Designing Digital Topography: Opportunities for Greater Efficiency with a Primitives and Operators Approach

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ABSTRACT

This paper focuses on characterizing *proposed* human-built topographic forms and describing them parametrically. Two basic approaches exist for characterizing shape algorithmically: *parametric* descriptions, which describe discrete geometries, and *non-parametric methods*, which for the most part work on fields. This paper offers a brief overview of the range of parametric modeling options for topography, a set of criteria that need to be fulfilled for any successful landform design system, and a *primitives* and *operators* approach that offers some specific advantages in the AMG context.

Key words: DTM—design—landform

INTRODUCTION

Reshaping land to meet societal needs is a complex, disruptive, time consuming, and costly effort. Industry increasingly relies on Digital Terrain Models (DTMs) as the principle medium for landform design and the basis for autonomous construction machinery (AMG). However, controlling DTM geometry remains a non-trivial algorithmic problem. At the project concept stage and later during construction, existing 3D manipulation methods are cumbersome and unwieldy, adding to downtime, guesswork and inefficiencies in the field.

Landform Design

Landform as a creative, expressive medium

Landforms may be used as design elements unto themselves, and also to organize and establish the base upon which other elements may be composed on a site. Landscape architects and engineers think of topography in both functional quantitative and spatial qualitative terms [1-3]. Through use of slope, elevation change, convex and concave re-grading, both subtle and dramatic meanings can be achieved [4].

Landscape designers use a variety of abstractions which help to organize or synthesize their design of landform, including 'signatures' of contour lines in plan [2, 4, 5]; compositions of regular geometric solids [6] and flat planes with break lines and transitions [5]; and processes of land formation: erosion, deposition, scraping and piling, etc. [7, 8]. The topographic condition of a site is therefore regarded as an essentially plastic one.

Through 3D modeling, rendering and visualization, designers try out an assortment of design alternatives on a topographic surface. Through manipulation of 3D models or images design alternatives are seen, changed, and analyzed [9]. For environmental designers, visualization works in close concert with manipulation and quantitative and qualitative analysis. The editing and analysis tasks can be more closely integrated in the digital medium, as shown in Figure 2.

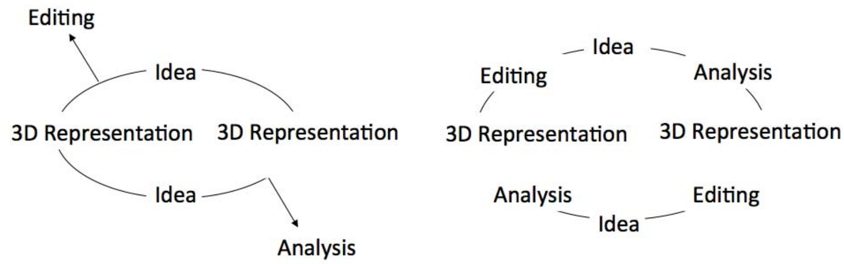


Figure 2: Iterative design loop for topography that shows how digital methods can integrate editing and analysis tasks more tightly in the iterative life cycle of a design project.

Digital landform representation

Landform is challenging to represent in any medium [10] especially computationally where large scales, fuzzy edges, continuous surfaces, and huge datasets pose particular challenges [11-14]. **Digital Terrain** in this project is defined as the elevation of the earth's surface above some reference geoid. Over the last few decades ever-larger quantities of terrain data with higher accuracy in (x, y) and z have become available to represent existing earth surface geometry. **Digital Terrain Models** (DTMs) are an important class of surface models [14] increasingly becoming the principle medium for landform design and construction [15, 16, 19].

Automated Machine Guidance

Dramatic advances with AMG in recent decades allow a remotely operated bulldozer to construct a landform from a precise 3D DTM [16-19-30]. Landscape architects and civil engineers work from existing site survey DTMs to propose and revise many drafts of proposed topographic surface geometry both on paper and with software to produce a final landform design, called a *grading plan* by landscape architects [2], or *the design* in the engineering domain [25]. Designers typically hand-off a grading plan to the earthworks contractor only once so the final construction is often the first and only full-scale built realization of a design that the team encounters. However, a lot can happen to the design once it is taken into the field and construction begins. *Site conditions, equipment incompatibilities, weather factors, personnel skill, preference and taste issues* are categories of unforeseen factors that can significantly impact a design once construction gets underway. Thus DTMs often require editing during construction to avoid downtime in the system and guesswork in the field [19, 20, 21, 25, 30].

Control criteria for DTM geometry over the lifecycle of a grading project

Controlling DTM geometry remains a non-trivial algorithmic problem [31, 32]. Methods for changing DTM geometry are cumbersome and unwieldy [34], thereby limiting the ability to creatively explore, modify, and optimize topographic form. These shortcomings yield serious inefficiencies throughout the lifecycle of a project and result in a need for improved tools for landform design that fulfill the following **criteria**:

3D
Local geometric control
Ease of handling
Quick response time
Quantitative accuracy

What is generally missing is the ability to iteratively revise, update, edit, modify, manipulate – i.e., “sculpt” DTMs, both *before* and *during* the construction phase as a way to insure quality design.

Approaches to DTM Manipulation
3D model manipulation strategies for topography have evolved chiefly in the CAD and geographic information system (GIS) digital domains [10], with the former focusing primarily on the parameterization of objects, the latter on combinations of spatial attribute information with digital terrain models in several representations (TINS, DTMs, contours, e.g., see [34]) The simplest and most common of these is the regular tessellation, mesh, displaced as a raster array. Large raster arrays are reasonable to use for representation of arbitrarily shaped “natural” existing features such as the earth’s surface, but the manipulation tools available make them neither an efficient nor expressive medium for design.

Geographic information systems (GIS) have evolved to handle the large datasets characteristic of landscape, but have mostly focused on the display and analysis of elevation data, rather than on active tools for manipulating landform. Figure 3 shows the manipulation scopes of action available in many GISs which allow only either global or ‘local’ changes to a model: a local change is a change that happens to a single vertex, a global change is one that affects the entire topographic dataset, e.g., scale changes, which exaggerate the Z value [35].

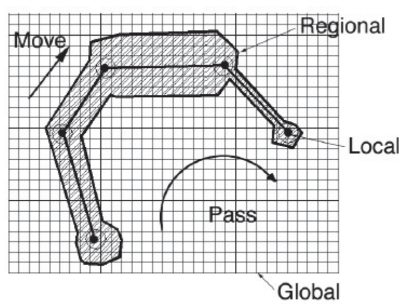


Figure 3: Local, regional, global scopes of action.

While some operations exist to limit the scope of activity to a mask of pixels or a specific polygon, these techniques are not especially useful for landform design. An example of a DTM editor developed to resolve artifacts resulting from elevation data interpolation has been an interesting approach [36]. As have algorithms for compression [37-42], line of site, shortest path, drainage [43], multiple observers[40], local maxima and minima, and drainage patterns[44] and siting from first principles. These approaches, while promising, have focused on data extraction and algorithmic techniques acting on geospatial data for *existing landform geometry* of a digital terrain surface, rather than *proposed* geometry – the target concern here.

A key advantage of digital/virtual methods is the ability to directly manipulate a 3D representation [45-49]. The following list, adapted from [50] and [51] summarizes some of the 3D topographic modeling tools available in current industry-standard CAD software packages:

Data Structures

Contours—Landform design using 2D CAD systems relies heavily upon the representation of 3D form as contour lines; an abstraction well suited to representation, but notoriously cumbersome for design. It is also a data structure with key disadvantages: Oversampling along, and under-sampling between lines. Manipulating contour lines effectively with CAD systems remains a daunting challenge, requiring spline curves and geometric constraints that have nowhere yet been satisfactorily packed for—much less mastered by—designers from any discipline.

B-Rep—Boundary Representations—The surface of an object is described as a description stored as a list of vertices, lines joining the vertices, and list of faces. These include Bezuer-spline curves (B-splines), Non-uniform rational basis spline (NURB) surfaces

Primitives—A set of simple, generic, 3D models (cube, sphere, cylinder, cone, torus, wedge, lane and others). These primitives can be scaled, translated, and rotated within the application, often both interactively (such as with a mouse), and by numerical input.

CSG—Constructive Solid Geometry—An object is represented as a combination of simple primitives such as cues, spheres, and cylinders. These basic solids are used as building blocks for more complex objects by means of a system that uses Boolean combinations (union, intersection, and difference) to describe the logical operations of adding two objects, subtracting one from another, or designing the overlap between two objects.

Voxels—Volume/Solid Modeling. Spatial occupancy enumeration divides – dimensional space into cubic units called voxels, or a 3D pixels.

Operators:

Swept Forms—a 2-dimensional (XY) section ‘swept’ along a third (Z) dimension.

Extrusion—a template is swept in a direction orthogonal to the plane in which it lies.

Surface of Revolution—a 2D template, closed or open, rotated about an axis.

Skin—the ability to construct a ‘skeleton’ of a form and then wrap a surface skin around it to create an object

Patches—same as skin except using boundaries as the skeleton.

Curved Patches—while popular remain too computationally intensive to be justified or affordable for most landform design.

Primitives

What is called for is a specification of landform primitives—mound, swale, plane, for example – that carry their own parametric definitions and constraints, and so enable ‘regional’ changes, between local and global in their scope, in which slopes, radii and other dimensions may be user-specified and propagated (Figure 3). Geometric modeling with pure Euclidean shape primitives such as cones and cylinders is promising [8], but by itself is too limited for most landform design, which more often than not involves the design of a continuous surface rather than of a solid. While some efforts for landscape are promising [51, 53] no unifying ontology, or organizing Landscape Information Model (LIM) currently exists.

A wide variety of disciplines and scales use a range of terms and parameters to describe discrete topographic shape, and they vary qualitatively and quantitatively. Moreover, landform shapes are frequently described in terms of an underlying DTM Data structure. I.e., there are contour line specific forms, or signatures, TIN specific data structures. A sampling of this diversity includes:

- *Geomorphological forms*, landforms produced by the earth's natural processes (e.g. drumlins, eskers, moraines, saddles, valleys, cliffs, glacial forms) [7, 8, 54-58]

- *Domain-specific forms, e.g.,* Contour line signatures [3-5], American Disabilities Act design specifications [59].

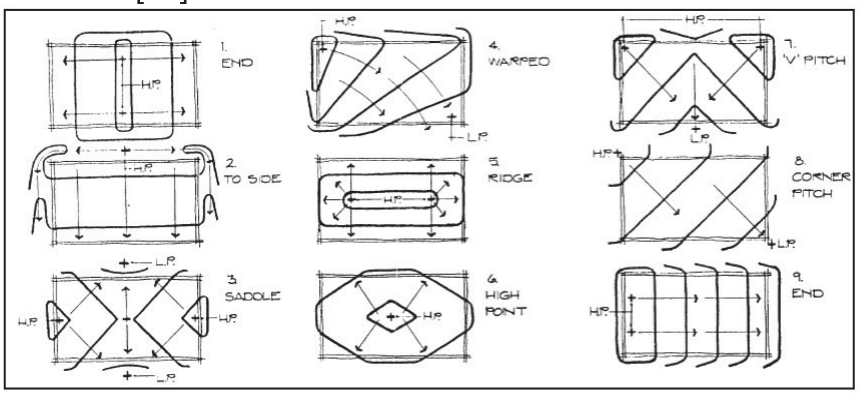


Figure 4: Contour line signatures.[60]

- *Project-type specific* (e.g., roadways, levees, sand dunes, water management, golf courses, battlefields, gaming environments, American Disabilities Act (ADA) compliant features)

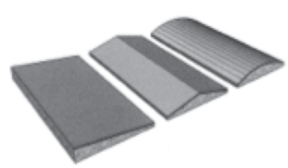


Figure 5: Road profile primitive forms [5]

- *Individual Project specific forms*, A particular project may standardize its own set of topographic forms for re-use throughout a project.[61]

- *Tool-based forms*, shovels, rakes, particle guns.

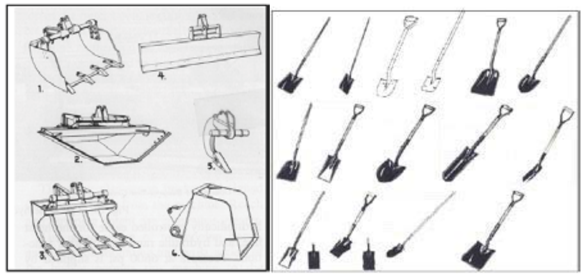


Figure 6: Example tool-based specific forms.[62]

Operators
Defining a universal set of geometric parameters for landform, coupled to a way to combine the primitives together, would contribute to dramatically improved geometric control over a DTM surface. Specification of a set of operations, such as cutting or filling tools, with parametrically defined shape characteristics (such as angles of slope, depth of fill, etc.) to be performed along a path. This set of operations is then swept along the path, either over an existing base terrain, or on a blank surface, and the result is a terrain geometry, which has the desired shape.

Conceptual framework for a primitives and operators approach

A simple and useful way to generalize all topographic forms as four generic shapes derivable from either a point- or line-based feature. General concavity or convexity are subsequent shape descriptors.

Mounds – point-based convex surface
Craters – point based concave surface
Berms – line-based concave surface
Swales – line based convex surface.

Figure 7 shows this initial set, with their blade and path shapes abstracted and combined using a sweep (extrude) algorithm.

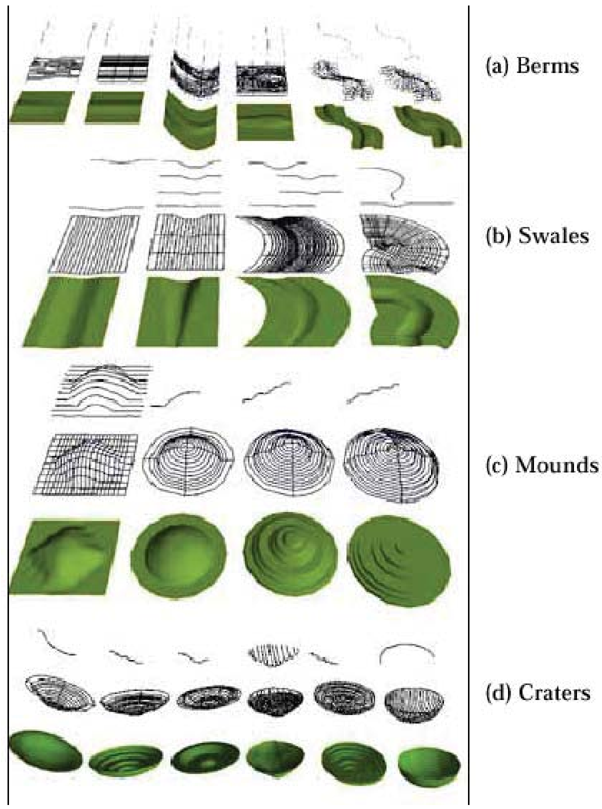
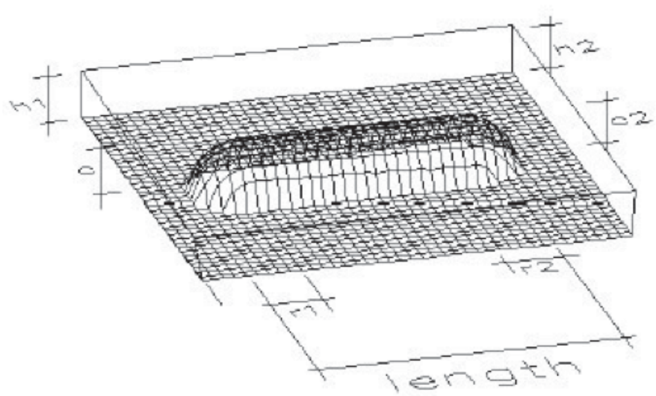


Figure 7: Generic subset of topographic primitives, abstracted as blades and paths shapes

Operators to generate these sorts of geometries as part of a continuous surface were then prorammed as a plug-in software to AutoCAD. Figures 8 and 9 show these initial results.



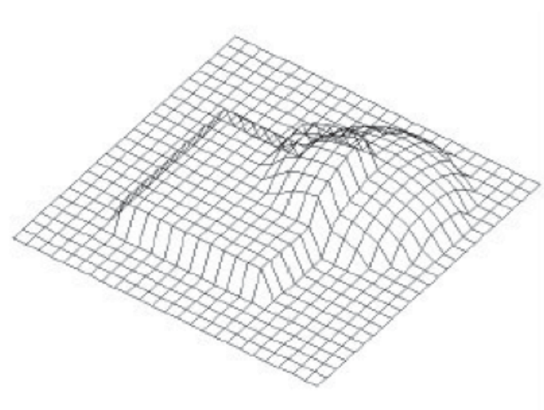
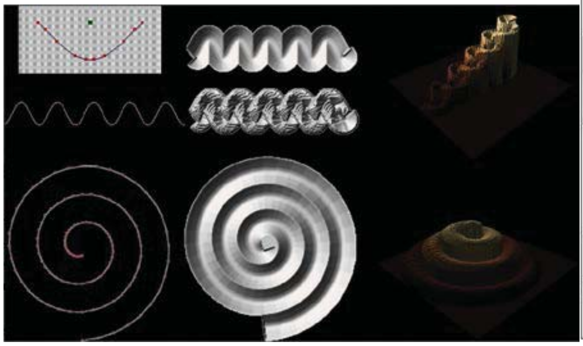


Figure 8. A parameterized berm primitive left.

Figure 9. Boolean combination operators on mound primitives on the right

A stand-alone prototype software was then generated as a generic sculpting tool definition, Figure 9.T his implementation kept geometric change parameters separate from any underlying DTM data structure description, Figure 10.



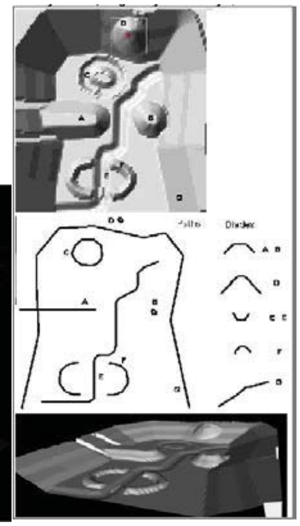


Figure 9: Left Topographic surface sculpting generic tool.[50]

Figure 10: Right Blade and path abstractions as alternative descriptions[63]

Summary & Discussion

A set of blades and path primitives describe proposed topographic form such that the following criteria for a digital terrain design system are fulfilled: 3D, local geometric control, ease of handling, quick response time, quantitative accuracy. A primitives and operators formalism represents an intermediate internal data structure that is independent of the underlying DTM data structure, and therefore would represent an exciting opportunity for increased efficiency in the AMG context.

The following are some outstanding challenges that would need to be resolved for this to happen:

Challenge 1: Primitive shapes can have a wide range of relationships with one another. In the case of a primitive blade shape that is extruded along a primitive path shape, what is the desired relationship, symmetrical, static, dynamic with other primitive models. How to provide interactive handles to the user for setting and varying these shape parameters.

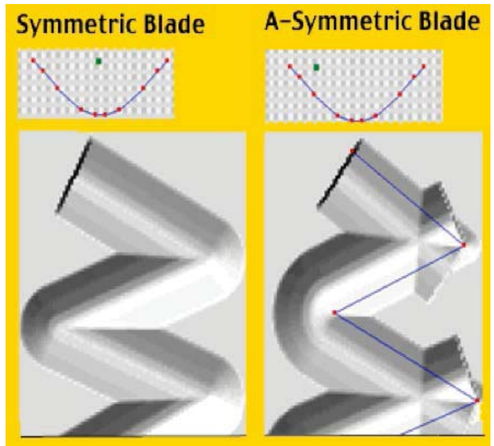


Figure 11: Symmetrical versus A-Symmetrical blade and path relationships [65]

Challenge 2: Should the relationship between primitives simulate real world on-the-ground tool behavior or physical phenomena? E.g. shovels, bulldozers, graders, rakes, etc.? What soil-type, moisture content is assumed? Gravity? Since final DTM geometry is the priority, and simulation of the manipulation process itself is of secondary importance, those geometry determining “real-world” parameters which affect final landform shape will be prioritized.

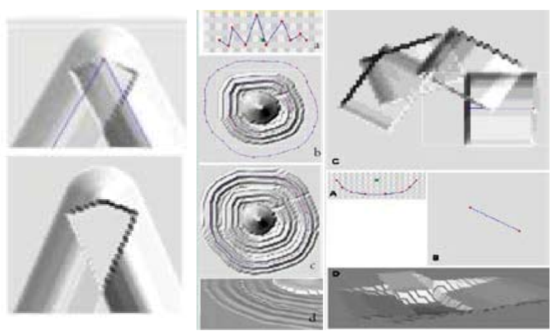


Figure 12: Left, corner and overlap options.

Figure 13: Middle, rake simulation blade

Figure 14: Right, shovel simulation blade

Challenge 3: Embedding into the underlying terrain – how does the blade-path complex embed in the underlying DTM surface? Is it an absolute or relative relationship? How are these relationships parameterized to optimize interactive user control.

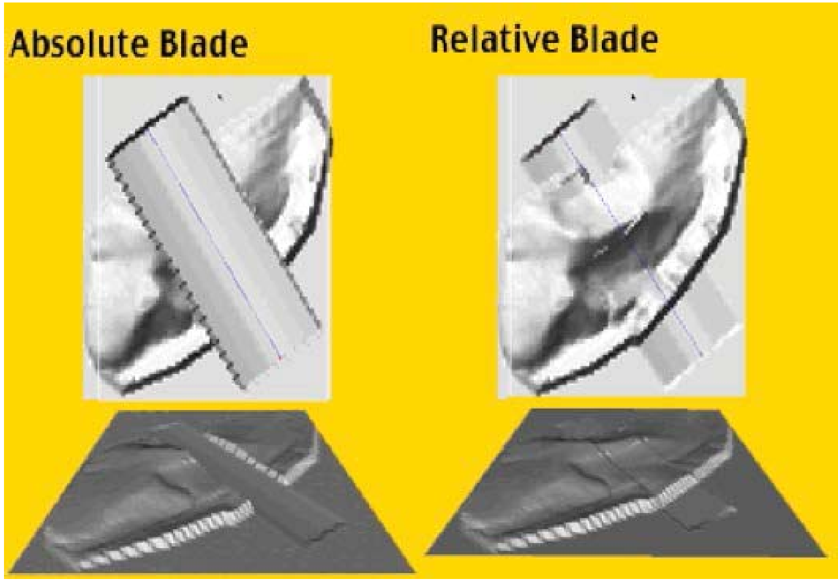


Figure 15: Absolute versus relative relationship of the blade-path-relationship with the underlying terrain data.

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