Short Papers

A Linear Time Algorithm for Computing Exact Euclidean Distance Transforms of Binary Images in Arbitrary Dimensions

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Abstract—A sequential algorithm is presented for computing the exact Euclidean distance transform (DT) of a k-dimensional binary image in time linear in the total number of voxels N. The algorithm, which is based on dimensionality reduction and partial Voronoi diagram construction, can be used for computing the DT for a wide class of distance functions, including the $L_p$, and chamfer metrics. At each dimension level, the DT is computed by constructing the intersection of the Voronoi diagram whose sites are the feature voxels with each row of the image. This construction is performed efficiently by using the DT in the next lower dimension. The correctness and linear time complexity are demonstrated analytically and verified experimentally. The algorithm may be of practical value since it is relatively simple and easy to implement and it is relatively fast (not only does it run in $O(N)$ time but the time constant is small). A simple modification of the algorithm computes the weighted Euclidean DT, which is useful for images with anisotropic voxel dimensions. A parallel version of the algorithm runs in $O(N/p)$ time with $p$ processors.

Index Terms—Euclidean distance transform, closest feature transform, Voronoi diagram.

1 INTRODUCTION

A k-dimensional (k-D) binary image is a function $I$ from the elements of an $n_1 \times \cdots \times n_k$ array to $\{0, 1\}$. The elements are called pixels when $k = 2$ and voxels when $k \geq 3$. Voxels of value 0 and 1 are called background voxels and foreground or feature voxels (FVs), respectively. For a given distance metric, the distance transform (DT) of an image $I$ is an assignment to each voxel $x$ of the distance between $x$ and the closest feature voxel (CFV) in $I$. The closest feature transform (FT), also known as the nearest feature transform and the nearest neighbor transform, of an image $I$ is an assignment to each voxel $x$ of the identity of the CFV in $I$. It is clear that a DT can be computed from a FT in time linear in the total number of voxels $N = n_1 \times \cdots \times n_k$.

DTs are useful for a variety of image processing and computer vision applications [25]. Examples include nearest-neighbor interpolation, planar tessellation, morphological image processing (e.g., thinning, thickening, and skeletonization), pattern matching (e.g., object detection and stereo feature matching), robot collision avoidance, and path finding. DTs are widely used in medical image processing. For example, in surface-based image registration, the DT of a binary image in which the FVs represent a surface provides a convenient and efficient method for precomputing and storing point-to-surface distance [12, 14], [19], [39], [40]. DTs have also been used in nonrigid image registration [22], [27], morphological image segmentation [15], volume visualization (distance-based acceleration techniques for ray-tracing) [37], [49], and shape-based interpolation [16], [32].

The Euclidean DT (EDT) is the DT for which the metric is Euclidean distance. Sometimes the DT is used, but often, even when an exact DT is desired, an approximation of the DT such as the chamfer DT is used because it is substantially faster to compute. For some applications, an exact DT is required. For example, various approximations of the EDT have been used to generate skeletons of binary objects [1], [24], but only the exact EDT can produce an accurate skeleton that is reversible (i.e., allows exact reconstruction of the object), rotation invariant, and minimal [13]. The 3D EDT has recently been used to generate skeletons of radiosurgical targets (e.g., brain tumors) for treatment planning and optimization in multiscan stereotactic radiosurgery [45], [46].

The exact EDT of a k-D image can obviously be computed by using a brute-force exhaustive search for CFVs, which is a procedure that inherently requires $O(N^2)$ time. Algorithms for computing the exact EDT of a 2D image have been reported that require $O(N^{3/2})$ time [25], [26], and $O(N \log N)$ time [20]. It is clear that the exact EDT of a k-D image can be computed in $O(N \log N)$ time by calculating the Voronoi diagram of the FVs [6], [29]. A relatively efficient, but not linear time, algorithm for computing the DT of a k-D image was achieved using gray-scale morphology decomposition [18].

A substantial amount of effort has been devoted to algorithms that compute the DT by propagation. One type of algorithm propagates distance values from voxels to neighboring voxels. Algorithms that require $O(N)$ time for computing the DT of a k-D image for the $L_1$, $L_{\infty}$, and chamfer (a weighted $L_1$ metric that provides an approximation to the $L_2$ metric) metrics with a two-pass sequential raster scan are well-known [4], [5], [25], [26], [34], [35], [48]. The weights in the kernel (propagation mask) can be chosen to optimize the approximation of a chamfer DT to the EDT [3], [5], [33], [38], [41], [44]. This type of approach has also been used to compute constrained DTs, which are DTs where distance is defined only within a specified constraint region [28], [42]. An alternative type of algorithm propagates the position of the CFV (a vector pointing to the CFV) rather than distance (a scalar). This idea was originally proposed as a sequential raster-scan algorithm for 2D images [9] and was later generalized to arbitrary dimensions [31] and images with anisotropic voxel dimensions [23]. These raster-scan algorithms require $O(N)$ time and produce an approximate EDT with small error (the maximum error in 2D is less than one pixel [9]). An alternative to raster-scan propagation is ordered propagation. In these algorithms, the information (distance [28], [42] or a vector pointing to the CFV [8], [10], [30], [43]) is propagated from each voxel to its neighbors, starting from the contours of the object and using a dynamic list to store the pixels in the propagation front. Standard propagation algorithms provide only approximate EDTs because the tiles of the Voronoi diagram on a discrete lattice are not necessarily connected sets (the tiles on a continuous plane are connected sets). Parallel algorithms can overcome this limitation and provide exact EDTs by allowing multiple propagation fronts to follow each other [11], [18], [47]. Ordered propagation can provide an exact EDT by emulating multiple-front propagation [10], [23], [30], but the multiple propagation mechanics common to these exact EDT algorithms require many unnecessary computations while successive propagation fronts reach the same voxel and update its value, and these algorithms require $O(N^{3/2})$ time for some 2D images [8]. One recent algorithm first computes an approximate EDT using an ordered propagation scheme and then produces an exact EDT by restoring the connectivity of the Voronoi tiles by considering larger neighborhoods on the tile boundaries [8] (a similar approach using raster-scan propagation has also been reported [7]). This is the only propagation algorithm we are aware of that produces an exact EDT in apparently $O(N)$ time, but the time complexity was verified only experimentally, and extension to multidimensional or anisotropic images has not been reported.

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Saito and Toriwaki [36] presented an algorithm for computing the exact EDT of a 2D or 3D image that is based on dimensionality reduction, that is, at each dimension level, the EDT is determined by using the EDT in the next lower dimension. They used some geometrical bounds to reduce search intervals. The computational cost of their algorithm is image dependent and requires \(O(N^{3/2})\) time for some 2D images; this time complexity has been observed experimentally by us (unpublished) and others [7, 8]. Breu et al. [6] presented an algorithm which also uses the idea of dimensionality reduction for computing the Euclidean FT of a 2D image in \(O(N)\) time by constructing the intersection of the Voronoi diagram whose sites are the FVs with each row of the image. Then, the EDT is computed from the FT. Guan and Ma [17] improved the computational performance of the Breu approach by taking advantage of the fact that neighboring voxels tend to have the same CFVs. They propagate CFV information in the form of the slice thickness \((3D\text{ image volumes are frequently stacks of 2D image slices where} \)for images with anisotropic voxel dimensions. For example, medical images.

Property 3. Triangle inequality. \(\Delta(x, y) \leq \Delta(x, z) + \Delta(y, z)\) for any \(x, y, \) and \(z\).

Property 4. Monotonicity. Let \(x\) and \(y\) be two \(k\)-tuples that differ only in the values of the \(d\)th coordinates \((i.e., x_i = y_i, i \neq d)\). For concreteness, assume that \(x_d < y_d\). For any \(u\) and \(v\) such that either

\[\Delta(u, v) \leq \Delta(x, v) \text{ and } \Delta(y, v) < \Delta(u, v) \text{ or } \Delta(x, u) < \Delta(u, v) \text{ and } \Delta(y, v) \leq \Delta(u, v) \text{ holds, } u_d < v_d.\]

Property 5. Let \(x\) and \(y\) be two \(k\)-tuples that differ only in the values of the \(d\)th coordinates \((i.e., x_i = y_i, i \neq d)\). Let \(u\) and \(v\) be two \(k\)-tuples with identical values of the \(d\)th coordinates \((i.e., u_d = v_d)\). If \(\Delta(x, u) \leq \Delta(x, v), \text{ then } \Delta(u, y) \leq \Delta(y, v).\)

It is well known that the \(L_p\) weighted \(L_p\) and chamfer metrics satisfy Properties 1-4. Property 5 follows from the contrapositive of Property 4. Thus, any distance function that satisfies Property 4 also satisfies Property 5. Property 5 is not an independent property, but it is convenient to include for later reference.

In the next section, we give an algorithm for computing the FT of a \(k\)-D binary image for any dimensionality that satisfies Properties 1, 2, 3, 4, and 5. This algorithm is not appropriate for all distance functions. For example, consider the distance function \(\Delta(x, y) = |x_i - y_i|\), which is given as an example in [26]. This function satisfies Properties 2 and 5 but not 1, 3, and 4.

3 The Feature Transform Algorithm

The Voronoi diagram \(V_d\) of a set of Voronoi sites \(S = \{v\}\) for \(i = 1, \ldots, n_s\) consists of a set of disjoint Voronoi cells \(V = \{C_i\}\) for \(i = 1, \ldots, n_s\) [2, 29]. The Voronoi cell \(C_i\) is the set of all points whose closest point is \(f\) together with the cell boundary formed by points equidistant from \(f\) and one or more other Voronoi sites. The Voronoi site \(f\) is also known as the Voronoi center of \(C_i\). The FT of a binary image can be thought of as a discretized version of the Voronoi diagram whose Voronoi sites are the FVs of the image. If the complete Voronoi diagram is constructed, the FT can be computed easily by querying the Voronoi diagram, i.e., by recording for each voxel the Voronoi site of the Voronoi cell in which the voxel lies. In this algorithm, we do not construct the complete Voronoi diagram. Instead, our approach is based on the idea of dimensionality reduction and partial Voronoi diagram construction. At each dimension level, the FT is determined by constructing directly the intersection of the Voronoi diagram whose Voronoi sites are the FVs with each row of the image. This construction is performed efficiently by using the FT in the next lower dimension.

The algorithm takes as input the \(k\)-D binary image \(I : [1..n_1] \times \ldots \times [1..n_k] \rightarrow \{0, 1\}\) and outputs the FT

\[F : [1..n_1] \times \ldots \times [1..n_k] \rightarrow [1..n_1] \times \ldots \times [1..n_k].\]

For each voxel \(x\) in \(I, F(x)\) is the CFV in \(I\). If two or more FVs are equidistant from \(x\), then one of them is chosen arbitrarily to be \(F(x)\).

The DT can be computed easily from \(F\). Let \(I_{x_k}\) denote the \(d\)-dimensional subimage that is the restriction of \(I\) to the subspace whose last \(k-d\) coordinates are identical to the corresponding coordinates of \(x\). Let \(F_0\) denote the FT at the \(d\)th dimension level, where for each voxel \(x\) in \(I, F_0(x)\) is the CFV in \(I_{x_d}\). If two or more FVs are equidistant from \(x\), then one of them is chosen arbitrarily to be \(F_0(x)\).


### 2 Distance Functions and Properties

We are interested in the \(L_p\) distance metric

\[
\Delta(x, y) = \left( \sum_{i=1}^{k} |x_i - y_i|^p \right)^{1/p},
\]

where \(x\) and \(y\) are \(k\)-tuples, \(x_i\) and \(y_i\) are the \(i\)th coordinates of \(x\) and \(y\), and \(1 \leq p \leq \infty\). The \(L_1\), \(L_2\), and \(L_\infty\) metrics are known as the Manhattan or city-block, Euclidean, and chessboard distances, respectively. We are also interested in the weighted \(L_p\) distance metric

\[
\Delta(x, y) = \left( \sum_{i=1}^{k} |w_i(x_i - y_i)|^p \right)^{1/p},
\]

where \(w_i\) is the weight of the \(i\)th coordinate of \(x\) and \(y\). This is useful for images with anisotropic voxel dimensions. For example, medical 3D image volumes are frequently stacks of 2D images. The slice thickness \(w_i\) is different from the in-slice pixel size \(w_i = w_{xy}\). We are interested specifically in Euclidean and weighted Euclidean distance. We are interested more generally in distance metrics \(\Delta : \mathbb{R}^k \times \mathbb{R}^k \rightarrow \mathbb{R}\) that satisfy the following properties:

**Property 1.** Positive definiteness. \(\Delta(x, y) = 0\) if and only if \(x = y\).

**Property 2.** Symmetry. \(\Delta(x, y) = \Delta(y, x)\) for any \(x\) and \(y\).

**Property 3.** Triangle inequality. \(\Delta(x, z) \leq \Delta(x, y) + \Delta(y, z)\) for any \(x\), \(y\), and \(z\).

**Property 4.** Monotonicity. Let \(x\) and \(y\) be two \(k\)-tuples that differ only in the values of the \(d\)th coordinates \((\text{i.e., } x_i = y_i, i \neq d)\). For concreteness, assume that \(x_d < y_d\). For any \(u\) and \(v\) such that either

1) \(\Delta(u, v) \leq \Delta(x, v)\) and \(\Delta(y, v) < \Delta(u, v)\) or
2) \(\Delta(x, u) < \Delta(u, v)\) and \(\Delta(y, v) \leq \Delta(u, v)\) holds, \(u_d < v_d\).
Remark 1. Let \( f = F_{d-1}(x) \), where \( x \) is a voxel on the row \( S_d \).
Clearly, the \( R \) and \( g \) be any other FV belonging to the set \( S_d \) such that \( f \) and \( g \) have identical values of the \( d \)th coordinate (i.e., \( f_0 = g_0 \)). From the definition of \( F_d \), \( \Delta(x, f) \leq \Delta(x, g) \). Let \( y \) be any other point on the row \( R_d \). By Property 5, \( \Delta(y, f) \leq \Delta(y, g) \), i.e., all points on the row \( R_d \) are at least as close to \( f \) as they are to \( g \). This means that either the Voronoi cell for site \( g \) does not intersect \( R_d \) (\( \Delta(x, f) < \Delta(x, g) \)), or that the Voronoi cells for sites \( f \) and \( g \) both intersect \( R_d \) along a common boundary (\( \Delta(x, f) = \Delta(x, g) \)). The choice of \( f \) or \( g \) is arbitrary. Since all FVs in the set \( S_d \) are in the set \( S_d' \) or have the same \( d \)th coordinate as a FV in the set \( S_d' \), \( V_d = V_{S_d} \cap R_d = V_{S_d} \cap R_d \). Thus, to construct \( V_d \), it is sufficient to consider the set \( S_d' \) (rather than the larger set \( S_d \)).

Let \( S_d \) denote the subset of \( S_d \) that are the Voronoi sites (FVs) of Voronoi cells in \( V_{S_d} \), i.e., that are the Voronoi sites of Voronoi cells in \( V_{S_d} \) that intersect \( R_d \). Clearly, \( S_d \subseteq S_d \subseteq S_d \). Fig. 1 shows an illustrative example of the relationship among \( S_d, S_d' \), and \( S_d \).

Remark 2. Let \( f \) and \( g \) be FVs belonging to the set \( S_d' \). Let \( x \) and \( y \) be voxels on the row \( R_d \) that lie in the Voronoi cells \( C_d \) and \( C_g \), respectively. By Property 4, if \( x_0 < y_0 \), then \( f_0 < g_0 \). Also, if \( f_0 < g_0 \), then \( x_0 < y_0 \). Thus, \( V_d \) is a set of disjoint line segments \( V_d = \{ C_d \} \), where the set of Voronoi sites (FVs) \( S_d \) are sorted by the \( d \)th coordinate, the associated Voronoi cells are similarly ordered. That is, as the row \( R_d \) is traversed from low values of the \( d \)th coordinate to high values, \( C_d \) is visited before \( C_g \) iff \( f \) precedes \( g \) in the ordered set \( S_d' \). To compute \( F_d \) for each voxel on the row \( R_d \), it is not necessary to actually construct \( V_d \) = \( \{ C_d \} \). It is sufficient to determine the ordered set \( S_d' \) and visit each voxel by traversing the row in \( d \)th coordinate order.

Remark 3. Let \( u, v, \) and \( w \) be three FVs belonging to the set \( S_d' \). Clearly, \( S_d \subseteq S_d \subseteq S_d \). As noted in Remark 1, it is sufficient to consider the set \( S_d' \). Let \( x_{eq} \) denote the point on the line \( R_d \) that is equidistant from \( u \) and \( v \), i.e., \( \Delta(u, x_{eq}) = \Delta(v, x_{eq}) \), and let \( (x_{eq})^{**} \) denote the \( d \)th coordinate of this point. Let \( x_{eq}' \) denote another point defined analogously. By Property 4 and Remark 2, \( C_0 \) does not intersect \( R_d \) if \( (x_{eq})^{**} > (x_{eq})^{**} \).

The algorithm for computing the FT \( F \) from the binary image \( I \) is performed with the initial invocation \( \text{COMPUTEFT}(k) \). The algorithm variables \( I, F, n_1, \ldots, n_k \) are passed as global variables. The procedure \( \text{COMPUTEFT} \) (Fig. 2) implements dimensionality reduction using recursion. The procedure \( \text{VORONOIFT} \) (Fig. 3) constructs and queries the partial Voronoi diagram \( V_d = V_{S_d} \cap R_d = V_{S_d} \cap R_d \). The algorithm variable \( F \) contains successively \( F_0, F_1, \ldots, F_{k-1}, F_k = F \). It contains \( F_{d-1} \) before the call to \( \text{VORONOIFT} \) and \( F_d \) upon return. The algorithm does not actually construct \( V_d \) upon return but instead determines the ordered set \( S_d' \) (VORONOIFT, lines 1-14) and queries the diagram (visits each voxel) by traversing the row in \( d \)th coordinate order (lines 18-24). The set \( S_d' = \{ g \} \) is constructed from the set \( S_d = \{ f \} \) by deleting those FVs in \( S_d' \) that are the Voronoi sites of Voronoi cells that do not intersect \( R_d \). As noted in Remark 1, it is sufficient to consider the set \( S_d' \). This is the fundamental basis of the dimensionality reduction approach. The set \( S_d \) is constructed in lines 1-14. It is initialized with the first two FVs of \( S_d \). In the outer loop, additional FVs are added from \( S_d' \) one at a time. In the inner loop, FVs that are the Voronoi sites of
Voronoi cells that do not intersect $R_d$ are removed. This is accomplished with the procedure \textsc{RemoveFT}$(u,v,w,R_d)$, which returns TRUE if $(x_{\text{FV}})_d > (x_{\text{FV}})_d$ FALSE otherwise (see Remark 3). Let $S'_d = \{g_1, \ldots, g_i, x_{\text{FV}}, \ldots, x_{\text{FV}}\}$ denote an intermediate set of FVs during construction. Before entering the outer loop, $S'_d = \{f_1, \ldots, f_d\} = S'_0$. It is easy to verify that at the end of the inner loop, $V_{\text{FV}} \cap R_d = V_{\text{FV}} \cap R_d$. It is also easy to verify that at the end of the inner loop, all Voronoi cells in $V_{\text{FV}} \cap R_d$. Thus, after exiting the outer loop, $S'_d = \{g_1, \ldots, x_{\text{FV}}, \ldots, x_{\text{FV}}\} = S'_d$. In summary,
\[
V_d = V_{\text{FV}} \cap R_d = V_{\text{FV}} \cap R_d = V_{\text{FV}} \cap R_d.
\]

There are two subtleties in \textsc{VoronoiFT}, line 20 worth noting. First, although an if statement may seem sufficient, in fact the \textbf{while} statement is necessary. The reason is that although the FT is discrete, the Voronoi diagram $V_{\text{FV}}$ and the row $R_d$ are continuous. All Voronoi cells in $V_{\text{FV}} \cap R_d$ may contain several cells, even if index $d$ only where the $\text{th}$ coordinate is negative (an example is illustrated in Fig. 1). Also, it is possible that a Voronoi cell in $V_{\text{FV}} \cap R_d$ intersects $R_d$, but the first several cells may, for example, intersect $R_d$ only where the $\text{th}$ coordinate is negative (an example is illustrated in Fig. 1). Also, it is possible that a Voronoi cell in $V_{\text{FV}} \cap R_d$ intersects $R_d$ only between two consecutive voxels $x_i$ and $x_{i+1}$ and, thus, the intersection does not contain any voxel on $R_d$. Second, the "$>"$ symbol in the distance comparison could be replaced with the "$\geq"$ symbol. When two FVs are equidistant from the voxel $x_i$, $F_0(x_i)$ is not unique and the choice is arbitrary.

Initialization of $F_0$ (\textsc{ComputeFT}, lines 2-8) takes $O(N)$ time. At each dimension $d$, the procedure $\textsc{ComputeFT}$ is executed for each of the $N/nd$ rows. For each row, construction of $S'_d$ takes $O(nd)$ time, since there are $nd$ FVs in $S'_d$ and each FV is added to and removed from $S'_d$ at most once. This assumes that calculating $x_{\text{FV}}$ requires $O(1)$ time. Querying (visiting each voxel by traversing the row) simply requires $O(nt)$ time. Thus, at each dimension, the time complexity is $O(nx \times N/nd) = O(N)$, and the algorithm for computing the FT of $I$ runs in $O(N)$ time. Finally, it is clear that the DT of $I$ can be computed from the FT in $O(N)$ time.

4 The Euclidean Distance Transform Algorithm

If the distance metric is the $L_2$ metric (Euclidean distance), then the procedure \textsc{RemoveFT} can be implemented simply using only integer arithmetic. The distance between $u$ and $x_{\text{FV}}$ can be computed as

1. $l \leftarrow 0$
2. $l \leftarrow 1$
3. $x_l \leftarrow (j_1, \ldots, j_{d-1}, 1, j_{d+1}, \ldots, j_k)$
4. if $(f_l \leftarrow F(x_l)) \neq 0$
5. if $l < 2$
6. $l \leftarrow 1 + l$
7. $f_l \leftarrow f_l$
8. $\text{while } l \geq 2 \text{ and } \text{RemoveFT}(g_{l-1}, f_l, g_l, R_d) \text{ do}$
9. $l \leftarrow l - 1$
10. $\text{endwhile}$
11. $l \leftarrow 1 + l$
12. $f_l \leftarrow f_l$
13. $\text{endif}$
14. $\text{endif}$
15. if $(f_l \leftarrow 0)$
16. $f_l \leftarrow f_l$
17. $\text{return}$
18. $\text{endif}$
19. $\text{if}$
20. $\text{endif}$
21. $\text{return}$
the squared EDT algorithm procedures COMPUTEEDT (Fig. 4) and VORONOIEDT (Fig. 5).

The algorithm for computing the squared EDT \( D \) from the binary image \( I \) is performed with the initial invocation COMPUTEEDT \( (k) \). The algorithm variable \( D \) contains successively \( D_0, D_1, \ldots, D_k \), and \( D_k = D \). It contains \( D_{d-2} \) before the call to VORONOIEDT and \( D_d \) upon return. In VORONOIEDT, the procedure variable \( f_i = D_{d+1} (x_i) = \Delta^2 (f_i, \mathcal{R}_d), g_i = \Delta^2 (g_i, \mathcal{R}_d) \), and \( h_i \) is the \( d \)th coordinate of \( g_i \). The FV deletion procedure for the squared EDT algorithm is REMOVEEDT \( (\Delta^2 (v, \mathcal{R}_d), \Delta^2 (v, \mathcal{R}_d), \Delta^2 (v, \mathcal{R}_d), w_0, w_1, w_2) \), which returns TRUE if the inequality in (2) holds, FALSE otherwise.

5 DISCUSSION

The EDT algorithm as presented above produces the squared EDT for isotropic voxels of unit dimension. All computations can be implemented in integer arithmetic. The EDT can obviously be obtained simply from the algorithm output by taking the square root of each element. The output can be scaled to account for the root of each element. All computations can be implemented in integer arithmetic. The EDT can obviously be implemented more efficiently as a simple forward-and-reverse distance propagation than as a call to the procedure VORONOIEDT. This requires a maximum of eight integer arithmetic operations per voxel. Also, we note that the number of arithmetic operations in VORONOIEDT, line 20, can be reduced by taking advantage of similarities in successive computations instead of treating them as independent ones; the distance comparison requires only four arithmetic operations when \( l \) is incremented. Using these simple optimizations, the squared EDT algorithm requires a maximum of \( 8 + 33(k - 1) \), which is 41 for \( k = 2 \) and 74 for \( k = 3 \), integer arithmetic operations per voxel, not including index increment/decrement, indirect, and assignment operations.

The squared EDT algorithm executes substantially faster than the FT algorithm because much of the distance computation necessary for the FV deletion procedure (see (2)) is inherently stored in \( D_{d-1} \). We measured the execution time of straightforward (but not necessarily well optimized) implementations of the FT and squared EDT algorithms for 2D and 3D images over a wide range of sizes and content. Our tests included images with a single FV in a corner; images with randomly generated FVs where the number of FVs was set at 1, 2, 5, 10, 20, 50, 80, 90, 95, 98, or 99 percent; images with solid circles/spheres or squares/cubes where the number, size, position, and orientation of the objects were randomly generated; and medical images (CT and MR images) of heads, where FVs were obtained using various edge operators. The fastest execution times occurred for the special cases of one FV in a corner or with a small number of randomly generated FVs. This is probably due to the fact that for images with sparse FVs, execution of line 8 in VORONOIEDT is frequently skipped. Except for these special cases, the execution times were remarkably constant and independent of image content, and there was little variation of execution time per voxel with the total number of image voxels \( N \). The execution time of the squared EDT algorithm was approximately \( 0.23 \mu s / v o x e l \) (4.3 Mvoxel/s) for 2D and 0.38 \( \mu s / v o x e l \) (2.6 Mvoxel/s) for 3D on a Sun Microsystems SunBlade 2000 workstation with 1.05 GHz UltraSPARC III cpu, and approximately 0.21 \( \mu s / v o x e l \) (4.8 Mvoxel/s) for 2D and 0.36 \( \mu s / v o x e l \) (2.8 Mvoxel/s) for 3D on a PC with 2.2 GHz Pentium 4 cpu. The execution time of the FT algorithm was approximately four times longer in each case than that of the squared EDT algorithm. The memory requirements of the EDT algorithm are approximately half

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**Fig. 4. Procedure ComputeEDT \( (d, j_{d1}, \ldots, j_{dk}) \).**

```plaintext
1. if \( d = 1 \) then /* Compute \( D_{d-1} \) */
2. for \( i_1 \leftarrow 1 \) to \( n_{d1} \) do
3. if \( I (i_1, j_{d1}, \ldots, j_{dk}) = 1 \) then
4. \( D (i_1, j_{d1}, \ldots, j_{dk}) \leftarrow 0 \)
5. else
6. \( D (i_1, j_{d1}, \ldots, j_{dk}) \leftarrow \infty \)
7. endif
8. endfor
9. else
10. for \( i_d \leftarrow 1 \) to \( n_{d} \) do
11. \( D (i_1, i_2, \ldots, i_d, j_{d1}, \ldots, j_{dk}) \leftarrow \infty \)
12. endfor
13. \ldots
14. for \( i_{d-1} \leftarrow 1 \) to \( n_{d-1} \) do
15. \( \text{VORONOIEDT}(d, i_1, \ldots, i_{d-1}, j_{d1}, \ldots, j_{dk}) \)
16. endfor
17. \ldots
20. endfor
21. return
```

**Fig. 5. Procedure VORONOIEDT \( (d, j_{d1}, \ldots, j_{dk}) \).**

```plaintext
1. \( l \leftarrow 0 /* \text{Construct partial Voronoi diagram} */
2. for \( i \leftarrow 1 \) to \( n_{d} \) do
3. \( x_i \leftarrow (j_1, \ldots, j_{d-1}, i, j_{d+1}, \ldots, j_{dk}) \)
4. if \( (f_i - D (x_i)) \neq 0 \) then
5. if \( l < 2 \) then
6. \( l \leftarrow l + 1, g_i \leftarrow f_i, h_i \leftarrow i \)
7. else
8. while \( l \geq 2 \) and \( \text{REMOVEEDT}(g_{l-1}, g_l, f_l, h_{l-1}, h_l, i) \) do
9. \( l \leftarrow l - 1 \)
10. endwhile
11. \( l \leftarrow l + 1, g_i \leftarrow f_i, h_i \leftarrow i \)
12. endif
13. endif
14. endfor
15. if \( (n_{d} \leftarrow l) = 0 \) then
16. return
17. endif
18. \( l \leftarrow 0 /* \text{Query partial Voronoi diagram} */
19. for \( i \leftarrow 1 \) to \( n_{d} \) do
20. while \( l < n_{d} \) and \( g_i + (h_l - i)^2 > g_{l+1} + (h_{l+1} - i)^2 \) do
21. \( l \leftarrow l + 1 \)
22. endwhile
23. \( D (x_i) \leftarrow g_i + (h_l - i)^2 \)
24. endfor
25. return
```
that of the FT algorithm because no intermediate FT is computed. We also experimentally verified the correctness of the squared EDT algorithm by comparing the output with EDTs computed using two other algorithms [18], [36] and an implementation based on k-D binary search trees. We observed no differences between the outputs of the squared EDT algorithm and the outputs of the other algorithms for more than one million randomly generated tests.

Because both the FT and squared EDT algorithms work one row at a time, they can be easily parallelized. Since the \(N/\nu_x \) row computations at the \(d\)th dimension level are independent of each other, all computations at the \(d\)th dimension level can be performed in \(O(\nu_x \times N/\nu_x \times 1/p) = O(N/p)\) time with \(p\) processors, \(1 \leq p \leq N/\nu_x\). Thus, parallel versions of these algorithms run in \(O(N/p)\) time with \(p\) processors, \(1 \leq p \leq \min(n_1, \ldots, n_d)\). This approach is similar to the parallel method in [36]. It is fundamentally different from the one in [11], which is a divide-and-conquer algorithm that parallelizes a raster-scan propagation DT algorithm [21].

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