Ecological Robotics

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Abstract: This research presents a novel method for paste-based robotic planting. Our method for robotically extruding seeds in a paste of clay and planting media enables precise, algorithmic planting. This additive manufacturing process builds microtopography, while planting seeds. With this 3D printing process designers can engage with the geomorphological and ecological processes that shape landscapes. Microtopography can be designed to direct flows of water, while planting can be designed to foster biodiversity, form ecotones, and control erosion. As a proof of concept, we demonstrate how algorithms can generate precise planting patterns such as pseudorandom gradients. We envision unmanned ground vehicles with seed printing systems planting entire landscapes with algorithmic designs.

Keywords: Robotics, planting, ecology, computational design, additive manufacturing

1 Introduction

Research on autonomous construction in architecture has explored the novel creative, material, tectonic, performative, and aesthetic potential for the computational design of the built environment (GRAMAZIO & KOHLER 2014, MENGES 2015). Similarly, the autonomous construction and planting of landscape promises unique aesthetic opportunities and new ways of engaging with ecology and geomorphology. Designers have experimented with robotic processes for constructing landforms such as soil 3D printing (MITTERBERGER & DERME 2019, 2020) and autonomous excavators (JUD ET AL. 2021, HURKXKENS ET AL. 2022). Robotic processes for planting have been developed such as vacuum seeding robots (GOLDBERG 1995, FARMBOT 2020, PRESTEN et al. 2021), autonomous seed drilling tractors (GROß 2013), and seed sowing with unmanned aerial systems (MOHAN et al. 2021). While sowing seeds is an imprecise process with low survival rates, seed drilling is more precise and has higher survival rates, but mechanically disturbs soil, increasing the risk of soil erosion. Our paste-based extrusion method for autonomous planting has millimeter precision, high survival rates, does not disturb soil, and creates microtopography. Potential applications include landscape architecture, land art, ecological restoration, and precision agriculture.

2 Methods

In our method for robotic planting, seeds are extruded in a paste of clay, planting media, and water (Fig. 1). As an additive manufacturing process, paste-based extrusion of seeds builds landforms layer by layer. The proportions of the paste are calibrated so that it can be extruded smoothly, while supporting seed germination. Clay is used for plasticity for the sake of extrusion. Planting media is used to provide nutrition for plants, retain water, and provide pore space for root growth. Water is used to wet the clay and germinate the seeds. The paste is 3D printed, i. e. extruded, directly onto soil. After printing, the seeds embedded in the paste have the shelter, nutrients, and moisture they need to germinate. Once the seeds have germinated, the roots of the seedlings grow into the soil below.

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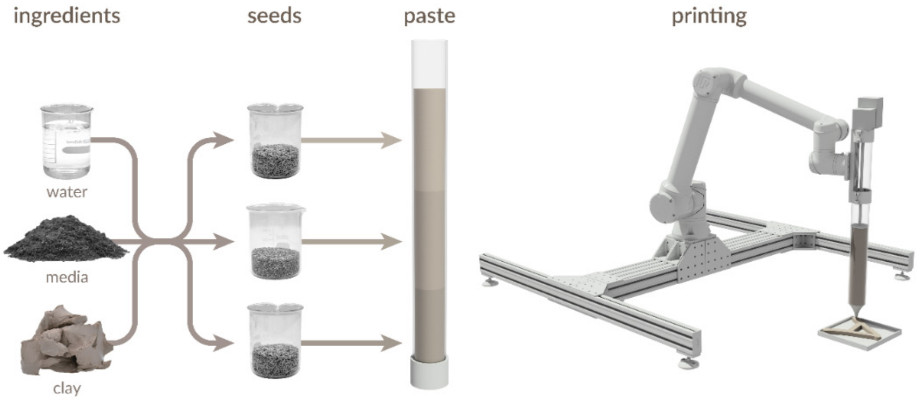


Fig. 1: Robotic paste-based seed extrusion

As a proof of concept, we developed a prototype with a linear actuator ram mounted on a 6-axis robotic arm. Industrial robots are reliable, versatile systems that can easily be adapted to new tasks, making them well suited for creative experimentation with novel material processes (GRAMAZIO & KOHLER 2014, 16). For this prototype, we used a UR10e industrial robotic arm because its 12.5 kg payload was enough for a large extruder with 2000 ml of paste and its reach of 1300 mm allowed for a large build space. Grasshopper, a visual programming environment for computational design (MCNEEL 2021), was used to generate geometry for robot path planning. The Robots ex Machina framework (GARCÍA DEL CASTILLO Y LÓPEZ 2019) was used to control the robot and extruder.

To test this method, a series of planting patterns were robotically printed in the lab. We tested designs such as space filling curves, landforms derived from trigonometric waves, landforms derived from cellular texturing, landforms derived from procedural noise (Fig. 2 & Fig. 3), and generative typography (Fig. 4). For ease of printing and cultivation in a laboratory setting, designs were printed in growing trays and stored on racks with grow lights. Each 250 by 250 mm tray was filled with planting media as a substrate for the print. We used plants such as perennial ryegrass (*Lolium perenne*), annual ryegrass (*Lolium multiflorum*), arugula (*Eruca vesicaria*), radish (*Raphanus sativus*), alfalfa (*Medicago sativa*), Siberian kale (*Brassica* napus) and broccoli (*Brassica oleracea* var. *italica*). For the landforms, the extruder was filled with layers of different seeds to create an elevation gradient of species. Over the course of the study, the prints were photographed daily to record the growth of the plants.

3 Results

The planting designs printed cleanly and precisely as the crisp letterforms in Figure 4 demonstrate. Plants grew most healthily and vigorously in prints that were 5 or 10 mm tall, composed of 1 or 2 layers, because the seedlings' roots had easier access to the porous, nutrient rich substrate of planting media below. Furthermore, plants grew more vigorously in narrower forms with widths of 20-40 mm because this ensured that seedlings had less competition and more access to sunlight and substrate. While paste-based extrusion of seeds creates microtopography, the scale of appropriate landforms is highly constrained by growing conditions.

Fig. 2: Polycultural print generated from procedural noise

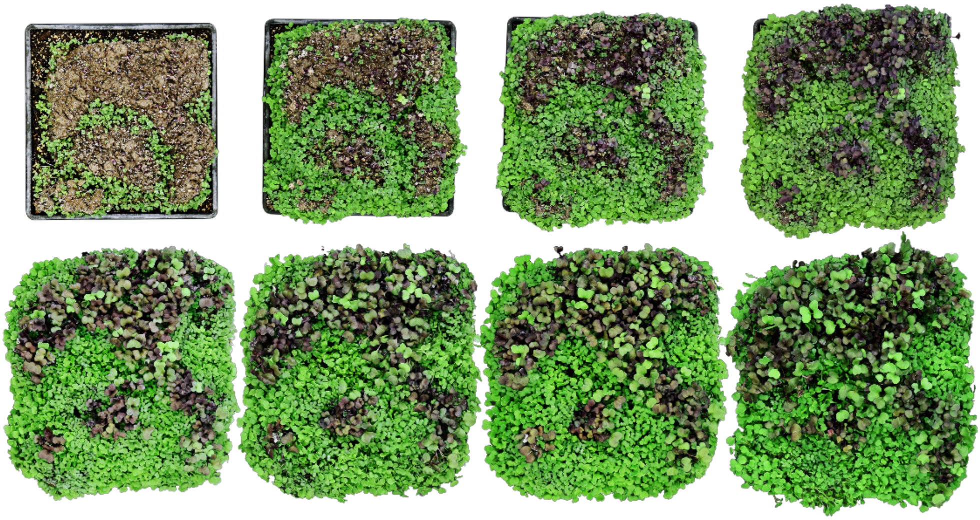


Fig. 3: Daily time series of a polycultural print generated from procedural noise

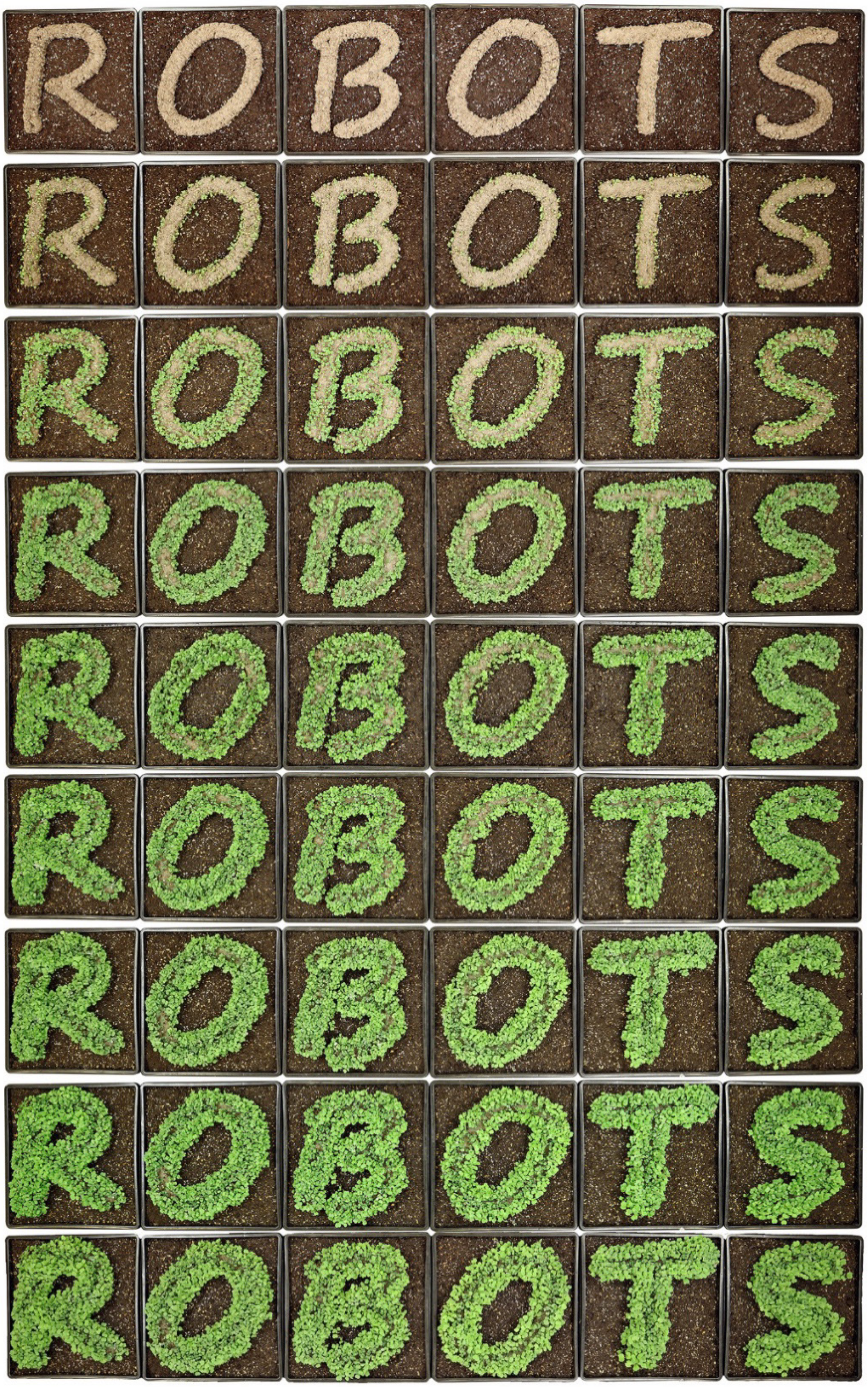


Fig. 4: Daily time series of living typography grown from seed

4 Future Work

To further this research, we are investigating alternative media for the paste, testing different types of extruders, integrating sensors into the system, and integrating the system onto an unmanned ground vehicle for landscape-scale planting (Fig. 5). We are testing pastes composed of biochar that release nutrients slowly and biopolymers that biodegrade rapidly. We are integrating moisture sensors, depth sensing, lidar scanners, and multispectral imaging for adaptive planting and monitoring. Using these sensors, we plan to conduct experiments with controls, replicates, and quantitative measures to assess the efficacy of this method with different pastes. To plant at landscape-scale, we plan to integrate the robot arm, extruder, and sensors onto an unmanned ground vehicle with real-time kinematic positioning. We plan to use lidar, positional data, and simultaneous localization and mapping algorithms for autonomous navigation and for positioning the extruder relative to the ground in real time. For field trials, we will use lidar and multispectral imaging on unmanned ground and aerial vehicles to conduct repeated surveys at high spatial and temporal resolution to assess plant growth.

5 Conclusion

With paste-based robotic planting, computational designs for planting patterns can be autonomously seeded with high precision. While this experiment was conducted in the lab, robotic planting could be done at scale in the field with unmanned ground vehicles. With generative design enacted by field robots, landscape architects would be able to design dynamic landscapes as ongoing performances – as ecological processes guided by design interventions. Unmanned aerial systems could collect imagery and elevation datasets at high spatial and temporal resolution that could inform the ongoing design and management of landscapes. As unmanned aerial systems monitor how landscapes evolve, unmanned ground vehicles could adaptively plant and replant in response, catalyzing new assemblages of plants and wildlife. We hypothesize that algorithmic planting based on ecological principles could foster spatial heterogeneity, complexity, and thus biodiversity. We envision field robotics giving rise to an algorithmic aesthetic of ecology.

New media scholar Laura Marks describes algorithmic aesthetics as a semiotic process of enfolding and unfolding, a process in which infinite possibility is transcribed into information and then image (MARKS 2010). This is a performative aesthetics of infinity and contingency – an aesthetics that explores what is revealed and what is hidden; an aesthetic in which creativity is a means of discovering the infinite. Design projects like GRAMAZIO KOHLER Research's Endless Wall (2011), SNØHETTA'S MAX IV Laboratory Landscape (2016), and MAEID'S Magic Queen (2021) evoke such an algorithmic aesthetic. With systems for precise autonomous planting, landscape architects would have the means to express ecological complexity and contingency with a visibly algorithmic logic. Computational design processes such as procedural noise, cellular noise, and fractional Brownian motion (Figures 2, 3 & 6) could be used to generate planting patterns with high spatial heterogeneity and ecological gradients between drifts. Such computationally designed planting would simultaneously evoke the accidental and intentional, the actual and virtual.

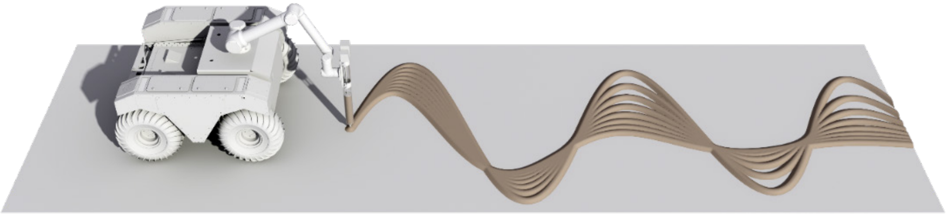
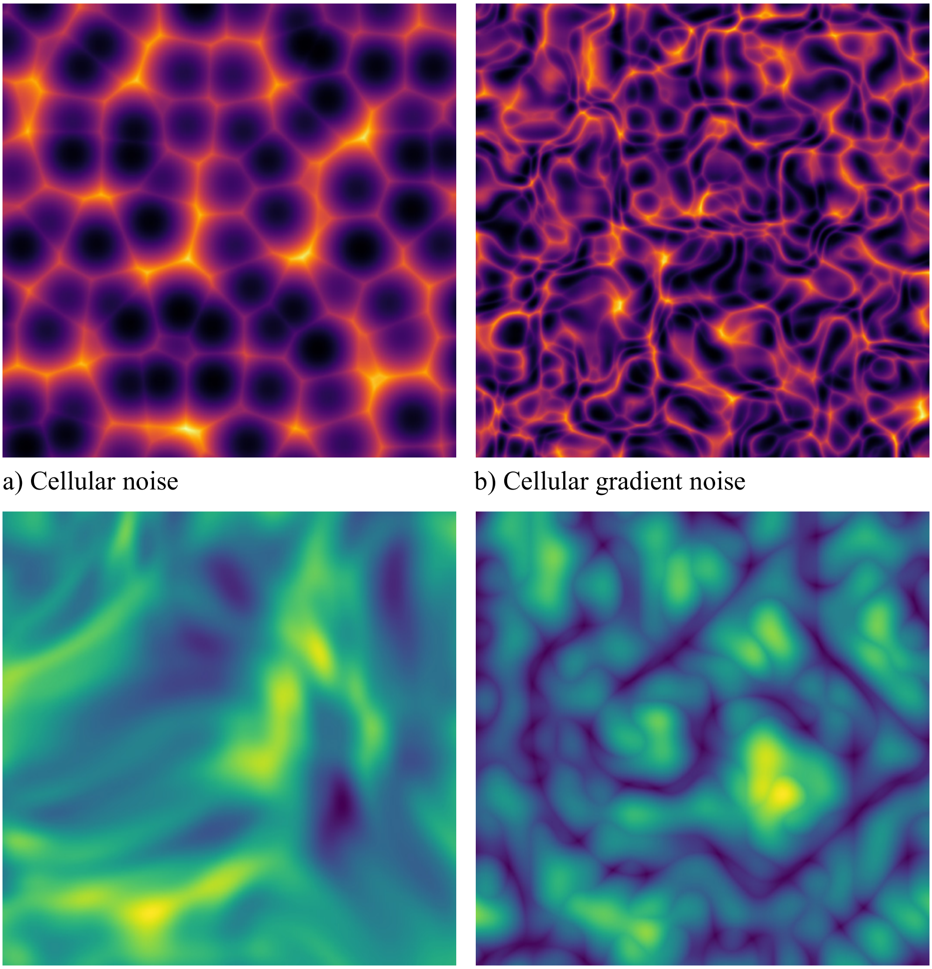


Fig. 5: Paste-based seed extruding field robot



a) Cellular noise

b) Cellular gradient noise

c) Perlin fractional Brownian motion noise

d) Perlin billow noise

Fig. 6: Procedural noise

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