

# MARCHING CUBES IN AN UNSIGNED DISTANCE FIELD FOR SURFACE RECONSTRUCTION FROM UNORGANIZED POINT SETS

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**Keywords:** Marching cubes, Surface reconstruction, Point set, Unsigned distance field.

**Abstract:** Surface reconstruction from unorganized point set is a common problem in computer graphics. Generation of the signed distance field from the point set is a common methodology for the surface reconstruction. The reconstruction of implicit surfaces is made with the algorithm of marching cubes, but the distance field of a point set can not be processed with marching cubes because the unsigned nature of the distance. We propose an extension to the marching cubes algorithm allowing the reconstruction of 0-level iso-surfaces in an unsigned distance field. We calculate more information inside each cell of the marching cubes lattice and then we extract the intersection points of the surface within the cell then we identify the marching cubes case for the triangulation. Our algorithm generates good surfaces but the presence of ambiguities in the case selection generates some topological mistakes.

## 1 INTRODUCTION

Surface reconstruction from an unorganized point set has been a widely studied problem in the computer graphics field. The problem can be defined as given a set of unorganized points which are near to a surface. A new surface is reconstructed from that points. Which is expected to be near to the original one.

Acquisition systems like laser scanners, depth estimation from images, range scan data, LIDAR and other methodologies results in an unorganized point set. Geometry analysis (Miao et al., 2005) and visualization process (Gross and Pfister, 2007) could be done with this input, however the presence of noise, out-layers or non scanned regions could generate problems in the reconstruction and analysis process.

Reconstruction of the surface could be made in several forms, like nurbs, polygonal meshes, implicit or explicit functions. Triangular meshes are the most common form of representation of surfaces. This representation allows an easy extraction of the properties of the surface like curvatures, boundaries, and

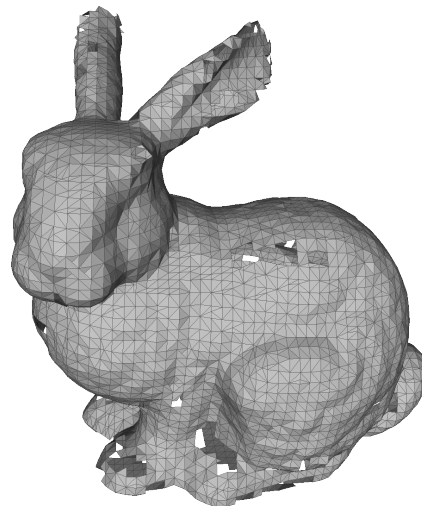


Figure 1: Reconstructed bunny model using marching cubes in an unsigned distance field with a grid of  $50^3$  cells with more than 140.000 points representing the surface.

other characteristics. Also the possibility of extension from this output to visualization process are straightforward with the current graphic hardware.

The contribution of this paper is the extension of Marching Cubes algorithm by analyzing more information inside each cell, for each edge inside the cell the value of the middle point in the edge is calculated as a other vertice. With the new information the intersection points of the surface with the edges of the cell are calculated, and the triangulation case for each cell is selected generating the triangular surface of the 0-level iso-surface.

The remainder of the paper is structure as follows: In section 2 we review previous work in surface reconstruction from point sets and their different approximations. In section 3 we present the methodology of surface reconstruction of our algorithm. And in section 4 we present the results of the algorithm testing different quality measurements in the outputs of the algorithm, conclusions and future work is presented in section 5.

## 2 RELATED WORK

Surface reconstruction from unorganized point set has been solved with two different and predominant methodologies. The first one is by Voronoi-Delone and by implicit functions, the difference between the methods are the base division of the process. Voronoi-Delone the methods are point centric data calculation process and the triangulation is created following the point set. Implicit functions methodology divide the space and the local characteristics of the surface inside are identified for further rendering with methods like Marching Cubes.

Reconstruction of surfaces with Voronoi-Delone methodologies are explored in (Amenta et al., 1998) where a 3D voronoi diagram is created of the point set and a crust is generated. (Amenta et al., 2001) a medial axis transform is calculated from the point set and the surface is generated following the distance to the medial axis.

Approximation made by (Hoppe et al., 1992) which for each point the normal direction is calculated using the neighborhood of the point and then calculating the tangent plane in that point with a least squares algorithm. A consistent plane orientation for all the points should be made assuring that all the point faces to the same direction which is an NP problem. Finally a signed distance function is generated and a triangular mesh is generated with the marching cubes algorithm. This methodology is improved in the work of (Kazhdan et al., 2006).

Marching cubes (Lorensen and Cline, 1987) is an algorithm to generate triangular meshes from volumetric data. This algorithm defines a type of trian-

gulation for each cell in the volume or space given the values of the vertices, given a desired iso-value the vertices are compared against this value and then a triangulation case is selected (Figure 2) and then a triangulation is generated for each cell. The algorithm has been widely studied (Newman and Yi, 2006) and several extensions had been made to solve topological problems with techniques (Chernyaev, 1995), (Lewiner et al., 2003) also methodologies to obtain more accurate representations were studied (Congote et al., 2009). One of the biggest advantages of the algorithm is their complexity  $O(n)$  where  $n$  is the number of cells in the volume, so the time taken by the algorithm to the process could be easily controlled in real time process because it is constant and can be modified changing the number of cells.

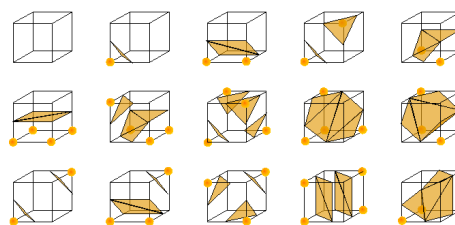


Figure 2: Marching Cubes cases.

The distance field generated from the set of points represents a challenge for the marching cubes algorithm because the distance is always a positive value, and the surface which represents the points are defined in the isovalue 0 which can not be represented without the presence of negative values in the field. To solve this problem a signed distance field must be generated where, for each point in the set, the normal of the surface is calculated, and must be congruent in all the surface. This process is very complex and we avoid this step in our work.

Previous approximations of modified marching cubes algorithm from point sets has been made. (Fujimoto et al., 2008) which uses the vertices as the places where the surface pass, to obtain better geometry approximation the vertices are translated to the nearest point, and a new marching cubes cases are formulated where the surface is in the vertices. (Hornung and Kobbelt, 2006) creates an offset surface around the points and then a cut between the offsets represent the surface of the points.

## 3 METHODOLOGY

Our algorithm takes as input an unorganized point set. A bounding box is created which contains the set of points. A cubical grid is generated inside the

bounding box, where each vertex of the grid contains the minimum distances from the vertex to the nearest point of the point set. A parabolic interpolation defines the points of intersection of the surface to the grid. Then for each cell the marching cube case is selected given the intersection points of the edges of the cell. For each cell the triangles are generated with following the marching cubes case obtaining the triangular mesh which represent the surface of the point set.

The problem as defined by (Hoppe et al., 1992) takes as input an unorganized point set  $\{x_1, \dots, x_n\} \subset \mathbf{R}^3$  on or near an unknown manifold  $\mathbf{M}$ , and reconstruct a manifold  $\mathbf{M}'$  which approximates  $\mathbf{M}$ . No information about the manifold  $\mathbf{M}$  as the presence of boundaries or geometry of  $\mathbf{M}$  are assumed to be known in advance.

Given a set of unorganized points  $P = \{p_1, p_2, \dots, p_n\}$  which are on or near to a manifold  $\delta M$ , our goal is to construct a manifold  $\delta M'$  which are close to  $\delta M$ . Each point of  $P$  is represented by a 3-tuple of real values. The manifold  $\delta M'$  is represented as a set of planar triangles of  $\mathbf{R}^3$

The algorithm is subdivided in the following steps:

1. Bounding box  $B$  calculation of  $P$ .
2. Generation of a cubical grid  $G$  inside  $B$ .
3. Calculate the minimum distance for each vertex  $v_{i,j,k} \in G$  to  $P$ .
4. Calculate the intersection points  $I$  in the edges of the cells of  $G$ .
5. Identify for each cell of  $G$  the marching cube case which match the intersection points  $I$ .
6. Generate the simplexes of each cell of  $G$  given the calculated case.

### 3.1 Bounding Box Calculation

The calculation of the bounding box  $B$  could be made following the word axis identifying the minimum and maximum values of  $(x, y, z)$  in  $P$ . There is no exact rule for the creation of the bounding box, which can be parallel to the global axis, rotated or static. The bounding box define the region in the space where the triangular mesh is going to be generated.

### 3.2 Cubical Grid Generation

Inside the region defined by  $B$  a cubical grid  $G$  is defined, the number of cells that are inside  $G$  define the resolution of the surface, but a high number of cells without a proper density of points defining the case

inside each cell could generate ambiguities in the reconstruction process. also the number of cells defines the level of detail of the object. For each cell the vertices of the grid are define as  $v$ , also a number of auxiliary vertices in the middle of each edge of the cell must be created  $v_{aux}$ .

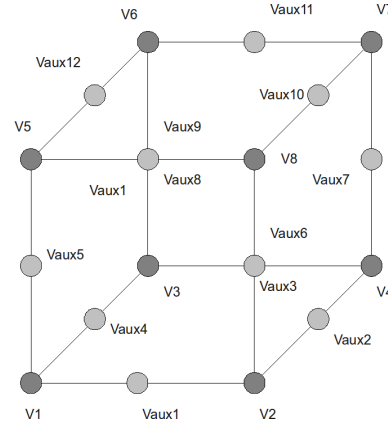


Figure 3: Vertices  $v$  and auxiliary vertices  $v_{aux}$  for each cell.

### 3.3 Distance Calculation for each Vertex

For all the vertices  $v$  and  $v_{aux}$  defined in  $G$  the minimum distance from the vertex to the point cloud should be calculated (Figure 3). Given the regular form of the grid  $G$  for each point in  $P$  the nearest vertex could be calculated in  $O(1)$  time, then the nearest vertex is assigned with the value calculated, if various points are near to the same vertex  $v$  then only then minimum distance is stored.

### 3.4 Intersection Point Calculation

Edges of the cells  $C$  a possible intersection point is calculated by Equation 1, where an intersection point inside the edge is defined, this intersection point are based with a tolerance value, which define if the point is close enough to the edge to be defined as an intersection,

For each edge  $e$  of the cells  $C$ , we have 3 vertices,  $v_1, v_2, v_3$  where  $v_1$  and  $v_3$  are the vertices of the lattices of the grid and  $v_2$  is the middle auxiliary vertex calculated  $v_{aux}$ . Our methodology is to suppose that vertices are aligned in the  $x$  axis in  $D$  plane with the values of  $x_1 = 0, x_2 = 0.5$  and  $x_3 = 1$ , and the values of  $y_1 = v_1, y_2 = v_2, y_3 = v_3$  which are a distance from vertices to the surface point, are values in  $y$  axis of  $D$  plane. Then we can assume that a normal signed surface which cut the edge forms a line in the plane  $D$ , as shown in Figure 4 but as the distance is a positive value the intersection is presented as a line in the positive region of  $D$ . We approximate the intersection as-

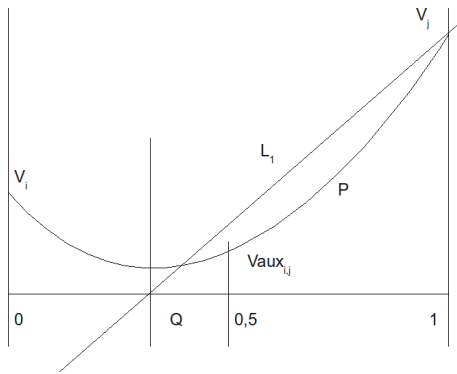


Figure 4: Parabola showing the intersection point  $q$  for the unsigned distance field as a comparison between the original distance function  $L_1$  and a parabola  $p$  which values  $v_i$ ,  $v_j$ ,  $v_{aux}$  represent the distance to the surface.

suming the as the intersection point can be expressed as a parabola, which is aligned with the  $y$  axis in  $D$ . Given the 3 points measured in the plane a parabola  $p$  could be calculated solving the equations of 1 given the parameters of  $p$ ,  $a$ ,  $b$ ,  $c$  in Equation 2.  $v_x$ ,  $v_y$  are the coordinates of the vertex of the parabola  $p$  as defined in Equation 3, the value  $v_x$  gives the position in the edge where the surface cuts the edge and  $v_y$  could be assigned as a tolerance value, which define how close is the surface to the edge.

$$\begin{aligned} y_1 &= ax_1^2 + bx_1 + c \\ y_2 &= ax_2^2 + bx_2 + c \\ y_3 &= ax_3^2 + bx_3 + c \end{aligned} \quad (1)$$

$$\begin{aligned} a &= -\frac{-x_2y_1 + x_3y_1 + x_1y_2 - x_3y_2 - x_1y_3 + x_2y_3}{(x_2 - x_3)(x_1^2 - x_2x_1 - x_3x_1 + x_2x_3)} \\ b &= -\frac{y_2x_1^2 - y_3x_1^2 - x_2^2y_1 + x_3^2y_1 - x_2^2y_2 + x_3^2y_2}{(x_1 - x_2)(x_1 - x_3)(x_3 - x_2)} \\ c &= -\frac{x_3y_2x_1^2 - x_2y_3x_1^2 - x_3^2y_2x_1 + x_2^2y_3x_1 + x_2x_3^2y_1 - x_2^2x_3y_1}{(x_2 - x_3)(x_1^2 - x_2x_1 - x_3x_1 + x_2x_3)} \end{aligned} \quad (2)$$

$$\begin{aligned} v_x &= \frac{-b}{2a} \\ v_y &= c - \frac{b^2}{4a} \end{aligned} \quad (3)$$

### 3.5 Cell Case Identification

Given the intersection points for each cell, the marching cubes lookup table is used, to define which case of marching cubes had the same edges intersected, if the case is found then the cell is labeled with that case, if there is not case which is defined by the marching

cubes look up table, then this cells had an ambiguity case. These cases are produced because the points around the cell had a lot of noise or there is no enough density of points to identify the triangulation in that region. At the time we don't make any processing to solve this ambiguity and that cells are simply assigned as empty, but global process could be done to eliminate this ambiguities.

### 3.6 Triangulation Generation

Each cell of the Grid  $G$  had been labeled with the marching cubes case which represents. Then following the rules of generation of triangles or simplexes of marching cubes. The number of cases which marching cubes gives is 14 in their original definition, because the number of possible combination of edges is  $2^8 = 256$  but eliminating redundant cases with rotations or mirrors is only 14 cases. With our approach the number of cases is equal to the number of possible intersections of the edges  $2^{12} = 4096$ , where we map to the 14 cases of marching cubes, as explained before there is some configurations which gives ambiguity forms this cases are not generated in our algorithm.

## 4 RESULTS

Our algorithm generates triangular mesh which is a good representation of the surface defined by the set of points. The mesh is not created to be correct in a topological level because the original marching cubes algorithm used to generate the triangulation have topological errors, and the process of calculation is very sensitive to noise or poorly density regions of points. The mesh is generated in a fast way. Even though the results represent a qualitative good representation of the surfaces. This algorithm focus in the problem of generation of the surfaces without the calculation of the normal direction of the surface extending the uses of the Marching Cubes algorithm for unsigned implicit functions in the representation of the isolevel 0.

## 5 CONCLUSIONS AND FUTURE WORK

We present an extension of the marching cubes algorithm for the extraction of the 0-level iso-surface in an unsigned distance field. The generated meshes present a lot of topological mistakes because the algorithm can not identify correctly the marching cubes



Figure 5: Reconstructed elephant model with a grid of  $200^3$  cells.

cases where the edges in the cell are intersected with a different pattern as the marching cubes cases present. New set of marching cubes cases have to be generated to correct implement the triangulation step.

The algorithm could represent a big part of the surface without calculating the normal, eliminating an costly step commonly used in other algorithms opening a new method for reconstruction for non-orientable surfaces, and because the local nature of the algorithm it can process without problems surfaces with holes or boundaries.

The quality of the meshes without considering the errors produce by the ambiguities are the same as the marching cubes original algorithm. For futher improvements in the quality of the meshes could be applied using the different techniques developed for marching cubes algorithm because the modification of our extension to the original algorithm is minimal.

## ACKNOWLEDGEMENTS

This work has been partially supported by the Spanish Administration agency CDTI, under project CENIT-VISION 2007-1007. CAD/CAM/CAE Laboratory - EAFIT University and the Colombian Council for Science and Technology – COLCIENCIAS –. The data set of bunny is courtesy of the Stanford Computer Graphics Laboratory.

## REFERENCES

- Amenta, N., Bern, M., and Kamvyselis, M. (1998). A new voronoi-based surface reconstruction algorithm. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 415–421, New York, NY, USA. ACM.
- Amenta, N., Choi, S., and Kolluri, R. K. (2001). The power crust. In *SMA '01: Proceedings of the sixth ACM symposium on Solid modeling and applications*, pages 249–266, New York, NY, USA. ACM.
- Chernyaev, E. V. (1995). Marching cubes 33: Construction of topologically correct isosurfaces. Technical report, CERN.
- Congote, J. E., Moreno, A., Barandiaran, I., Barandiaran, J., and Ruiz, O. (2009). Adaptive cubical grid for isosurface extraction. In *4th International Conference on Computer Graphics Theory and Applications GRAPP-2009*, pages 21–26, Lisbon, Portugal.
- Fujimoto, K., Moriya, T., and Nakayama, Y. (2008). Surface reconstruction from high-density points using deformed grids. In *WSCG'2008 Communication Papers Proceedings*, pages 117–120, Plzen - Bory, Czech Republic. University of West Bohemia.
- Gross, M. and Pfister, H. (2007). *POINT-BASED GRAPHICS*. Elsevier.
- Hoppe, H., DeRose, T., Duchamp, T., McDonald, J., and Stuetzle, W. (1992). Surface reconstruction from unorganized points. In *SIGGRAPH '92: Proceedings of the 19th annual conference on Computer graphics and interactive techniques*, pages 71–78, New York, NY, USA. ACM.
- Hornung, A. and Kobbelt, L. (2006). Robust reconstruction of watertight 3d models from non-uniformly sampled point clouds without normal information. In *SGP '06: Proceedings of the fourth Eurographics symposium on Geometry processing*, pages 41–50, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- Kazhdan, M., Bolitho, M., and Hoppe, H. (2006). Poisson surface reconstruction. In *SGP '06: Proceedings of the fourth Eurographics symposium on Geometry processing*, pages 61–70, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- Lewiner, T., Lopes, H., Vieira, A. W., and Tavares, G. (2003). Efficient implementation of marching cubes' cases with topological guarantees. *journal of graphics, gpu, and game tools*, 8(2):1–15.
- Lorensen, W. E. and Cline, H. E. (1987). Marching cubes: A high resolution 3d surface construction algorithm. *SIGGRAPH Comput. Graph.*, 21(4):169–169.
- Miao, Y., Feng, J., and Peng, Q. (2005). Curvature estimation of point-sampled surfaces and its applications. In *Computational Science and Its Applications – ICCSA 2005*, pages 1023–1032. Springer Berlin / Heidelberg.
- Newman, T. S. and Yi, H. (2006). A survey of the marching cubes algorithm. *Computers & Graphics*, 30(5):854–879.