Informing Grounds

A Theoretical Framework and Iterative Process for Robotic Groundscaping of Remote Sites

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1 Robotic sand-forming simulating remote autonomous lunar groundscaping (Confluence Institute/MTRL, 2019)

ABSTRACT

Advancements in robotic fabrication are enabling on-site construction in increasingly larger scales. In this paper, we argue that as autonomous tools encounter the territorial scale, they open new ways to embed information into it.

To define the new practice, this paper introduces a protocol combining a theoretical framework and an iterative process titled *Informing Grounds*. This protocol mediates and supports the exchange of knowledge between a digital and a physical environment and is applicable to a variety of materials with uncertain characteristics in a robotic manufacturing scenario. The process is applied on soil and demonstrated through a recent design-to-fabrication workshop that focused on simulating digital groundscaping of distant lunar grounds employing robotic sand-forming.

The first stage is 'sampling'—observing the physical domain both as an initial step as well as a step between the forming cycles to update the virtual model. The second stage is 'streaming'—the generation of information derived from the digital model and its projection onto the physical realm. The third stage is 'transforming'—the shaping of the sand medium through a physical gesture. The workshop outcomes serve as the basis for discussion regarding the challenges posed by applying autonomous robotic tools on materials with uncertain behavior at a large-scale.

INTRODUCTION AND BACKGROUND

The freedom from machine boundaries enables the application of autonomous construction to increasingly larger scales as well as for on-site robotic construction (Buchli et al. 2018). This renders digital fabrication more ubiquitous as well as more autonomous at a territorial scale. In this context, robotic fabrication could shape not only objects, but also entire environments.

Territorial-Scale Autonomous Construction

As larger scales are approached, advanced fabrication robots show preliminary abilities to operate in-situ and on multiple ground conditions, enabling a direct transformation of natural terrains through digital information (Giftthaler et al. 2017; Hurkxkens Girot and Hutter 2017). In this context, research on integrating information into the landscape for means of physically transforming it focused mainly on the methodology towards approaching the site and its analysis; the autonomous tools employed in the process; on various material exploration aspects, and on ways for linking physical landscapes and digital environments (Hurkxkens et al. 2017; Cantrell and Mekies 2018; Girot and Hurkxkens 2018).

Processes for Remote Digital Groundscaping

While speculative design workshops begin to explore these digital and physical links, there is still a gap in terms of workflows and processes that can aid digital groundscaping and digital fabrication with uncertain materials at large. This gap stems both from the physical distance between the operator and the material, and from the uncertainty inherent in soil (Thornton 2015). When the operator and the material are proximate, the operator can respond to on-site scenarios. However, while the two are distant, as is the case in autonomous robotic fabrication set in natural terrains, this ability is reduced. Current research addresses this difficulty by exploring ways for mediating between robotic tools, the environment, and material processes (Dubor et al. 2016; Raspall 2015).

Addressing Uneven Substrates

In addition, advanced capacities for surface-scanning enable to better cope with fabrication on uneven substrates as in plaster and stucco (Bard et al. 2016). However, there is still a need to expand this capacity to support granular materials, as well as to provide a structured iterative process that can narrow the described gap. To address this, the paper presents a theoretical framework and an iterative fabrication process for informing uncertain materials (as soil) using robotic tools. The paper also demonstrates the applicative use of the iterative process through several experimental projects.

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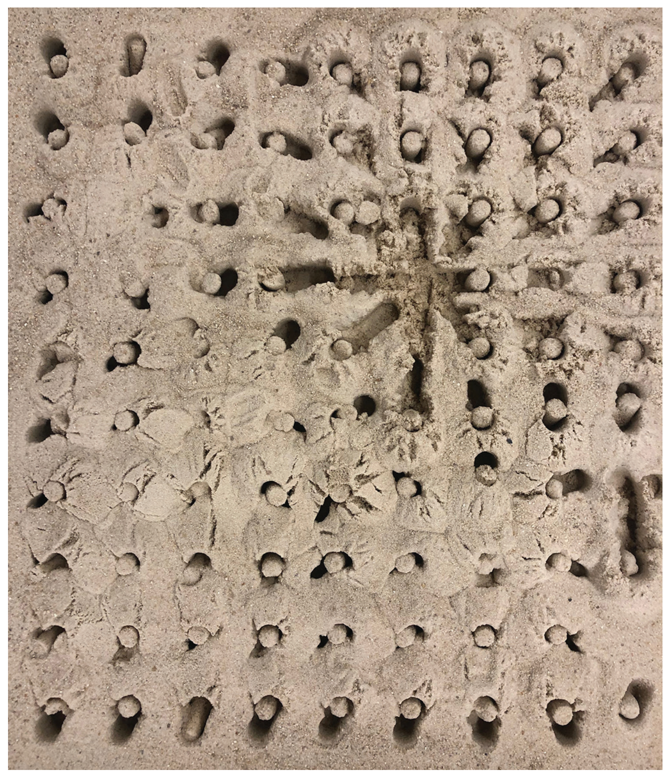

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2 *Robotic Moonscaping* workshop sand-forming process outcomes: "Scratching the Surface" project (Confluence Institute/MTRL, 2019)

3 *Robotic Moonscaping* workshop sand-forming process outcomes: "Controlled Craters" project (Confluence Institute/MTRL, 2019)

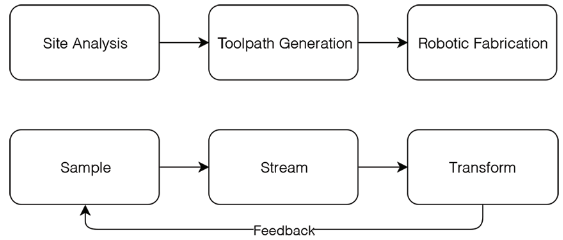
INFORMING GROUNDS

A Theoretical Framework

Historically, in digital architecture, there has been a distinction between the digital and physical realms (Kolarevic 2004). Recent advancements in architectural robotics have bridged the two, as information is embedded into matter, and by doing so, robotic fabrication in architecture has given rise to the notion of 'digital materiality'—the interweaving of information and matter (Gramazio and Kohler 2008). Since the notion was coined, the process of enhancing matter with digital information has been extensively explored, resulting in the rich exchange and interplay between data and material which now characterizes digital making. The impact of information on matter is defined through several parameters related to the increase in the intensity, extensity, and potentiality of digital architecture (Sprecher and Ahrens 2014).

The Uncertainty of Natural Terrains

Certain classes of materials, among them natural terrains, present a high degree of complexity for digital fabrication due to their irregularity. In the field of robotics, this condition is defined as uncertainty (Donald 1988; Du Toit and Burdick 2012; Shaked and Dubin 2019). The uncertainty stems from variations between the virtual model and the actual environment, the unpredictable material behavior in the encounter between them, and motion planning and control challenges arising from them. The framework proposed here addresses these challenges through an iterative robotic fabrication process. In contrast to the common linear process, the proposed method handles uncertainty as it mediates between the virtual and the physical (Figure 4). These sequential stages are then presented in detail as a protocol for *Informing Grounds* and uncertain materials at large (Figure 5).



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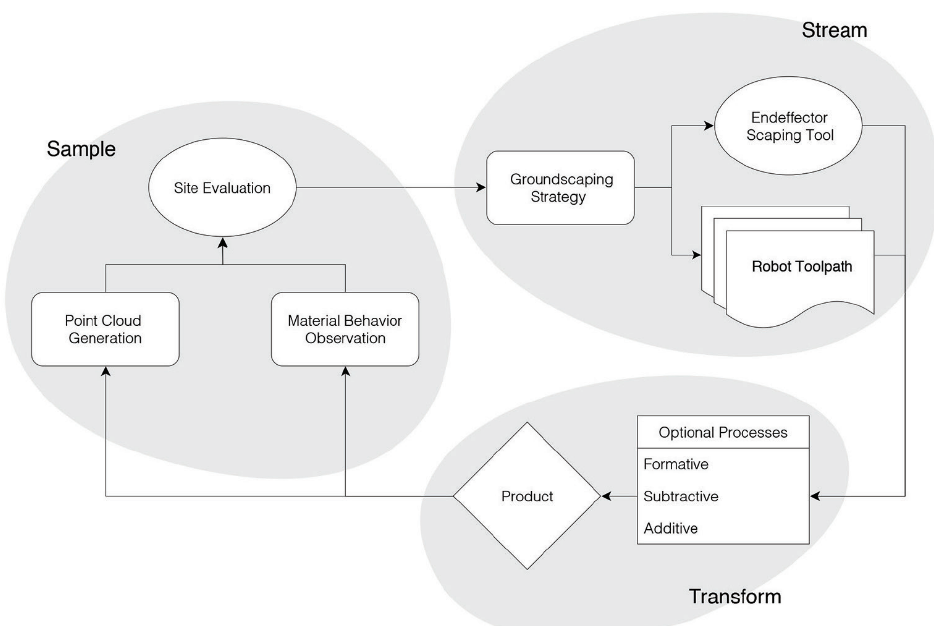
The linear process in robotic fabrication includes analyzing the site, generating a toolpath, and executing the work. Moving from a linear to an iterative process requires a shift in terminology:

- Site analysis is replaced by a repetitive sampling of the ground at the end of each iteration. The first sampling produces a 3-dimensional model of the site. The following samples generate a model representing both the site as well as the product of the groundscaping action.
- Toolpath generation is broken down to a set of robot commands, which are streamed onto the site model. The streaming process allows to deploy robot motion commands in response to changes in the site model and handle uncertainties that arise from material behavior or environmental conditions.



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4 (top) A linear robotic fabrication process; (bottom) *Informing Grounds*, the core of the proposed iterative process

5 *Informing Grounds*: The iterative process in detail

- Robotic fabrication as a singular action with a determined or a predetermined end is replaced by transformation: a continuous cycle of shaping the ground or the uncertain material.

PUTTING THE FRAMEWORK TO TEST

'Robotic Moonscaping' Workshop

The proposed framework and fabrication method were explored during an intensive architectural workshop at the Confluence Institute for Innovation and Creative Strategies in Architecture led by the authors in February 2019. The workshop was designed in line with the overarching theme of the spring semester, which focused on investigating strategies for lunar construction. In this context, the objective was to get students acquainted with basic skills and tools for robotic fabrication through the research topic. The workshop explored and developed strategies for remote groundscaping of lunar soil for space habitats, and included simulating remote digital scaping and experimenting with robotic tools on a physical analog using the proposed protocol. The goal was to correlate the workshop investigations with current research on space architecture, which seeks to combine the use of native matter and remote autonomous construction (Lim et al. 2017).

Workshop Protocol

The sequence of the workshop followed the iterative stages of *Informing Grounds* (Figure 5), and protocol stages, described below, were based on an iterative model. The workshop was performed through a combination of digital tools (Rhinoceros 3D, Grasshopper, and KUKA WorkVisual), and was conducted using a KUKA KR 6 R900 industrial robotic arm, an Intel RealSense D400 depth camera, and 70x70x10cm square sand beds for modeling and experimenting.

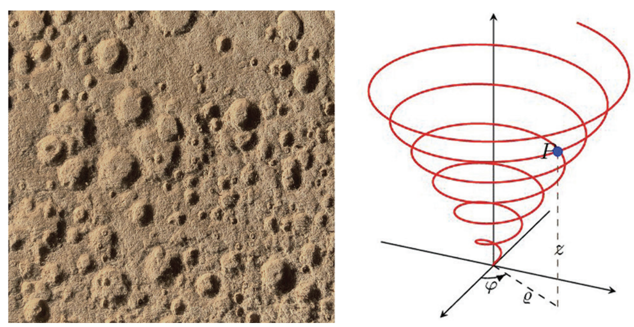
The workshop was conducted in groups comprised of 4-5 students. To facilitate exchange of knowledge, group presentations took place in-between the various workshop phases. Due to the uneven levels of robotics skills within each group, the workshop began with a basic introduction to operation procedures: toolpath planning, simulation, and collision detection. Each group was asked to perform a speculative research on digital scaping strategies for a specific remote location using a custom end effector.

The site analysis was based on a topological design approach, combining scientific and aesthetic digital methods on landscape design, through integrative design processes (Girot 2013). The initial end effector development was intuitive, based on manual experimentation, and produced simple land forming tools. As the different strategies solidified, the tool design was optimized for better usability. Throughout the process, the difference between the expected result and the final outcome served as a central criterion for the validity of the process.

Workshop Steps

First iteration:

- Sampling: This stage consisted of the initial modeling of the given sites, which were then projected on a CNC-milled site model for the purpose of developing groundscaping strategies for the site in relation to space habitats. In the course of this step toolpath strategy explorations were performed in tandem with the prototyping of custom end effectors for groundscaping (Figure 6, Figure 9).
- Streaming: Once a groundscaping strategy was developed and modeled (using Grasshopper), and its accompanying tool (or set of tools) produced, the next step was streaming the code onto the sand box model (Figure 7).
- Transforming: As the information was projected on the physical model, it informed the sand medium through the combined effect of the toolpath and the unique physical gesture created by each end effector (Figures 8, 10).



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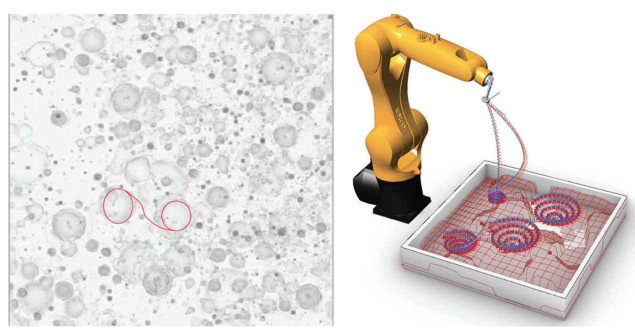

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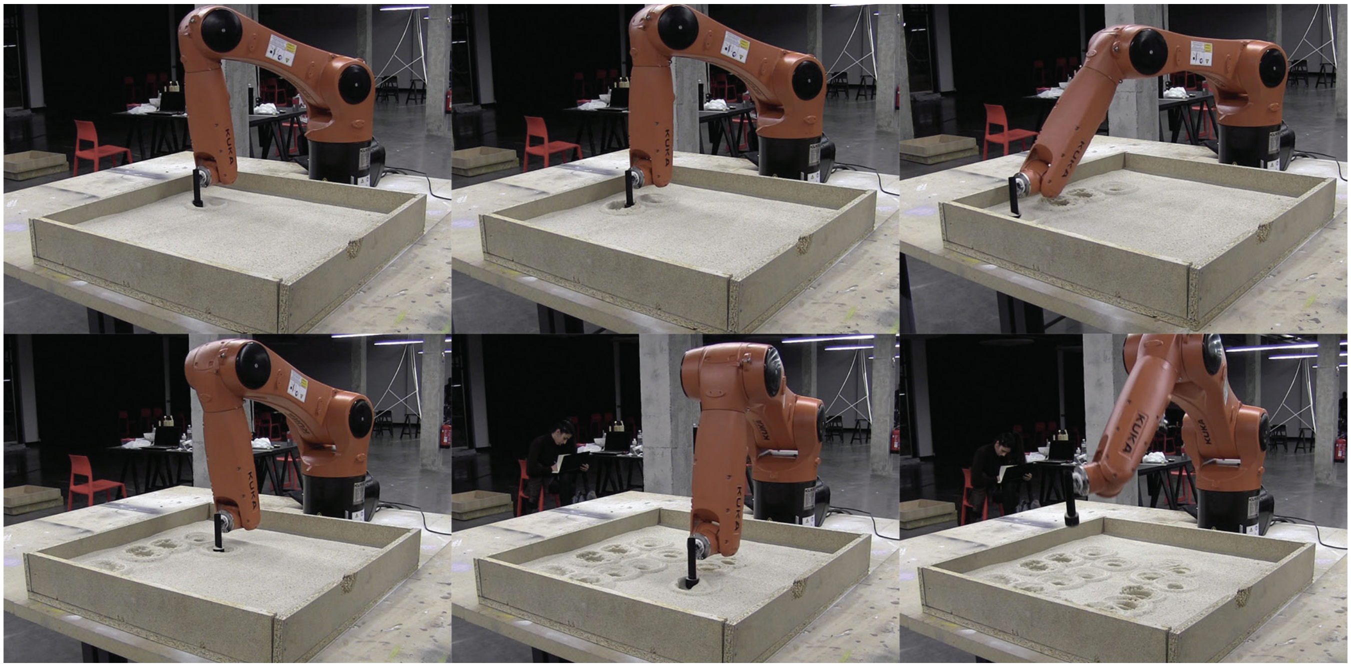
6 Sampling, Project 1, "The Far Side of the Moon": (left) CNC-milled site evaluation model; (right) developing a respective spiral toolpath strategy forming a protected circulation path along the craters' edges

7 Streaming, Project 1: (left) toolpath projected onto the initial 3D pointcloud model of the site; (right) toolpath simulation with the custom end effector



8 Project 1, transforming the analog based on the previous sampling and streaming phases (Confluence Institute/MTRL, 2019)

Workshop Steps

Following iterations:

- Sampling: The transformed model was scanned using a depth camera, measuring the difference in point location between the resulting point cloud and the previous model (Figure 12). A visual evaluation of the new virtual model followed, and then the insights were used to adjust the end effector and toolpath (Figure 10). In addition, this phase was used by some groups to alter or improve the material mix.
- Streaming: Information based on the revised virtual model was then exported and projected onto the leveled sandbox model (once or even multiple times), using an improved toolpath and custom end effector (Figures 10, 11).
- Transforming: The sand was then re-shaped, further transforming the model (Figures 10, 11). In light of the instability of sand, this step could potentially be performed repeatedly before resuming the feedback loop, thus reducing sampling cycles and optimizing the entire process.

The iterative process also included material explorations testing the stabilizing and solidifying of the sand models using cement and various binders. The same iterative approach guided the process, and as the students progressed, they further refined their toolpath in light of digital, visual, and material feedback from the different prototypes. The tools were assessed by the effectivity of their interaction with the material in its various mixes.

DISCUSSION

The encounter between soil and robotic tools as tested in the presented workshop highlighted the need for iteration in digital groundscaping. The workshop enabled to test the proposed iterative model, yet also to refine it during its course. A few noteworthy aspects emerged in the course of the workshop and are discussed below in relation to the three core steps of the process.

Sampling

The uncertain characteristics of natural terrains, as exhibited by the sand and the various sand mixtures, underscored the need for frequent feedback and iteration in this context. Whereas a single sample might suffice for a linear, object-focused digital fabrication, resampling is crucial to groundscaping where, as previously mentioned, sands and soils present a high degree of uncertainty.

Streaming

In sand and soil, there is a disparity between the information the robot streams and its imprint on the physical model. This disparity is rooted both in the material behavior, and in the form of the end effector. The latter serves as the robotic tool, and hence determines the encounter between the code and the material.

Multiple iterations were performed on the toolpaths as well as on the end effectors aimed to bridge this disparity much as possible. Higher degrees of correlation between the desired (i.e. virtual) and the physical outcome were obtained following several prototyping iterations. These included gradual modifications of the toolpath, the tool, and the material mix.

Transforming

In the proposed groundscaping strategies, robotic tools were seen as potential construction means. As such, they enable the digital exploration a long-lost art of 'scaping' soil using digital tools in remote terrains (Girot and Hurkxkens 2018).

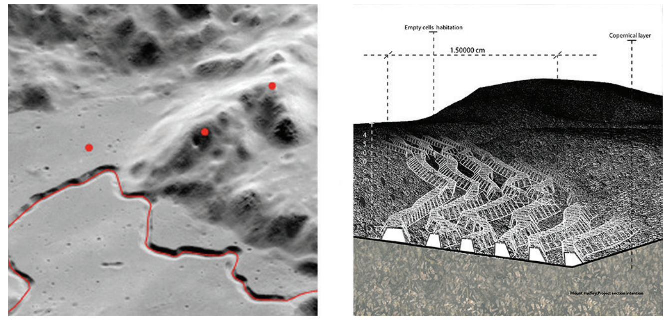
Three issues were central to the transformation of the knowledge from the digital to the physical for means of shaping the sand. The first, was the tool-development strategy, which was linked to the amount of material that needed to be moved or stabilized. The second issue was the robotic gesture, which was tied to the specific shaping act/action, and the third issue was the adjustment of the toolpath to best serve the tool's gesture as applied on the material.

CONCLUSION

The paper proposes an iterative framework for automating earthwork and allowing the production to adapt to on-site results. The framework intends to minimize the uncertainty inherent in earthwork that is a result of the unpredictability of the medium's behaviour. *Informing Grounds*, the iterative process proposed here, provides a theoretical framework and fabrication process for operating robotic tools on natural terrains.

The framework was tested and demonstrated through an intensive architectural robotic fabrication workshop, which conducted speculative research into the potentialities of incorporating industrial robotic arms in groundscaping. In the course of prototyping, the three-step process—sampling, streaming and transforming—allowed the digital model and the physical environment to converse in a continuous dialogue. This exchange assisted in increasing the compatibility between the model and the outcome and enabled workshop participants to tackle a few dimensions of uncertainty presented by the encounter between robotic tools and uncertain matter.

While the experiments were performed on scale-models, they helped establish a theoretical foundation—for an iterative process of remote groundscaping—that carries a wider range of potential applications and materials beyond groundscaping, and allows production processes to adapt to on-site results. It is anticipated that larger scales will present additional challenges for in-situ fabrication. Nevertheless, the scale-free nature of the framework facilitates increasing the examined scale in future explorations.



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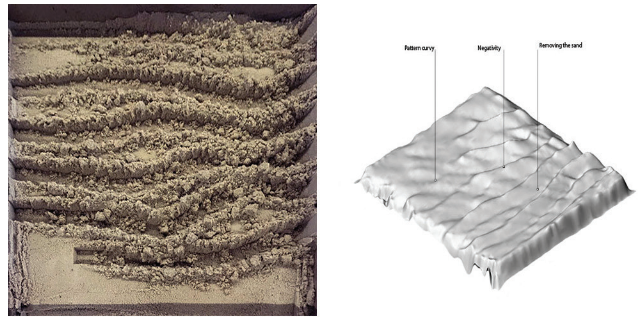

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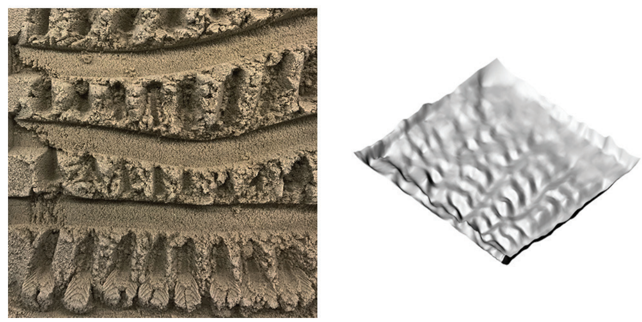

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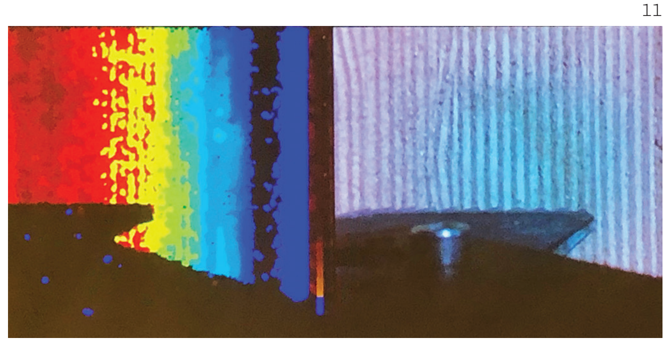

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9 Sampling, Project 2, "Mount Hadley": the site includes a delta and a rill that are suggested to be a result of volcanic vents and lava flows

10 Project 2: (left) Transforming, a groundscaping strategy aimed to create a network of habitable units along the rille's ridge; (right) Resampling the model to updated the point cloud after initial transformation

11 Project 2: Presenting a more precise result as the iterative process converges towards the desired result

12 Tool vision: The end effector is mounted with a depth camera that transmits the data beck to the server in real-time, allowing the tool to react to local material conditions during the transformation phase

13 *Robotic Moonscaping* workshop sand-forming detail, "Controlled Craters" project (Confluence Institute/MTRL, 2019)

Future research will therefore address a larger fabrication scale; handling and reconstitution of local materials; and fabrication methods for stabilizing soil. These avenues of inquiry are expected to enhance the capacity of large scale, in-situ robotic fabrication.

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IMAGE CREDITS

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REFERENCES

Bard, Joshua, Richard Tursky, and Michael Jeffers. 2016. "RECONstruction." In Robotic Fabrication in Architecture, Art and Design 2016, edited by D. Reinhardt, R. Saunders, and J. Burry, 262-73. Cham: Springer International Publishing.

Buchli, Jonas, Markus Giftthaler, Nitish Kumar, Manuel Lussi, Timothy Sandy, Kathrin Dörfler, and Norman Hack. 2018. "Digital In Situ Fabrication - Challenges and Opportunities for Robotic In Situ Fabrication in Architecture, Construction, and Beyond." Cement and Concrete Research 112: 66-75.

Cantrell, Bradley, and Adam Mekies, eds. 2018. Codify: Parametric and Computational Design in Landscape Architecture. Oxon: Routledge.

Donald, Bruce R. 1988. "A Geometric Approach to Error Detection and Recovery for Robot Motion Planning with Uncertainty." Artificial Intelligence 37(1-3): 223-71.

Du Toit, Noel E., and Joel W. Burdick. 2012. "Robot Motion Planning in Dynamic, Uncertain Environments." IEEE Transactions on Robotics 28(1): 101-15.

Dubor, Alexandre, Guillem Camprodom, Gabriel Bello Diaz, Dagmar Reinhardt, Rob Saunders, Kate Dunn, and Marjo Niemelä. 2016. "Sensors and Workflow Evolutions: Developing a Framework for Instant Robotic Toolpath Revision." In Robotic Fabrication in Architecture, Art and Design 2016, edited by D. Reinhardt, R. Saunders, and J. Burry, 410-25. Cham: Springer International Publishing.

Giftthaler, Markus, Timothy Sandy, Kathrin Dörfler, Ian Brooks, Mark Buckingham, Gonzalo Rey, Matthias Kohler, Fabio Gramazio, and Jonas Buchli. 2017. “Mobile Robotic Fabrication at 1:1 Scale: The In Situ Fabricator.” Construction Robotics 1(1-4): 3-14.

Girot, Christophe, Anette Freytag, Albert Kirchengast, and Dunja Richter. 2013. Topology: Topical Thoughts on the Contemporary Landscape, Landscript series, Vol. 3. Berlin: Jovis.

Girot, Christophe, and Ilmar Hurkxkens. 2018. “Robotic Landscapes: Nature, Computation, and the Design Space of Autonomous Terrain Modeling.” Landscape Architecture Frontiers 6(2): 64-75.Gramazio, Fabio, and Matthias Kohler. 2008. Digital Materiality in Architecture. Baden : Lars Müller Publishers.

Hurkxkens, Ilmar, Christophe Girot, and Marco Hutter. 2017. “Robotic Landscapes: Developing Computational Design Tools Towards Autonomous Terrain Modeling.” In Acadia 2017 Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture, edited by T. Nagakura, S. Tibbits, and C. Mueller, 292-297.

Kolarevic, Branko. 2003. Architecture in the Digital Age: Design and Manufacturing. New York; London: Taylor & Francis.

Lim, Sungwoo, Vibha Levin Prabhu, Mahesh Anand, and Lawrence A Taylor. 2017. “Extra-Terrestrial Construction Processes – Advancements, Opportunities and Challenges.” Advances in Space Research 60(7): 1413-29.

Raspall, Felix. 2015. “A Procedural Framework for Design to Fabrication.” Automation in Construction 51: 132–39.

Shaked, Tom, and Uri Dubin. 2019. “Exercises in Style: A Transdisciplinary Discussion.” In Instabilities and Potentialities: Notes on the Nature of Knowledge in Digital Architecture, edited by A. Sprecher and C. Ahrens. New York; London: Routledge.

Sprecher, Aaron, and Chandler Ahrens. 2014. “Processing Transdisciplinary Knowledge: Intensity, Extensity and Potentiality in Digital Architecture.” The International Journal of Technology, Knowledge and Society 9(4): 207-223.

Thornton, Colin. 2015. Granular Dynamics, Contact Mechanics and Particle System Simulations 2015. [Erscheinungsort nicht ermittelbar]: Springer International Publishing AG.

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