Shifting Sands: Experimental Robotic Earth-Moving Strategies in Dynamic Coastal Environments

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Abstract: The increased prevalence of storm surge events that cause extreme erosion in coastal environments points to the delicate balance that exists in the perpetual formation processes of dunes. While coastal defence structures and traditional beach nourishment strategies can alleviate some of the damaging force of ongoing wave action, they don't provide a lasting solution and often produce undesirable side-effects. Design authority in this contested area of landscape transformation is often limited to engineers and shaped by reductionist economic or risk management factors. Through investigations in digital landscape fabrication techniques, this paper reconsiders the role of design in these evolving systems while demonstrating the potential for on-site, adaptive, and dynamic construction processes. By creating resilience through adaptive topographies of natural granular material, this paper proposes to establish a new equilibrium between natural processes and robotic earth-moving strategies. By combining a wave tank with natural beach sand, computational modelling and robotic beach sand manipulations, emergent topologies and open-ended design proposals are enabled under the continuous influence of water movements. The experiments were conducted in a two-week international masterclass at the School of Architecture, University of Technology, Sydney, where adaptive feedback systems for coastal remediation were studied in relation to the Northern Beaches of Sydney. As such, this paper presents a novel coastal design approach towards autonomous construction in dynamic environments, combining various technologies to generate new paths of research and design investigation.

Keywords: Coastal erosion, robotic processes, granular resilience, digital landscape fabrication, soft engineering

1 Introduction

In the summer season of 2020, up to 25 meters of the Collaroy and Narrabeen beaches in northern Sydney, Australia, were swept away by multiple storm surges. Existing rigid defence structures from wood, stone, and concrete suffered severe damage, sinking slowly into the loose granular dune area as their foundations were eroded away. While comprehensive maintenance strategies are developed to replenish the beaches with sand, Australia doesn't have the equipment, the policies, nor enough locally available sand to conduct them (SIDDEEK 2020). Instead of using conventional engineering methods, this design experiment applies robotic processes and natural processes towards continuous maintenance strategies for dynamic coastal defence structures, focusing on local material shifts and bathymetry manipulation.

This work builds upon a growing body of research into similar robotically enacted dynamic landscape tending processes (GRAMAZIO et al. 2014), (ESTRADA 2018), (BAR-SINAI et al. 2019), (HURKXKENS 2020). It also relates to work in sensor-enabled adaptive robotic fabrication in architecture (VASEY et al. 2014). The key contribution of the research described in this paper emerges from the change in context. Focusing on coastal environments provides a

Journal of Digital Landscape Architecture, 6-2021, pp. 66-74. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-705-2, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537705003.

constant energy-source (the waves) that necessitates repeated action and provides the opportunity to collaborate with and productively harness an otherwise destructive process.

Here, the ultimate goal is to find topographies and intelligent adaptive maintenance processes that use the formative potential of erosion and sedimentation to minimize the mechanical manipulation required to achieve coastal remediation goals. These goals typically prioritize the protection of adjacent structures but also include a reduction of erosion and therefore the requirement to import supplementary material, the increased stability of the coastline and increased safety. The methods here described have the potential to allow for the greater fulfilment of ecological and habitat preservation goals along with the support of recreational activity, embodied energy minimization and improved aesthetics together with a reduction in the scale and consequences of unexpected side-effects.

The first step towards that goal is to establish whether sand topographies can be produced and dynamically maintained in interaction with wave motion and to assess the design potentials revealed. The second step is to begin to produce landscape formations that demonstrate positive interactions with wave and sand motion. Rather than a restrictive experimentation environment, the combination of technologies aims to reveal unexpected synergies or potentials for further investigation.

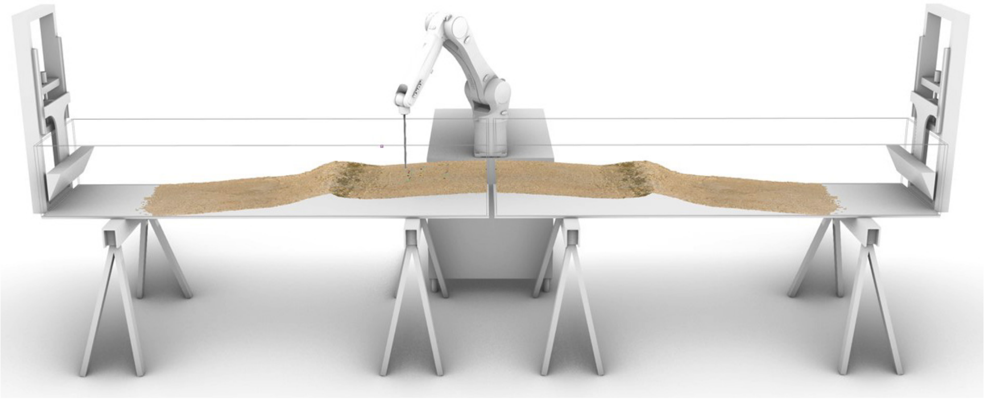

Fig. 1: Robotic Setup with wave tanks, wave actuators, beach sand and robotic manipulator

2 Robotic Wave Tank

The design experiments consisted of two phases. The first phase uncovered the object of study through five separate lenses: site, natural processes, granular material, environmental perception and robotic processes. This phase divided the tasks and methods among the participants of the masterclass and focussed simultaneously on digital craft and incremental investigation. These parallel investigations provided the groundwork for the second phase of the research, which synthesized these findings and techniques in comprehensive experiments.

To explore erosion and sedimentation processes on sloped beaches, two wave tanks were constructed (see Figure 1 and 3). Beach sand was then put into the tank to construct the berm, swash zone and surf zone (see Figure 2). The wave machines were controlled by time-interval scripts, which enabled the creation of precise wave patterns perpendicular to the beach profile to simulate storm surges. The robotic setup consisted of a six-axis robot arm, tool holder, and a 3D scanner to enable a computational response to changes in the topography by wave action. Starting from initial robotic movements designed to shift the granular material in the wave tank, the topography further informed their dimensional parameters like depth, length, and orientation. In this way, a dynamic response was created to either counter, accelerate or steer erosion and sedimentation processes depending on evolving insights during the experiments. This process was further monitored by high-res 3D scans using photogrammetry. This enabled a precise understanding of volume loss, particle transportation, and slope angles. Through an iterative feedback loop between scanning, designing and fabrication, experimental formal outcomes in continuous transformation arose (see Fig. 4). This allowed computational processes to be fine-tuned to come to resilient structures capable of withstanding multiple storm surges.

Fig. 2: Experimenting with the robotic feedback loop. Visible in the top-right is the tool holder on the robotic arm and perpendicularly attached to it the 3D scanner.

While the experiments were conducted as precisely as possible, physical processes are hard to control due to the scale of the wave tank and the mismatched scales of the 1:1 sand granules and the reduced scale of the waves and beach topography (LEMOS 2009). The difficulties and limitations facing attempts to understand complex water systems with scale models have been extensively and eloquently described in Martin Reuss' famous essay "The Art of Scientific Precision: River Research in the United States Army Corps of Engineers to 1945" (REUSS 1999). The outcomes should therefore not be seen as directly scalable and deployable techniques but rather as a first proof-of-concept of the methods and creative explorations of material and robotic processes to extract initial insights to be extended through future research.

The most obvious need is a set of experiments to establish and verify the appropriate scale-factors and coefficients necessary to extrapolation of results from scale models to the real world, along with an understanding of the limits of such extrapolation. But more importantly, the experiments change the way designers interact with the object of study: from conceiving static and final images to defining feedback systems that continuously change over time (McGee and Pigram 2011). Here, robotic processes form a natural fit to continuously evolving granular material systems under the influence of waves.

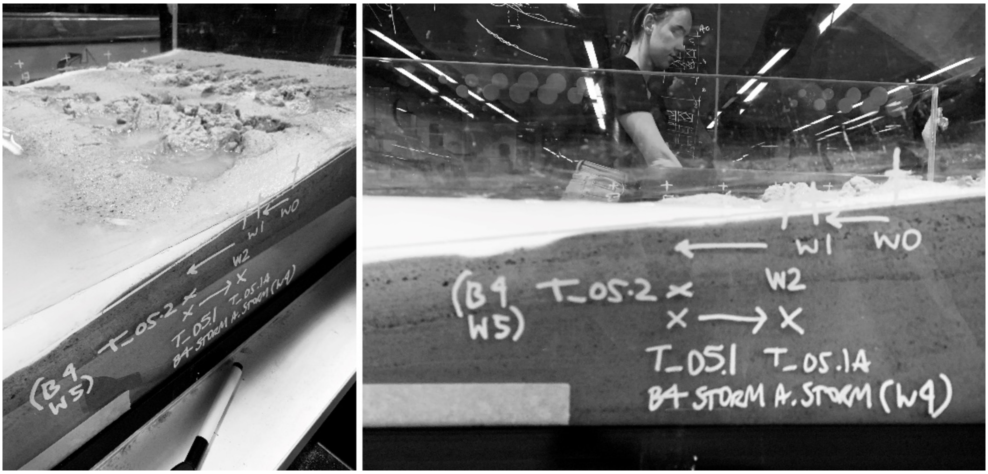

Fig. 3: Documenting a storm surge on the side of the water tank. From left to right the surf zone, swash zone, berm, and dune region in relation to the average water levels.

3 Experiments

A beach site's natural dynamic equilibrium of erosion and nourishment can maintain a safe, though continuously evolving sand dune without intervention. However, the existence of artificial constructions place limits on this possibility. The status quo requirement for current buildings and roads to stay in their current position on the beaches of Collaroy and Narrabeen, makes human intervention unavoidable. For this experiment, the natural process of wave action was calibrated to mimic the average wave height, length and frequency as well as waves during high tide combined with stormy weather found at Collaroy and Narrabeen beaches. This knowledge was combined with the material system of natural granules. Here, well rounded and sorted sand particles have only a limited formal design space, as the maximum slope angle is roughly 33 degrees. While this is true in large scale landscapes, the wet sand in the wave tank did achieve higher slope angles due to the small scale of the testing setup. Through the use of large- and small-scale photogrammetry, an understanding of the site's existing and newly proposed beach profile became possible. The robotic processes followed a clear procedure starting with a 3D scan of the sand in the wave tank, topographic analysis, the mapping of topographic transformation onto robotic movements to encode a dynamic response and finally, the execution of the robotic movements. This iterative robotic intervention adapts its patterned response based on the scan data, balancing the legibility of the original terrain geometry with an approach to an equilibrium in the system, often requiring smaller, targeted robotic interventions.

As referred to earlier, the two sequential yet complementary research phases of individual technique research and synthesis allowed for calibration of each method; the translation of these separate techniques into the synthesized experiments of phase two was a key aspect of the didactic process, requiring strategic debate.

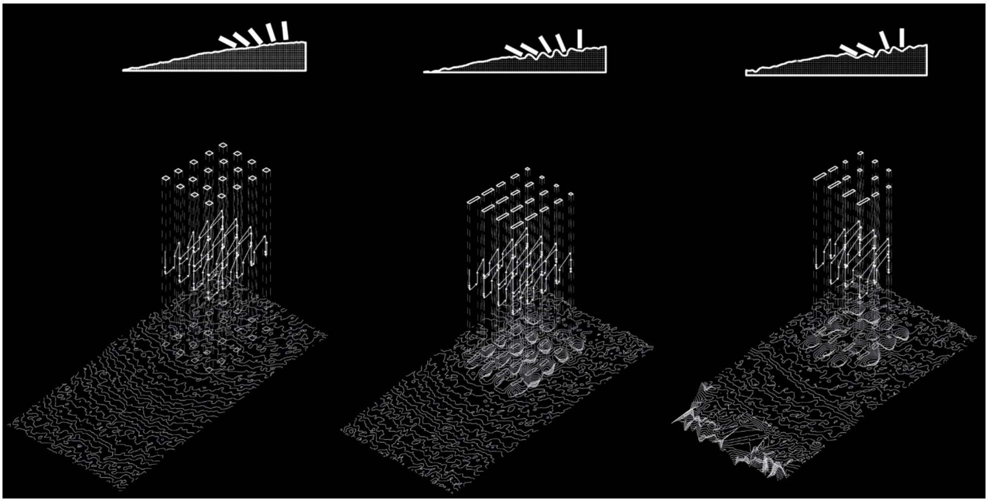

Fig. 4: Three iterations of the robotic feedback loop between scanning, computational modelling, and robotic response. Clearly visible is the change in motion from step 1, 2 and 3 which is solely due to the evolving topography of the sand in the wave tank.

Survey Technique

The scans were completed using an Intel RealSense Depth Camera and with photogrammetry. The challenge here was not resolution or frequency as in similar experiments (HURKXKENS et al. 2019), but scanning underwater topographies. During these experiments, the wave tanks were successively filled and emptied in order to scan the model's representation of the oceans floor. This is obviously not possible in the field, though other technologies are capable of scanning subaquatic landscapes (CASTILLÓN 2019).

Tool Shape

The manipulations deployed in this experiment are most closely associated with grader-style manipulations in that sand was relocated relatively close to its original location rather than deposited from elsewhere. A number of sand-manipulating tools were tried, initially by hand and then as robot end-effectors. A spatula manipulator had the characteristic of being highly directional: producing dramatically different results depending on the manipulator's angle relative to that of the motion. With its thin edge pointing in the direction of travel, the card slides effortlessly through the sand with minimal consequence. It had the benefit of being able to be used like a grader (being pushed at an angle to the direction of motion) with sand being deposited on the trailing side. A 20 mm × 20 mm square-section timber was the manipulator ultimately chosen for the final, longer robotic experiments. The primary benefit that this tool offered over others was the ability to press directly down into the sand, compressing it, and producing a stable imprint. These compressed depressions survived longer in the surf zone, or even below the water surface, then uncompressed depressions. Additionally, as the variable width markings enabled by the other tools proved to be of marginal benefit, the relatively constant width of the tool simplified the generation of robotic motion paths.

Adaptive Robotic Motion

The prevailing natural tendency during storm surges is for sand move downward on the beach and out to the sea. This is conventionally addressed through beach nourishment. We responded to this with robotic motions that begin by plunging to the low side of the beach slope and then move upwards, bringing sand back to the berm. After each scan, a map was created that identified the change in height of all areas. As mentioned above, the general tendency was for high areas to subside and for low areas to rise by being filled in, and this was accompanied by the more general tendency for all areas to subside gradually. Both of these tendencies were amplified by the increased presence of water as well as by the increased presence of wave energy. Various responses to the height deltas were tested. The first was to attempt compensation by moving sand towards the areas where height decreased and away from the areas where height increased. We expect that many of these findings regarding general tendencies would remain true for larger-scale implementations of these experiments with specific adjustments depending on the beach profile. As such, the parameters underlying the adaptive response would need to be re-discovered for each site's wave, coastline and sand characteristics, but these experiments provide a place to start.

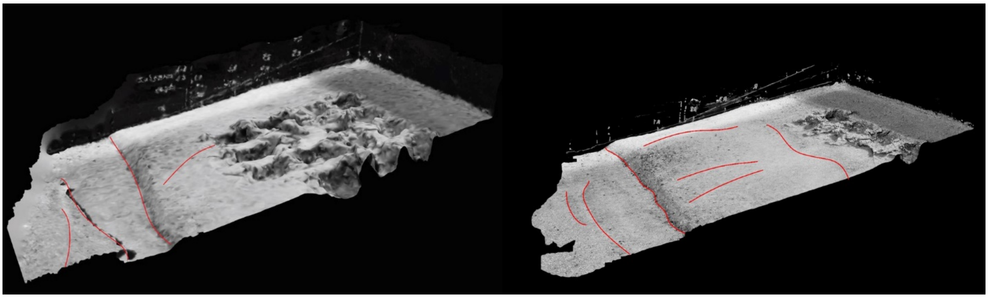

Fig. 5: High-resolution scan of two iterations between wave action and robotic manipulation. The wide dune structure does erode but keeps the sand in place, creating a large sandbank reducing wave action on the berm.

Landscape Formations

The general tendency was revealed by before and after wave-action scans: sand formations regress to the mean where high points became lower and low points became higher. This was particularly true when the sand became saturated. In order to achieve results that outperformed this general condition, specific conditions needed to be studied. In all cases, multilayered formations were more successful than single-layered formations. Here, the first layer reduced the wave energy, which can be seen largely as a reservoir of sand that will be relocated via wave action to the lower edge of the surf zone. Formations at an angle between approximately 30 and 50 degrees to the wave motion proved successful at capturing sand. Secondary benefits such as the dissipation of wave energy through redirection could be witnessed there as well. It became apparent that while a single breakwater can withstand a storm surge for a certain time-frame, its failure would immediately create a large natural disaster. Instead, strategies that modulated a larger surface and a lower maximum height performed much better. While the wave-action started to erode the front of the defence structure, it took much longer to reach its point of failure. This was made possible by trapping sedimentation within the structure itself, creating a larger sandbank between the swash zone and the berm (see Fig. 5).

4 Conclusion

Notwithstanding the aforementioned issues around scale, the conducted experiments were able to reveal a series of behavioural tendencies and insights in the key areas of landscape formations, tool shape, adaptive robotic motion and surveying techniques. Desired performance outcomes included increased formation longevity, the wave-powered accumulation of material in desired areas typically higher up the beach; the creation or preservation of landscape structures that diminished peak wave energy; and reduced storm penetration beyond the normal shoreline. While wave tanks are often referred to as more of an art than a science (OUMERACI 1999), the value of the physical representation and the scalable accuracy of many key fluid phenomena is clear. The Collaroy beach was chosen for its specific absence of ocean phenomena such as cross-shore drift, which is difficult to simulation in a small-scale linear wave tank. Despite clear shortcomings, the many strengths of physical wave tanks are well documented (OUMERACI 1999), including observability, measurability, repeatability, input control and process control, as well as the clear didactic strengths of a physical representation of the phenomena observed; the students were able to draw resulting phenomena directly onto the sides of the tank.

The experimental setup of the wave tank and the robotic arm enabled a dynamic response to a dynamic environment. It showed how digital landscape fabrication changes the design process from envisioning a single final form to defining the parameters of a potentially continuous feedback loop between robotic manipulation and natural erosion and deposition processes. Within the iterations of the experiments, it was possible to either reach apparent equilibrium or even build-up shoreline through well-defined iterations; however, these differed from the Collaroy Beach context. The masterclass participants demonstrated sophisticated interaction with elementary material and fluid properties and of the individual techniques and their synergy by designing and implementing the final strategies in detail.

The experiments demonstrate the integration of formal, environmental, material, and topological aspects of a landscape with computational tools to come to site-specific interventions with on-site autonomous machines, opening up new coastal management strategies that leverage natural processes. At the same time, working solely with locally found materials creates potential for a resilient and sustainable construction approach. With the recent advent of autonomous earth-moving machines (VASEY AND MENGES 2020), emergent and open-ended design strategies for specific dynamic coastal environments become a possibility. While this paper uncovers some of the potentials that a dynamic model of beach maintenance may offer, further work remains to be undertaken before this model could be put into practice. Having said this, the continuous adaptive nature and the scale of intervention of the processes proposed inherently lends itself to real-world experimentation.

Fig. 6: Robotic sand formation after one manipulation cycle and a single simulated storm surge

Acknowledgements

The authors would like to gratefully acknowledge the University of Technology, Sydney [UTS] Advanced Fabrication Lab [AFL] especially the contributions to the construction of the wave tanks by Gwyn Jones; the design and fabrication of the wave-making mechanisms by Tran Dang, Gwyn Jones, Tran Quoc Quan Phan and Dane Voorderhake; and the contribution of Greg Martens to implemented risk and safety procedures. For their many insights we thank the Water Research Laboratory (WRL) from the School of Civil and Environmental Engineering at UNSW Sydney. Last but not least, the authors want to thank the students for their dedication to the work: Alexandra Adams, Natasha Aguma, Kazey Calibo, Man Ho Chair, Chin Fai Chon, Samuel Clare, Tallon Creber, Miron Denno, James Elias, Ali Makari, Thomas Ng, Benjamin Riach, Gabrielle Veringa, Srujan Vichare, Yizhan Xia and Wanqing Zhao.

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