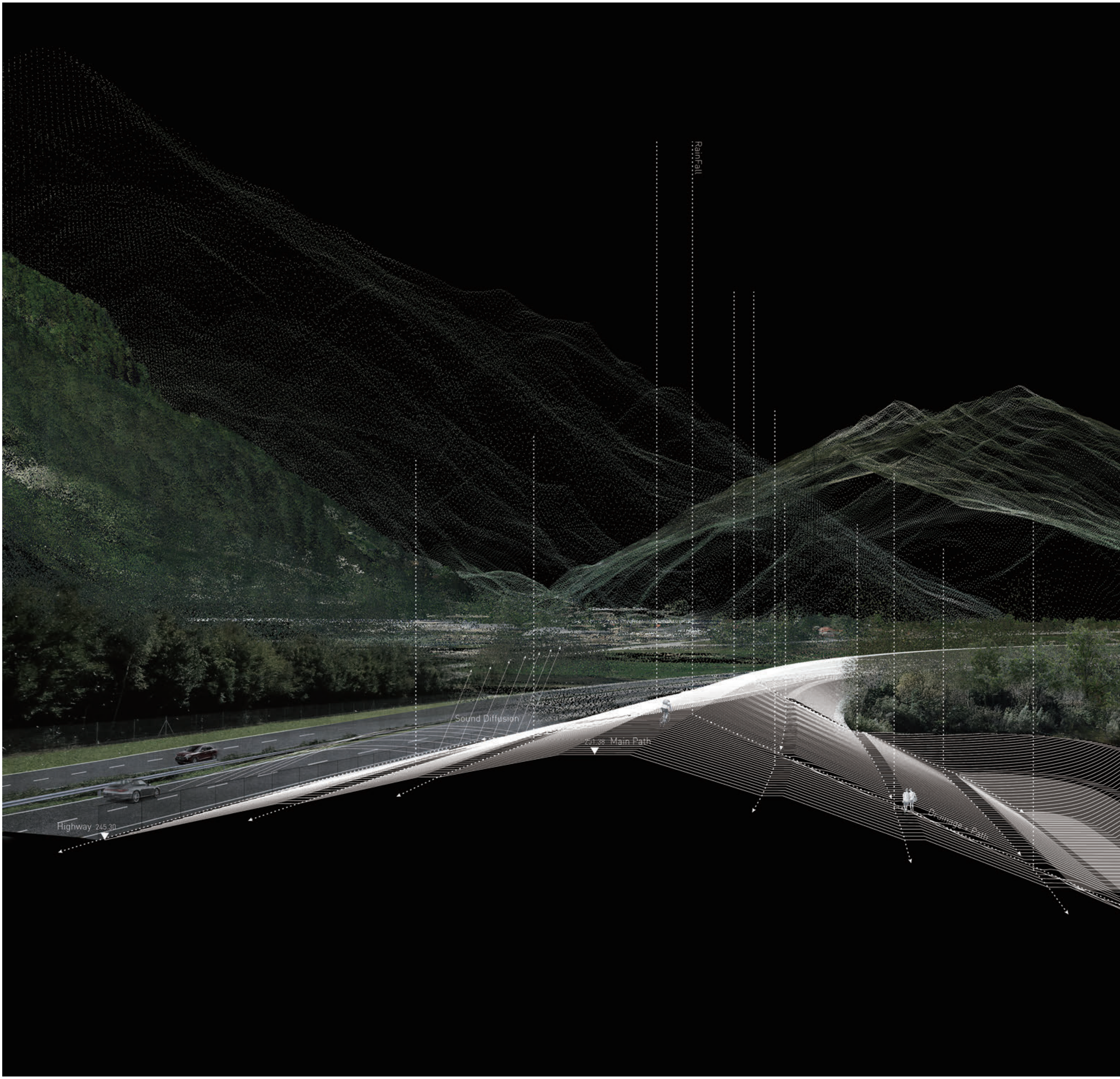
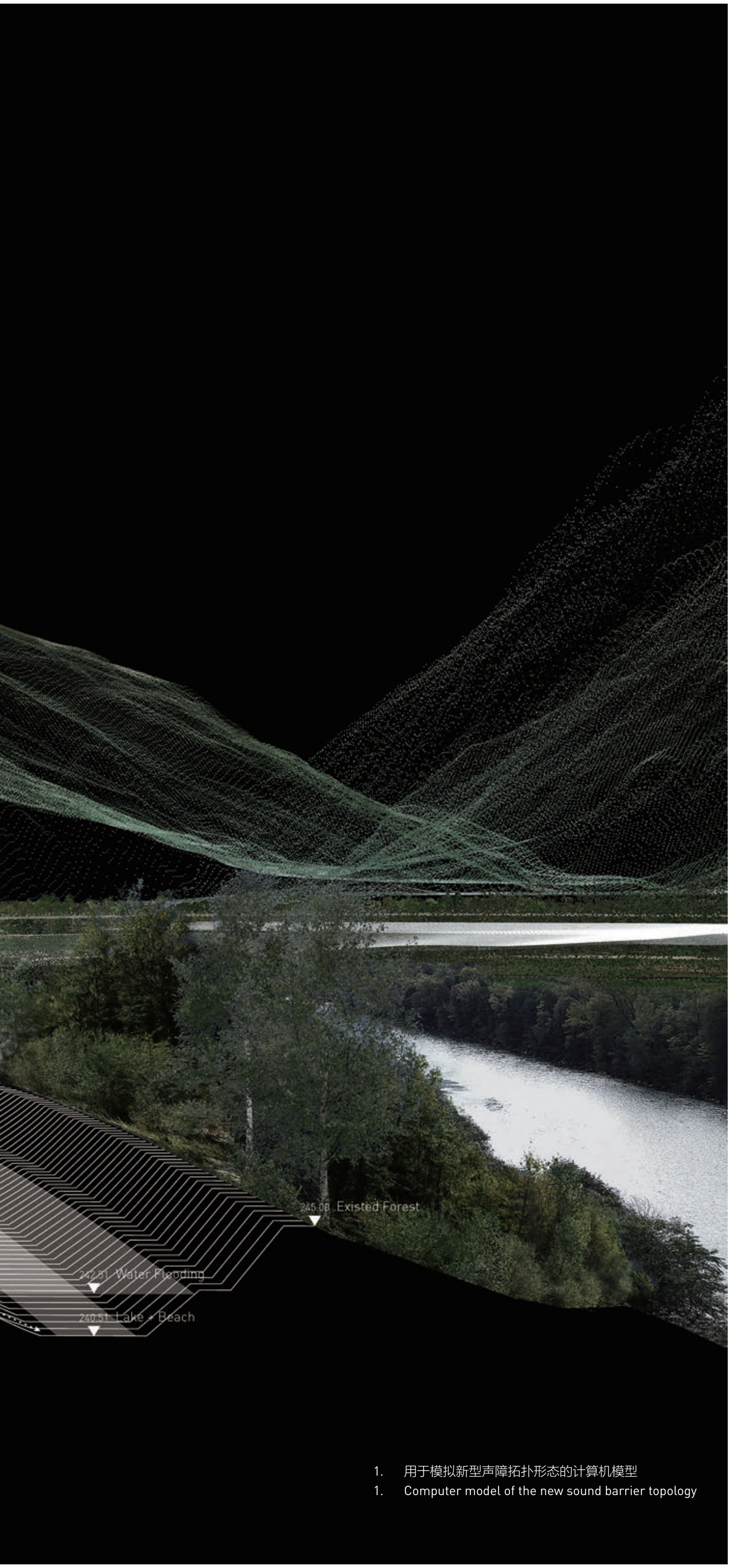

RainFall
Sound Diffusion
251.38 Main Path
Highway 245.30
Drainage + Path

机器人自动化建造的景观
——自然、运算，以及自动化地形建模中的设计空间

ROBOTIC LANDSCAPES
— NATURE, COMPUTATION, AND THE DESIGN SPACE OF AUTONOMOUS TERRAIN MODELING

克里斯托弗·吉鲁特，伊尔玛·赫尔克斯肯斯 / Christophe GIROT, Ilmar HURKXKENS*
*ETH Zürich, HIL H.55.3 Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland
hurkxkens@arch.ethz.ch



1. 用于模拟新型声障拓扑形态的计算机模型
1. Computer model of the new sound barrier topology

1 © Maximilien Durel, Shohei Kunisawa, Nicolas Wild

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摘要

2017年秋，苏黎世联邦理工学院与瑞士国家科研能力中心数字化制造小组就瑞士提契诺州坎顿地区的一条高速公路进行了实验性设计。该项目展示了一系列运用计算机程序和机器人原理研发的设计，基于覆盖整个提契诺河谷的激光雷达点云数据集的景观模型为项目中所有的地形塑造提供了基础。经过历时15周的探索后，项目获得了可喜的成果，同时展现出了一种通过机器人自动化设计来构思景观的新途径。

关键词

机器人自动化建造的景观；自动化地形建模；点云数据集；人类世

ABSTRACT

An experimental studio on a highway site in Canton of Ticino in Switzerland held at the ETH in the fall of 2017 is the result of a collaborative project with the National Center of Competence in Research Digital Fabrication, ETH Zürich. The work shows a series of designs that were developed through procedural and robotic principles. The landscape models based on a Lidar point cloud data set of the entire Ticino Valley served as the basis of all terrain operations. The results obtained after a 15-week studio are encouraging and show the way towards a new way of conceiving landscapes through robotic design.

KEY WORDS

Robotic Landscape; Autonomous Terrain Modeling; Point Cloud Data Set; Anthropocene

整理、译 田乐
EDITED AND TRANSLATED BY Tina TIAN

景观设计学定义

当代文明的不断发展造成了物质空间的巨大变化，全球范围内还未被打上人类文明烙印的自然地表可谓少之又少。[1]城市建设中常常用到的土地平整、挖沟和筑堤等工程手段正决定着世界的面貌，共同造就了所谓的“人类世”时代。[2]人类世是一个地质时代，人类活动在很大程度上改变了地球上的生态系统。在此过程中，景观、建筑和基础设施相互交织，且逐渐成为一个高度人工化的复合体；随着我们所处环境的日益复杂化，其会慢慢地，但最终必定会形成一个连续的统一体。[3]由于市政工程和环境工程的标准化施工，相关从业人员正以其在城市和景观规划的政治体制方面的专业知识，主导着当下的景观形态。然而，这些数据驱动型学科似乎无法回应景观设计学科的基本问题：我们脚下的土地如何能同时为人们提供功能和美学上的服务？[4]接下来的问题是，当代景观设计正聚焦于建筑、基础设施和生态之外的剩余空间，而这却有悖于景观设计学科对城市和基础设施进行设计的初衷——该学科恰是为了解决19世纪中叶的城市扩张问题而诞生。[5]随着地球上越来越多的土地受到人类活动的

项目地址：
瑞士提契诺州里维埃拉河谷
项目开展时间：
2017年9~12月
指导教师：
苏黎世联邦理工学院景观设计系教授Christophe Girot（教学助理：Ilmar Hurkxkens、Fujan Fahmi、Benedikt Kowalevski）；建筑和数字化建造系教授Fabio Gramazio、Matthias Kohler（教学助理：Ammar Mirjan）
合作专家：
苏黎世联邦理工学院机械与工艺工程系机器人系统实验室教授Marco Hutter（助理：Dominic Jud）；瑞士材料科学与技术研究所声学与噪音控制实验室Kurt Heutschi；苏黎世联邦理工学院可持续建造系Sasha Cisar
参与学生：
Philippe Airoldi、Alessandro Canonica、Michele Capelli、Maximilien Durel、Kenichiro Endo、Nina Feix、Milan Jarrell、Dominik Keller、Shohei Kunisawa、Abraham David Noah、Marius Oneta、Ladina Ramming、Thorben Westerhuys、Nicolas Wild、Bing Yang、Gabriel Fiette、Laura Rickli

LOCATION:
Valle Riviera, Ticino, Switzerland
STUDIO:
September to December, 2017
DIRECTORS:
Prof. Christophe Girot, Chair of Landscape Architecture, ETH Zürich (Assistants: Ilmar Hurkxkens, Fujan Fahmi, Benedikt Kowalevski); Prof. Fabio Gramazio, Prof. Matthias Kohler, Chair of Architecture and Digital Fabrication, ETH Zürich (Assistant: Ammar Mirjan)
COLLABORATIVE EXPERTS:
Prof. Marco Hutter, Robotic Systems Lab, Chair of Mechanical and Process Engineering, ETH Zürich (Assistant: Dominic Jud); Kurt Heutschi, Laboratory Acoustics / Noise Control, EMPA Zürich; Sasha Cisar, Chair of Sustainable Construction, ETH Zürich
STUDENTS:
Philippe Airoldi, Alessandro Canonica, Michele Capelli, Maximilien Durel, Kenichiro Endo, Nina Feix, Milan Jarrell, Dominik Keller, Shohei Kunisawa, Abraham David Noah, Marius Oneta, Ladina Ramming, Thorben Westerhuys, Nicolas Wild, Bing Yang, Gabriel Fiette, Laura Rickli

影响，我们显然不得不重拾景观设计学科最初的目标——助力确定城市和乡村的整体形态。

机器人自动化建造

建造设备和机械化进程正在经历一场巨大变革，其可能彻底颠覆我们思考和构建景观及基础设施的逻辑。随着强大液压设备的快速发展，景观建造中就地取材的传统已经发生变化。手工制作和用当地材料精心徒手搭建的意义已被机械化的异地物料输送带来的便利性所湮没。由于缺少对于生态、可持续性和美学等方面因素的综合考量，目前的建造实践给场地带来了颇多负面影响。机器人自动化施工设备（如推土机和挖掘机）的新近发展为大尺度基础设施和景观项目开辟了全新的拓扑和应用范畴。鉴于景观建造即将发生的变化，2014年，苏黎世联邦理工学院（ETH）瑞士国家科研能力中心（NCCR）数字化制造小组与马可·哈特教授的机器人系统实验室（RSL）合作开展了一项利用现有材料进行机器人景观建造的研究。[6]该研究包括由ETH景观设计系克里斯托弗·吉鲁特教授与建筑和数字化建造系法比奥·格拉马齐奥和马提亚斯·科勒教授共同指导的三个设计研究项目，以对机器人自动化建造过程和应用进行测试。本文介绍了2017年秋季开展的第一个项目所取得的研究成果。该项目对河道沿岸和高速公路两侧的不规则裸土地块进行了不同形状和不同坡度的改造，以形成更好的声音反射和噪音隔离效果，并促进河床修复和休闲活动空间设置。

研究项目

该项目以拓扑设计方法展开——过去十年间，在吉鲁特教授的大力推动下，拓扑设计方法不断发展，其将特定地点的物质、科学和材料特性整合为一个有意义的整体。在该项目中，学生们需为人工改造地形制定可持续方案，并构想基于不同方式和目的的场地利用场景。随着时间的推移，机器人自动化施工过程改变了山谷的景观，加强了其原始状态（自然过程）和人类改造（人工过程）之间的关系。该项目主要通过精心塑造地表和地形来进行景观设计练习。

项目场地位于提契诺河河岸之上，经过

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2. 学生们对由ETH与NCCR数字化制造小组研发的自动行进挖掘机进行测试。

2. Students testing the Autonomous Walking Excavator under development at the NCCR Digital Fabrication and ETH Zürich.


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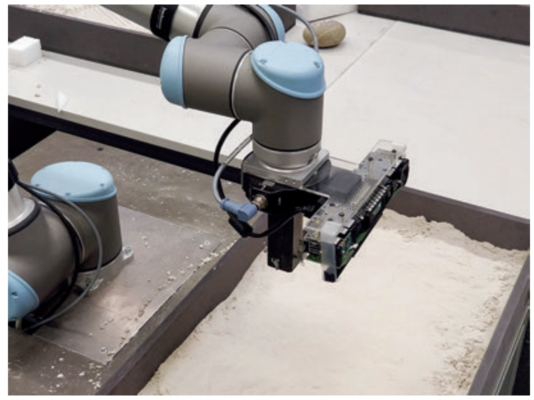
3-1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3-2


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3-3

3-1. 学生通过机器臂和末端执行器在沙盒中探索了各种拓扑形态。
3-2. 为该项目研发的实体化/数字化设计系统包括配有3D扫描仪、力学传感器和工具接口的机器臂和末端执行器。
3-3. 由学生设计的末端执行器以不同方式在沙盒中进行地形塑造模拟。

3-1. Students exploring various topologies in the sand box with a robotic arm and end-effector.
3-2. The physical / digital design system developed for the studio including the robotic arm and end-effector with 3D scanner, force sensor, and tool holder.
3-3. End effector tools designed by students to model sand in different ways.

数千年的沉积，比亚斯卡和贝林佐纳两个城镇之间形成了里维埃拉河谷。在1888~1912年间河道渠化之前，该地区曾是一片广阔的沼泽地。如今，不再波澜涌动的河流景观被框限在河道之中，履行着人类赋予其的功能。通过研究河谷的历史，人们意识到河流的不断变化，以及这一人造系统不断增加的复杂性。河谷犹如一个多层复合体，其中的自然、农业和城市网络会随时间而变化。于20世纪60年代建造的A2沿河高速公路成为了连接河谷内外的纽带，但同时也是河谷的主要硬质边界和噪音来源。提契诺河渠化的河道以及高速公路一同构成了谷底的主要基础设施。不幸的是，作为河谷最主要的特征，这些基础设施的建造却只考虑了实用性和技术因素。

目前大规模景观建造正在向机器人自动化施工方向发展。进行机器人自动化设计所需的参数化工作首先在合成砂模型上进行实验测试，以实现初始模型的快速设计。这为选择适应场地地形的景观设计形式提供了多种新的可能性。对于拓扑界面来说，什么才是在一个连续的拓扑中（而非单独个体）提供便捷交通、噪音屏障、休闲活动及水体径流的基础？数字化景观建造中的机器人自动化施工过程，通过采用全新的形式来呈现场地中的物质空间转化，实现了形式与过程的无缝衔接。让我们来畅想一下这个河谷百年后的面貌：届时，谷底的设计将兼顾实用性和景观设计层面的考量，大规模景观建造的重要部分皆由机器人自动化施工完成。

运算

该项目主要运用了RSL近期研发的实物大小的自动行进挖掘机（图2）。该设备拥有激光雷达和19°全自动自主操作臂，还能够对所有驱动器进行实施力反馈，以实时感知其所处环境。为了测试自动行进挖掘机的潜力，学生们使用了一个机器臂（图3-1），其带有自定义末端执行器（图3-2），能够进行3D扫描、力度与力矩感应，并支持各种

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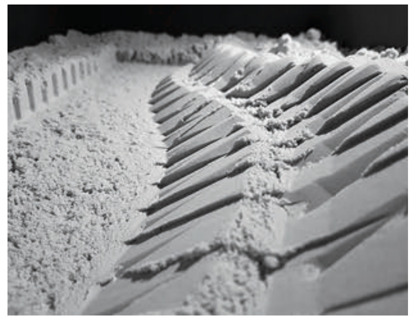

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4-3

沙盒设计工具（图3-3）。这形成了机器人自动化设计操作中的反馈回路，可以感知沙盒模型的拓扑结构与密度（图4）。为了使运算性设计工具更好地利用新兴的机器人自动化施工方法，该机器臂确定了一组参数矩阵，以帮助辨别决定性参数（即对于关键位置的参数设定）和执行参数（图5）。决定性参数针对的是场地中无法变更的现有人造事物，或最终的几何形态；执行参数用于与执行设计目标（而非拓扑形态）相关的最终设计。例如，一个执行参数定义了一条路径，规定一个人从A点移动到B点，且最大斜率为6%。只要满足这两个参数条件，就没有必要预先定义其确切的拓扑形态或空间位置。运算性设计工具支持现场条件的改变，这也会使所得路径的拓扑形态发生相应的变化。在整个河谷的点云①模型的帮助下，学生们需维持场地土壤的现有体积不变，这就要求他们在进行下压、移动、挖掘和填土等操作时需非常谨慎。这一约束条件限制了场地内材料的移动，却因此促进了可持续施工方法的产生（图6）。如此一来，项目自然而然地顺应了河谷的地形坡度，河床与新建高速公路声障形成了一种连续的拓扑形态。从而，一种基于物质过程和自然过程的第三过程——机器人自动化建造过程——被引入河谷之中（图1，7）。这一过程基于场地点云模型的计算而实施，包括对场地内的尺度、密度、高程和坡度进行各种规则的运算。随着时间的推移，场地潜在的拓扑形态会塑造出形态各异的地块（图8）。在学生们所进行的项目中，机器人自动化建造过程结合了场地中的自然与物质过程，并主导了场地景观的塑造。该项目中的数控机床模型使机器人自动化地形建模成为了人类世时代的一个典型代表。

结论

运算工具的出现促使每个场地的建造方式都独具特色。[7]通过直接影响施工和制造过程，这些运算工具使得设计师更深入地接触场地实际的物质空间。[8]各种独特的参数设定使得设计师能够将景观视为一系列拓扑关系或一个强大的执行界面。这将改变景观设计师和整个景观设计学科的角色。

“景观都市主义”和“景观基础设施”在近期的运动中呼吁扩大景观设计学科的研究领域。建筑学始终秉持着对建筑物的构造表达的追求，而景观设计学却似乎已经忘记了其本身是为了塑造乡村和城市景观的形态而诞生的。然而，无论是乡村景观还是城市景观，都往往忽视了地球表面的物质形态，而这些物质形态恰是一种随着时间推移而承载了自然和文化力量的富有表现力的材料。本文介绍的研究和设计项目旨在唤回景观设计作为将特定场地中的物质、科学和材料特性整合到一个有意义的整体中的学科的角色。[4]机器人自动化建造过程通过涵盖所有连续性和复杂性，创造出一种新的地形塑造智能。从这个意义上说，其提供了一种揭示某一场所潜力的方法和技术。这一机器人自动化建造景观项目探索了塑造地表几何形状的可能性并将之作为景观建造的方式，且尤其关注于地表结构内空间关系及邻近性的组织。回应及塑造地球地表的设计方式在所有弹性设计实践中都应予以重视。该方法为景观设计这一承载着对当代城市和景观的形式进行设计之使命的学科提供了新的基础。**LAF**

① 一个点云即为空间中的一组数据点。点云一般由三维扫描设备通过扫描测量物体外表面上的大量点而生成。作为3D扫描处理的输出成果，点云可应用于众多领域，包括为制造零件创建3D的CAD模型、度量衡和质量检验，以及服务于多种可视化、动画、渲染和大规模定制化产品。

4. 机器人自动化建造在沙盒中的模拟结果
5-1. 沙盒实验的运算过程

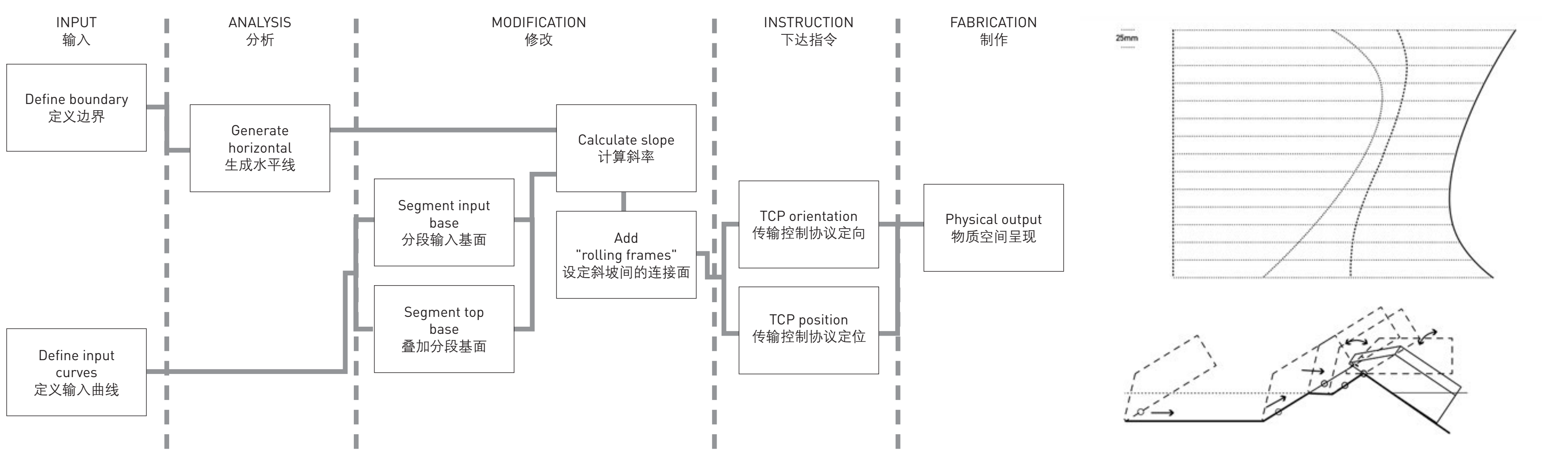
4. Output of the robotic process in the sand box
5-1. Computational process of the sand box experiment

Landscape Architecture Definition

The physical alteration of the ground — connected to the modern development of contemporary civilization — now exceeds the remaining natural land surface around the globe.[1] Land leveling, trenching, and embankment building concurrent to the construction of cities partially define what we call the Anthropocene.[2] The Anthropocene is a geological era where human activities are in a significant way defining earth's ecosystems. In this process, landscape, architecture, and infrastructure have become more and more entangled as a single large artifact with the increasing complexity of our environment slowly but surely becoming a continuous whole.[3] Normative practices in civil and environmental engineering are now dominating the shaping of landscape by fostering their expertise in the political structures of urban and landscape planning. However, these data-driven disciplines seem to be unable to cope with the fundamental question of Landscape Architecture: How does the territory exist functionally and aesthetically for people?[4] Subsequently, contemporary Landscape Architecture is treating the remaining bits of spaces left between architecture, infrastructure, and ecology. However, the profession was initially rooted in the urban and infrastructural arts. Its appearance was an answer to questions of urban expansion in the middle of the nineteenth century.[5] With an increasing amount of earth's surface marked by human activities, it becomes apparent that we have to relate Landscape Architecture back to its origins where its main goal was to help define the overall shape of the city and countryside.

Robotics

A revolution in construction equipment and mechanization is underway that might completely invert the logic of how we think and construct our landscapes and infrastructures. The tradition of resourcing local materials in landscape construction has changed over recent times with the development of powerful hydraulic equipment. The value of handcraft and careful manual assembly balancing local material was replaced by the ease of mechanized material transport to and from a site. Current construction practices have had a negative impact on sites because of the



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5-1

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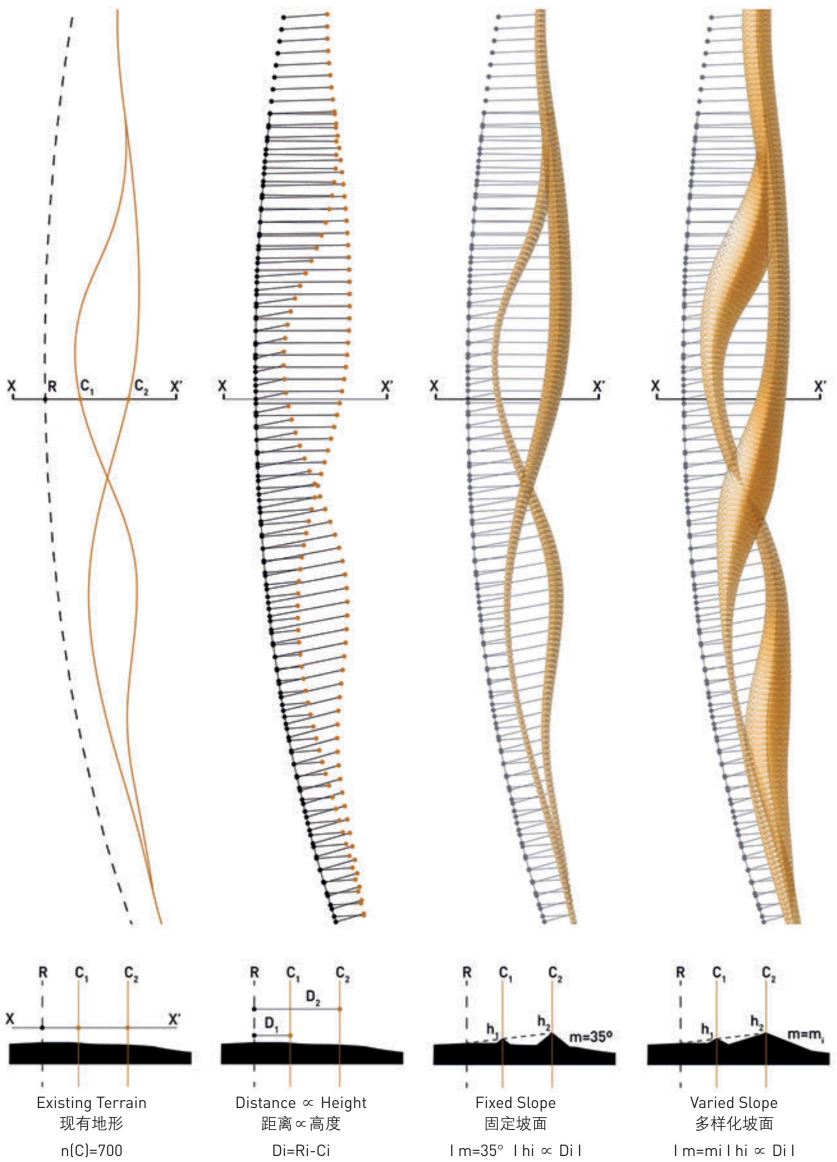
5-2



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5-3

5-2. 建模步骤图（从左到右依次是）：挖掘区域、场地参数、场地土方工程、机器人自动拓扑形态，以及声障模拟。

5-3. 决定性参数和执行参数的拓扑形态示意图

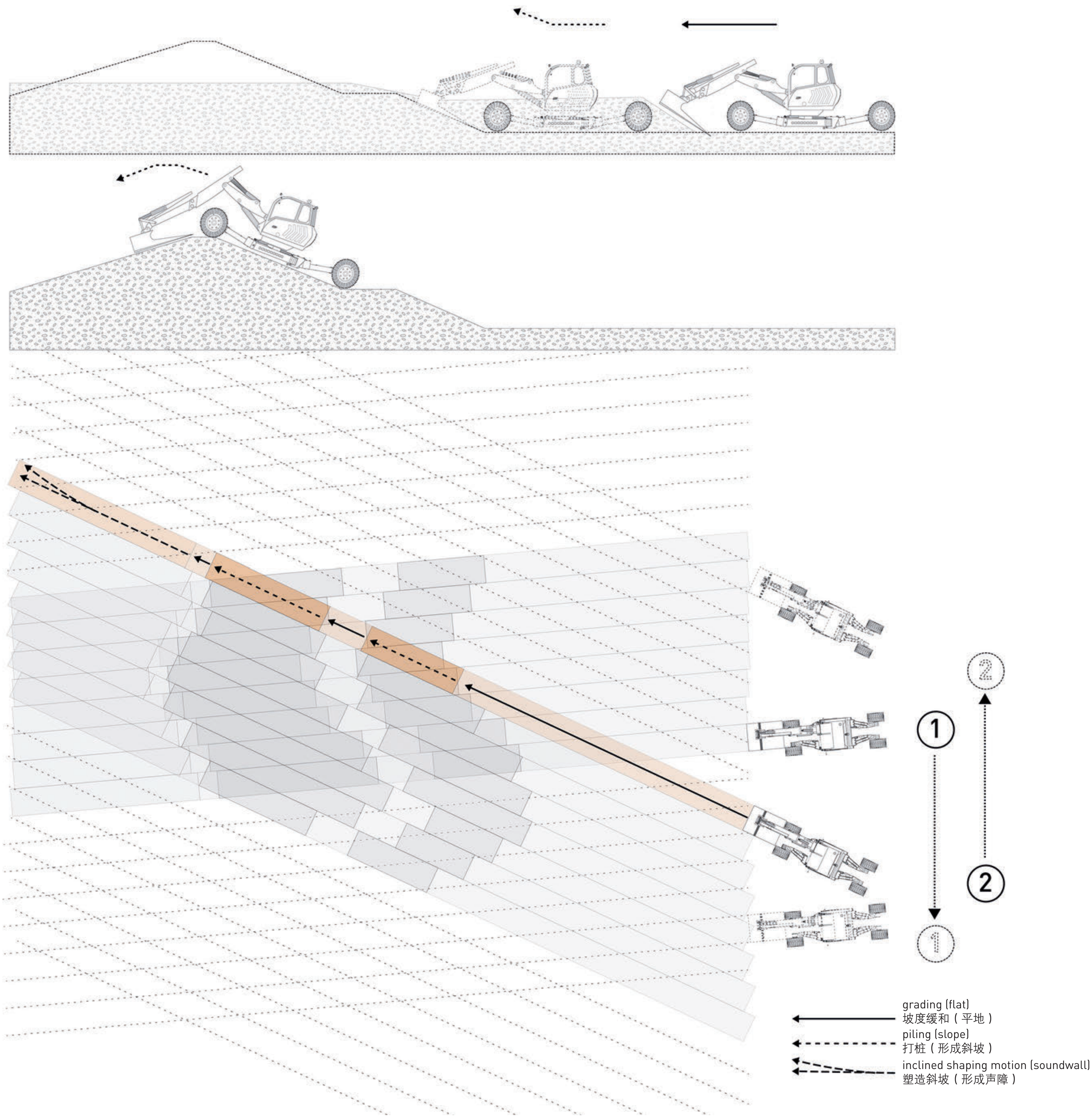
6. 自动行进挖掘机的填挖方作业示意图

5-2. Formation diagrams, from left to right; excavation area, site parameters, cut and fill, robotic topology and sound barrier performance.

5-3. Topological illustration of the fixed and performative parameters

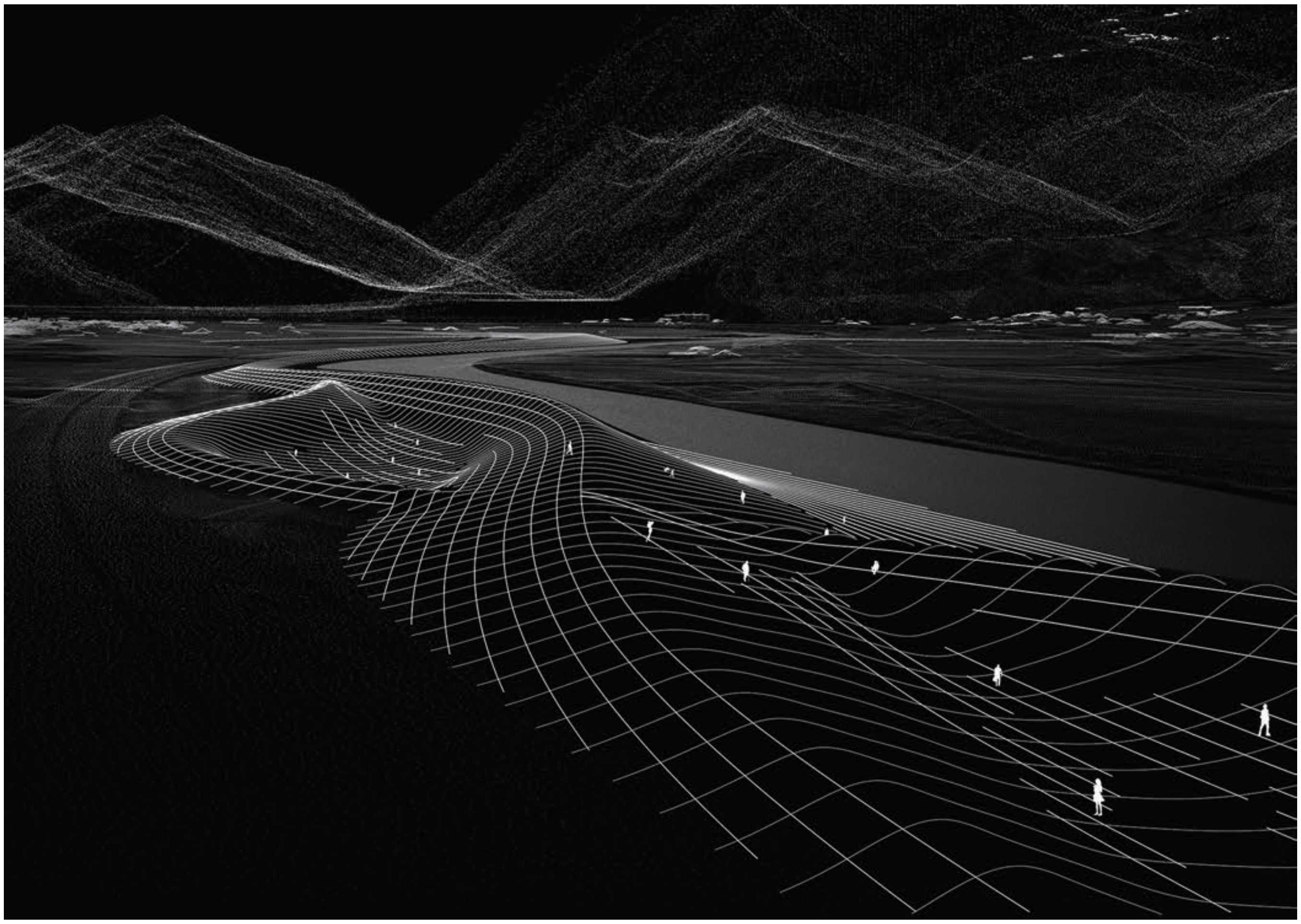
6. Illustration of the pit-operations of the autonomous walking excavator explaining cut and fill.

failed integration of ecological, sustainable, and aesthetic considerations. The recent developments in robotic construction equipment (think bulldozers and excavators) open up a whole new category of possible topologies and applications for large-scale infrastructures and landscapes. In light of these upcoming changes in the production of our landscapes, a research on the robotic construction with found materials was launched in 2014 by the National Center of Competence in Research (NCCR) Digital Fabrication at the ETH in Zürich with the Robotic Systems Lab (RSL) of Professor Marco Hutter.[6] An integral part of the research is the test of robotic construction processes and applications through three Design Research Studios directed by the Chair of Landscape Architecture of Professor Christophe Girot in collaboration with the Chair of Architecture and Digital Fabrication of Professors Fabio Gramazio and Matthias Kohler. The results of the first studio held in the fall of 2017 are presented here. This studio explored the transformation of shapeless soil material along a river course and motorway in a geometry of inclined surfaces in various configurations for sound reflection and protection, riverbed remediation, and leisure activities.



2
1
2
1
grading (flat)
坡度缓和（平地）
piling (slope)
打桩（形成斜坡）
inclined shaping motion (soundwall)
塑造斜坡（形成声障）

6



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7-1

Studio

The studio was conducted following a topological design approach. This technique has been developed by Prof. Girot over the past ten years, integrating the physical, scientific, and material properties of a particular site in a single meaningful whole. In the Fall studio of 2017, students were asked to balance the artificial displacement of material providing a sustainable way for topographic transformation, and to imagine scenarios that will use and modulate the topography in a variety of ways and purposes. The robotic construction process transforms the landscape of the valley over time reinforcing the relationship between its origin (natural processes) and human transformation (artificial processes). The studio was mostly concerned as an exercise in landscape design through the elaborate shaping of land surfaces and topography.

The site of the studio was located on the Ticino River where sediments deposited over thousands of years created the Valle Riviera between Biasca and Bellinzona. Up to the river correction between 1888 and 1912, the area was an incredibly large marshland. Today, we see a seemingly static channeled river landscape that is defined by its use. By studying the history of the valley, one becomes aware of the constant change to the river and ever increasing complexity of this artifact. The valley is like a palimpsest, a superimposition of natural, agricultural, and urban networks changing over time. The A2 highway, constructed in the 1960s along the river, is the main connector but at the same time main border and noise emitter in the valley. The Ticino River correction, together with the highway, form the main infrastructural works of the valley floor. Being the most dominant features in the valley, it is unfortunate that they were only considered on a utilitarian and technical level at their time of construction.

Current development in large-scale landscape construction is moving towards robotically controlled machinery. The parametric work required to initiate robotic design first experimented test runs on

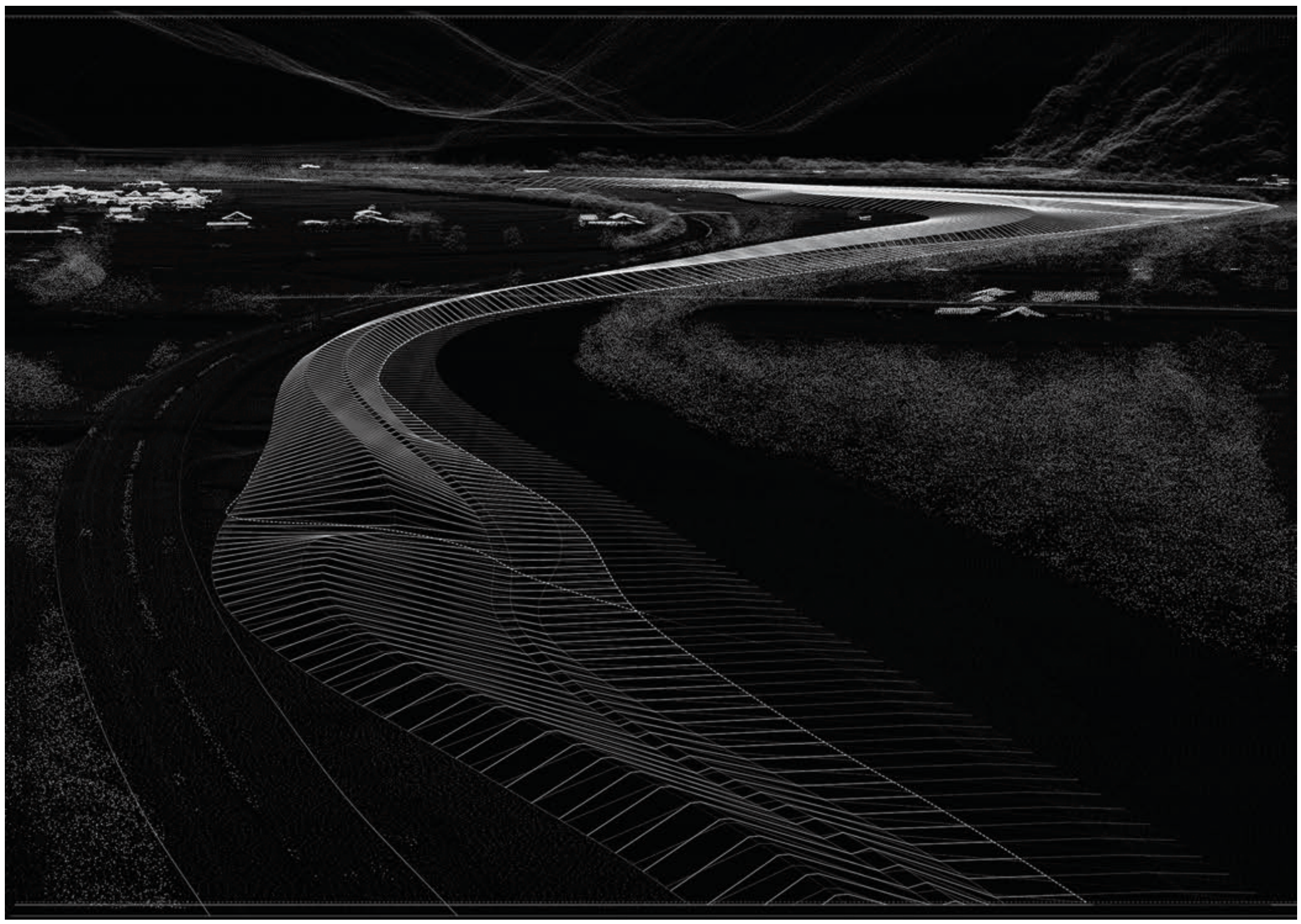
7. 用于模拟新型声障拓扑形态的计算机模型

7. Computer model of the new sound barrier topology

synthetic sand models which enabled rapid prototyping. This enabled a completely new catalog of possibilities in landscape architectural form in ways to adapt to the local topography. What does it mean for a topographic surface to provide the foundation for circulation, noise relief, leisure activities, and water runoff in one continuous topology instead of isolated objects? Robotic processes in digital landscape fabrication allow for a seamless reconciliation between form and process by mediating the material reality of a site into new formal expressions. Let us think about this valley in one hundred years and imagine a different valley floor that is considered on both a utilitarian and landscape architectural level that allows for robotic processes to take over significant parts of large-scale landscape construction.

Computation

The studio was based on the capabilities of the real-size Autonomous Walking Excavator (Fig. 2) currently in development at the RSL. Featuring Lidar and full autonomy in 19 degrees of freedom, this platform also implemented force feedback on all actuators to interact with its environment. To test the potential of the Autonomous Walking Excavator in the studio, students used a robotic arm (Fig. 3-1) with custom end-effector (Fig. 3-2) that was able to make 3D scans, sense forces and moments and hold various tools (Fig. 3-3) to interact with the sand box. This enabled a feedback loop within the robotic design operations, responding to the topology and density of the sand (Fig. 4). For the computational



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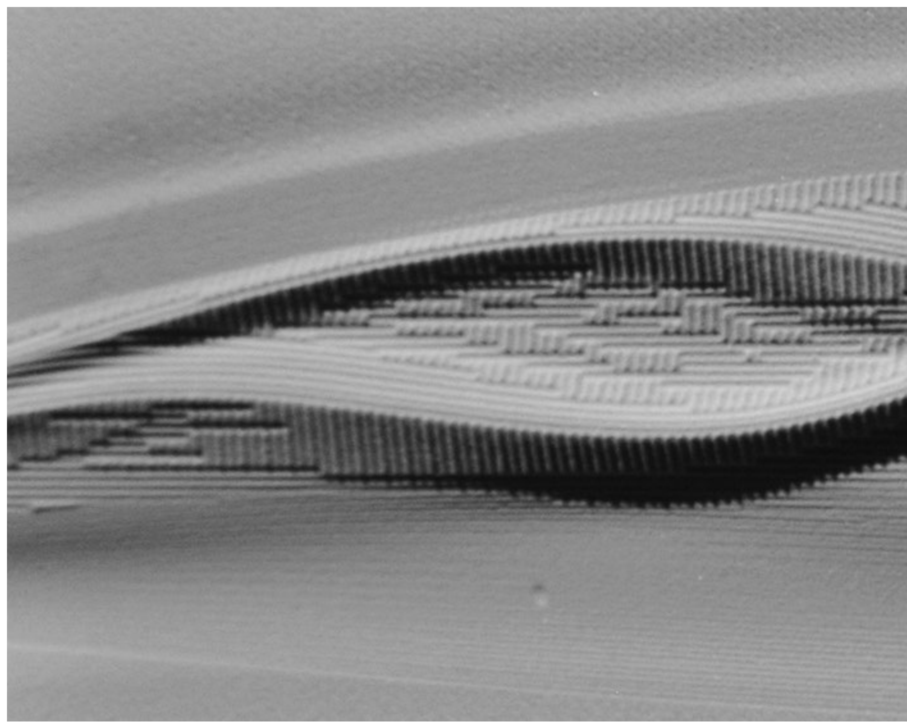
8-1

① A point cloud is a set of data points in space. Point clouds are generally produced by 3D scanners, which measure a large number of points on the external surfaces of objects around them. As the output of 3D scanning processes, point clouds are used for many purposes, including to create 3D CAD models for manufactured parts, for metrology and quality inspection, and for a multitude of visualization, animation, rendering, and mass customization applications.

8-1. 数控机床打磨器制作出的涵盖场地的更大尺度模型（1:200）
8-2. 数控机床打磨器制作出的模型（1:200）俯视图

8-1. Milling the CNC of the larger territory at 1:200
8-2. Plan view of CNC model at 1:200

design tool to take better advantage of novel robotic construction methods, a matrix of parameters was defined in order to help distinguish between fixed (i.e., position-critical) parameters and performative parameters (Fig. 5). Fixed parameters relate to either existing artifacts on site that cannot be altered or a final geometric definition. Performative parameters relate to a final design in relation to its performative goals instead of its topology. For example, a performative parameter defines a path that can take a person from point A to point B with a maximum slope of 6%. As long as the two parameters are met, it is not necessary to pre-define its exact topology or position in space. The computational design tool allows for changing site conditions to occur and therefore affect a changing topology of the resulting path. Going from the point cloud[①] model of the whole valley, students were asked to maintain the existing volume of soil on the site, thus limiting operations to pressing, shifting, cutting, and filling. This constraint limited material movement within the site thus providing a sustainable construction method (Fig. 6). In this way, the projects responded naturally to the slope of the valley, the riverbed, and the new highway sound barrier, resulting in one continuous topology. Starting from the material processes and the natural processes, a third robotic process was introduced in the valley (Fig. 1, 7). Implementations of this process were computed on the point cloud model of the site, using various rules of scale, density, level, and slope. Over time, this resulted in various shapes depending on the underlying topology of the site (Fig. 8). In the projects of the students, the robotic process was the protagonist of the landscape, operating side by side with the natural and material processes on site. Computer Numerical Control (CNC) models of their projects finally illustrated the robotic terrain modeling as a moment in time.



Conclusion

The computational tool promotes and differentiates the performative aspects of each site.[7] It brings the designer closer to the actual materiality of a place by directly influencing the process of construction and fabrication.[8] The distinctive parameters of form and performative will enable designers to understand a landscape not only as a set of topological relations, but also as a strong performative surface. This will change the role of the landscape designer and the discipline as a whole.

Recent movements in "landscape urbanism" and "landscape infrastructure," make a plea towards a broadening of the discipline to include larger territorial systems. While the architectural discipline is founded in the tectonic expression of buildings, Landscape Architecture seems to have forgotten its disciplinary origin that of shaping the forms of both rural and urban landscapes. Both directions tend to neglect the physical shape of the earth's surface as an expressive material modeled by natural and cultural forces over time. The research and design studio presented here help recover Landscape Architecture as a discipline that can integrate the physical, scientific, and material properties of a particular site in a meaningful whole.[4] The robotic process creates a new intelligence of terrain by encompassing all in its continuity and complexity. In this sense, it searches for a method and technique to uncover the hidden potential of a place. This studio in robotic landscapes seeks to uncover the geometry of the ground as a result of its means of production; specifically relating to the organization of spatial relationships and proximities within surface structures. The craft of responding to — and shaping of — the earth's surface should be seen as a vital aspect of any resilient design. The approach proposes a new foundation for Landscape Architecture as the form-giving discipline of contemporary cities and landscapes. LAF

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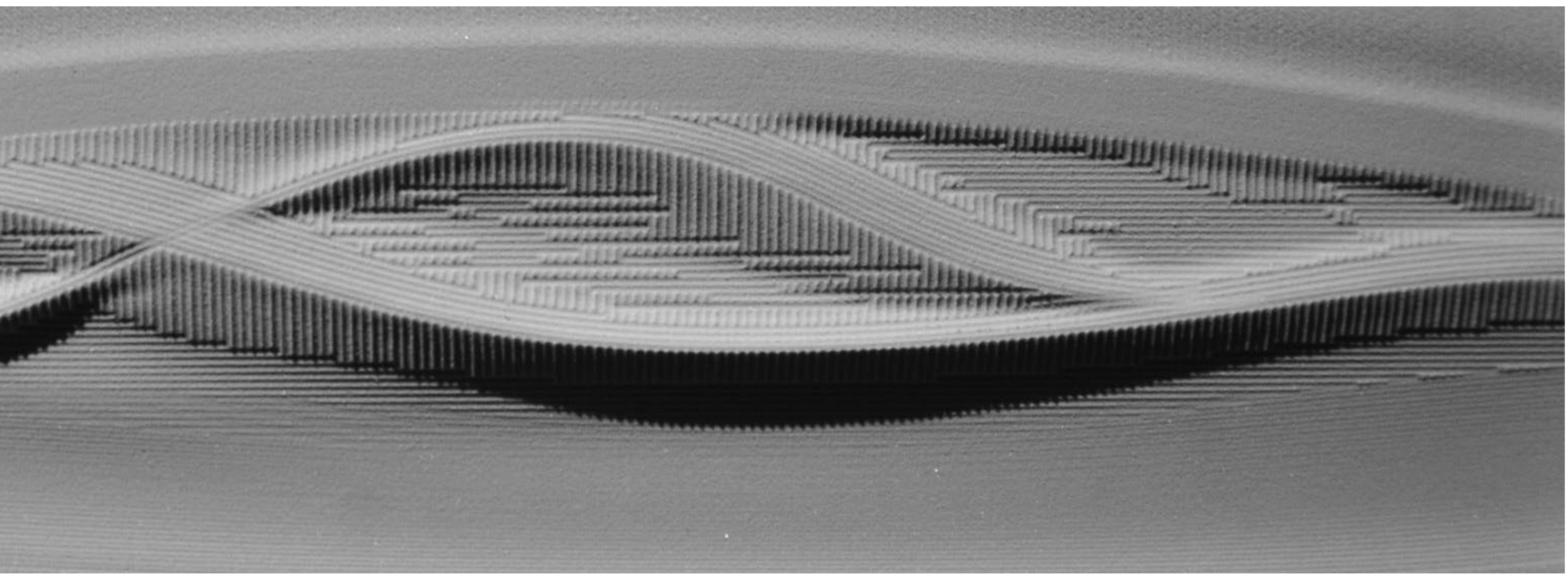

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