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Original paper

A new algorithm to compute an unbranched subset of the medial axis

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Abstract: This paper introduces an innovative algorithm, The Curve of Incircles (IncirCu), designed to compute an unbranched subset of a shape's medial axis (MA). The medial axis itself is a skeletal representation that encapsulates the shape's interior, making it invaluable in various shape analysis applications. Traditionally, the medial axis is a branched structure, posing significant challenges for applications that rely on a single, unbranched curve. This new algorithm effectively overcomes these challenges by directly computing ordered set of vertices situated on the medial axis points. These vertices can then be transformed into a single polygonal chain that is unbranched and free of loops, effectively eliminating the need for removal of MA branches to obtain a single curve. Consequently, the algorithm is highly applicable in any context that requires an unbranched input curve, such as cartography and land surveying. To validate its performance, the results of IncirCu were compared with those of existing algorithms such as Straight Skeleton, Medial Axis, and iCMR. Conducted tests showed the average distance between the IncirCu output and the reference Medial Axis to be near zero. While the axis comparison against iCMR and the Straight Skeleton revealed differences greater than zero, these discrepancies remained negligible when scaled against the input objects' overall size. It offers a practical solution to a longstanding problem of MA branch elimination, broadening the scope of possible applications and enhancing the efficiency and accuracy of shape analysis in various technical fields connected with civil engineering.

Keywords: shape analysis, geometry processing, unbranched medial axis, polygon collapse

1. Introduction

The Medial Axis (MA), one of the most popular methods to generate the topological skeleton, is a fundamental concept in computational geometry that represents the essence of an object's shape. Introduced by Blum (1967), MA captures an object's core features by identifying points with multiple closest points on the object's boundary. These points, known as medial axis points, form a skeletal structure that highlights the object's salient features. The medial axis has proven to be a powerful tool in a wide range of applications, including shape analysis, classification, segmentation, and pattern recognition.

To understand the idea behind Blum's solution one can use a comparison to the fire spreading through the grassland. Let's assume the shape's boundary is on fire and the flames move inward at the same speed. The set of points indicated by places where at least two different fire fronts meet and both extinguish is the set of medial axis points (Blum, 1967; Chin et al., 1995; Tagliasacchi et al., 2016; Dong et al., 2017). This picturesque idea illustrates the definition of the medial axis as a locus of points of an ambient space with more than one distance realizing point in the set (Bialozyt, 2022). If each point preserves information about its distance to the boundary, the medial axis skeleton can be interpreted as a lossless shape descriptor. Due to its computational complexity, it is difficult and expensive to compute accurately medial axis in 3D and higher-dimensional spaces (Culver et al., 2004). Despite the extensive usage, the mathematical theory and notions of medial axes are widely dispersed. Results of late concern mainly the practical aspect of the medial axis. The race for the most efficient algorithm gravitated towards medial axis decompositions and approximation.

Despite its extensive usage, the mathematical theory and fundamental notions of the medial axis are widely dispersed across the literature. Results of late have predominantly concerned the practical aspect of the medial axis, driven by a "race for the most efficient algorithm" (Bialozyt, 2022). Consequently, most contemporary work focuses on medial axis decompositions and approximations, seeking quick computational solutions rather than delving into the theoretical roots and comprehensive understanding of the axis's features. Generally, medial axis algorithms may be classified into four categories: thinning algorithms, distance field computations, algebraic methods, and surface sampling approaches (Foskey et al., 2003).

Most common applications in engineering surveying require algorithms computing unbranched axes. Therefore, skeletonization algorithms, such as the medial axis, are omitted, or additional computations are needed to extract an unbranched subset. In this paper, the author introduces a novel algorithm to compute an unbranched polygonal chain approximating the medial axis of a 2D polygon. It was designed for surveying applications such as measurements of long structures like chimneys. Similar to the previously conducted studies on algorithms CMR (Buczek, 2017) and iCMR (Buczek, 2022, 2023), the described algorithm requires a division of the object's boundary into two polygonal chains and sets of sampled points on them. Tests were conducted on several theoretical cases of different shapes, and results were compared with the results of iCMR, Medial Axis, and Straight Skeleton algorithms. The obtained results prove the worth of the described algorithm in surveying applications such as polygon collapse, centerline extraction, and assessment of long engineering structures.

2. Medial axis

Researchers studied an entire family of skeletal structures: medial axes, symmetry sets, central sets, Voronoi diagrams, conflict sets, and others (Bialozyt, 2022). Medial Axis-related results were obtained by many scientists (Voronoi, 1908; Erdös, 1945, 1946; Federer, 1959), but the name itself was first used by Blum (1967) in his studies about pattern recognition. The Medial Axes' vital virtues are lossless compression of information about the set shape and the ability to preserve the information about the shape while reducing its complexity (Bialozyt, 2022). Each point of the Medial Axis is equidistant from at least two points on the shape's boundary. If MA points are endowed with their corresponding distances, the complete reconstruction of the entire boundary representation is possible. Such an object is called a Medial Axis Transform (MAT).

Due to these features, Medial Axis algorithms are one of the most commonly used skeletonization techniques. In recent years, the development of efficient algorithms for computing the medial axis has further enhanced its applicability in many fields such as shape analysis (Lee, 1982; Fritsch et al., 1994; Shaked and Bruckstein, 1998; Makem et al., 2014), feature recognition (Cao and Liu, 2008; Makem et al., 2020), computer graphics (Tam and Armstrong, 1991; Fogg et al., 2016), 3D printing (Zhang et al., 2015; Ding et al., 2016), path planning (van Toll et al., 2016), and navigation (Opiyo et al., 2021). Despite the easy-understandable definition (comparison to the grassfire), applications of the medial axis might be limited because of its instability and algebraic complexity (Foskey et al., 2003; Attali et al., 2009; Chambers et al., 2022). The lack of a single, universal method pushes scientists to present novel approaches how to compute the Medial Axis or improve algorithms' results (Choi et al., 1997; Culver et al., 1999, 2004; Lan et al., 2017; Wang et al., 2022; Fontana and Cappetti, 2024).

Chin et al. (1995) presented a simple method to compute the medial axis by defining the boundary polygon's vertices and edges as basic elements. If the distance of a point to two or more basic elements is equal, such a point is considered a point on the medial axis. The set of all the Medial Axis points in a polygon is the medial axis of a polygon. Such a model is very accurate to calculate simple polygons, but not very good for complex polygons, such as polygons containing free curves, arcs, and island holes.

Foskey et al. (2003) described an algorithm θ-SMA to compute a subset of the Medial Axis. The separation angle θ refers to the angle formed by the vectors connecting a point on the medial axis to its corresponding closest points on the object boundary. The θ-SMA is the set of medial axis points for which the separation angle exceeds θ. The presented algorithm is based on a spatial subdivision scheme and uses fast computation of a distance field and its gradient using graphics hardware. The complexity of the algorithm varies based on the error threshold that is used and is a linear function of the input size. As a result, the computed subset of the Medial Axis detects and captures most of the sharp features of the original model. Its performance was constrained by grid resolution, memory usage, and hardware capabilities. In addition, the approach was limited to polygonal models and did not support curved or procedural geometries.

Giblin and Kimia (2004) introduced a hypergraph-based skeletal representation for 3D shapes, grounded in a formal classification of the medial axis's generic structure. They identified five types of skeletal points, categorized by their order of contact, which organize into sheets, curves, and isolated points. Using this structure, they derived a pointwise reconstruction formula that enables surface recovery from the medial axis hypergraph. Their work demonstrates that this representation fully characterizes 3D shapes and supports applications in recognition, morphing, design, and manipulation. The algorithm's primary constraint is the strict classification into five point types, which enforces a hierarchical hypergraph organization essential for efficient skeleton recovery.

Linardakis and Chrisochoides (2006) introduced a Medial Axis- based method for geometric domain decomposition, aimed at improving parallel mesh generation. Their approach ensures that subdomain separators form favorable angles with both internal and external boundaries. The enhanced method (Linardakis and Chrisochoides, 2008) was evaluated using three key criteria: internal boundaries must meet a specified angle tolerance, separator size should be small relative to subdomain area, and subdomain areas should be well-balanced. Their findings show that a static geometric medial axis yields efficient, scalable decompositions with strong geometric integrity, particularly suited for complex 2D domains.

Leonard et al. (2016) presented a novel approach to analyzing the structure of 2D shapes, particularly focusing on their decomposition into parts and the identification of similarities between these parts. The proposed method utilized the medial axis to construct a hierarchical representation of the shape. Unfortunately, any noise on the boundary would produce a new branch of the medial axis. Changes in boundary sampling may change the branching structure, which makes any naïve parts decomposition based on branches unstable. Wang et al. (2021) presented the application of piece-wise B-splines to represent Medial Axis Transforms of binary images. First, the raster's MAT is simplified using a salience metric, then segmented into branches, and finally fitted with B-splines. The result yields a much higher compression ratio at the cost of a slightly lower image quality.

Szombara (2013) proposed a fully automated method for dimension reduction that explicitly ties the collapse decision to the map scale by utilizing the Medial Axis Transform, the standard based on Chrobak's elementary triangle, and the Perkal method's elementary disc. This approach ensures the resulting linear object preserves strict georeference and the essential shape of the original feature, thus producing an unambiguous and objective result regardless of the operator. The core innovation lies in the combination of the Medial Axis Transform with the elementary disc to determine the threshold width at which an areal object must be represented as a line to maintain legibility at the target scale.

Szombara (2015) addressed a critical challenge in cartographic generalization by evaluating the performance of various skeletonization algorithms for simplifying areal objects (polygons) into linear representations (skeletons or centerlines). Specifically, the comparison revealed that the Medial Axis Transform (MAT) yields the most favorable results, consistently producing the smallest distortion and deviation values across the analyzed objects. This finding is significant for applications requiring accurate and geometrically representative reduction of cartographic features, as it suggests the MAT method is superior for maintaining the essential geometry and centeredness of the original areal object in its simplified linear form.

Lewandowicz and Flisek (2020) proposed a structurally robust, vector-based approach to overcome the inherent sensitivity of the Medial Axis Transform to boundary irregularities, especially in complex geometries. The presented approach first involved partitioning the elongated polygon into discrete segments derived from a TIN model or determined perpendicular to the local flow direction. The centerline was subsequently constructed by connecting the calculated midpoints of these cross-sections. This method fundamentally differs from MAT by imposing a topological constraint during construction, effectively preventing the formation of spurious branching artifacts. The resulting centerline was a single, continuous line that more accurately reflected the watercourse's one-dimensional path for hydrological modeling and cartographic generalization.

3. The curve of incircles

The lack of one, universal method applicable to any object or shape drives researchers to develop new algorithms. In this paper, a new algorithm to compute a subset approximating the Medial Axis has been presented. The algorithm is called The Curve of Incircles (IncirCu), and it is dedicated to engineering surveying applications. It is designed for 2D geometrical objects representing long engineering structures e.g. chimneys. The goal of the presented new approach is to compute a single polygonal chain without branches, contrary to other Medial Axis algorithms. The algorithm requires the input data in the form of two polygonal chains. If the object has a closed boundary, it should be divided into two continuous parts, and their common points are also the endpoints of the computed IncirCu curve. There cannot be a situation in which the boundary's segment belongs to none of these two curves, or belongs to both of them at the same time.

The computation process consists of two phases using both polygonal chains. Figure 1 depicts the next steps of a single phase of the computation process. Consecutive IncirCu vertices are computed using points on one of those polygon chains, called c1. The second polygon chain, called c2, is used to determine the position of the computed vertex (Fig. 1a). In the second phase, the polygonal chains are replaced with each other as c1 and c2. As a result, the final axis depends equally on both edges, contrary to the author's algorithm presented before (Buczek, 2017).

Let's define a pointset P on the curve c1 consisting of the curve's vertices and equidistant points. Adjusting the interval between the sampling points results in a different number of computed vertices. The normal line to the curve at an element point Pi of the pointset P (Fig. 1b) covers the center points of tangent circles of any radius at this point (Fig. 1c). The goal is to find the smallest circle having at least one common point with c2. Such a common point on c2 might be a vertex or a tangent point. The center point of the smallest circle is considered a vertex of the computed curve (Fig. 1d). The procedure is repeated for all elements from the set P (Fig. 1e). At the end of the phase, a new set of vertices is created (Fig. 1f). From the definition, all computed vertices lay on the Medial Axis.

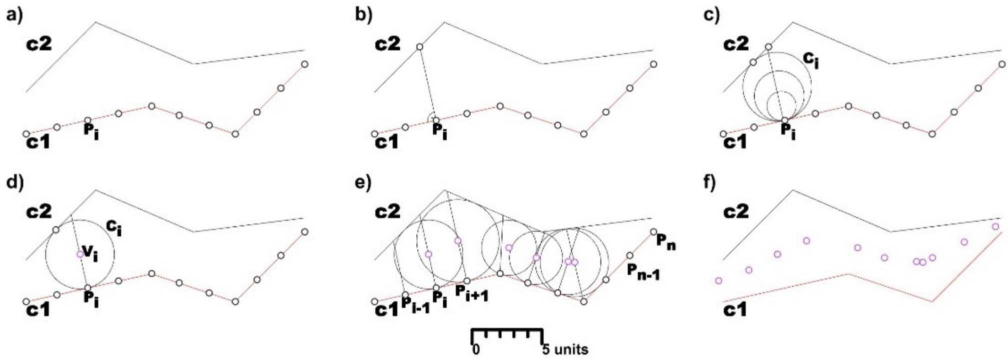

Fig. 1. Following steps to compute the IncirCu curve. Scale bar in dimensionless units (own elaboration)

The point Pi is skipped if the smallest circle tangent to c2 intersects also c1. The smallest circle might be tangent to one curve in more than one point, but it still has to be tangent to both curves. Otherwise, it is rejected, because its center point lays on the branch of the Medial Axis. As stated before, the computation presented in Figure 1 is done twice for both edges. As a result, two point sets are computed (Fig. 2). In the end, a single point set is created as a union of sets. Due to the introduced conditions, an unbranched polygonal chain may be constructed out of the computed set of vertices.

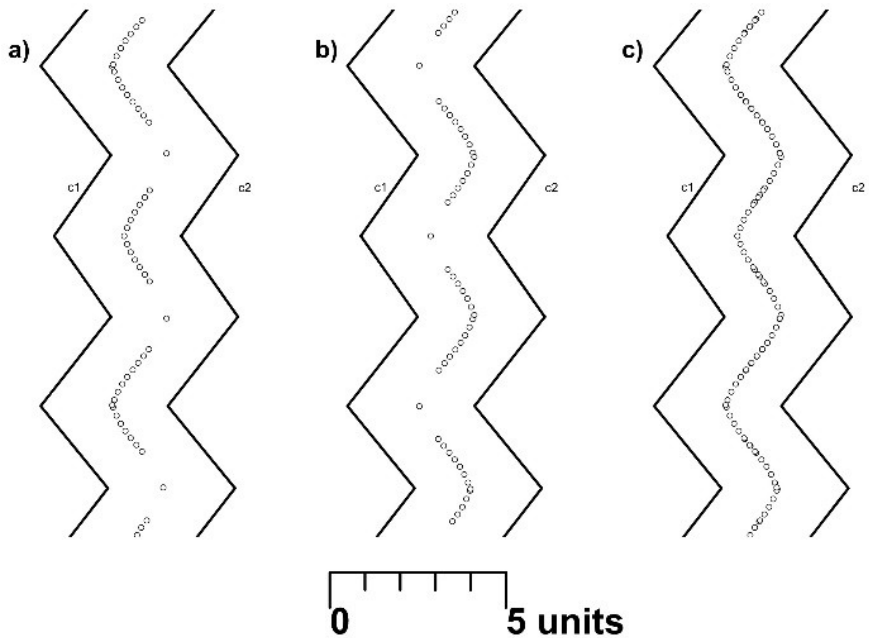

Fig. 2. The computed pointsets: from the left curve (a), from the right curve (b), and the union of pointsets (c). Scale bar in dimensionless units (own elaboration)

4. Discussion

The described algorithm is called The Curve of Incircles (IncirCu) due to the way the axis's vertices are determined. Figure 3 presents axes computed with algorithms Medial Axis (Blum, 1967), Straight Skeleton (Aichholzer et al., 1995), iCMR (Buczek, 2023), and IncirCu.

Algorithms IncirCu and iCMR generated axes without branches, which is considered a feature of these algorithms in terms of engineering surveying requirements. Branches of Straight Skeleton and Medial Axis generated full skeletons, therefore the unnecessary branches are presented in the gray color. In most cases, the Straight Skeleton has more branches than the Medial Axis, because it consists of branches to all boundary's vertices, while the Medial Axis has only to convex vertices. The usage of these algorithms in similar applications would require a method to extract a single curve out of it.

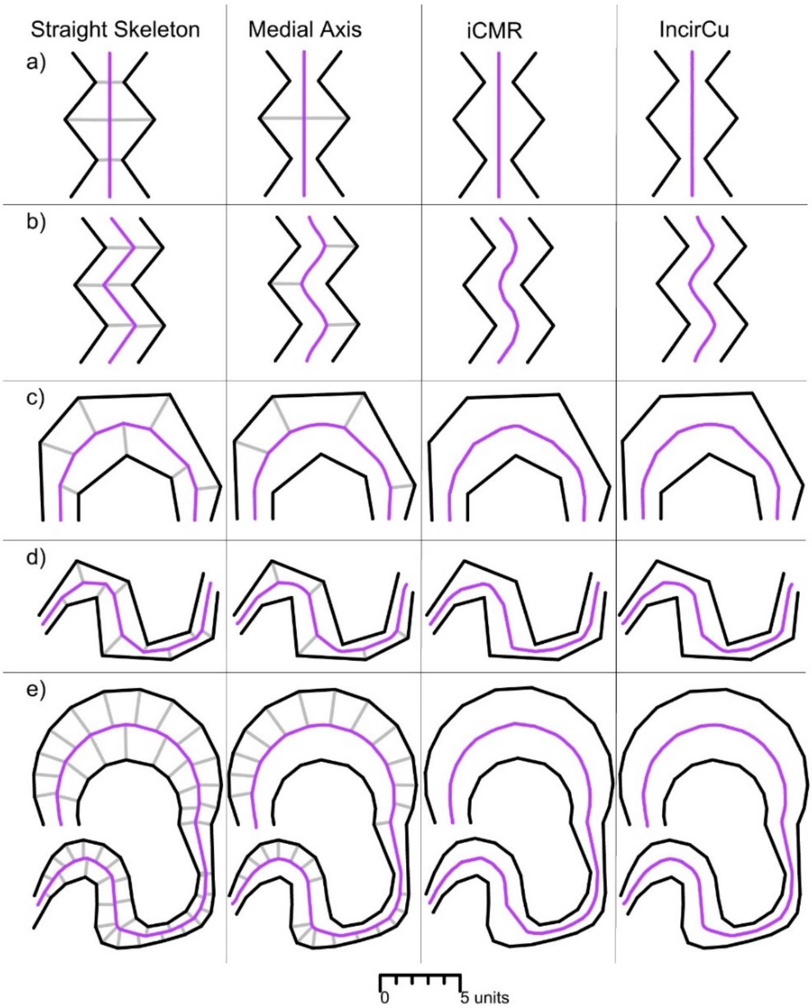

Fig. 3. The comparison of results of Straight Skeleton, Medial Axis, iCMR, and IncirCu in the dimensionless scale. Scale bar in dimensionless units (own elaboration)

The density and number of computed vertices depend on the number of points on the edges used in computations. All calculated points lie on the object's Medial Axis, therefore the polygonal chain constructed on them is an approximating one of the Medial Axis branches. Additionally, vertices computed out of edges' vertices are identical to corresponding Medial Axis branching points. As a result, IncirCu might be used as a fast approximation algorithm to obtain an unbranched part of the Medial Axis skeleton (Fig. 3). The more points used in calculations, the greater the similarity to the Medial Axis (Fig. 4).

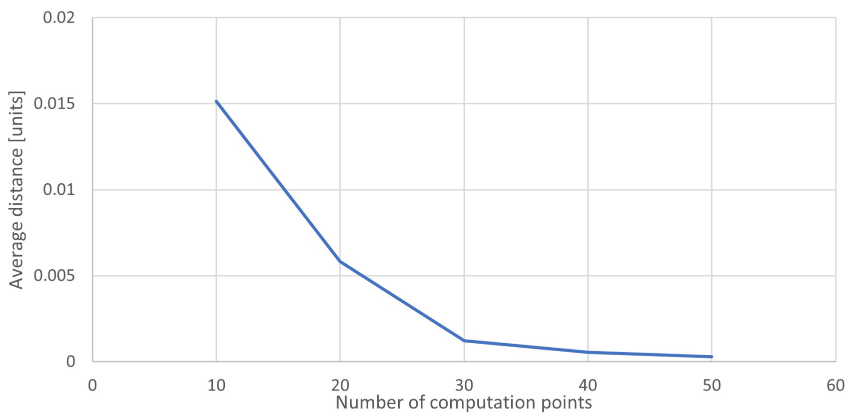

Fig. 4. The average distance between IncirCu and Medial Axis depending on the number of points used in computations (case d) (own elaboration)

In comparison, Straight Skeleton generates axes without smooth parts around concave vertices, while iCMR axes are even smoother than Medial Axis in these places (Fig. 3b). Also, in the middle part of the case d and lower part of the case e iCMR axis is placed closer to one of the edges than the other axes. Such differences are caused by differences in algorithms' definitions. Medial Axis and IncirCu axes might be considered as a compromise solution to replace the other two algorithms. An adequate method should be selected every time, depending on the purpose of the axis generation.

The accuracy of the algorithm's results was assessed by comparison against axes derived from other methods, with the average distance between each axis pair and between the vertices of c1 and c2 detailed in Table 1. All reported values are dimensionless; this non-dimensionalization was applied to simplify the comparison of average distances relative to the objects' sizes, making the results universally applicable for objects across different scales. The edge distances of the input models spanned a range from 1.6 to 6.8 units, meaning that the obtained values (not larger than 0.07 units) observed were extremely fine relative to the overall size and feature dimensions of the shapes being tested.

Table 1. The average distance between computed axes and between edges' vertices in a dimensionless scale

	Straight Skeleton	Medial Axis	iCMR	Avg. vertices dist.
a)	0.00	0.00	0.00	3.69
b)	0.05	0.00	0.04	3.61
c)	0.01	0.00	0.07	3.47
d)	0.01	0.00	0.06	1.69
e)	0.01	0.00	0.05	2.51

The geometric accuracy of the IncirCu algorithm was substantiated by an average distance consistently close to zero in all test cases, establishing its practical equivalence to the desired subset of the Medial Axis required for centerline extraction. Comparison against other benchmark methods, specifically iCMR (best at 0.04 in case b) and the Straight Skeleton (best at 0.01 in cases c, d, and e), showed differences greater than zero, yet these remained negligible when scaled against the overall size of the input objects. The largest relative error, observed in case d, showed the average distance to iCMR was approximately 3.5% of the input object's average width. Furthermore, the algorithm demonstrated exceptional stability: even in the geometrically most complex case e, defined by a higher number of boundary vertices, the IncirCu axis maintained high accuracy, with a maximum observed difference of only 0.05 units when compared to iCMR. This high fidelity suggests the algorithm is a robust candidate for applications where precise skeletal representation is critical.

More significantly, the ability of IncirCu to generate an unbranched skeleton directly addresses the crucial need for a single, continuous curve. However, its construction is constrained by the a priori definition of the two opposite boundary curves of the input polygon. Furthermore, the resulting accuracy is dependent on the number of points used to discretize these edges, introducing a necessary trade-off between computational speed and geometric fidelity. This process inherently bypasses the formation and costly subsequent removal of all unnecessary or spurious branches of classic Medial Axis caused by boundary noise. This unbranched representation serves as an efficient approximation of the Medial Axis for specific use cases, providing a simplified, topologically clean structure that is exceptionally useful for downstream tasks such as hydrological modeling, cartographic generalization, and computing axes of long engineering structures, all of which demand a robust, continuous spine rather than a complex, noisy MA continuum.

5. Summary

The IncirCu algorithm is presented as a method to generate an unbranched polygonal chain that approximates a functional subset of the Medial Axis for 2D polygons. The algorithm's construction is based on points derived from two a priori defined polygonal chains representing the object's opposite edges. For each edge separately the result set is generated, and the final point set is created as a union of these two sets. All calculated points lie on the object's Medial Axis; therefore, the polygonal chain constructed from the result set is an approximation of an unbranched subset of the Medial Axis.

The conducted tests proved the IncirCu axis achieves practical equivalence to the subset of the Medial Axis. This conclusion is supported by the numerical results, which consistently showed the average distance between the IncirCu output and the reference Medial Axis to be near zero. While the axis comparison against other benchmark methods, such as iCMR and the Straight Skeleton, revealed differences greater than zero, these discrepancies remained negligible when scaled against the input objects' overall size. IncirCu axis's shape is also smoother than the Straight Skeleton around the edge's concave vertices, similarly to the Medial Axis. The novel axis is unbranched, in contrast to the Medial Axis, and Straight Skeleton, which is considered feature of the presented algorithm. Therefore, it's easily applicable for cartography and surveying purposes requiring single polygonal chain axes. But it might be used in any field where 2D axes without branches are required.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The pseudocode of the described algorithm is available on: https://github.com/Butcho.

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