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Computational Terrain Modeling with Distance Functions for Large Scale Landscape Design

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Abstract: The act of reshaping terrain to meet cultural, infrastructural and ecological demands becomes an increasingly important practice with upcoming challenges like sea level rise, landslides, floods and drought. While recent hardware innovation in 3D sensing and autonomous construction machinery has opened up the digital recording and digital fabrication of large-scale topographies (HURKXKENS 2017), 3D modeling of digital terrain is still a complex and time-consuming task. The found geometry of the ground, largely irregular in shape and material constitution, poses serious problems and limitations for an efficient digital workflow today. Based on digital elevation data, this paper demonstrates a powerful computational landform editing tool using 2D distance functions.

Keywords: Computational terrain modeling, procedural design, signed distance functions, large scale landscape design, digital fabrication

1 Introduction

Most designer-oriented software packages use boundary representations (BReps) in NURBS or mesh surfaces to provide a 3D visual interface to the designer. Using BReps in large scale landscape design have proven very tedious and difficult to work with. Often a combination of the two is used to create clean-cut topography in NURBS which is embedded in a mesh for the project surroundings (WALLISS & RAHMANN 2016). The digital equivalent of terrain modeling is best described as Boolean operations that tend to be problematic on large NURBS or meshes, quickly reaching the limits of the conventional software packages from Autodesk, Nemetschek or McNeel (MCNEEL 2000). The found geometry of terrain has the disadvantage of being unstructured and irregular, which makes it computationally intensive for efficient digital manipulation using BReps. On top of this, large scale landscape architecture is rarely aimed at a final, static state of the topography. Geological and hydrological processes change the topography over time increasing for the need of a continuous transformation of the digital terrain model for simulation purposes. Finally, with the advent of autonomous construction machinery that iteratively fabricates a landscape over time, an efficient, flexible and mostly computational approach to digital terrain modeling becomes a fundamental prerequisite for future landscape design.

2 State of the Art

The survey of a topography, often completed by satellite-radar, aerial or terrestrial laser scanners, delivers an unordered point cloud of the surface of the earth. This digital surface model (DSM) is then filtered to attain the digital terrain model (DTM) of only ground points. Current modeling tools for designers either focus on point cloud editing tools, like Volvox and Tarsier, or create BReps for further surface editing. The digital tools are usually centered on the creation

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of objects (architectural, industrial) instead of the continuous transformation of a surface condition. Some GIS applications have demonstrated computational generation of river corridors or simple cut and fill operations on grid data (WESTORT 1998) as function representations (FRep). These tools are proven limited in scope and don't offer a visual interface to interact with the topography. Bison, a Rhino Grasshopper plugin for terrain mesh editing (BISON 2019), has demonstrated promising tools for large mesh surfaces, however it falls short in tools specifically oriented to precise and iterative topographic modeling. The scattered tools and methods relating to digital terrain modeling means that a landscape architect has to combine various software packages and approaches before reaching the desired design.

In the history of computer aided design and computational geometry, two main conceptual approaches can be distinguished, that have always been developed in parallel since the 80s. One is to describe geometry by a collection of points, curves and surfaces, that describe their outer shell, the other is to describe them mathematically as a function (BLINN 1982). The nomenclature for the latter varies across the literature, e. g. BLOOMENTHAL et al. (1997) distinguish between implicit and parametric surfaces, PASKO et al. (1995) between BRep and FRep. In the next paragraph, we will outline the advantage of FReps as a unified workflow for digital terrain modeling with distance functions.

3 Methodology

3.1 Distance Functions

The difference between the two computational design concepts is the way geometry is encoded and what data structure is required to store it. The simple case of a two-dimensional rectangle with sides a and b in boundary representation is described as follows:

V(a/2, b/2), V(a/2, -b/2), V(-a/2, -b/2), V(-a/2, b/2)

L(1, 2), L(2, 3), L(3, 4), L(4, 1)

V stands for vertex with x, y-coordinate pairs and L for line with vertex index pairs. As a signed distance function (SDF) of a point (x, y), the same rectangle is defined as the function:

d = max(abs(x-a/2), abs(y-b/2))

This function can be evaluated for any arbitrary point in 2D space. If the return value d is positive, the point lies outside of the rectangle, if it is negative the point lies inside and wherever the function evaluates to zero, these points are on the edge of the rectangle. While this method has wide applications in 2D graphics, e. g. for a smooth screen rendering of fonts at various scales (FRISKEN et al. 2000), we adapt the distance functions to serve as the generator for a height map. The SDFs can be used to either procedurally generate an artificial topography from scratch or also to deform an existing topography. The same mathematical principles are also applied for the generation of 3D architectural geometry (BERNARD et al 2018).

By applying distance functions to topographic data, we have developed the digital terrain modeling tool Docofossor. It consists of a collection of modeling components for Grasshopper (see Figure 1), a visual programming plugin for McNeel's Rhinoceros 3D modeling environment. It is developed to easily model cut and fill operations on digital terrain models without the need to learn any coding skills. Nevertheless, due to its open and low-level exchange data structure, it is easily extensible with custom Python scripting components.

3.2 Input/Output

The industry standard for large scale topographic models is the Digital Terrain Model (DTM) which can be represented as a raster or vector-based network describing the earth's surface without objects or vegetation. Usually the gridded model is a derivative of unstructured point cloud data from topographic surveys. Docofossor's tools operate on regular point grids and it is therefore easy to digitally exchange the data between various geographic information systems (like ESRI's ArcGIS), simulation packages (Christen et al. 2012) and 3D machine control systems (Petschek 2014). However, the signed distance functions are not bound to work with regular point grids only, but could just as well be applied to unordered point clouds or the vertices of a mesh surface. Docofossor is also designed to be integrated with mobile robotic mapping libraries for autonomous navigation and excavation (Jud 2017). Finally, it is able to read and write industry standard point grid formats such as *.ASC or *.XYZ.

Fig. 1: Docofossor's toolbar in the visual scripting environment Grasshopper for Rhinoceros. Functions include the Absolute and Relative cut and fill operations, analysis tools, BRep construction, DTM import and export, and various grid operations.

3.3 Data Structure and Geometry

A common layout of points in a DTM is a rectangular grid, where it is sufficient to specify the bottom left corner, cell size and number of columns and rows, followed by a one-dimensional list of z-values (elevation above sea level). To keep the memory footprint low, we adopt this data structure for the exchange between the components. However, most of the modification operations would just as well work on any arbitrary point distribution as only their z-values are affected, and the surface mesh topology does not change. Therefore, Docofossor's data structure is based on a single list that defines a regular spaced quad grid from topographic data. The Docofossor list (df) consist of a header part (dimension list) that defines the properties of the grid such as the cell size, the number of rows and columns, and the coordinates of the local and global origin of the grid. The header information is followed by z-values coming from a Digital Terrain Model (DTM) in column-major order starting bottom left. It is roughly based on the ESRI ASCII raster format (ESRI 2019). All the operations are done consecutively after another, which can be visualized in the end by making a quad-grid mesh (BRep) or 3D points of the cell value data. This has the advantage that the boundary representation only needs to be made once, thus increasing performance. The order of the operations becomes important when using cut and fill operations in sequence, or when operations change the location, cell size, crop or resolution of the grid.

3.4 Grid Operations

The orthogonal grid data structure makes it possible to implement operations known from raster image editing software. Docofossor allows to both down-sample to a coarser resolution for quick prototyping by sparsely striding a high-resolution input, and to up-sample low resolution input (e. g. output from simulation) by interpolation. For the same reason of speed gains, the user can also work on a cropped region subset of the points. Currently implemented is e. g. a Gaussian blur using a 2D convolution kernel to smoothen noisy artefacts in the terrain. Several geo-referencing components allow the user to work in a local coordinate system, while keeping the global coordinate system available at export time. This enables easy transitions between architectural drawings and site data.

3.5 Cut and Fill Operations

Cut and fill operations form the core functionality of Docofossor. There are two editing modes, absolute and relative (see toolbar in Figure 1). The absolute mode takes points, open curves or surfaces as input and operates directly on the terrain in place. It moves the existing terrain to a specific new location. The relative mode takes points, open curves or closed curves as input but instead operates in relation to the found topography. It moves the existing terrain by a specific distance. Both relative and absolute modes exist as cut, fill or a combined cut & fill operation (see Figure 2). One big advantage of modeling with SDFs is that Boolean operations are only a question of pure arithmetic. For a cut, the smaller of the two z-values (existing and calculated) is chosen, for a fill the larger one. Geometric calculations of intersection curves between surfaces hence become obsolete. This proves to be a big benefit, as they are very often prone to failure. All of the tools allow the user to specify a draft angle by which the limit of the operation should approach the existing terrain around it. This relates directly to the manipulation of natural granular material that is only stable under certain slope angels. The operations for paths additionally ask for a width where the cut/fill should remain horizontal to the curve, ideal for modeling roads or riverbeds in the terrain. In addition to that, all operations constantly keep track of and output the volume delta of the cut and/or fill operation as the product of the cell area and delta-z. This serves the user with valuable information about the need for raw material or the removal thereof.

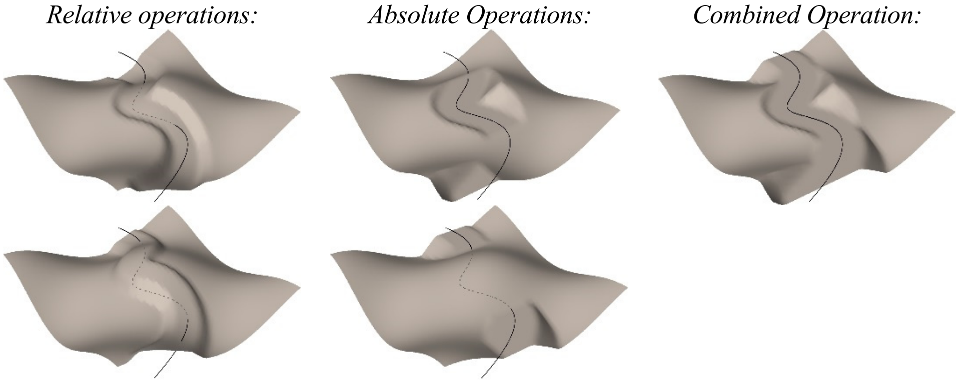

Fig. 2: Top to bottom, left to right: Relative cut in path, Relative fill in path, Absolute cut in path, Absolute fill in path, Absolute cut and fill in path. Apart from operations in paths, similar operations exist in Docofossor that follow the same logic using points, areas or surfaces as input.

3.6 Analysis

The analysis tools build upon various 2.5D GIS tools to inspect topographic formations in the modeling environment of Rhino Grasshopper. This becomes particularly interesting in understanding the landscape performance (e. g. water runoff, visibility, slope stability) or to create parametric constraints for autonomous robotic excavation. The slope component let users calculate the gradient vector for every cell to verify the slope stability (OSHA 2019). The viewshed component lets the user calculate a binary map of all the visible and invisible parts for a specific location and eye height or create a visibility map (visible surface area) for all the points, using a modified Bresenham line drawing algorithm (Figure 3, center). And lastly, the grid can also be interpreted as a planar graph with each node (point in the grid) being connected to either four or eight neighbor nodes. Using Dijkstra's shortest path algorithm – with the possibility to specify both a binary obstacle map and a specific height penalty – offers the possibility to embed the planning of transportation infrastructure seamlessly into the design process (see Figure 3, left).

Fig. 3: Left: shortest path with height penalization. Center: visibility analysis from one specific view point. Right: gradual degree of noise patterning.

3.7 Generative

The last set of tools leverages signed distance functions by creating synthetic topographies using only formulas. This allows for procedural generation of textures on the existing topography. Implemented so far is the Perlin noise algorithm that displaces the terrain in a pseudo-random fashion (PERLIN NOISE 2019) and various trigonometric functions. The functions can be limited to a specific area contained by a closed boundary curve and smoothly blend to the existing terrain (Figure 3, right).

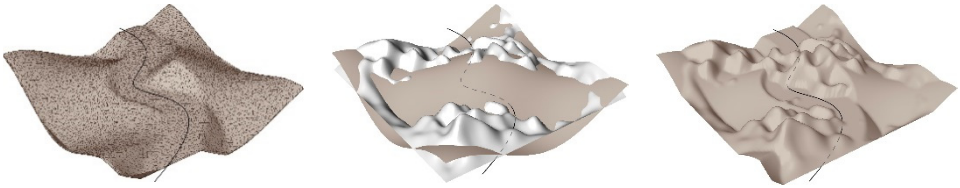

Fig. 4: Left: combined cut and fill operation on an unordered mesh. Center: multi-layer approach with varying materiality; rock and sand. Right: combined absolute cut and fill operation on a multi-layer df-list, where the rock layer stays untouched.

Currently under development is an optional extension of the topographic data structure to multiple layers, representing e. g. different time steps, current and target state or strata of different material densities. An example is shown in figure 4, center and right. The state before the operations (center) shows two interwoven layers of e. g. rock and sand, distinguished by color for readability. The combined absolute cut and fill operation only affects the "sand" layer and constantly checks against the rock layer. The result shows the combined intersection of the operation (Figure 4, right).

4 Application

As a first step in fall 2018, we tested Docofossor in the landscape architecture design studio 'Robotic Landscapes' of Professor Christophe Girot in collaboration with Gramazio Kohler Research, applying robotic fabrication methods to model debris flow channels in the Swiss Alps. Since 2011, a chain of major tectonic events has deeply affected the valley since the partial geological collapse of the Piz Cengalo Mountain requiring urgent remedial measures. In response to the challenges posed by the disaster, this studio asked students to develop creative topographic solutions using sand, gravel and rock from the landslide through robotic fabrication principles and procedural design solutions that can mediate future material transport. It was a unique opportunity to imagine a reconciliation between natural processes and designed environments. Since debris flows happen repeatedly over time due to heavy rain or instantaneous rock fall, the studio studied the continuous transformation of the terrain.

Three moments in time were highlighted in a digital 3D model (see Figure 5). Using parametric modeling aids from Rhino Grasshopper plugin, the site was prepared with cut and fill operations. After this initial step, directed deposition strategies were studied and modeled on the topography (see Figure 6). Because a change in geometry only needs the adaption of a single curve, this happened quickly and iteratively. The solutions were tested using rapid mass movement simulation software (RAMMS 2019) on their capability of diverting and collecting the expected debris flows of up to 500,000 m^3. The resulting deposition by the debris flows was added onto the designed topography. This was done in an iterative fashion, resulting in the continuous transformation of the terrain over time by natural and construction processes. Docofossor proved to be a valuable tool to model precise topographies, iterate quickly between various design phases and understand parametric relations between cut and fill operations and maximum slope angles.

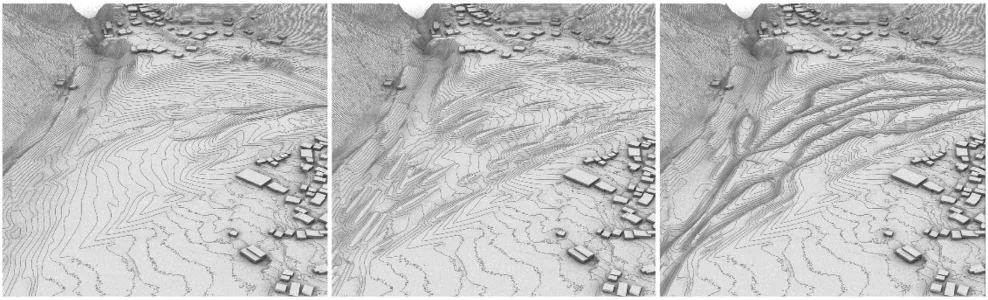

Fig. 5: Three design phases illustrated in a digital terrain model from the Landscape Architecture design studio by students Lip Jiang Lee, Matthew Lee and Yorika Sunada. They illustrate robotic construction processes and natural processes over time.

Because the three time-scales were dependent on each other, a change in the one model echoed automatically throughout the consecutive studies as well. While the estimate of the amount of material flowing through the site was known, the models balanced cut and fill operations using the volume calculation feature of Docofossor, resulting in sustainable construction and a resilient material culture. Finally, with the possibility of creating smooth or rough terrain, material properties could be represented easily in the same topographic model (see Figure 7). It quickly became clear that the design studio approach would not have been possible without a computational approach to terrain modeling. The modeling of three large scale landscapes without prior knowledge within a 14-week timeframe would have taken up all the student's time. In addition, robotic fabrication allowed for many repetitive excavation and deposition cycles, which would be extremely tedious to model by hand. The feedback from the design students allowed us to optimize the tool and add requested features.

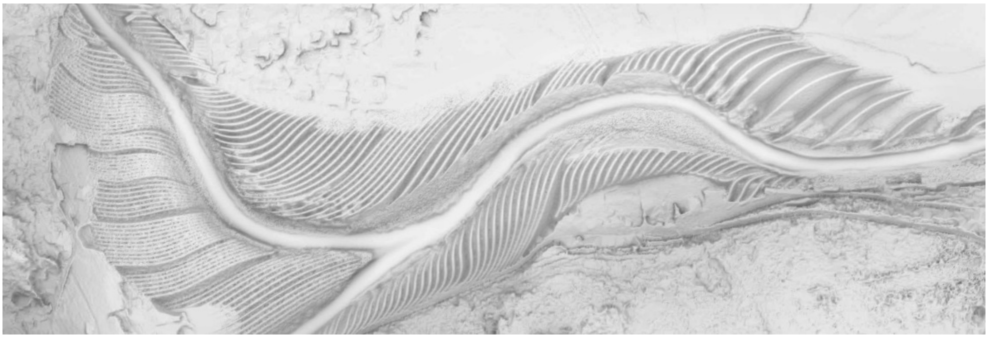

Fig. 6: Illustration of the Docofossor quad mesh of an *absolute deposition in path* operation using only the curves and 30° slope angle by students Roma Guldimann and Jonas Haldemann

5 Conclusion and Outlook

The proliferation of digital tools both in simulation (for instance hydrologic performance of river corridors) and fabrication (autonomous grading or excavation machinery) asks for a precise modeling tool for digital terrain models. Docofossor provides a set of tools that enables the application of computational strategies on large scale digital terrain models. It will open up incredible potential in working with difficult terrains and enacting ecological restoration projects. The application of informed terrain modeling can enable the designer to understand a landscape not only as a set of topological relations, but also as a strong performative surface under the influence of natural processes. Future improvements will focus on implementing fabrication aware modeling for autonomous excavation to limit operations that specific construction equipment is capable of modeling, most notably the addition of a multi-layer approach. Dynamic modeling strategies will be implemented, focusing on feedback of tactile or spatial perception hardware. Analysis and simulation tools will be added to make powerful GIS tools available from within Docofossor. But mostly, we will increase the number of tools for cut and fill operations creating more flexibility in digital terrain modeling. Since Docofossor builds 2.5D surfaces, it is particularly effective but not limited to large scale landscape modeling. Other applications like acoustic panels, milled wooden facades, design of efficient surface reinforcement ribs or molds for concrete casting are being explored as well. Now that Docofossor has successfully been tested with a user group a public release is forthcoming in spring 2019.

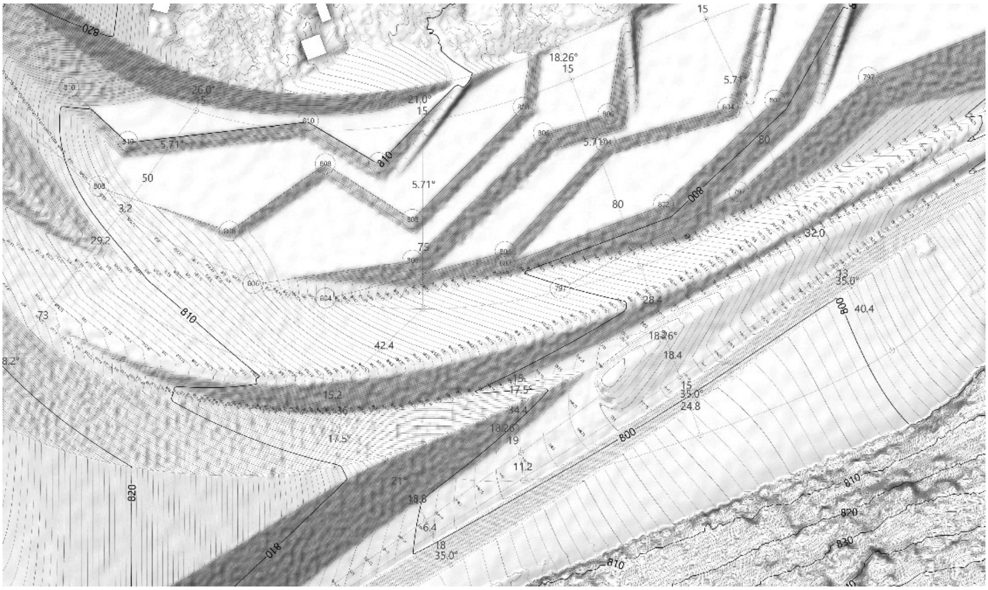

Fig. 7: Technical plan of the new topography modeled with Docofossor as one continuous surface of existing and newly designed areas. Clearly visible is the difference in surface treatment between sand (smooth) and rocky ground (rough) using a generative component by students Kelly Meng and Dawit Tadesse.

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The work presented here has been developed in the Chair of Landscape Architecture of Professor Christophe Girot and at Digital Building Technologies of Professor Benjamin Dillenburger both from the ETH Zurich. The research is funded through the NCCR Digital Fabrication of the ETH Zurich. The two ‘Robotic Landscapes’ design studios were held at the Department of Architecture as a collaboration between the Chair of Professor Christophe Girot (studio lead: Ilmar Hurkxkens, assistants Fujan Fahmi and Benedikt Kowalewski) and the Chair of Architecture and Digital Fabrication of Professors Fabio Gramazio and Matthias Kohler (assistants Ammar Mirjan and Jesús Medina Ibáñez) at the ETH Zurich. Mathias Bernard was the invited expert on 3D modeling in the studios.

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