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Virtual World Reconstruction Using the Modeling and Simulation Extended Vector Product Prototype

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The modeling and simulation (M&S) communities for both the Navy and Marine Corps are not currently satisfied by the data provided by the Defense Mapping Agency. In particular, deficiencies exist in both the lack of a continuous surface representation and an inconsistent view of elevation throughout a single database. The M&S Extended Vector Product (MSEVP) prototype being developed is an extended vector product format-based product containing a continuous surface representation and a consistent view of elevation across the thematic coverages contained within a database.

A continuous surface representation is provided in the MSEVP prototype as a Triangulated Irregular Network (TIN) and stored in the MSEVP elevation coverage. This report also examines how a TIN representation of the transportation network is constructed from a two-dimensional linear representation. Each linear road is widened to provide a more realistic representation of its real work counterpart and then overlaid over the elevation TIN to ensure that the road adheres to the surface characterized by the elevation coverage. This overlay process ensures that a consistent view of elevation will exist across coverages.

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EXECUTIVE SUMMARY

The modeling and simulation (M&S) communities for both the Navy and Marine Corps are not currently satisfied by the data provided by the Defense Mapping Agency. In particular, deficiencies exist in both the lack of a continuous surface representation and an inconsistent view of elevation throughout a single database. The M&S Extended Vector Product (MSEVP) prototype being developed is an extended vector product format-based product containing a continuous surface representation and a consistent view of elevation across the thematic coverages contained within a database.

A continuous surface representation is provided in the MSEVP prototype as a Triangulated Irregular Network (TIN) and stored in the MSEVP elevation coverage. This report also examines how a TIN representation of the transportation network is constructed from a two-dimensional linear representation. Each linear road is widened to provide a more realistic representation of its real work counterpart and then overlaid over the elevation TIN to ensure that the road adheres to the surface characterized by the elevation coverage. This overlay process ensures that a consistent view of elevation will exist across coverages.

VIRTUAL WORLD RECONSTRUCTION USING THE MODELING AND SIMULATION EXTENDED VECTOR PRODUCT PROTOTYPE

1.0 INTRODUCTION

The Defense Mapping Agency (DMA) holds the responsibility of providing large geographic data sets to a wide range of users. Among the users receiving data from the DMA are the modeling and simulation (M&S) communities for both the Navy and Marine Corps. This report focuses on providing solutions via an Extended Vector Product Format (EVPF) to the deficiencies of the DMA's Vector Product Format (VPF) as they relate to the Navy and Marine Corps Digital Mapping, Charting, and Geodesy Requirements for M&S (Shaw et al. 1996).

VPF is a military standard data format (Mil-Std-2407) that serves as a foundation from which database products are designed using its georelational data model (Department of Defense 1993). The data model defines geographic entities as a collection of node, edge, and/or face primitives. Features and their accompanying attribute data are then linked to the appropriate primitives. Individual products are constructed using the VPF data model to contain different sets of feature classes and attribution. Among the current DMA products are Digital Nautical Chart (DNC), Urban Vector Smart Map, and Digital Topographic Data (DTOP). DNC contains selected marine-significant physical features collected from harbor, approach, coastal, and general charts (Defense Mapping Agency 1993).

Products based on the VPF standard, including those above, have insufficient feature and attribution content to completely fulfill the requirements of the M&S community (Shaw et al. 1995). Attribute data such as radar reflectivity and infrared signatures are among those not currently provided by the DMA (Shaw et al. 1995). The level of resolution and accuracy of the terrain and integrated surface feature classes must also be increased to meet M&S requirements. The problems with VPF extend beyond content to the capabilities of the format itself. Contour lines that represent the most common method of distributing elevation data in VPF products fail to provide a continuous surface representation regardless of the resolution. The Digital Terrain Elevation Data (DTED) series of elevation grids could be extended to include higher resolution data, but the high storage requirements and lack of a continuous surface remain to be solved. Triangulated Irregular Networks (TIN) provide the ability to store a high-resolution continuous surface in an efficient manner. EVPF is the result of the integration of TIN data tables into VPF, based on the investigation of various TIN data structures and VPF as presented in (Abdelguerfi et al. 1995). The M&S Extended Vector Product (MSEVP) prototype being developed is an EVPF-based product containing the M&S required feature and attribute content, as well as TIN data representation for the elevation coverage and transportation network.

In Sec. 2.0, EVPF and MSEVP are briefly reviewed. Data structures will be presented for the efficient storage of TIN primitive and feature tables as presented in more detail by Abdelguerfi et al. (1995). Section 3.0 will present methods for populating these tables to create a virtual world. The first stage in the development consists of constructing the elevation TIN for the desired region.

Once a continuous and unambiguous representation of elevation is available, surface features can be integrated into the virtual world. Edges of zero width representing the transportation network were extracted from DTOP and converted to polygons with real-world width. These polygons, as well as other arbitrary area features such as woodland areas, were then integrated into the virtual world by overlaying them onto the elevation TIN. Unlike existing VPF products, MSEVP allows the rendering of surface features in a three-dimensional (3-D) environment, as well as ensuring consistent elevation values between those found in the elevation and other coverages.

2.0 EXTENDED VECTOR PRODUCT FORMAT

The first part of this section will briefly review the actual data structures (i.e., table definitions) used to store the improved triangle-based approach and the relationships between them. For a complete description of the improved triangle-based data structure, the interested reader is referred to Abdelguerfi et al. (1995). This will be followed by an explanation of how these primitives can be linked to geographic features such as lakes, roads, and mountains. The section will conclude by addressing the MSEVP prototype on an abstract level, while the data generation will be presented in the following section.

2.1 EVPF Primitive Table Definitions

The first stage in the integration of TINs into VPF begins with the incorporation of the improved triangle-based data structures into the primitive data model. Figure 1 shows the primitive directory

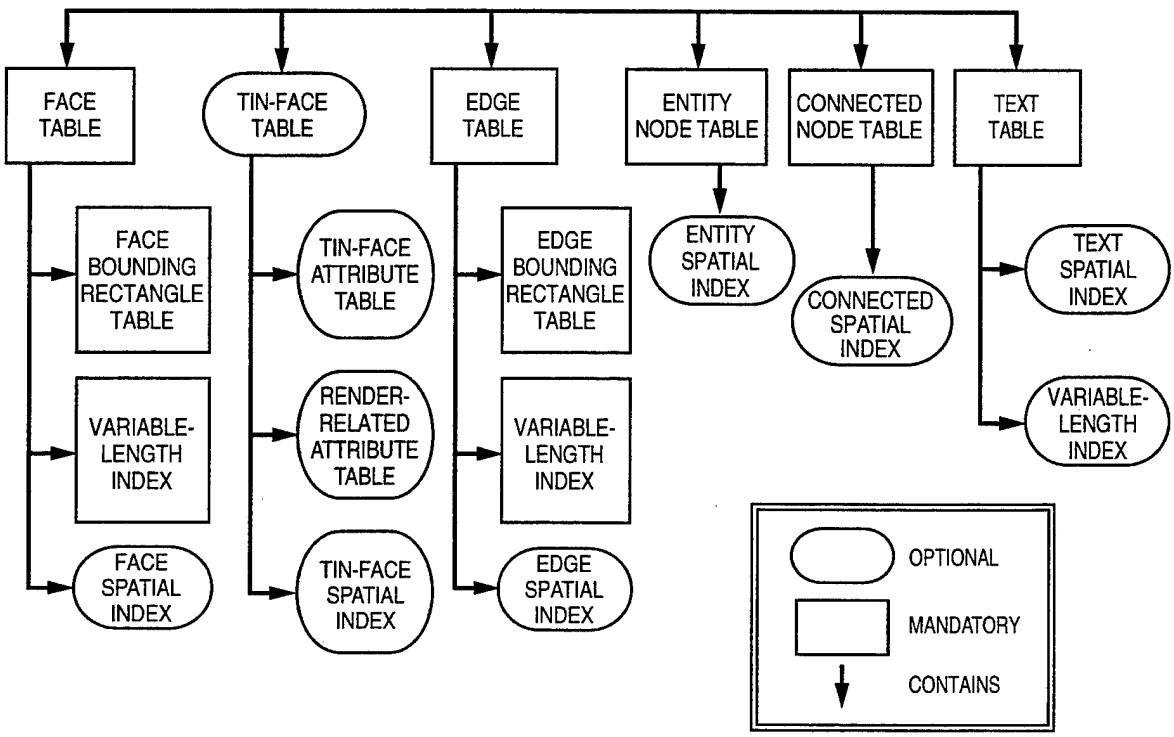


Fig. 1 — Extended primitive directory (topology level 3)

of EVPF. The optional TIN-face table has been added for topology level 3 and comes with optional attribute, render-related attribute, and spatial index tables. In the EVPF TIN-face table shown in Table 1, vertices and adjacent triangles are stored in a counterclockwise fashion. Table 2 shows the definition of a modified connected-node table. The new table includes an additional column, First-TIN, that implements the partial relationship between a connected node and its containing triangles.

While the TIN-face and the connected-node tables can be used to generate a wire mesh frame, a complete 3-D image requires more information about each primitive. To provide this information, a TIN-face attribute table must be introduced to store attribute data for each TIN primitive. Although stored at the primitive level to remain transparent to the user, this table can be compared with an area feature table storing attribute data for the corresponding face primitives. The TIN-face attribute

Table 1 — TIN-Face Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	TIN primary key	I	P	M
VERTEX_ONE	First vertex (foreign key to the connected-node table)	I	N	M
VERTEX_TWO	Second vertex (foreign key to the connected-node table)	I	N	M
VERTEX_THREE	Third vertex (foreign key to the connected-node table)	I	N	M
ADJACENT_ONE	ID of triangle adjacent to current triangle along edge between vertex one and two	I/K	N	M
ADJACENT_TWO	ID of triangle adjacent to current triangle along edge between vertex two and three	I/K	N	M
ADJACENT_THREE	ID of triangle adjacent to current triangle along edge between vertex three and one	I/K	N	M

Table 2 — Connected-Node Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	Node primary key	I	P	M
*.PFT_ID	Point feature table ID	I	N	OF
CONTAINING_FACE	Always null (included for compatibility)	X	N	O
FIRST_TIN	TIN key (foreign key to the TIN table	I	N	MI
FIRST_EDGE	Edge key (foreign key to the edge table	I	N	M1–3
COORDINATE	Node coordinate	C/Z/B/Y	N	M

table stores attribute data for every triangle regardless of its relation or lack of relation to an area or TIN feature. Each triangle in the TIN table must be rendered to display a continuous surface even though each triangle may not be used to define a specific area or TIN feature, such as triangles between two lakes. The definition of the TIN-face attribute table is shown in Table 3.

To render 3-D surfaces and objects adequately, certain attributes must be defined for each triangle or for each vertex of each triangle. Among the attributes that could be defined are color, ambient reflection, diffuse reflection, specular reflection, emissions, and shininess. The color could be represented by a 3-tuple (R, G, B) of floating-point values between 0 and 1. The RGB values represent the primary colors: red, green, and blue. Black is represented by (0, 0, 0) and white by (1, 1, 1). The grayscales are represented in between by equal RGB values. The other values listed above are used to determine shading and various effects light has on the object. To eliminate redundancy, these values are stored in a related attribute table and referenced by a number of individual triangles in the TIN-face table. The actual values needed by an individual rendering package can vary, and as a result, no standard fields are defined. The definition of the render-related attribute table is shown in Table 4.

2.2 EVPF Coverage Level Tables

Besides the addition of primitive level tables, there are three new coverage level tables that closely resemble the area feature tables in both structure and usage. These tables can be used to store features such as roads, lakes, and buildings, as well as arbitrary attribution for each feature class. These tables are the TIN-feature table, the TIN-feature index table, and the TIN-feature join table. The new coverage level feature structure is shown in Fig. 2. The TIN-feature table is used to store attribute information for a given real-world entity represented by the TIN primitives. Any existing area feature or 3-D object can be triangulated and stored using the TIN coverage- and primitive-level tables. The TIN-feature table definition is shown in Table 5. The TIN-feature join

Table 3 — TIN-Face Attribute Table Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	TIN feature primary key	I	P	M
RENDER_VALUE	Render values for this triangle (foreign key to the render.rat table)	I	N	O
<Attribute *n*>	*n*th attribute	Any	Any	O

Table 4 — Render-Related Attribute Table

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	Render primary key	I	P	M
<Attribute *n*>	*n*th attribute	Any	Any	O

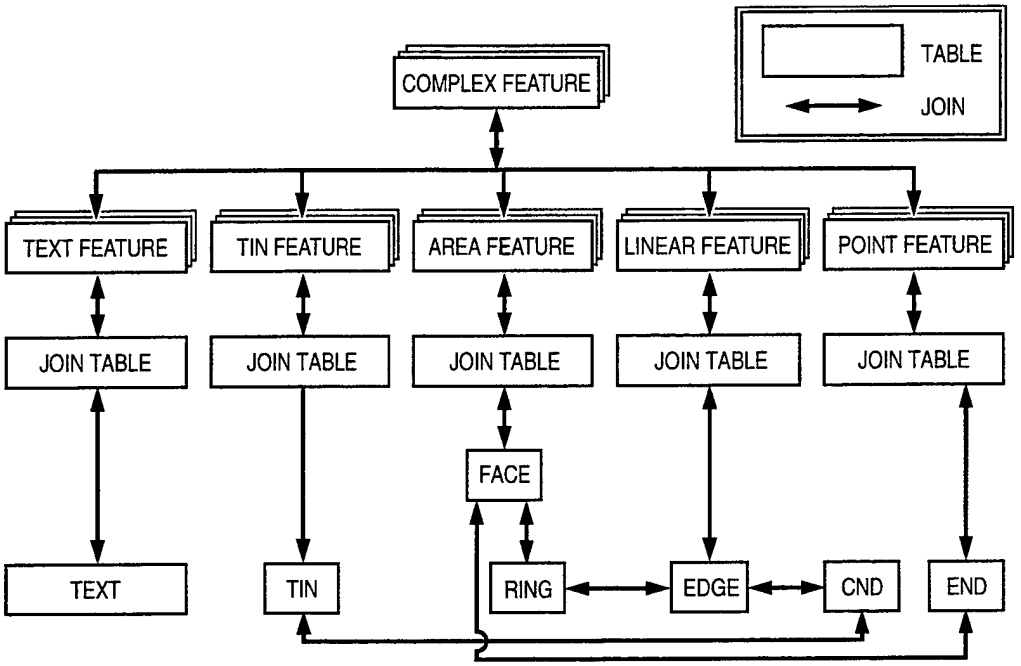


Fig. 2 — New feature class schema

Table 5 — TIN Feature Table Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	Feature primary key	I	P	N
TILE_ID	Tile reference ID	S	N	MT
TIN_ID	Primitive ID	S/I/K	N	M
<Attribute *n*>	*n*th Attribute	Any	Any	O

table, shown in Table 6, is meant as a link from a specific feature class to the primitive records used to construct the individual feature. This provides an excellent method of selective rendering of features. The TIN-feature index table, shown in Table 7, serves as a comprehensive join table between TIN primitives and related features. From any TIN primitive, i.e., triangle, the feature index table can be used to obtain the feature class ID and feature ID that uses it. The feature class schema table is accessed using the class ID to obtain the name of the proper TIN-feature table. These TIN-feature classes have entries in the feature-class attribute table just as the area, the linear, or point features classes would.

2.3 TINs in Tiled Coverages

VPF allows cross-tile referencing via the introduction of a triplet ID data type. Each triplet ID begins with an 8-bit type byte depicting the format for the rest of the field. The three fields composing the triplet ID are referred to as: ID representing the internal tile primitive ID, TILE_ID representing the external tile reference ID, and EXT_ID representing the external tile reference

Table 6 — TIN Feature Join Table Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	Row ID	I	P	M
*_ID	Feature key	I	N	M
TILE_ID	Tile reference ID	S	N	MT/O
TIN_ID	TIN primitive primary key	I/S/K	N	M

Table 7 — TIN Feature Index Table Definition

COLUMN NAME	DESCRIPTION	COLUMN TYPE	KEY TYPE	OP/MAN
ID	Row ID	I	P	M
PRIM_ID	Primitive ID	I	N	M
TILE_ID	Tile reference ID	S	N	MT
FC_ID	Feature class ID	I	N	M
FEATURE_ID	Feature ID	I	N	M

primitive ID. The first 2 bits of the type byte indicate the length of the internal ID; the second 2 bits indicate the length of the TILE_ID field; the third 2 bits indicate the length of the EXT_ID; the final 2 bits are reserved. The field length is either 0, 1, 2, or 4 bytes, depending on the value stored in the 2 bits (i.e., 00 indicates 0 bytes while 11 indicates 4 bytes).

When a triplet ID is encountered, the type byte is analyzed and the resulting values used to find the correct primitive(s). In reference to an adjacent triangle, the existence (nonzero length) of the TILE_ID and EXT_ID fields indicates that the edge of the triangle is on a tile boundary and the adjacent triangle primitive is included in the tile specified by the TILE_ID. The EXT_ID is then used within the correct tile to find the appropriate primitive. This primitive should have a corresponding triplet ID pointer to the original triangle.

In a tiled coverage, triangles will not be allowed to cross tile boundaries. In addition, care must be taken so that triangles at the edge of a tile have at most three neighboring triangles (including the neighboring triangle in the adjacent tile). The tile boundaries could be used as breaklines to ensure this property. This would ensure that no triangles are bisected by the tile boundary while also preserving the adjacency requirement.

2.4 Modeling and Simulation Extended Vector Product

With the introduction of EVPF, the attention now turns to the production of an Extended Vector Product for the M&S community. The production of a prototype database begins with the selection of a representative area of interest. To address the feature and attribute deficiencies adequately and demonstrate the TIN capabilities, the area must contain a wide range of surface

characteristics. A region over Killeen, TX, was chosen for this reason. The selected area spans a 5′ × 5′ section (–97° 30′ to –97° 35′ longitude and 31° 5′ to 31° 10′ latitude) of Killeen, TX, and has sufficient variances in elevation, as well as multiple bodies of water to demonstrate the capabilities of the TIN data structures adequately. In addition, numerous DMA products exist for the region, providing an excellent source of data from which to populate the prototype.

The MSEVP prototype as presented in Shaw et al. (1996) consisted of eleven coverages: Basic Earth Surface, Data Quality, Demarcation, Elevation, Hydrography, Industry, Physical Geography, Population, Transportation, Utilities, and Vegetation. The basic Earth surface coverage consists of all data relating to all Earth surfaces including coastal and bottom types of hydrological features. The data quality coverage follows the VPF standard of specifying the reliability and accuracy of data contained in the database. The demarcation coverage delineates boundary information for the region of interest. The elevation and transportation coverages will be elaborated on in the next section. It contains a TIN representation of the terrain and transportation network, respectively. The hydrography coverage contains all water-related feature classes such as reservoirs and lakes. Industrial sites, factories, power plants, and related features are divided among the industry and utility coverage. The physical geography coverage is used to store information concerning natural terrain features such as ridge lines. The population coverage contains information on population density and related information.

The culmination of new feature and attribute data, as well as the newly integrated TIN data structures, offers a significant step toward satisfying the needs of the M&S community.

3.0 POPULATING MSEVP TABLES

VPF and EVPF represent a means by which large geographic data sets can be distributed. While the VPF specification does not place any requirements as to how to populate the data structures, it is important to demonstrate how the proposed EVPF TIN tables can be populated using current DMA data. Although not discussed in great detail, superior alternatives are mentioned when not restricted by currently available data.

The procedure for EVPF data generation begins with the construction of the elevation TIN from gridded elevation values, as well as any breaklines being used to enhance the representation of the terrain. Road polygons are then generated using linear road features and elevation values interpolated from the elevation TIN. These road polygons and other area features are then overlaid onto the elevation TIN to provide an integrated representation of the surface. The process is summarized in Fig. 3 and explained in detail in the remainder of this section.

DMA data in the form of level 2 DTED and DTOP data exists for the MSEVP prototype region of Killeen, TX, and will be used in the construction of the MSEVP TIN data for the elevation coverage. The transportation edges stored in DTOP have been extracted, widened, and overlaid onto the elevation TIN, thereby providing a "real-world" view of the surface and roads. Additionally, existing two-dimensional (2-D) area features extracted from DTOP, such as woodlands, are also overlaid onto the elevation TIN.

3.1 Generation of Elevation TIN

The first stage in the development of an EVPF product begins with the production of the elevation coverage. The TIN mesh representing the terrain will be used in assigning elevation

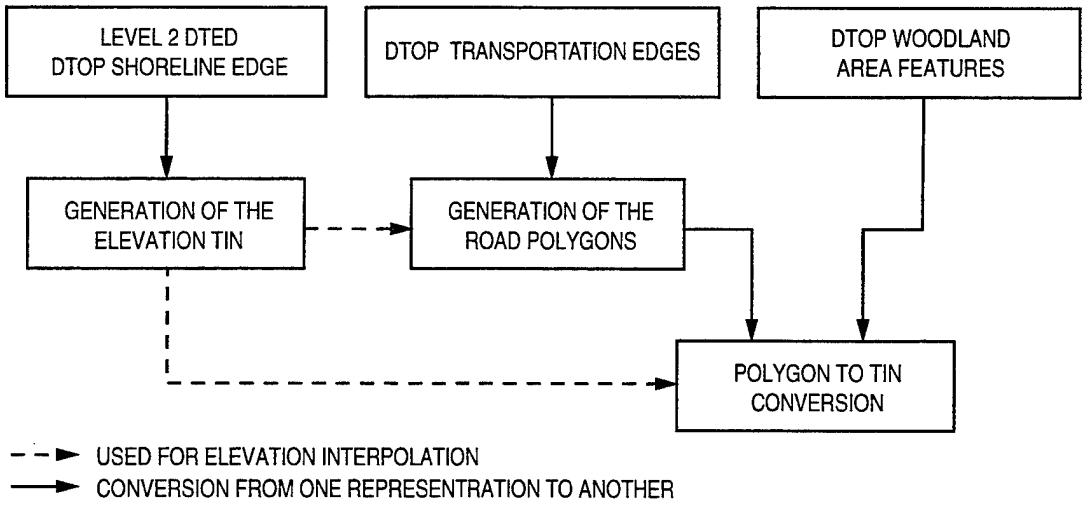


Fig. 3 — Overview of EVPF data generation procedure

values to the nodes in the remaining coverages. Once the coverages (i.e., primitive tables) are complete, TIN data can be converted to a second format and displayed using a 3-D rendering package.

TIN data can be generated from a variety of input sources, such as elevation grids, contour lines, arbitrary collection of edges, or previously generated TINs. This section will trace the populating of the elevation coverage of the MSEVP prototype using 90,300 nodes extracted from level 2 DTED and 639 nodes from five shoreline edges extracted from the hydrography coverage in DTOP.

The elevation points were used to create an ARC/INFO lattice, which serves as the foundation for building an initial TIN for the area. A z-tolerance of 10.0 m was chosen for the construction of this TIN in an effort to balance the need for a high-resolution surface representation while maintaining a manageable data set. The shorelines defined for the area in DTOP were added to the original triangulation as breaklines. The ARC/INFO *ungeneratetin* command was performed on the constrained TIN to create an ASCII file containing the TIN wire frame of the region.

Rendering values based on the elevation of the terrain were assigned for each triangle and each vertex to highlight the versatility of the TIN attribute and render-related attribute tables. The bodies of water, whose elevation can be determined by the color/elevation of the land surrounding it, were assigned a constant color of blue regardless of the elevation. In addition to the assignment of attribute values, a first_tin value for each connected node and adjacency relationships for each triangle side is computed before writing the EVPF primitive tables described in the previous section. Figure 4 provides a flow chart describing the complete procedure for the generation of the elevation TIN. The results of this process are shown in Fig. 5.

3.2 Generation of Road Polygons

With the elevation coverage completed, attention can be turned to the addition of other surface features to the surface model. The transportation network is represented by VPF edges in DTOP and all other current DMA products. The transportation network has been converted from an edge

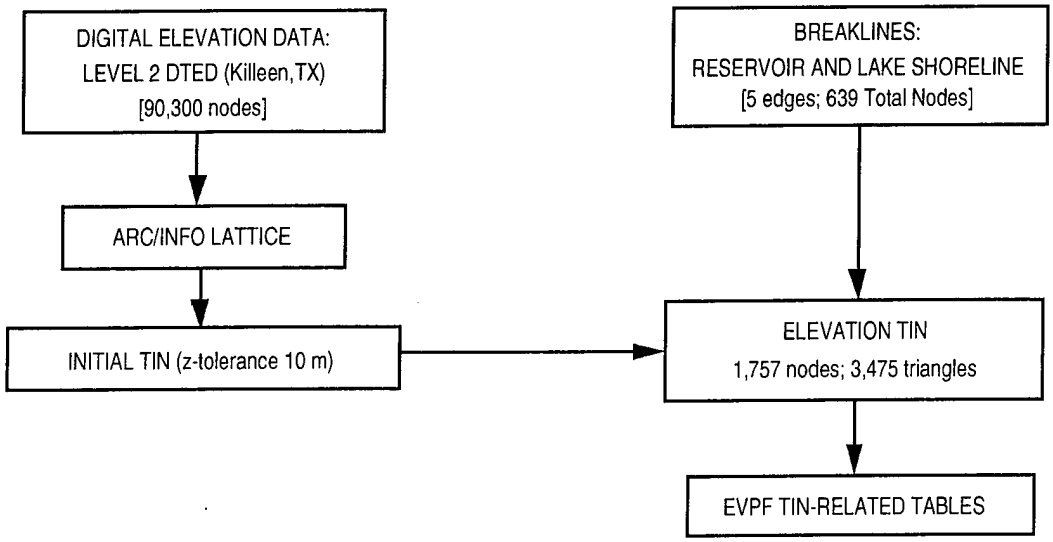
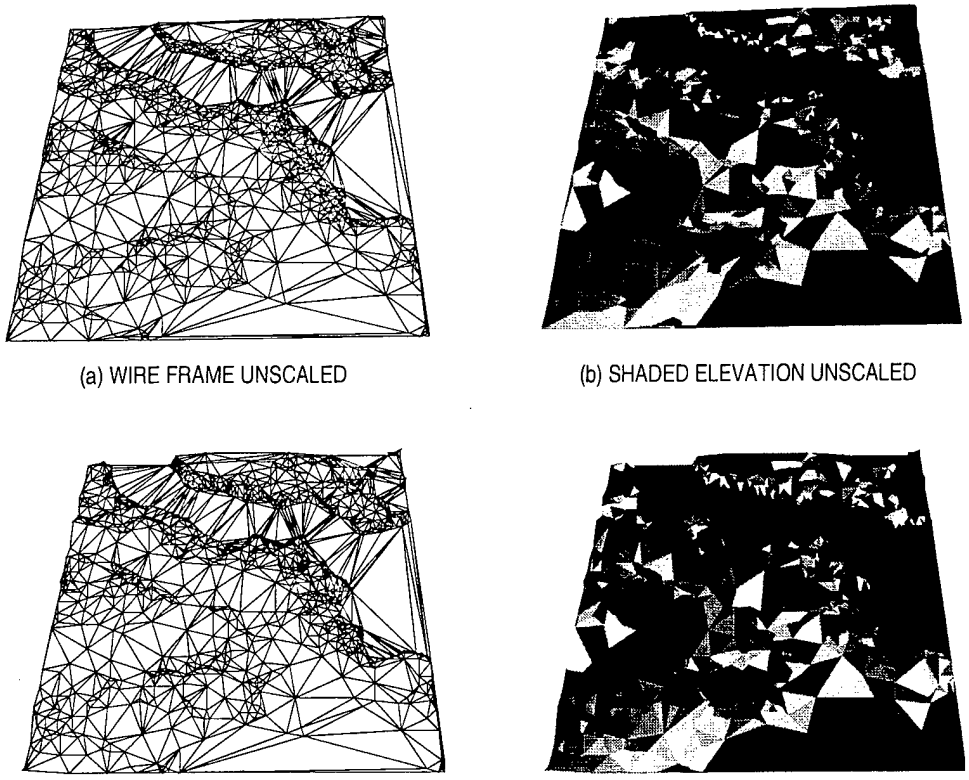


Fig. 4 — Generation of EVPF elevation TIN (Killeen, TX)



(a) WIRE FRAME UNSCALED

(b) SHADED ELEVATION UNSCALED

(c) WIRE FRAME SCALED BY 4

(d) SHADED ELEVATION SCALED BY 4

Fig. 5 — Examples of Killeen, TX, elevation TIN

with zero width to a polygon with a real-world appearance. This represents the first stage in the construction of the transportation TIN data.

Each VPF edge consists of a series of coordinates in 2- or 3-D space. Based on the coordinate values, as well as on the elevation calculated from the elevation TIN, polygon points are defined to the left and right of the original points. Each edge node is either a start node, intermediate node, or end node. Start and end nodes are handled in essentially the same manner, while intermediate nodes must be treated differently. Figure 6 displays the ultimate goal of expanding an edge to a polygon.

As stated above, this task is accomplished by adding new nodes to the left and right of each original node. The process begins by defining the left and right nodes for the start node. These new nodes are maintained in separate structures/lists for the left and right. The new nodes are added along the vector perpendicular to the first segment and contained in the plane defined by the triangle containing the start node. The slope of each edge segment is calculated and used to determine the equation of the vector perpendicular to the segment. The new nodes will be added along this vector at a fixed, predetermined distance, as shown in Fig. 7.

The intermediate nodes cannot be handled in this way because of the obvious difference in the slope of the segments before and after the node. Single points to the left and right of each intermediate node are calculated by first determining temporary left and right points based on the segments before and after the current intermediate node. The intersection of the lines parallel to the original segments that intersect the temporary points are added as the new left and right points for that intermediate node. The complete procedure for processing intermediate nodes is depicted in Fig. 8.

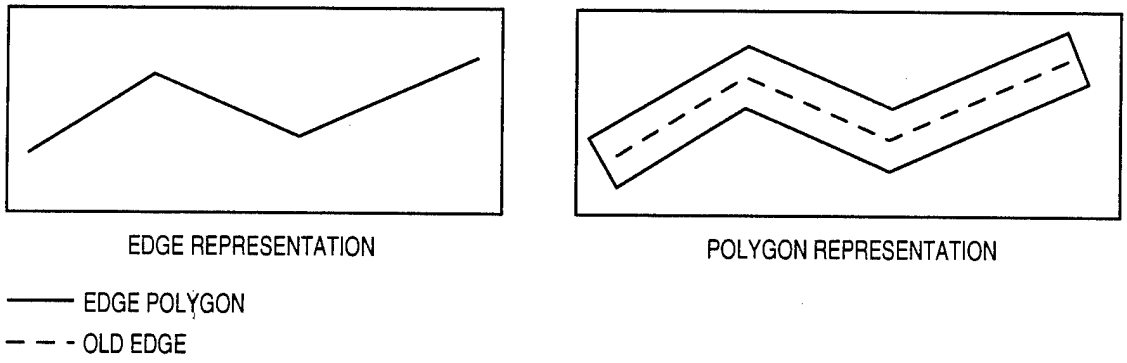


Fig. 6 — Edge-to-polygon conversion

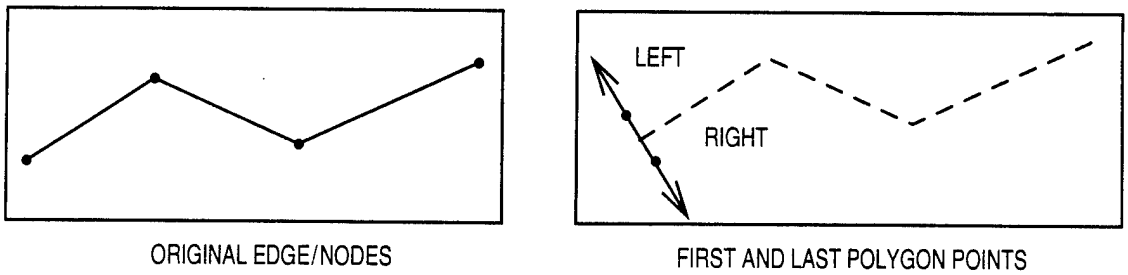


Fig. 7 — Left and right start node determination

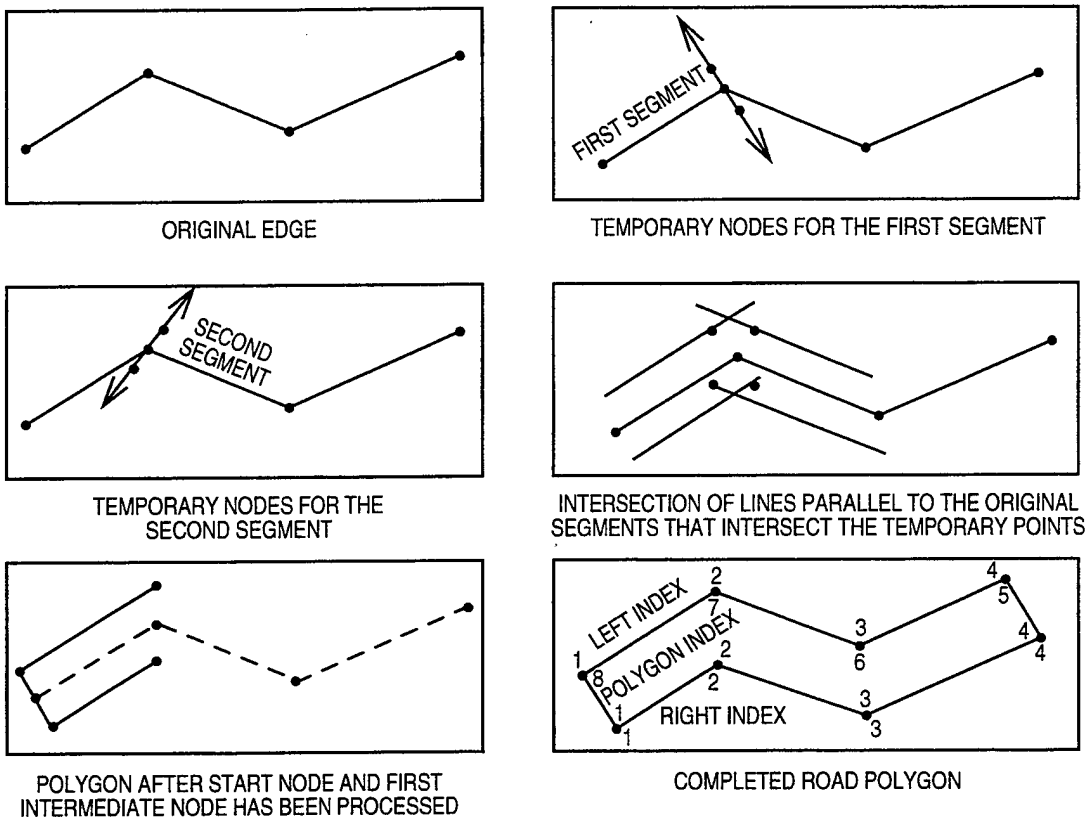


Fig. 8 — Intermediate node processing

After each intermediate node is processed, the left and right coordinates for the end node are calculated and added to the appropriate list. The polygon is then determined by listing the new points in counterclockwise order. This is achieved by listing the right points from the first to the last node followed by the left points from the last to the first node. Since the polygon is not required to be convex, points must be listed in counterclockwise order (which is ensured by listing the right points in order followed by the inverse left points). The pseudo-code of our road-widening algorithm is given in Fig. 9. Figure 15(a) depicts actual road polygons constructed from transportation edges for the prototype region. The boundary of the polygon gives absolute x,y coordinate values for the road. This polygon will then be overlaid and triangulated as described in the next section.

Research into the automated construction of large-scale virtual worlds performed at Carnegie Mellon University (CMU) was presented in Polis et al. (1995). Their work included both terrain representation using TINs as well as a polygonal representation of roads. Their initial terrain TIN is constructed and then altered by the road polygons. The resulting integrated terrain skin consists of the road polygons surrounded by terrain triangles. Although this approach appears to work extremely well in the representation of a site model using a single collection of polygons, VPF and EVPF segregates primitives into disjoint groups (i.e., coverages). Under this approach, the representation of the complete transportation network would be duplicated in both the transportation and elevation coverages.

Ideally, the transportation polygons would be directly extracted from the maps or satellite imagery currently being used to generate the road edges. In this case, the absolute longitude and

```
Variables:
   orig_pnt[num_road_points]      -- Original points in the road edge
   left[num_road_points]          -- New points added to the left of the original nodes
   right[num_road_points]         -- New points added to the right of the original nodes
   tmpl[2], tmpr[2]               -- Temporary determined from each intermediate node

Functions:
   find[left,roght]node(pnts,index,segment)      -- Determines the left/right node given a set of points,
                                                    the index of the desired source node, and whether
                                                    to use the first or second segment (i.e.,slope
                                                    of segment (index-1..index) or (index..index +1)).
   intersection(node1, node2, i)  --Determines the intersection of lines through node 1 and node 2
                                    with slopes equal to segment (i-!..i) and (i..i+1),
                                    respectively.

Algorithm:
   for  i: = 0..num_road_points-1 do
        get orig_pnt[i]

   left[0]: =  findleftnode(orig_pnt[0], first)
   right[0]: = findrightnode(orig_pnt[0], first)

   for i: = 1..num_road_points-2 do  --Process Intermediate Nodes
   {
      tmpl[10]: =  findleftnode(orig_pnt[i], second)
      tmpr[0]: = findrightnode(orig_pnt[i], second

      tmpl[1]: =  findleftnode(orig_pnt[i], first)
      tmpr[1]: =  findrightnode(orig_pnt[i], first)

      left[i]: =  intersection(tmpl[0], tmpl[1], i)
      right[i]: =  intersection(tmpr[0], tmpr[1], i)
   }
  left[num_road_points-1]: =  findleftnode(orig_pnt[num_road_points-2], second)
  right[num_road_points-1]: =  findrightnode(orig_pnt[num_road_points-2], second)

  for i: = 0..num_road_points-1 do
     write(right[i])
  for i: = num_road_points-1..0 do
     write(left[i])
```

Fig. 9 — Pseudo-code of road expansion algorithm

latitude for the left and right bank of the road would be accurate regardless of the slope of the terrain. As performed at CMU, areas of high relief may require that a subset of the road polygons be used as breaklines to the original triangulation, as the shorelines are used to enhance the accuracy of the triangulation. Figure 10 demonstrates how the use of road polygons as breaklines would enhance the surface representation.

If the road was not used as a constraint but overlaid as described in the next section, the road would not be an accurate representation of its real-world counterpart. Moreover, the road would be at such a slope that the road would not be navigable. For this reason, there are cases in the generation of the database that the roads should be used in the creation of the elevation TIN. Cases

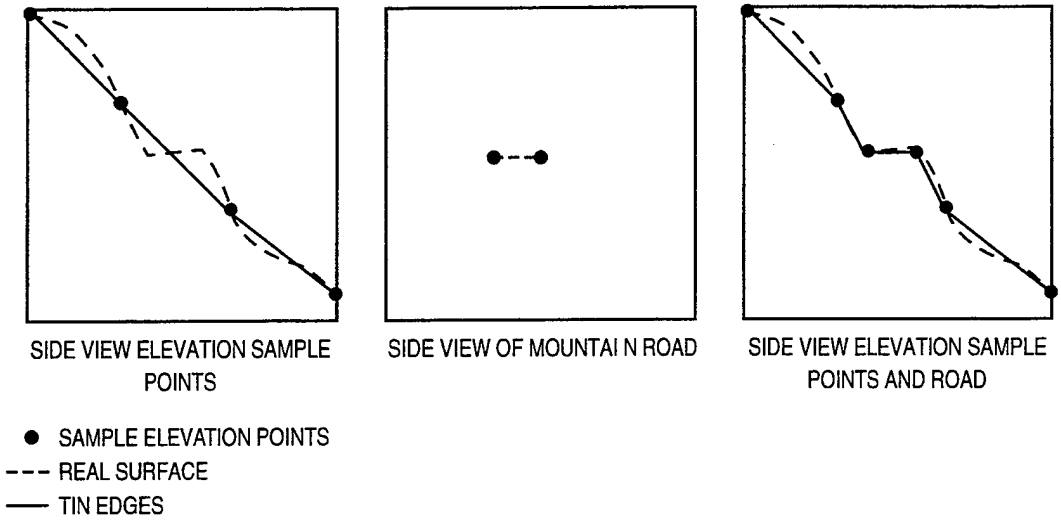


Fig. 10 — TIN enhancement using road polygon

where the terrain is "cut" into or altered by the creation of the road are the most obvious instance, but roads can also be used when the elevation data for the roads are believed to be more accurate than that of the elevation grid or contours available for the region. In these cases, road edges can still be widened by the process described above, but the elevation of each original edge node would be assigned to its new left and right nodes rather than interpolating the value from the elevation TIN. This would ensure that the road is flat from left to right while allowing the road's elevation to increase or decrease from segment to segment.

In summation, human decisions on preprocessing must be made based on knowledge of the terrain and real roads as to whether all or part of the transportation polygons are used to constrain the elevation coverage.

3.3 Polygon to TIN Conversion

The next stage of developing an integrated virtual world is ensuring the correspondence between area features (or road polygons) to the actual terrain representation in the elevation coverage. The process begins with a polygon with absolute x,y boundary coordinates. After determining which triangles contain these points, the polygon is overlaid by dividing it into one or more child polygons based on the elevation TIN edges. Once the child polygons are defined they are triangulated and written to standard EVPF TIN tables. The pseudo-code representation of the overlay process is specified in Fig. 11.

3.3.1 Overlaying the Polygon

The polygon must be broken into child polygons based on the elevation TIN edges to ensure a continuous surface above the terrain. This is necessary because of the change in slope encountered from triangle to triangle as displayed in Fig. 12.

In addition to adding points where polygon segments intersect triangle edges, triangle vertices or even whole triangles must be added when they are contained within the polygon. With these special cases in mind, the process to overlay the polygon can begin.

```
Variables:
    orig_pnts[num_points]          --Original polygon points
    temp_pnts[max_points]          --Original polygon points plus intersections of
                                     polygon and triangle edges
    poly_pnts[max_points]          --Child polygon to be triangulated

Algorithm:
    overlay(triangle, orig_pnts)
    {
      for i: = 0..num_points-1 do
       if (orig_pnts[i] in triangle)
           temp_pnts[count++]: = orig_pnts[i]
           if (orig_pnts[(i+1)% num_points] not in triangle)
               temp_pnts[count++]: = tagged as exit point: intersection of triangle &
                                     segment (orig_pnts[i]..orig_pnts[(i+l)%num_points])
       else if (orig_pnts[(i+1)%num_points] in triangle)
               temp_pnts[count++]: = tagged as entry point:  intersection of triangle &
                                     segment (orig_pnts[i]..orig_pnts[(i+l)%num_points])

      while not all temp_pnts processed
         {
           for i: = 0..count-1 do
             if temp_pnts[i] not processed
                   poly_pnts[poly_count]: = temp_pnts[i]
                 temp_pnts[i]: = processed
             if temp_pnts[i] is exit point
               if  closest entry point (in counterclockwise direction from exit) <i
                 i: = count
             else
                   i: = closest entry point index

           num_triangles += triangulate(poly_pnts)
         }
       for i: = 1..3 do
         if side[i] intersected then overlay(adjacent side[i], orig_pnts)
       for i: = 1..3 do
        if vertex[i] used
           for each triangle, t, using vertex[i]
             if overlay(t, orig_pnts) == 0
               add  t  to final triangle list
      return num_triangles
    }
```

Fig. 11 — Pseudo-code for polygon overlay algorithm

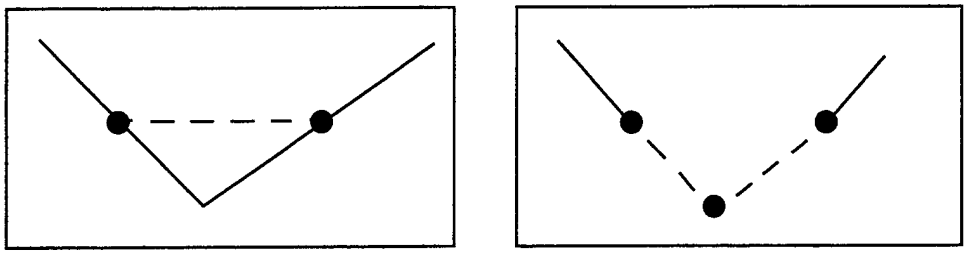


Fig. 12 — Side view of polygon segment spanning two triangles

The first step is to overlay the polygon onto the triangle containing the first polygon point. The algorithm determines the following cases (Table 8) while processing each of the original polygon nodes and takes the appropriate action:

Table 8 — Current and Next Node Position Cases

CURRENT NODE	NEXT NODE (Current + 1) *mod* TOTAL	ACTION
Inside Triangle	Inside Triangle	Add current to new list
Outside Triangle	Inside Triangle	Add intersection of current segment and triangle to list and tag as an entry point
Outside Triangle	Outside Triangle	If intersects triangle, add point of intersection closest to the current node as a point of entry and add the second intersection as a point of exit
Inside Triangle	Outside Triangle	Add intersection of current segment and triangle to list and tag as an exit point

After adding all new points to a list, the points must be converted to child polygon(s). These child polygon(s) must then be triangulated for storage in the EVPF TIN tables. The proposed algorithm constructs these child polygons starting with the first new node (which must be an entry or internal point) and adds it to a final polygon list. Subsequent points are added to the final list until an exit point is encountered. Whenever a point is added to the final list, it is marked as processed so that unprocessed points can be processed in subsequent passes through the new polygon list. When an exit point is found, the closest entry point is found by following the side intersected by the exit point in a counterclockwise direction. If a triangle vertex is found, the vertex is added to the final list and the search continues along the next edge. This process continues until the first entry point is encountered. The entry and exit points always occur in pairs because the polygons being overlaid are regular, enclosed polygons. When the index of the entry point is less

than that of the exit point, the child polygon has been completed. If the index of the entry point is greater than that of the exit point, the list pointer is set to the entry point and points continue to be processed. Figure 13 shows how a polygon with three pairs of exit/entry points is broken into two distinct child polygons that must be triangulated individually, and Fig. 14 shows how the vertices are added to the polygon when there is no entry point along the edge being exited.

The algorithm follows the processing of the triangle containing the first polygon node recursively to ensure that all triangles that are intersected by the polygon are processed as well as the triangles not intersected but contained within the polygon. The first stage of recursion begins by overlaying the polygon onto the triangles adjacent to intersected edges. Whenever a triangle edge is intersected, each triangle sharing that edge has a portion of its area inside the polygon and, therefore, the overlay algorithm must be performed for that triangle. Triangles that are completely internal to the polygon are determined by the triangle vertices that are used to construct triangles intersected by the polygon. All triangles having an interior vertex must be called for processing. If a triangle having an interior vertex is not intersected by the polygon, then it is completely internal to the polygon and the triangle itself should be added to the polygon TIN.

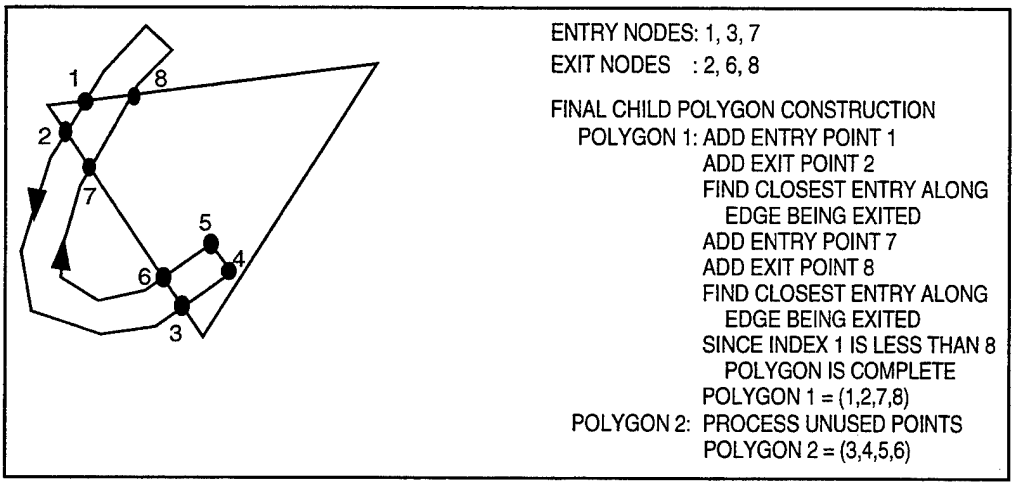


Fig. 13 — Defining distinct intersecting polygons

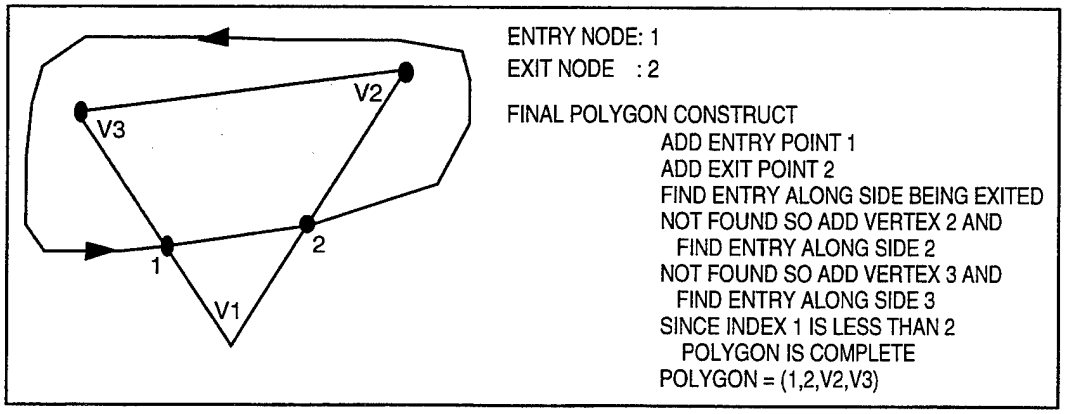


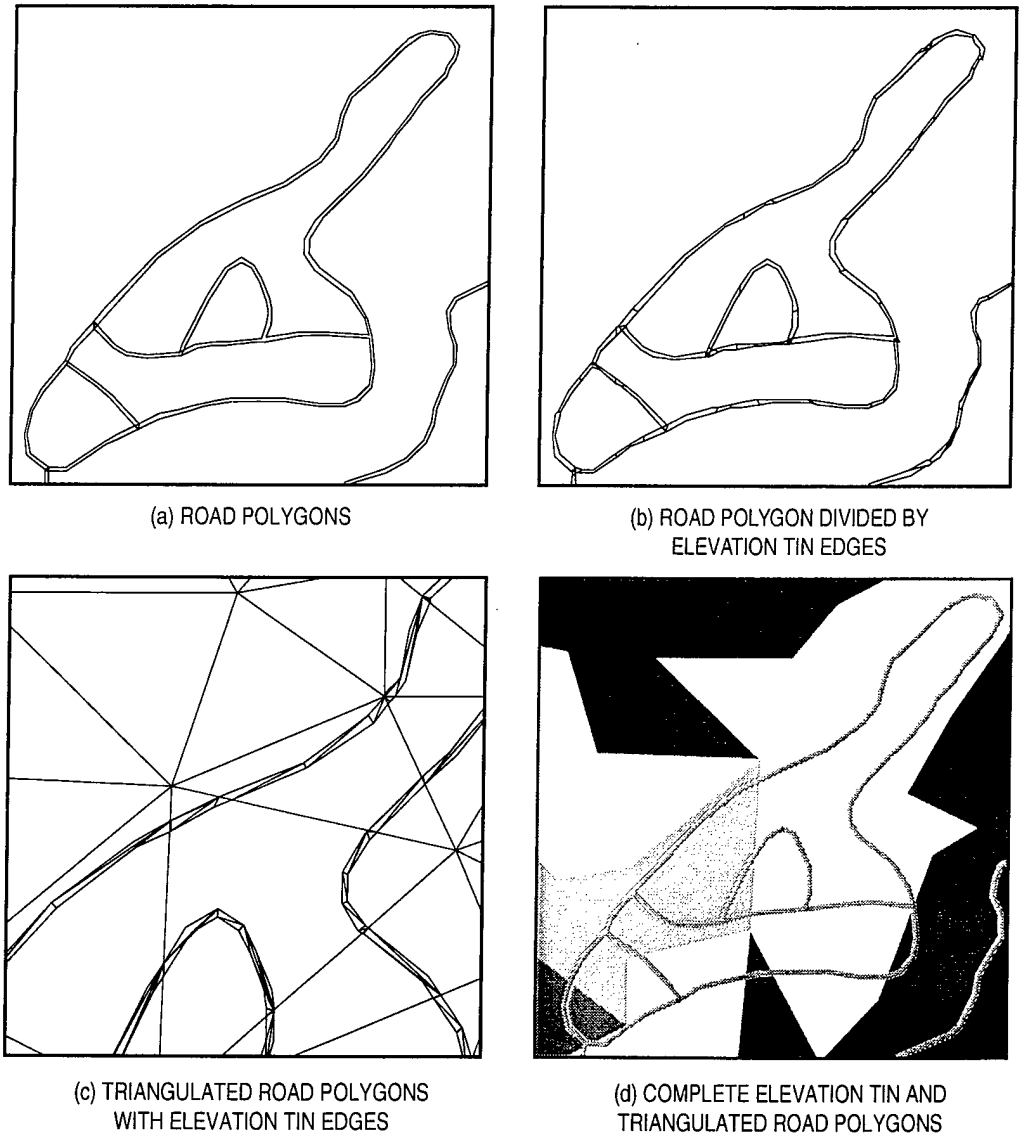
Fig. 14 — Adding triangle vertices

3.3.2 Triangulating Polygons

The child polygons created in the previous section must be triangulated for storage in the EVPF TIN tables. The method of triangulation is derived from the implementation in O'Rourke (1993). Three consecutive polygon vertices are treated as a triangle. If the triangle's sides are not intersected by any polygon edges and are in counterclockwise order (i.e., form a convex angle), the middle vertex is extracted from the list and the three points are stored as a triangle. The algorithm recurses on the remaining vertices (until a single triangle remains). The progression from road polygons to overlaid TINs is exhibited in Fig. 15.

3.3.3 Creation of the EVPF TIN Tables

Once all polygons (i.e., the entire transportation network) have been completely overlaid and triangulated on the TIN mesh, the first_tin for each connected node and the adjacency relations for



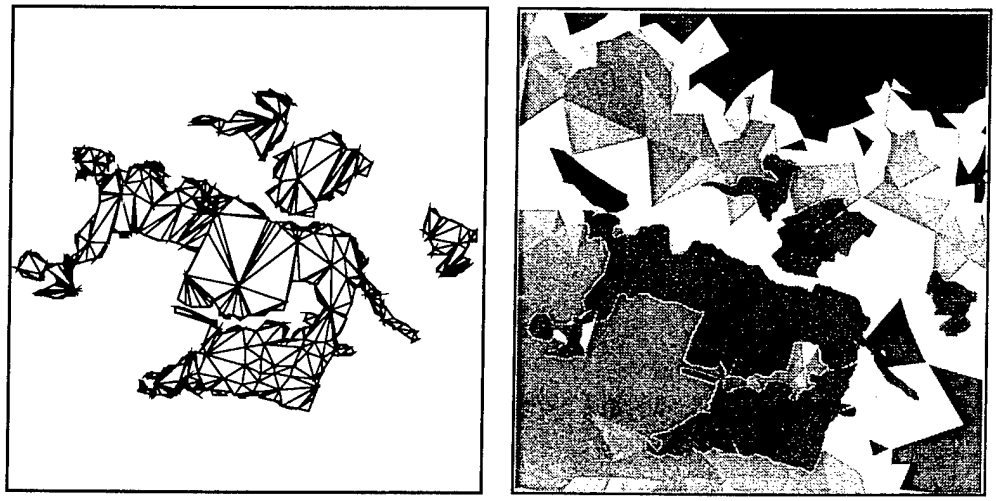
(a) ROAD POLYGONS

(b) ROAD POLYGON DIVIDED BY ELEVATION TIN EDGES

(c) TRIANGULATED ROAD POLYGONS WITH ELEVATION TIN EDGES

(d) COMPLETE ELEVATION TIN AND TRIANGULATED ROAD POLYGONS

Fig. 15 — Integration of transportation network



(a) TRIANGULATED AREA FEATURE

(b) TRIANGULATED AREA FEATURE WITH ELEVATION TIN

Fig. 16 — DTOP woodland area features

each triangle are computed. It is important to note that each original polygon is generally considered as its own TIN. Figure 16 exhibits this property through two completely disjoint area features. There certainly can be situations where two area features connect along edges, at which case there would be adjacency information for the two areas. This displays a key difference and an increased versatility over the VPF face which must completely exhaust the plane. Another improvement over the constraints of a VPF face are the fact that triangles from disjoint TINs can overlap without problems whereas VPF faces are mutually exclusive. Take, for instance, the spatial extent of a university campus being defined as a TIN feature (created as stated above). Individual buildings can also be independently stored as TIN features. The campus triangles and building triangles can then be rendered together (overlapping) or alone. While in this context buildings are considered as a single overlaid polygon, the following section describes a method by which to take that foundation and build a 3-D representation of surface features.

3.3.4 Creation of 3-D Objects

The spatial extent of a real-world, 3-D object, such as a building, can be defined as a polygon. This polygon can be overlaid as described above to adhere to the terrain. Once the foundation is established, the ceiling or top of the building can be defined directly above the base. The building would consist of the triangulated base and ceiling as well as each side. The sides would be defined by two consecutive vertices in the ceilings as well as the nodes below that edge. Note that the base segments may have intersected a triangle edge causing additional nodes to be entered. These sides would be triangulated and hold adjacency relationships to the top and bottom.

4.0 CONCLUSION AND RECOMMENDATIONS

This report has shown how an EVPF compliant product, MSEVP, can easily be generated using existing DMA data and used to store an integrated virtual world (note, this approach has not yet been adopted by DMA). As was shown in Abdelguerfi et al. (1995), the primitive and the feature

tables provide a compact and efficient storage structure for these potentially large data sets. One of the contributions of this work is the establishment of a methodology to construct the elevation TIN and populate the corresponding primitive tables. It has also been demonstrated how this elevation TIN can be used as a foundation from which to build the remaining coverages. One example of this has been presented in the form of an algorithm to widen the transportation network based on the elevation TIN. The expansion of a zero width, edge-based representation to a polygonal-based representation of the transportation network adds real-world dimensions and appearance to the network. An algorithm to overlay polygons of arbitrary size and shape, as those created from the transportation edges, onto the elevation TIN displays an excellent means to provide consistent evaluation values throughout an EVPF compliant database. Given the availability of data, this methodology can also be used to incorporate 3-D objects such as buildings into the virtual world.

The establishment and population of these TIN tables demonstrates VPF's deficiencies in truly representing a virtual world and, correspondingly, EVPF's strengths. Three-dimensional objects such as buildings can be stored as TIN objects but not as a collection of VPF faces. The only method for VPF to store 3-D features is via the face primitives, which by current definition must be mutually exclusive in the xy plane within a coverage. TIN primitives are truly 3-D in allowing triangles that compose an object to occupy the same xy coordinate while existing on different planes and meeting only at edges.

Although the research at CMU has resulted in a different method for representing the virtual world, the approach taken here is more appropriate, considering the disjoint nature of VPF coverages. The CMU method would result in a high storage cost for the elevation TIN as well as the duplication of information from other coverages in the elevation coverage. When viewed in the context of VPF, these methods of constructing EVPF and MSEVP prototype not only address many of the M&S requirements but also establish a solid foundation from which to expand to meet future M&S needs.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

Abdelguerfi, M., E. Cooper, and Christ Wynne, "Development of an Object-Oriented Digital Mapping Database with Modeling and Simulation Extensions to be Compared to an Extended VPF Database: An Extended Vector Product Format (EVPF)," Progress Report, Computer Science Report, University of New Orleans, New Orleans, LA, Oct 1995.

Defense Mapping Agency, "Digitizing the Future," Fairfax, VA, 1993.

Department of Defense, "Vector Product Format – Military Standard," MIL-STD 2407, May 1993.

O'Rourke, J. "Computational Geometry in C," Cambridge University Press, New York, NY, 1993.

Polis, M. F., J. G. Gifford, and J. McKeown, "Automating the Construction of Large-Scale Virtual Worlds," *IEEE Computer* **28**(7), 58–64 (1995).

Shaw, K., S. Kuder, S. Carter, S. Coughlan, J. Richard, C. Martin, C. Brown, H. Mesick, V. Miller, and R. Broome, "Comprehensive Analysis of Navy and Marine Corps Digital Mapping, Charting, and Geodesy Requirements for Modeling and Simulation," NRL/FR/7441--93-9435, Naval Research Laboratory, Stennis Space Center, MS, 1995.

Shaw, K., V. Miller, B. Ray, R. Broome, T. Lovitt, M. Abdelguerfi, E. Cooper, and C. Wynne, "An Extended Vector Product Format Profile for Modeling and Simulation," NRL/MR/7441--95-7704, Naval Research Laboratory, Stennis Space Center, MS, 1996.