Smart Cloud-of-Points Model: Point-based Digital Media and Tools for Architectural Design

Eyal Nir, Guedi Capeluto
Faculty of Architecture and Town Planning
Technion-Israel Institute of Technology
http://architecture.technion.ac.il

Abstract. *Abandoning the scale-model concept in favor of an abstract representation led us to the development of a digital design model based on point-clouds as design media. In this paper we examine the potential usage of point-clouds as design media. Extending the point-cloud model with a forth dimension represented as a numeric pointer to generative algorithms provides a parametric interface for the regeneration and alteration of the extended point-cloud model referred to as "Smart Cloud of Points".*

Keywords. *Point-clouds; parametric design; generative modeling*

1. Introduction

The development of digital design tools, ranging from the digital napkin to the widespread CAD applications encouraged the imitation of analog thinking processes in design. Building digital scale-models of the design, known as BIM – Building Information Model (AutoDESK, 2002), may allow the automatic extraction of design documents or even the fabrication of physical models, but prove to be time consuming when the design changes along the process. Hence grows the drive to develop new digital design tools. New approaches to digital design like Aish's custom objects harness the potential of CAD as an open system (Aish, 2000). CAD as an open system can be used as a platform for creating a multi-layered parametric model defining objects relationships which supports the changes along the design process.

On the expressive side of CAD, Versprille's NURBS (Versprille, 1975) have become an integral part of the architectural lingo (Terzopoulos and Qin, 1994), encouraging the use of free-form and twisted shapes in architectural design (Vollers, 2001) while exposing the realization gaps when a smooth design ends up a faceted building mainly due to fabrication costs of curvilinear building components.

The current discourse around digital design mainly discuss its visual output while the term "Digital" refers to an abstract numeric representation by digits. This numeric world allows us to describe 2 dimensional pictures with screen pixels, 3-dimensional objects with voxels or vectors, and any N-dimensional entity as a multi-layered matrix. In fact, the visual representation we see on our computer screen is merely an analog representation of a digital numeric model generally hidden from the designer view and referred to as internal representation (Fitzmaurice, 1998). Abandoning the scale-model concept in favor of an abstract representation model led us to start our research with the basic element of CAD – the point. This paper is based on the authors' ongoing doctoral research, proposing a point-based modeling environment moving from the widespread feature-tree modeling approach towards a point-based poly-logic modeling approach. The concept of the rhizome, where any point can be connected to anything other in multiple layers (Deleuze and Guattari, 1987), is applied as an exposed poly-logic internal representation system resulting in a novel approach to spatial modeling for architectural design.

2. Point-Clouds in Architectural Design.

We notice a growing use of point-clouds in architectural design, mainly in the last phases of design and throughout the fabrication process. Point-clouds, generally used for digitizing and surveying, are suggested in this work as design media. We identify two types of point-clouds; a non-structured point-cloud which contains no spatial information regarding its internal order (generally the product of CMM devices), and a structured point-cloud which can be described as a two dimensional matrix. The matrix dimensions represent the number of points in a point-string (a profile) and the total number of profiles defining a 3-dimensional object.

The point-cloud data of a virtual design model, one that can not be physically digitized, can be computed through its generation process. Employing generative modeling techniques to automate the creation of point-clouds defines a generative cloud of points. This point-cloud is algorithmically generated, resulting in a structured point-set data holding information about its generation process.

3.Generative Smart Cloud of Points: Extending the Cartesian Space

Storing the generative-process information, related to the cloud of points, requires an extension to the traditional Cartesian space. Adding a fourth dimension to the Cartesian system provides the required extension. This dimension stores a pointer to the algorithms used in the generation process (referred to in this work as the "i" dimension). Decoding the pointer value allows regenerating the point-cloud model while changing the "i" value of a point will affect every point related to it according to the generation process.

We annotate this proposed model as (x,y,z)*i. The model contains the range of parametric solutions that fulfills the design intent as described algorithmically within the "i" dimension, allowing the designer to easily generate a wide range of point-clouds alternatives and to shape the design to an optimal solution according to a desired evaluation criteria. The extended point-cloud is referred to in this work as Smart Cloud of Points (SmCP).

As a part of this work a smart cloud of points modeling tool was developed integrating spreadsheet software as a mathematical engine - providing the numeric interface, and VRML platform as a graphics engine - providing the graphics interface (figure 1). Creating a bi-directional link to an open CAD system allows the smooth integration of the prototype model to current architectural design processes. The prototype model implements the "i" dimension concept as a forth coordinate, extending the traditional Cartesian three-coordinates system. The value assigned to the forth coordinate indicates a route of behavior algorithms for a point to follow. Each "i" value is associated to a set of binary switches indicating whether an algorithm is active or not. Changing the "i"-coordinate of a given point string will result in a new typological representation of the smart cloud of points. Each typology is derived from the behavior algorithms assigned to the different "i"-coordinate values.

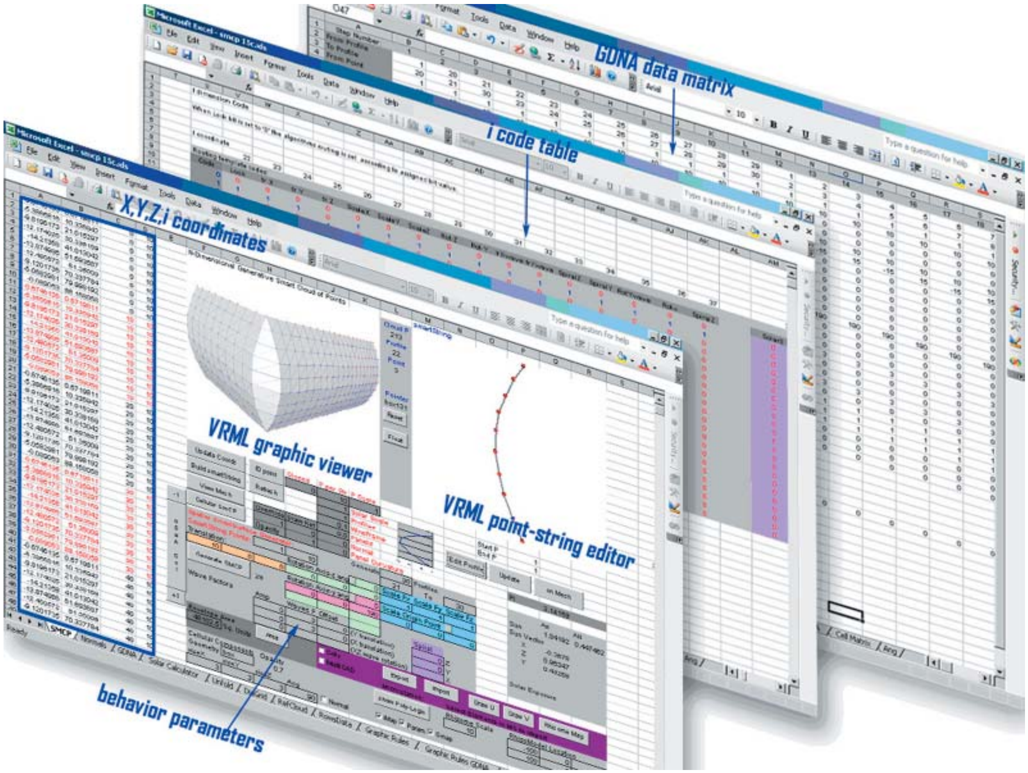

Figure 1. SmCP prototype application as a multi-layered matrix

The prototype model includes 12 behavior algorithms providing a modeling interface that operates on the six degrees of freedom; translation algorithms on X,Y and Z axes, rotation algorithms around the X,Y and Z axes, scaling algorithms about the X,Y and Z axes and wave functions that can be assigned to the X,Y and Z axes.

Documenting the generation process of the smart cloud of points as a separate matrix provides an additional design interface. This new layer of information contains the parameters assigned to each of the behavior-control algorithms together with the destination points it controls. Applying the information stored in this matrix to a point-string allows regenerating a complex smart cloud-of-points together with the ability to parametrically propagate design alternatives. We refer to this layer matrix as the geometric DNA (GDNA) of the smart cloud-of-points. The GDNA matrix layer allows the designer to alter the generation process of the model by editing the matrix data. In addition to altering the generative-algorithms parameters, the model regeneration can be processed according to the initial generation order or any other sequence assigned in the GDNA matrix. While the simple documentation of a model generation process results in a mono-logic feature-tree, the GDNA layer matrix is more of a poly-logic rhizome than a tree. The poly-logic defined in the SmCP matrix layers allows deleting, editing, duplicating or composing data in any of the matrix layers affecting the generated points-cloud in a non-linear way.

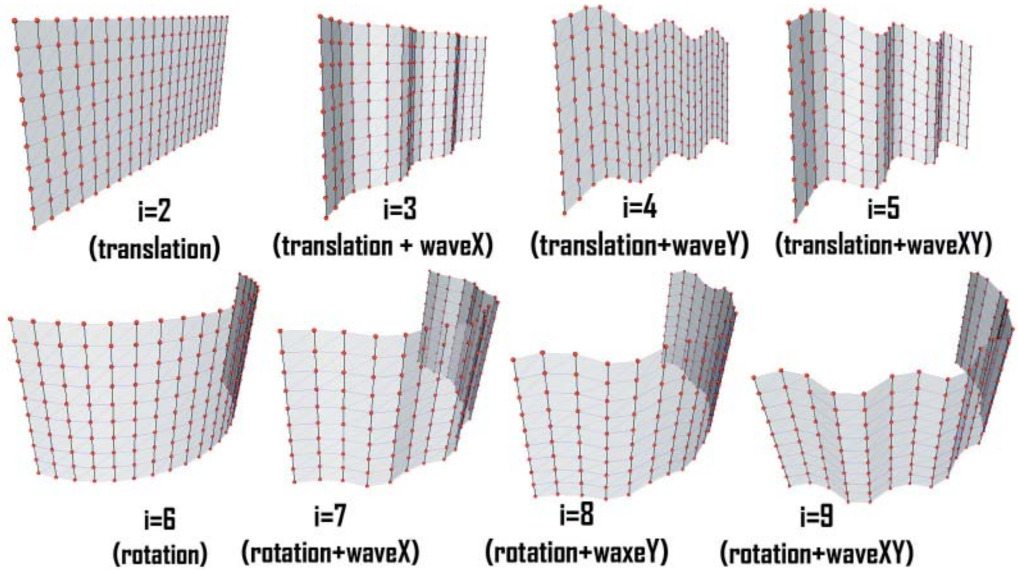

Figure 2. Applying various "i" values to the smart cloud of points model.

Lets assume a modeling process that begins with a point-string consist of 10 points sampled on a line element as a profile. The behavior algorithms parameters are set to a 10-units translation on the Z-axis, a 150 degrees rotation around the Y-axis and a waveform translation on the X-axis. Setting the "i" value codes defines the routing of each point through the behavior algorithms resulting in a generative spatial point-cloud. By applying the behavior pattern to 20 profiles we generate a 20x10 point-cloud matrix starting with "i=2" (translation) and explore the point-cloud transformations as we change the "i" value from 2 to 9 (figure 2).

Figure 3 shows a design session that take place by altering the original point-string shape and regenerating the point-cloud model. This allows a complex-geometry shaping process resulting in a sinusoidal parametric loft surface. Each point behavior pattern is set by its "i"-coordinate value while the magnitude of its transformation is defined by the parameters values assigned in the GDNA matrix. Modifying the algorithms parameters allows shaping the point-cloud in a controlled manner. Using the proposed model, various families of design alternatives can be explored. The GDNA and the "i" coordinate permit to regenerate and alter the point-cloud model in a non-linear way, transforming it from one typology to another (figure 3).

The behavior pattern stored in the GDNA matrix layer together with the i-coordinates creates a map of the smart cloud of points' model logic (figure 4). This map visualizes the internal representation of the smart cloud of points and provides a foundation for understanding the innovation behind this modeling approach. The traditional feature-tree model employs classical (hierarchic) mechanical logic where every child has a single mono-logic parent; the proposed model offers a poly-logic complex relationship array where at every point two or more parent trees can intersect. The resulted connections are of a rhizomatic nature.

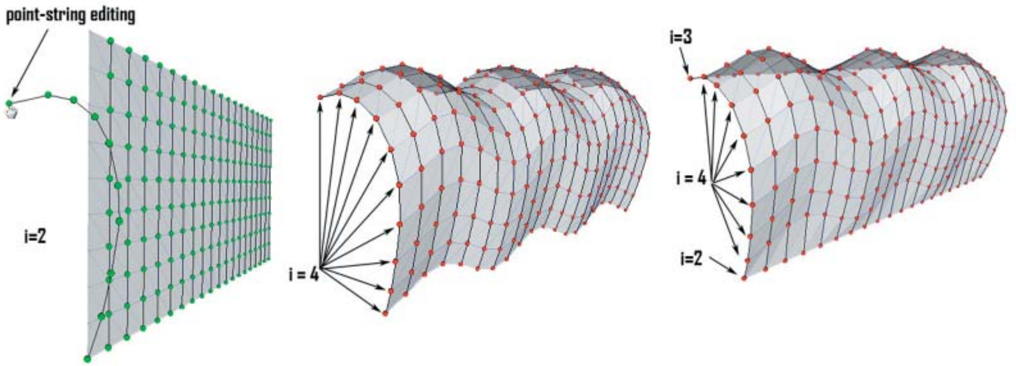

Figure 3. Exploring various typologies by assigning different "i" codes to the basic profile points.

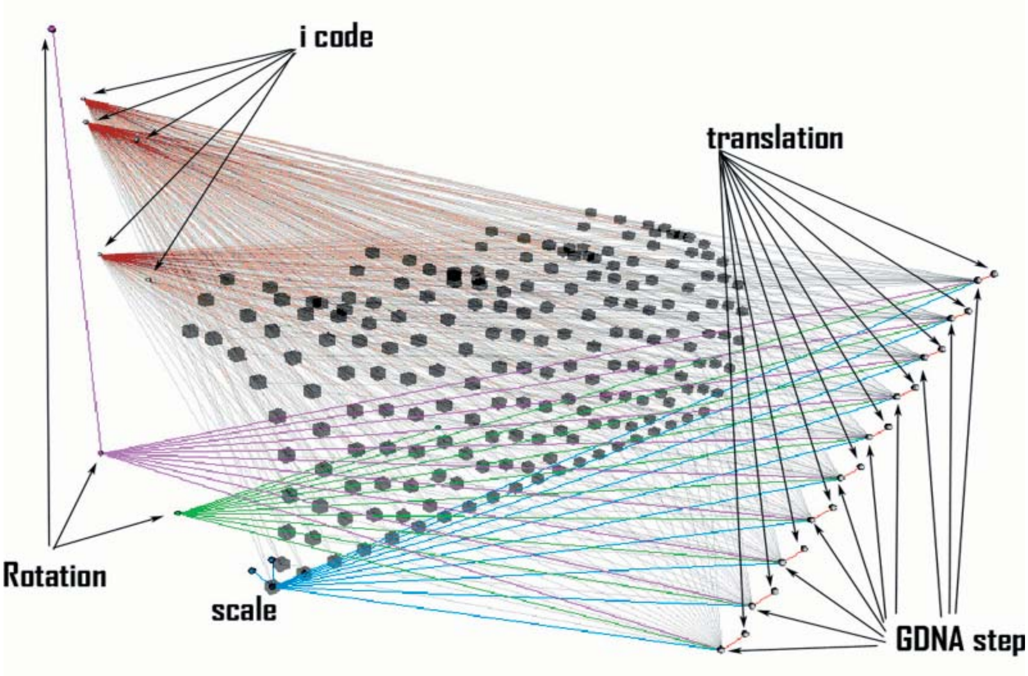

Figure 4. The poly-logic map of the SmCP using voxel representation.

4. Performative-Design Enabled

During the design process the architect explores many alternatives looking for an optimal solution for the specified task at hand. Using the proposed model, allows generating various families of design alternatives, represented by a smart cloud of points, which can be analyzed with evaluation scripts returning a numeric score for the criteria tested. The numeric score can be graphically represented by a color index for visual assessment. Combining the results delivers an overall perfor-

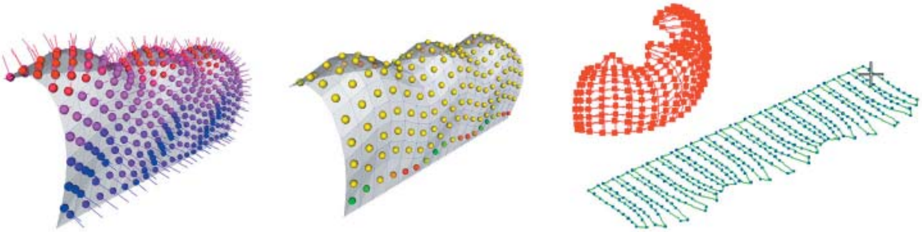

Figure 5. Solar exposure, panel curvature and unfolding pattern evaluation.

mance score for each alternative evaluated. Moreover, this score can be inputted back to the model for further elaboration of the SmCP. Propagating design alternatives with the regenerative SmCP model and applying multiple evaluation algorithms to it provides an interface for direct manipulation of the design according to selected performative aspects. The suggested prototype model calculates performance based on the triangulated mesh going through its points. Solar-exposure (figure 5 left) is calculated by measuring the orientation of each panel normal relative to the sun vector at a given time or over a period of time. The orientation of a panel can be constrained to a specified direction or within a specified range according to a desired solar exposure value.

This evaluation process can assist in developing shading solutions, designing effective photovoltaic envelope solution and optimizing the exposure to direct solar radiation. Calculating the envelope surface area assists in optimizing the envelope cost by adjusting the proportional relationships between the panels shape, joints and material cost relative to the building volume and its expected operation costs. The dihedral angle of each trapezoid panel (defined by a pair of triangles) provides a panel curvature evaluation (figure 5 middle) that assists in validating the envelope materials according to twisting factor. An unfolding evaluation (figure 5 right) based on the triangulated mesh assists in optimizing the design according to a proposed fabrication process evaluating the waste material and exploring various fabrication solutions like a standing seems versus a panelized solution from both economic and visual appearance (aesthetic) point of view. Additional evaluation algorithms can be implemented through the "i"-coordinate according to project needs.

5. Case Study: Studying the "Gherkin" with Smart Cloud of Points

The design process of Swiss-Re tower by Foster and Partners, as described in Foster Catalog 2001, involved the use of parametric modeling and a numeric spreadsheet. A mathematical model of the gherkin shape was used for the definition of the diamond grid nodes of its steel and glass structure. We explore the gherkin envelope as a showcase of working with the proposed design media and tools.

The gherkin shape can be described topologically as a surface of revolution or a loft surface providing the points order. Let's assume 40 points sampled along a B-Spline curve that was drawn according to the shape gherkin profile. In fact this profile can be produced based on a designer's hand sketch. These points provide a point-string

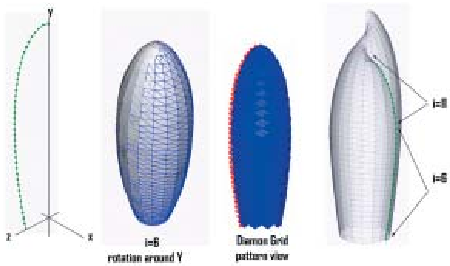

Figure 6. Surface of revolution SmCP modeling: From gherkin to seashell.

Step Number:	1	2	3	4	35	36	37	38	39
From Profile	1	2	3	4	35	36	37	38	39
To Profile	2	3	4	5	36	37	38	39	40
From Point	1	1	1	1	1	1	1	1	1
To Point	20	20	20	20	20	20	20	20	20
Trans X	0	0	0	0	0	0	0	0	0
Trans Y	5.292422	5.301998	5.311259	5.320178	4.441532	3.988015	3.075408	1.245112	1.1
Rot Y Ang	3	3	3	3	3	3	3	3	3
Rot Y Px	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324
Rot Y Py	168.8313	168.8313	168.8313	168.8313	168.8313	168.8313	168.8313	168.8313	168.8313
Rot Y Pz	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205
Scale Factor x	1.048985	1.044556	1.040564	1.03693	0.860707	0.813511	0.727871	0.543693	0.002636
Scale Factor y	1	1	1	1	1	1	1	1	1
Scale Factor z	1.048985	1.044556	1.040564	1.03693	0.860707	0.813511	0.727871	0.543693	0.002636
Scale Origin x	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324	207.2324
Scale Origin y	78.83128	84.13327	89.44453	94.76471	257.9478	261.9358	265.0112	266.2563	267.3563
Scale Origin z	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205	6.364205

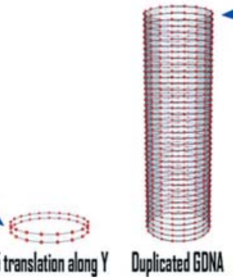

Figure 7. The gherkin GDNA matrix as tabular data.

representation of the building section. A rotation action was defined as "i=6" and applied to the point string repeating an 18 degrees rotation 20 times. Doing so generated a point-cloud matrix of 40x20 points (figure 6).

Triangulating a mesh through the point-cloud defines a surface of revolution. Alternating the mesh to define a diamond grid pattern, results in a SmCP model of the building envelope. Assigning various behavior patterns to the generative cloud of points as "i" values allows the designer to explore design alternatives parametrically (figure 6). Each "i" value defines a typological design space that can be parametrically shaped. As an example we define a progressive growth to the point-string profile along the revolution axis as "i=11". Applying this new pointer to the point-cloud and regenerating it using the recorded GDNA information propagates a typological change from a Gherkin to a Sea Shell. Doing so provides the designer with two levels of control. The first level is the algorithms parameters and the second is the control over the behavior pattern distribution set by the "i" value assigned to each point (e.g., controlling the sea-shell growth starting point).

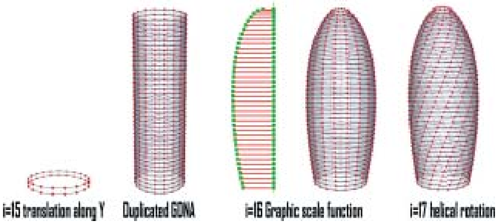

Figure 8. The gherkin loft surface study with SmCP.

The gherkin shape can be also modeled as a loft surface when starting with the definition of a point-string of the building circular plan. Sampling 20 points on the plan profile of the gherkin provides this representation. We define a translation along the Y-axis as "i=15" creating a simple cylindrical extrusion (figure 7). Duplicating the GDNA information that was generated by this action 39 times, creates a GDNA matrix (figure 7) storing the control parameters of all associated behavior algorithms.

The section point-string is applied as a graphic function describing the scaling of the plan profile. The differential values between the 40 points section-profile describe the scale ratio of the plan-profile in every step along its translation (figure 8). The values are written to the 39 steps of the GDNA matrix. Adding a rotation action to each GDNA step results in a helical pattern imposed on the gherkin envelope (figure 8).

Altering the parameters values assigned in the GDNA matrix together with defining various behavior patterns as "i" coordinate values allows exploring various typologies using the same point-cloud matrix data (figure 9).

The above modeling process demonstrates the application of exploring different typologies and design alternatives of a building envelope as an abstract dynamic model of a shape's logic; from cylinder to gherkin to onion.

6. Conclusions

This work presents a way of using point-clouds models as digital design media. A smart cloud of points (SmCP) concept is suggested as a means of incorporating a fourth coordinate to the Cartesian coordinate system, allowing the embedding of complex relationships between the model points. This model is represented both numerically as a point-matrix and graphically as a point-cloud. The graphic plot can be used to mesh through for surface representation, panelize, unfolded, section through or simply place graphics objects using the point-data as positioning points for cellular components. Documenting the parametric information of the generative modeling process created a second layer matrix as a regenerative modeling interface. Implementing the suggested model shows how geometric, aesthetic, and performance implications of proposed design alternatives can be analyzed at any given point during the design process without major drawbacks. The overall geometry of all affected parts will be updated accordingly. Rationalizing the information produced in the conceptual stage of the design in a parametric form provides a progressive modeling technique making it suitable for the whole design process. The prototype GDNA graphic and numeric control layer that has been developed is proposed as a novel modeling concept, an alternative to NURBS and feature-tree modeling approach.

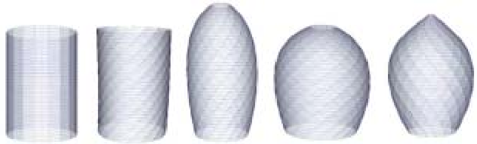

Figure 9. Regenerative modeling using the GDNA matrix and "i" coordinate values.

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