Robotic Landscapes

Developing Computational Design Tools Towards Autonomous Terrain Modeling

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1 The autonomous walking excavator on the test site at the ETH Zurich.

ABSTRACT

Until today, on-site robotic construction processes in landscape architecture have been limited to predefined and controlled environments like road building or mining pits. We are presently developing an autonomous walking excavator that paves the way for new and advanced on-site design strategies. The shift towards robotic construction in terrain modeling and landscape architecture demands an adaptive design approach, where the resulting topology is inherently linked to landscape performance and the local conditions of a site.

This paper discusses the computational design tools that may help redefine how design and construction processes can be better adapted to real-time topological and sensory data. This approach will, in due time, revolutionize how designers think, act and play with contemporary landscapes robotically, and reimagine their intrinsic relationship to infrastructure.

INTRODUCTION

The tradition of resourcing local materials in landscape construction has changed with the development of powerful construction equipment. The value of handcraft and careful manual assembly of local material has been diminished due to the ease of transporting material to and from a site. The goal of our research is to demonstrate the potential of a local use of materials in large-scale landscape projects by involving innovative robotic technologies in order to enhance sustainable practices. Current on-site robotic construction methods in landscape architecture are mainly focused on planning and horizontal grading through the optimization of material flow (Bock and Linner 1995) using GIS guiding systems (Petschek 2014). While these advances in automation and precision are significant, they do not yet address the specific intelligence of a project using the design potential of robotic construction methods in landscape architecture (see for example the paperless and stakeless grading of ASPECT Studios' Victorian Desalination Plant [Walliss and Rahmann 2016] and Snøhetta's Max Lab IV project [Snøhetta 2016]). To overcome existing limitations, we want to propose a model where local materials will be integrated into the process of construction through architectural, fabrication-aware material considerations. With the use of advanced topological methods in landscape architecture, the computational design tool will consider options for the transformation of locally resourced material into functional structures by applying principles of robotic construction.

AUTONOMOUS EXCAVATION

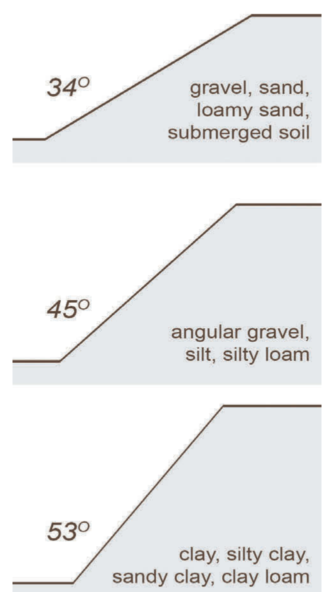
Robotic fabrication in landscape architecture has lagged behind other disciplines such as architecture and infrastructure engineering because of the inherent complexity of the reality on-site. Apart from bespoke elements like controlled forms of linear automation, landscape architecture demands a more responsive method to the local conditions in topology and materiality. Some efforts, for instance, have been made to control an excavator (Schmidt 2010). Unfortunately, these systems use position-based control for their excavation operations, which are inflexible for largely unknown soil and terrain composition. Two main technological innovations developed by our research team play a key role in the advancement of robotic construction technology for landscape architecture that can adapt to almost any site condition. The first is a precise state estimator that fuses GPS measurement, inertial measurements, and joint sensing to localize the excavator with respect to a world-fixed coordinate frame, as well as to the required design topology (Jud 2017). The second is force feedback control on all the axes of the excavator, which provides autonomous chassis balancing and tactile end-effector regulation (Hutter 2015). This enables automatically adjusted digging cycles that compensate for different soil compositions. For example, deep cuts are made in harder loam and shallow long cuts are used for soft clay (Jud 2017). These advances in robotic construction enable the field of landscape architecture to integrate digital fabrication and participate in the overall design process of a project. There is, however, a conspicuous lack of design-oriented research for robotic fabrication in the discipline of landscape architecture. The computational design tool for robotic terrain modeling outlined below will help define a new framework for digital landscape fabrication.

TERRAIN MODELING OPERATIONS

On-site robotic terrain modeling needs to be able to adapt to changing local conditions. It is very hard to sense or simulate the exact soil composition, which tends to change drastically in both horizontal and vertical directions. Furthermore, the volume of compacted vs. loose soil is hard to estimate. This specific condition is the reason why robotic landscape fabrication is such a challenge today. To be able to adapt in real time to changing site conditions, a design needs to be defined differentially and computationally. We equip the walking excavator with 3D laser scanners that scan the site continuously during the robotic cut and fill operations, which allows the planning and control tools to adapt to the ever-changing local characteristics during construction operations. Three main concepts of terrain modeling are essential for a proper understanding of the robotic soil operations. Below is a discussion of each of them and their influence on the design, computational performance, and architectural potential.

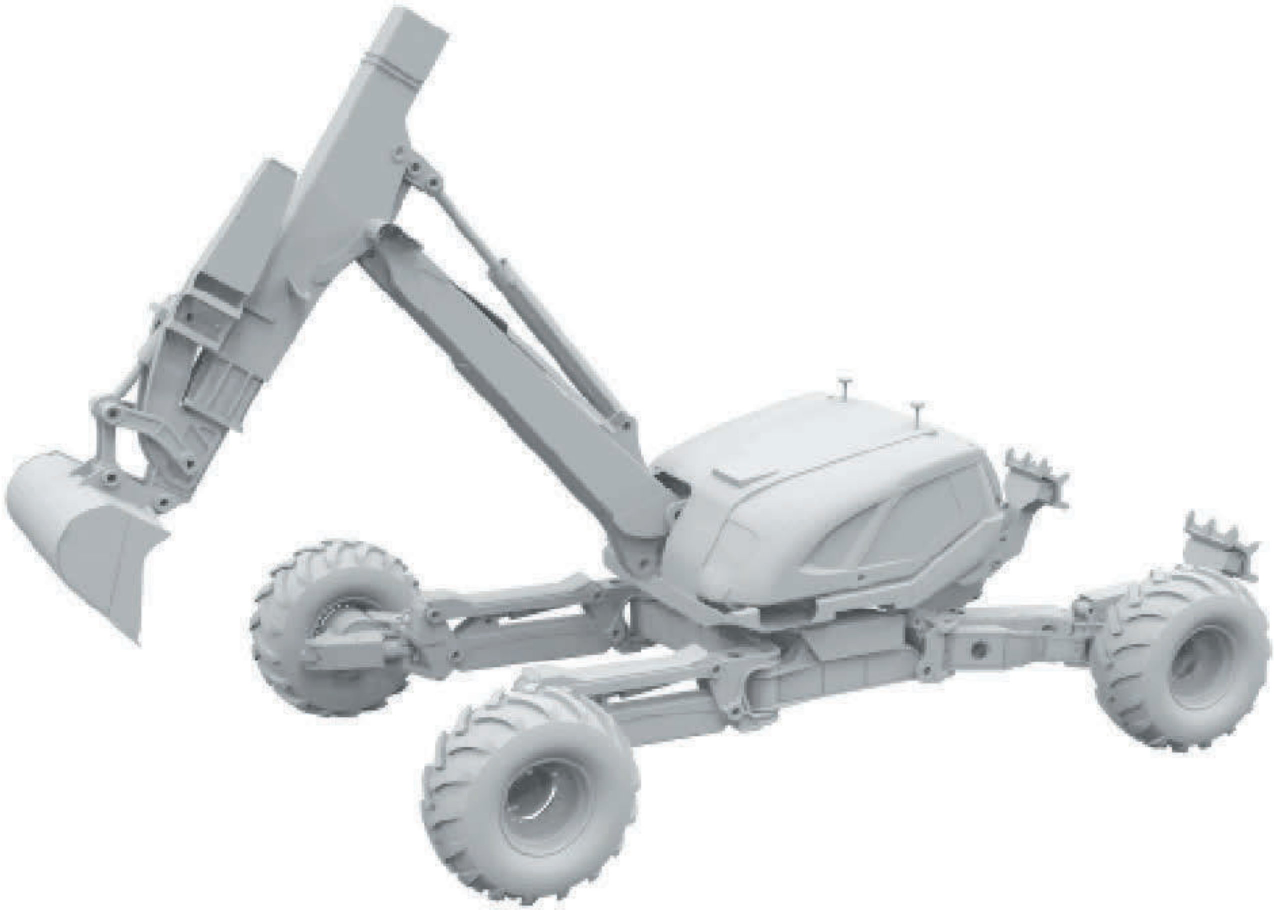
Excavation and Cutting Angles

Soil is composed of minerals, water, air and organic matter. There is a continuous distribution of particle sizes in soil ranging from large stones, to gravel, to sand and clay. The texture of soil smaller than 2 mm is classified by the percent of clay, silt, and sand of the soil (Untermann 1978). Its mixture greatly influences its modeling capacity. The maximum allowable slope angles depend heavily on the classification of the soil texture for excavation depths up to 6 meters.



2 Maximum excavation slope for excavations less then 6 m deep.

Currently there is no method that remotely senses soil



3 Perspective of the autonomous walking excavator with force controllable actuators, complete joint sensing and localization.

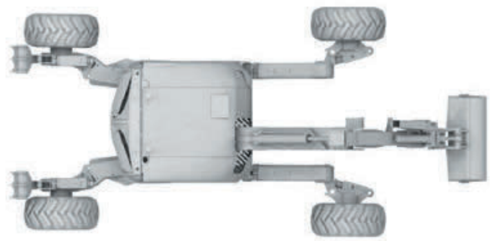
texture or density. This can only be defined by interacting with the soil directly. The forces exerted on the bucket during operation can be translated to soil texture and therefore determine maximum slope angles (Reece 1964). This implies that the modeling freedom in the topology can only be determined effectively during construction. Hence, the maximum slope angle must be defined as a parameter in the computational design tool that generates a new topology according to the presumed local soil texture. Furthermore, once the maximum slope angle for the soil in the immediate vicinity of the autonomous excavator is found, optimized cut and fill operations can subsequently be explored. The position estimation from the excavator provides immediate feedback for the final topology. This can allow for more freedom of expression in robotically fabricated landscapes.

Compaction and Volume

It is very hard to predict the increase in volume when a soil is loosened up after digging operations, as it is difficult to know how much volume is lost when soil is compacted for roads and embankments. The present approach to managing volume differences on construction sites is to add extra material or to take it away from the site. It can easily be argued that this current practice poses serious economic and ecological problems, in terms of sustainability, that should be solved locally. Both typical situations, either an excess or shortage of material, can be compensated for through a computational model that will be able to transform the topology of its landscape project according to the analysis of iterative scan data of the site before and during construction.

Planning and Soil Profiles

At larger scales, excavation processes and the movement of material through a site play a key role in the economic, sustainable, and topological outcomes of a project. Soil is not a homogeneous material, but instead varies greatly through vertical horizons. The soil profile of a particular site therefore can have an influence on how material should be displaced through a site. Topsoil needs to be stored temporarily and can be reapplied to finish the final topography of a project, allowing the reuse of all the minerals and nutrients to their full potential.



4 Top view of the autonomous walking excavator.

5 Elevation view of the autonomous walking excavator.

COMPUTATIONAL DESIGN TOOL

For the computational design tool to take better advantage of these novel robotic construction methods, a matrix of parameters is defined in order to help distinguish between fixed (i.e., position-critical) parameters and performative parameters. Fixed parameters relate to either existing artifacts on site that cannot be altered or to 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 at the two parameters are met, it is not necessary to pre-define its exact position in space. The computational design tool allows for changing site conditions to operate and therefore affect a changing topology of the resulting path. These fixed and performative parameters are categorized in three domains: 1) architectural intentions and performance, 2) fabrication constraints, and 3) material parameters. The architectural intentions specify a design strategy in terms of a precise topological definition. This may relate to a view axis or maximum slope angles on paths and roads, or even special surface treatments in paving and planting strategies. The fabrication constrains limit the topological freedom to the maximum freedom of movement given by the robotic excavator. In our case the excavator has a maximum excavation depth of 5.14 m and a maximum jib range of 8.21 m. The consecutive digging operations also relate to the larger scale inherent in the construction process, which also comprises all the material movement occurring through the site. In every excavation project there are various external issues at play, like the removal and storage of topsoil, material transport and storm water management during excavation. The planning tool could take this into account by managing iterative rules of cut and fill.

The goal of the computational design tool is to link architectural intentions to the fabrication and material constraints of autonomous terrain modeling. The ongoing development of the design tool uses a highly abstracted model to design and simulate the terrain modeling operations. We use the software package Rhino with the plugins Grasshopper and Python. Both the fabrication constraints and material parameters are applied to a simple 2.5D digital terrain model (DTM), which can then be operated upon. The landscape is surveyed with Lidar scanners (one in the air for planning and two on the machine for excavation) and subsequently filtered and gridded, where the resolution of the grid can be adjusted according to scale (Zwierzycki 2016). In large-scale projects, simulations can be made with a 1 m point distance, whereas smaller areas are simulated with a 20 cm raster that can then be simulated directly in rviz (Jud 2017). In smaller-scale topologies we expect a discrepancy between the topological simulation of the design tool and the excavation results because of the complexity of digitally shaping formless soil material. Simulations of soil mechanics are computation intensive and often limited to a single texture, humidity or density. For this reason we will have to implement an iterative design method that fuses real-world observations with the fabrication and material parameters. In addition to this, 1:10 to 1:50 scale models will inform the designer on how to control the designed topology and excavation processes. The combination of digital and analogue approaches for the developed tool should benefit the designer's understanding of both the mechanical performance as well as the tactile expression of the final landscape topology.

CONCLUSION

The computational tool outlined above promotes and differentiates the performative aspects of each site (Hurkxkens 2015). It brings the designer closer to the actual materiality of a place by directly influencing the process of construction and fabrication (Mah 2015). Distinguishing between form parameters and performative parameters can enable the designer 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. What used to be solved ahead of time on a formal level can now become an expression of the performance of the architectural intention, as

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6 Early prototype of the autonomous walking excavator.

7 Ecological restoration of the River Aire by Georges Descombes. This project serves as a topological example for autonomous terrain modeling, but it has been realized with conventional means.

combined with the resolution of the fabrication constraints and the inherent material properties of the site. The development of autonomous robotic construction equipment will speed up over the coming decade. It will open up incredible potential in working with difficult terrains and enacting ecological restoration projects (Girot 2013). Many large-scale infrastructural projects like airports, railroads, sound barriers or riverbank restoration could benefit from this new and performative construction and design method.

The authors are currently continuing the automation of a full-scale walking excavator and developing the computational design tool such that the work presented here can be integrated, simulated and verified with the real machine in a real environment.

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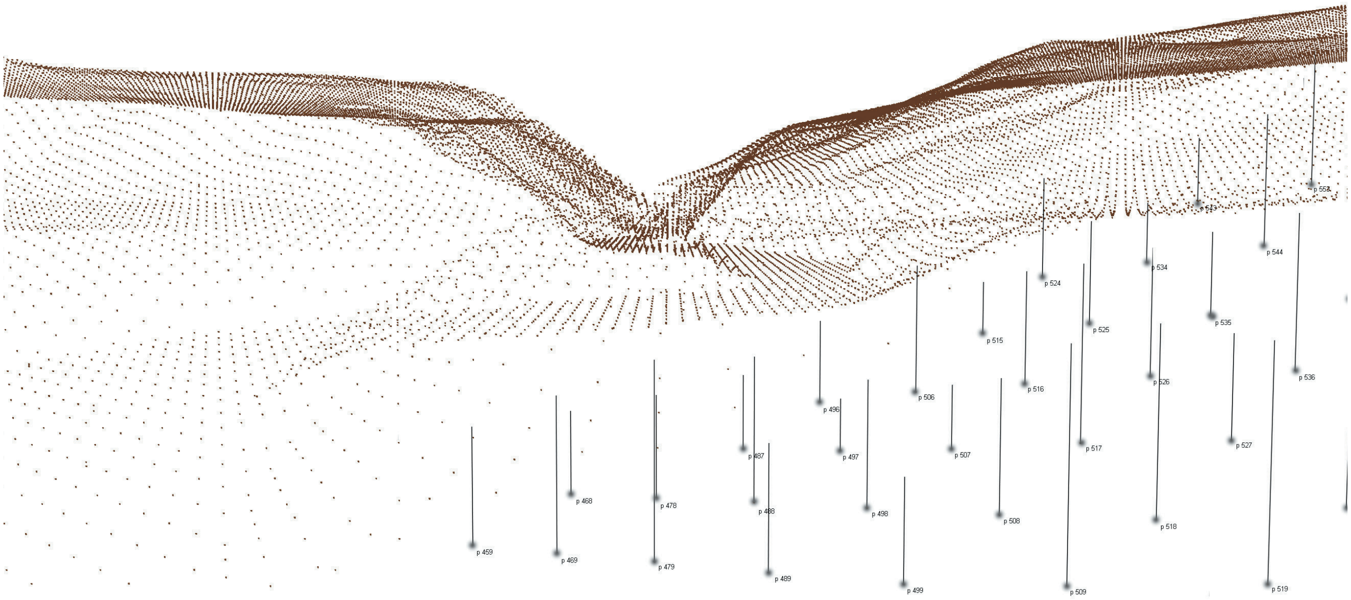

8 Prototype of the computational design tool for digital terrain modeling operations. Made visible is the raster-grid of 1m interval and the vertical translations per point. Every point has a set of fabrication and material constraints that limit its vertical freedom (in this example x and y are always fixed).

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IMAGE CREDITS

Figure 7: Fabio Chironi, © 2014.

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Ilmar Hurkxkens is a PhD researcher at the Chair of Landscape Architecture, ETH Zurich. He studied architecture at the Delft University of Technology, gruading with an honorable mention for the design of a linear sea dike that combines architecture with flood control. In 2013 he received the Young Researcher Award at the international conference Thinking the Contemporary Landscape in Herrenhausen, Germany, and in 2015 he founded his own firm Studio Ilmar Hurkxkens and co-founded Landskip, a laboratory for landscape transformation. Since the beginning of 2017 he investigates the potential of on site robotic construction following topological design methods in landscape architecture. He joined the NCCR Digital Fabrication in the beginning of 2017.

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