elevation analysis, we use programs written in Grasshopper to automatically recognize the slope gradient and aspect of a digital terrain, and display it in a preset color gradation. On this basis, we can also highlight terrain with favorable or unfavorable characteristics (such as a separate display of slopes greater than 25 degrees, which would be unsuitable for construction) to evaluate the development suitability of a site, further guiding the design (Fig. 10).

4.3 Obtaining Sections

Sections are visual tools for interpreting the vertical position of the site. We can use Rhino's native commands to directly output section profiles of any location to illustrate the vertical information of the site.

4.4 Cut and Fill Balance

The traditional grid method for earthwork calculation is a complicated process and often results in errors. We have developed a program which obtains more accurate earth-moving values by calculating the volume change between the original terrain surface and the designed terrain surface. The results of the calculation are displayed in real time in the form of square grids, with data of the original elevation, designed elevation, and elevation change displayed in grid intersections, and cut-fill values shown in the center of the grids. The program can also display fill and cut areas in different colors to show the earthwork balance in a more visual way. (Fig. 11)



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10. 坡度与坡向分析
11. 填挖方与土方平衡
12. 道路选线

10. Analyses of the slope gradient and aspect
11. Cut and fill balance
12. Auxiliary route selection

4.5 辅助道路选线

道路的选线受地形地势的影响较大，尤其是在丘陵地形中，道路选线需同时满足功能性与安全性要求。在设计道路选线时，我们可以直观地避开地形地貌中诸如冲沟等地质不稳定区域或需要避让的区域，但必须为满足道路的坡度要求而不断计算。为了简化这一过程，我们通过Grasshopper编写了一个能够实时显示各段道路坡度的程序：设计师只需在Rhino中绘制出道路的平面线形，程序便会自动将该线形投影至数字地形表面，形成道路的数字三维模型，并自动计算出各段道路的坡度，再以色阶的方式实时显示，设计师可以以此为参照重新调整道路线形，而无需再进行繁复的坡度计算。（图12）

4.6 地表径流模拟和分析

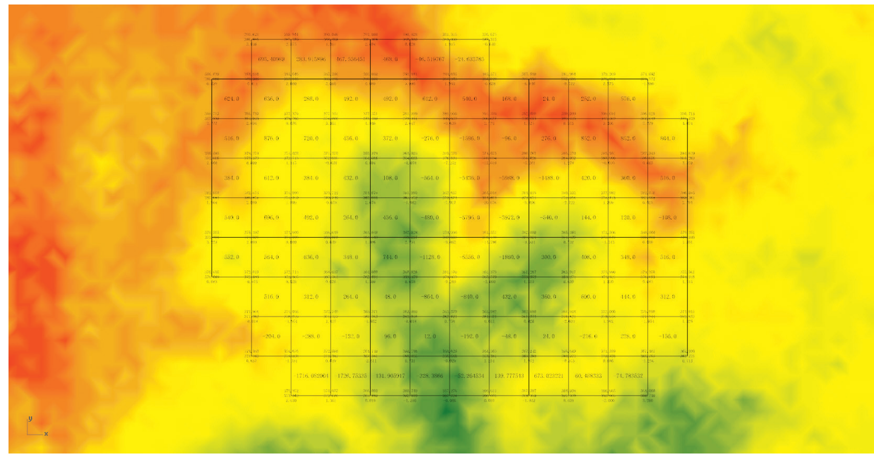
传统的场地汇水分析或基于侧重定性而非定量分析的GIS软件，或基于定量但无法模拟真实流向的SWMM软件。我们编写的地表径流模拟程序，既可以精准地模拟水流的实际流动状态（定性），也可以计算特定区域的集水数据（定量）。通过模拟地表径流，可还原场地内降水的径流过程，设计师依据模拟的情况，可以酌情在沙盒上手工修改地形或增加设施，有针对性地对地表径流进行导流、收集或缓释，以

4.5 Auxiliary Route Selection

Route selection is heavily influenced by existing terrain, especially in hilly sites. Route selection should meet not only functional, but also safety requirements. In the design of road alignment, we can easily avoid geologically unstable areas such as gullies. But we also have to conduct continuous calculations in order to meet road slope requirements. To simplify this process, we wrote a program in Grasshopper to display the real-time road slope gradient: designers can simply draw the desired road route in Rhino, and the program will automatically project the line to the digital terrain surface, forming a digital 3D model of the road, calculating the slope gradient of each road section, and displaying the slope on the surface with color gradation. Designers can then use it as a reference to re-adjust the road alignment, avoiding a great deal of complex slope calculations. (Fig. 12)

4.6 Surface Runoff Simulation and Analysis

Traditional site catchment analysis is based either on GIS software that focuses on qualitative rather than quantitative analysis, or on quantitative SWMM software that is unable to simulate real flows. The surface runoff simulation program we wrote, on the other hand, can accurately simulate both the actual flow (qualitative) and the catchment data (quantitative) for a particular area. Through simulation of surface runoff, it can reproduce the conditions of precipitation on the site. According to the simulation, designers can also manually modify the terrain or add facilities, thereby guiding, collecting, or releasing surface runoff to meet the landscape architectural requirements. By



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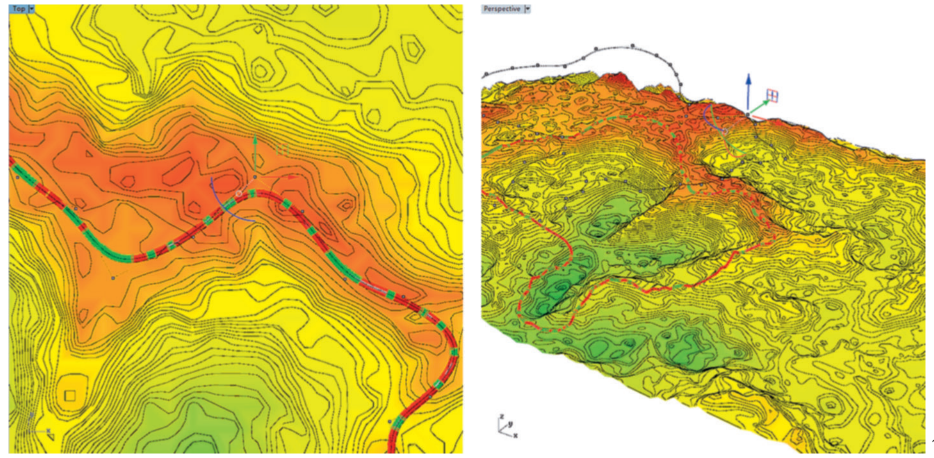

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满足景观设计的需求。若综合径流长度和汇流损耗系数（下渗、蒸发、生物滞留等），我们还可得到更具实际意义的汇流分析数据。（图13）

4.7 场地日照辐射和太阳阴影模拟分析

场地光照及积温直接影响场地的植物长势和使用感受，较为精准的场地光照及积温信息，能够让景观设计师更加理性地进行场地设计及种植设计。为此，我们使用了Grasshopper平台下的第三方插件Geco，此插件能够基于场地所处经纬度对应的全年太阳轨道、照射角度等气候及气象信息和场地周边构筑物等场地信息，分析计算出场地任意时间段内的日照时长、日照辐射量等数据。再通过Grasshopper编写一个程序将这些数据以自定义色阶的形式直观显示，或筛选出符合不同种植需求的场地（如日照时长或辐射量大于某一值的场地），以便针对性地进行植物种植设计或场地设计（如增加构筑物遮阴等）。

5 总结与展望

通过在沙盘中引入CAM技术和AR技术，造就了“沙盒”这种新的规划设计操作平台。一方面，CAM技术使得利用可反复塑形的材料精确还原现场成为可能，沙子物理模型既能直观表现复杂地形，又能承载手工设计操作。实践证明，人们面对三维实物时往往可以发挥更强

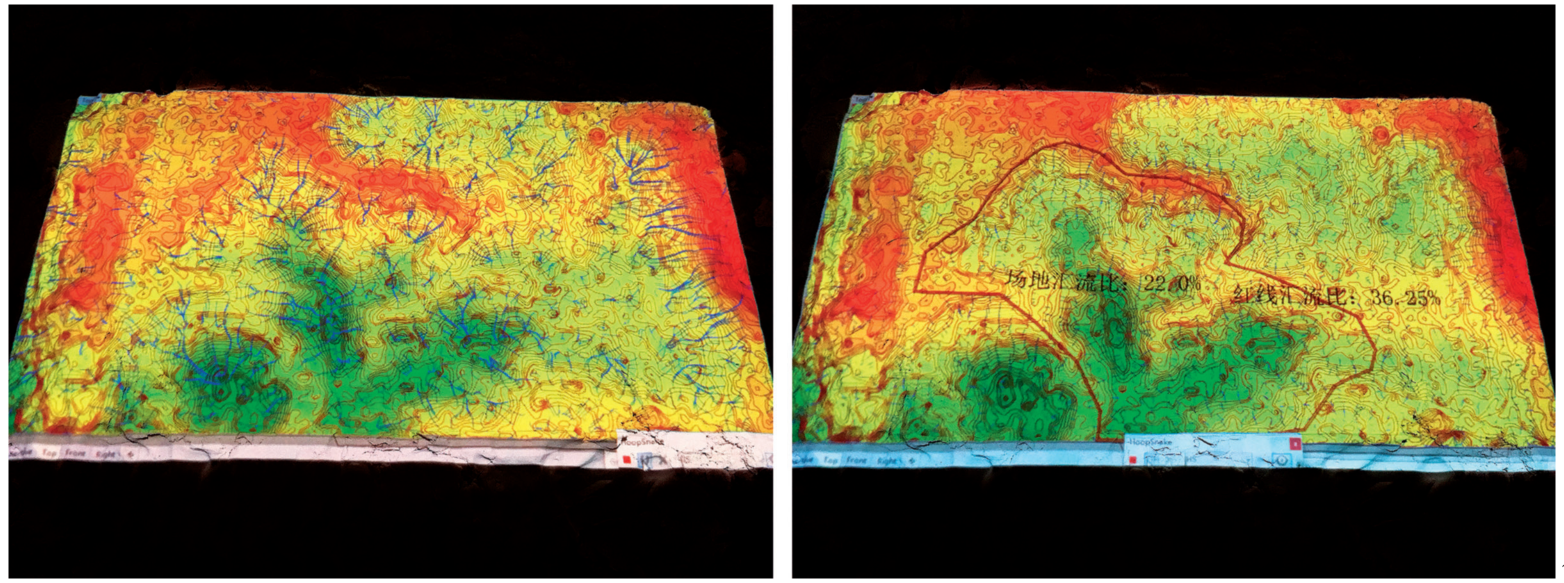
integrating runoff length and flow loss coefficient (from infiltration, evaporation, bio-retention, etc.), we can even obtain more practical flow analysis data. (Fig. 13)

4.7 Simulation Analysis of Sunlight Radiation and Shadow in Site

Sunlight and accumulated temperature directly affect plant growth and user experience on a site. Accurate information of site sunlight and accumulated temperature helps landscape architects achieve more rational site planning and planting design. We used Geco, a third-party plug-in under the Grasshopper platform, to analyze and calculate data of year-round sunshine duration and sunshine radiation based on weather and climate information, such as annual solar orbit and sun angle, as well as information about structures surrounding the site. We also wrote another program in Grasshopper to display these data in customized color gradation, or to screen out sites that meet specific planting needs (such as sites with greater sunshine duration or radiation), in order to conduct targeted planting design or site design (such as adding structures for shade, etc.).

5 Summary and Prospects

Through the introduction of CAM and AR technology to the physical modeling environment of the sand table, "Sandbox," a new planning and design platform, has been created. On the one hand, CAM technology makes it possible to accurately reconstruct the site using a reproducible material — the sand physical model is not only capable of visually representing complex terrain, but



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13. 地表径流模拟

13. Surface runoff simulation

大的创造力，手工的控制则更能够激发设计师对于空间的直觉和潜意识。另一方面，AR技术的介入，使得实时人机交互成为可能，基于识别和分析模块的数字信息，实时投射在物理模型上，使得景观设计师能够随时洞察设计操作所影响的动态系统，这种操作平台极大地提升了设计效率，较传统的“分析–设计–检验”流程要简便许多。

除了三维空间之外，时间对于景观而言也是一个重要的维度，这也是景观的生命之所在。传统的设计平台主要在二维平面上操作设计方案，CAM技术使得在三维空间直观地操作设计方案成为可能。更重要的是，通过模拟径流、日照等自然过程，我们有可能将时间这个维度以更直观的方式带入设计过程，让景观设计师拥有一个四维的操作平台。

目前，对于沙盒平台中人机交互功能的开发利用只是一个开端，通过引入或开发更强大的模拟分析软件系统，沙盒平台完全能够模拟诸如土壤侵蚀、植被生长、群落演替、人群行为等更复杂的自然和社会过程，这必然能够为景观设计师提供更强大的技术支持。随着数字化技术，特别是虚拟现实（VR）技术的发展，我们相信在不远的将来，当裸眼三维技术普及后，物理沙盒会被逐步淘汰，景观设计师将拥有像科幻电影中那样的纯虚拟现实操作平台。**LAF**

also undertaking manual design operations. Practice has proven that people can often show more creativity when faced with 3D objects, and the ability to manually manipulate material improves and inspires designers' intuition and consciousness of space. On the other hand, the involvement of AR technology makes real-time human-computer interaction possible. The real-time digital information based on the recognition and analysis modules are projected on the physical model, providing landscape architects with real-time insight into the dynamic systems affected by their design operations. This new operating platform greatly increases the efficiency of the design, and vastly simplifies the traditional "analysis-design-evaluation" process.

In addition to 3D space, time is also important for landscape: the fourth dimension in which the life of the landscape lies. Traditional design platforms mainly run the design operation in a two-dimensional surface. CAM technology, on the other hand, makes visualized operation in a 3D space possible. More importantly, by simulating natural processes such as runoff, sunshine, and shadows, it is possible to bring the dimension of time into the design process in a more visualized way, allowing landscape architects a four-dimensional operating platform.

At present, the development and utilization of the human-computer interaction function in the Sandbox platform is only in its beginning stages. By introducing or developing more powerful simulation analysis software systems, the Sandbox platform will be able to simulate more complex natural and social processes such as soil erosion, vegetation growth, community succession, and crowd behavior, which will undoubtedly provide more efficient technical support to landscape architects. It is expected that with the rapid development of digital technology, especially virtual reality (VR) technology, in the near future, after the popularization of naked-eye 3D technology, the physical sand table will be phased out and landscape architects might work on genuine virtual reality platforms as in science fiction movies. **LAF**

注释

北京林业大学风景园林规划设计研究院总设计师蔡凌豪，于2015年首先制作出一套类似“照亮的黏土”的原型机，在此基础上，北京林业大学风景园林规划设计研究院的数字景观研究中心研发出了本文的“沙盒”平台。

NOTE

Linghao Cai, Chief Designer of The Landscape Architecture Planning and Design Institute of Beijing Forestry University, first produced a prototype similar to "Illuminating Clay" in 2015. On this basis, the Digital Landscape Research Center of the institute developed the "Sandbox" platform examined in this article.

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