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# Monotonic sampling of a continuous closed curve from its Gauss digitization. Application to length estimation.

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## Abstract

Our study is about perimeter estimation of continuous shapes based on their digitization (i.e. their pixelated representation). To study the estimation error, we are led to propose the notion of *monotonically sampling back-digitization*, a mapping between the boundary of a digitized Jordan curve and the Jordan curve itself. This mapping ensures that the digital curve and the continuous curve are traveled together in a cyclic order manner. Then, we use back-digitization to prove the multigrid convergence of perimeter estimators that are based on polygons inscribed in the digitization. Furthermore, convergence speed is given for this class of estimators. The convergence is guaranteed provided the polygon edge lengths tend toward 0 and their edge sizes relative to the grid step tends towards infinity (thus the sampling of the digital boundary has to be both tight and sparse). All the proofs are established in the framework of *locally turn bounded curves* (LTB) presented in the previous article *Le Quentrec et al., Local turn-boundedness: A curvature control for a good digitization, DGCI 2019*. If, moreover, the continuous curves also have a Lipschitz turn, an explicit error bound is calculated. Besides, an equivalence between LTB-curves with a Lipschitz turn and curves of class  $C^{1,1}$  is subsequently established.

*Keywords:* digitization, integral curvature, turn, Jordan curve, perimeter discrete estimation

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## 1. Introduction

The estimation of a geometric feature of an object from its picture is required in several fields. One of the issues in this process is the discretization due to the image acquisition that reduces the information necessary to the estimation. Therefore, dedicated estimators are mandatory and their properties should be proved or evaluated. That is the problematic of geometric estimation in discrete geometry. Characteristics whose dimension is that of the ambient-space like area in the plane, have estimators which have been proved to be accurate

(see for instance Theorem 2.2, section 2.4.2 [2] or Theorem 8 [3]). For characteristics with dimensions lower than that of the ambient space, like perimeter or curvature in the plane, the accuracy of the proposed estimators is proved on specific curves [4], [5], [3], [6], [7], or illustrated on examples [8], [9], [10], [11] [12, 13]. The aim of this paper is to prove the accuracy of perimeter estimation (in a sense to be defined) for a wide class of estimators under some hypotheses on the shapes.

In the sequel of the article, we focus on the estimation of perimeter for shapes homeomorphic to a disk or equivalently to length estimation of Jordan curves. We provide here a brief overview of the perimeter estimation in discrete geometry. Length estimation methods can be based on a tangent estimation [12, 14], or consist in splitting the digital boundary into *patterns* (small sequences of boundary pixels) and summing the lengths associated to each pattern. In the latter class, the choice of the pattern size determines a classification on perimeter estimation methods. One can distinguish three classes: the local estimators for which the pattern size is constant, that is, it does not depend on the curve nor on the grid step; the Semi-Local and Non-Local estimators for which the pattern size depends only on the grid step, but not on the curve; and the adaptative ones for which the number of pixels in each pattern is determined by the estimation algorithm from the discrete curve. There are two types of adaptative length estimators, the Maximal Digital Straight Segments (MDSS) and the Minimal Length Polygons (MLP).

The evaluation of the accuracy of the perimeter estimators is made through their application on curve examples [15, 12], on curve classes [14] or by verifying an asymptotical property so-called the *multigrid convergence*: the estimation error has to tend towards 0 when the grid step tends to 0. Let's take a look to this property on the three estimator classes described above. Even if the local estimators are the easiest to use, they do not verify the multigrid convergence property for an important amount of curves [16]. On one hand, adaptative estimators have been proved to be multigrid convergent on convex curves [3]. On the other hand the proofs are difficult to generalize because of the adaptivity of the algorithms to each curve. Nevertheless, for adaptative estimators on curves of class  $C^3$  with positive curvature, it has been proved in [13] that the asymptotical pattern pixel number tends to infinity and its real size tends to 0. Keeping this behaviour in their definition (without being adaptative), the Semi-Local estimators, respectively the Non-Local estimators have been proved to be multigrid convergent for functions of class  $C^2$  [9], respectively Lipschitz functions [4]. But these results have been obtained on graphs of functions, not on curves. As the Non-Local estimators is an attempt to be a unified framework for adaptative and semi-local estimators [4], it seems relevant to extend it to planar curves. Nevertheless, the results depends on the estimators but also on the classes of the estimated curves. These classes are detailed in the next paragraph.

The length estimation error is always given for an estimator class on a class of curves (Table 1). In order to perform a geometric estimation on a curve, and taking into account the small quantity of information contained in its dig-

Estimator	Class of curves	Proof of multigrid convergence	Rate of convergence
MDSS	convex $C^3$ with positive curvature convex polygons	Thm 5.36 [14]	$O(h^{1/3})$
		Thm 12 [3]	$O(h)$
GC-MLP	convex curves	for Jordan digitization scheme Thm 4.15 [17]	$O(h)$
AS-MLP	convex polygon	Thm 2 [18]	$O(h)$
Non-local estimator	graph of Lipschitz function graph of $C^{1,1}$ function	Cor 1 [4]	-
		Cor 2 [4]	$O(M_1^h + \frac{h}{M_1^h})$
MDSS	graph of Lipschitz function	Thm 8 [4]	-

Table 1: The table gives the proved worst-case rate of convergence of several estimators on a specific class of curves. When not specified the convergence is studied for the Gauss digitization scheme. The class of  $C^{1,1}$  is the class of function whose derivative are Lipschitz.

55 itization, the complexity of the curve should be upper bounded. Geometric hypotheses on the continuous curve are needed to control this quantity of information. These geometric hypotheses should be invariant by rigid transformation and determine the grid step for which the digitization will encompass enough information to perform geometric estimation. One of the most used hypothesis 60 in discrete geometry is the  $\text{par}(r)$ -regularity (Definition 8). It was introduced by Pavlidis in [19], its definition was rephrased by Serra in [20], and by Latecki et al. in [21].  $\text{Par}(r)$ -regular curves verify some regularity hypotheses. In particular, polygons are not  $\text{par}$ -regular. There exist several attempts to generalize  $\text{par}(r)$ -regularity in order to include shapes with spikes: half-regularity [22], 65  $r$ -stability [23], quasi( $r$ )-regularity [24], the  $\mu$ -reach [25]. But none of them excludes artifacts of the continuous curve that prevent accurate length estimation. For a detailed state of the art on these notions, please refer to [26].<sup>1</sup>

In this article, we aim at providing a proof of multigrid convergence for some perimeter estimators and to bound their worst-case error on a wide class of Jordan 70 curves including both regular curves and polygons. In order to define such a class of curves, we choose to use a criterion based on the *turn* of the curve, which is a generalization of the integral of the curvature along the curve 2.1. Indeed the turn is the amount by which a curve deviates from being a straight line. In this article, we consider two families of curves: the curves having a turn being 75 a Lipschitz function of their length (Definition 9) and the curves whose small

<sup>1</sup>Other hypotheses can be chosen for curves that are graphs of a function: the function or its derivatives can be required to be Lipschitz (see [4])

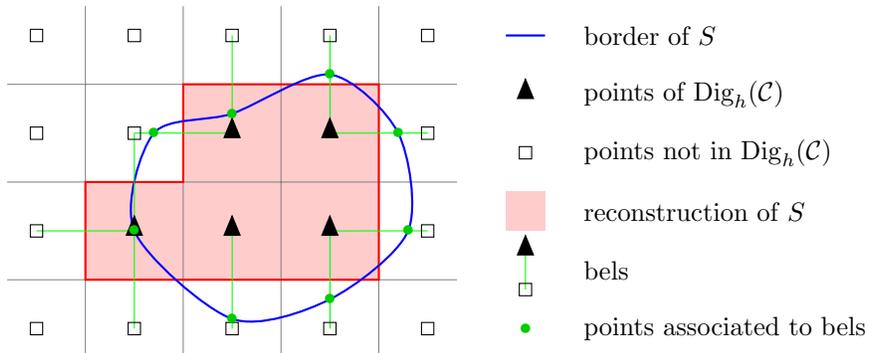


Figure 1: Each bel is associated to an intersection point of itself and the border of the shape  $S$ . Notice that several bels can be associated to the same point, but the order of bels is preserved by the back-digitization.

arcs have a bounded turn (*locally turn-bounded* curves, see Definition 1). The notion of local turn-bounded curve (LTB-curve) was introduced in a previous work [26].

Let us introduce the digitization process used in this article. Given a shape  $S$  and a grid step  $h$ , the Gauss digitization of  $S$  denoted by  $\text{Dig}_h(S)$ , is the discrete subset of  $S \cap h\mathbb{Z}^2$ . The *reconstruction* of  $S$  is the Minkowski sum  $\text{Dig}_h(S) \oplus P$  where  $P = [-h/2, h/2]^2$ . A boundary element of a digitized shape  $S$ , usually called a *bel* is composed of a pair of 4-adjacent grid points, one lying outside the shape and the other lying inside the shape, or on its boundary see Figure 1.

Since bounding the error of a non-local estimator consists in comparing the length of the curve and the length of a polygon whose vertices are derived from the digitization, an important step is to associate the edges of the polygon to arcs partitioning the continuous curve. In other words, we want to define a mapping from the ordered set of the digitization bels to an ordered sequence of points on the continuous curve  $\mathcal{C}$ . Furthermore, in order to guarantee the multigrid convergence, each bel has to be close to its image. In [27], the whole continuous curve is associated point by point to the boundary of its reconstruction using the projection to nearest point defined in [28]. This projection is well-defined only for sets having a positive reach, that is, for par-regular curves. Moreover, this projection is onto but not order-preserving (see Figure 2) even if the length of the “non-injective” part of the projection on  $\mathcal{C}$  can be upper bounded [27]. Notice that this step is not always necessary: for small classes of curves as the convex polygons, the bounding of estimation error is based on other arguments (see [3]).

Our contributions are of three kinds. The first one is the proof that a curve is par-regular if and only if this curve is locally turn bounded with Lipschitz turn (Theorem 1). The second and main contribution of the article is to define a mapping (Definition 5) from bels to points on the curve and to prove that this mapping is order-preserving. Besides, we show that the arcs of curve delimited

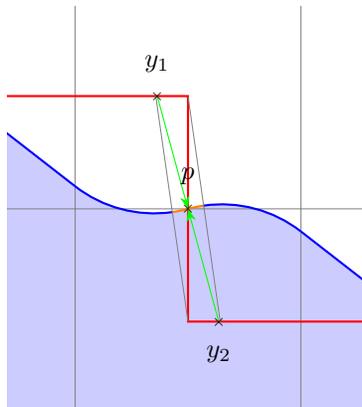


Figure 2: ([14, Figure B.2]) In blue and orange a Jordan curve  $\mathcal{C}$ , in red the boundary  $\partial_h(\mathcal{C})$  of the reconstruction of its interior. The projection on the curve  $\mathcal{C}$  is represented by the green arrows. The points  $y_1$  and  $y_2$  have the same image  $p$  by the projection on the curve. The set of points of  $\partial_h(\mathcal{C})$  having at least two preimages by the projection is represented in orange. When a point  $y$  in  $\partial_h(\mathcal{C})$  moves from left to right, this orange part is traveled three times.

105 by the image of the mapping have a limited turn. The whole section 3 is dedicated to this proof. The last contribution is the length estimation for locally turn-bounded curves. We prove the multigrid convergence of some Non-Local estimators (Theorem 3 and Theorem 4). We also provide rates of convergence depending on the mean and maximal size of patterns. Moreover we give an  
 110 explicit upper bound of the error of estimation for LTB curves with Lipschitz turn in order to enable a practical use at a fixed resolution.

## 2. Hypotheses on the continuous shape

In this section, we recall the definition and the main properties of *locally turn-bounded curves*. All this material comes from our previous article [26]. Section 2  
 115 also contains a new result, Theorem 1, that links locally turn-bounded curves having Lipschitz turn with par-regular curves [19] and curves having positive reach [28].

### 2.1. Turn

In this section, we recall the definition of the turn and some of its properties.  
 120 The main reference is the book of Alexandrov and Reshetnyak [29]. Nevertheless, the reader will find in our previous article [26] two pages presenting these properties with some comments and precise references inside the book.

Generally, the convergence of geometrical estimators is given under analytical hypothesis on the continuous curve. In most of the cases, the continuous  
 125 curve is supposed to be twice differentiable. But as noticed in [29]:

“It should be remarked that differential geometry commonly studies only the curves obeying certain conditions of regularity. These conditions are imposed by the requirement that the apparatus of differential calculus be applied, but they are hardly justified in a geometrical sense.” In this article, we choose to study geometrical features of the continuous curve based on the turn. In order to be able to consider both polygons and regular curves, we use the definition of the turn given in [29], [30]. But beforehand, let us clarify some notations.

- For practical reasons, a sequence of points  $(a_i)$  of a closed curve is indexed by the quotient group  $\mathbb{Z}/N\mathbb{Z}$ . This allows for instance to use the equality  $a_N = a_0$ . In particular, this notation will be used for the vertices of a polygon. The subset  $\{i, i + 1, \dots, j\}$  of  $\mathbb{Z}/N\mathbb{Z}$  is denoted by  $\llbracket i, j \rrbracket$  and  $\#\llbracket i, j \rrbracket$  stands for the cardinal of  $\llbracket i, j \rrbracket$ .
- The angle between two vectors  $\vec{u}$  and  $\vec{v}$  is denoted by  $(\vec{u}, \vec{v})$  ( $(\vec{u}, \vec{v}) \in \mathbb{R}/2\pi\mathbb{Z}$ ). The geometric angle between two vectors  $\vec{u}$  and  $\vec{v}$ , or between two directed straight lines oriented by  $\vec{u}$  and  $\vec{v}$  is denoted by  $\angle(\vec{u}, \vec{v})$ . It is the absolute value of the reference angle taken in  $(-\pi, \pi]$  between the two vectors. Thus,  $\angle(\vec{u}, \vec{v}) \in [0, \pi]$ . Given three points  $x, y, z$ , we also write  $\widehat{xyz}$  for the geometric angle between the vectors  $x - y$  and  $z - y$ .

We now give the definition of the turn.

- The turn  $\kappa(L)$  of a polygonal line  $L = [x_i]_{i=0}^{N-1}$  is defined by:

$$\kappa(L) := \sum_{i=1}^{N-2} \angle(x_i - x_{i-1}, x_{i+1} - x_i) .$$

- The turn  $\kappa(P)$  of a polygon  $P = [x_i]_{i \in \mathbb{Z}/N\mathbb{Z}}$  is defined by:

$$\kappa(P) := \sum_{i \in \mathbb{Z}/N\mathbb{Z}} \angle(x_i - x_{i-1}, x_{i+1} - x_i) .$$

- In the rest of the paper, we write  $C_{a,b}$  for an arc of curve between the points  $a$  and  $b$ ; moreover, the topology on the curve and its arcs is the topology induced on the curve, therefore, an open arc  $\overset{\circ}{C}$  is the arc  $C$  minus its endpoints.
- A sequence  $(a_j)$  of points of a simple closed curve  $\mathcal{C}$  forms a *chain* if for each pair  $(i, j)$ , the intersections of the two open arcs of  $\mathcal{C}$  from  $a_i$  to  $a_j$  with the set  $\{a_k\}$  are exactly the subsets  $\{a_k\}_{k \in \llbracket i+1, j-1 \rrbracket}$  and  $\{a_k\}_{k \in \llbracket j+1, i-1 \rrbracket}$ .
- A polygonal line (or a polygon) is said to be *inscribed* in  $\mathcal{C}$  if its ordered sequence of vertices forms a chain of  $\mathcal{C}$ .
- The turn  $\kappa(\mathcal{C})$  of a simple curve  $\mathcal{C}$  (respectively of a Jordan curve) is the upper bound of the turn of its inscribed polygonal lines (respectively of its inscribed polygons).

The turn has the following properties<sup>2</sup>

**Property 1** ([29]).

- The turn coincides with the integral of the usual curvature on  $C^2$  curves.
- 160 • (Fenchel’s Theorem) The turn of a Jordan curve is greater than or equal to  $2\pi$ . The equality case occurs if and only if the interior of  $\mathcal{C}$  is convex.
- Every curve of finite turn has left-hand and right-hand tangent vectors  $e_l(c)$  and  $e_r(c)$  at each of its points.

- For any arc  $C_{a,b}$  of finite turn containing a point  $c$ ,

$$\kappa(C_{a,b}) = \kappa(C_{a,c}) + \kappa(C_{c,b}) + \angle(e_l(c), e_r(c)).$$

- For any Jordan curve  $\mathcal{C}$  of finite turn containing a point  $c$ ,

$$\kappa(\mathcal{C}) = \kappa(\mathcal{C} \setminus \{c\}) + \angle(e_l(c), e_r(c)).$$

165 The turn can be understood as a measure of the quantity of information of a curve. Indeed, the turn is the amount by which a curve deviates from being a straight line.

## 2.2. Local turn-boundedness

We introduced in [1] a new local geometric feature based on the turn. It consists in locally bounding the turn of the curve in order to forbid the artifacts depicted in Figure 3. This new feature allows us to consider a wider class than 170 the par-regular curves usually used for estimation in discrete geometry.

**Definition 1** (LTB curves [1]). A Jordan curve  $\mathcal{C}$  is  $(\theta, \delta)$ -locally turn-bounded  $((\theta, \delta)$ -LTB) if, for any two points  $a$  and  $b$  in  $\mathcal{C}$  such that  $d(a, b) < \delta$ , the turn of one of the arcs of the curve  $\mathcal{C}$  delimited by  $a$  and  $b$  is less than or equal to  $\theta$ .

175 In particular it forbids the *angular points* in  $\mathcal{C}$  of turn greater than  $\theta$ , i.e. points  $c$  for which  $\angle(e_l(c), e_r(c)) > \theta$  (see [1, Proposition 3]).

Hereafter, we recall the properties of the LTB-curves that will be used in this paper. As the  $(\theta, \delta)$ -LTB-curve set is growing with  $\theta$ , the properties established for  $\theta = \theta_0$  are also available for  $\theta \leq \theta_0$ . The converse is false. In particular, the 180 maximal value of the angle  $\theta$  for which the notion of “straightest arc” (see below) is valid is  $\pi/2$ . Therefore, since it suffices to consider the case  $\theta = \pi/2$  to achieve the goal of this article, we give below, by taking systematically  $\theta = \pi/2$ , less general, but often simpler, statements of the properties published in [26]. In the rest of the paper, as  $\theta$  is fixed to  $\pi/2$ , we write  $\delta$ -LTB instead of  $(\pi/2, \delta)$ -LTB.

185 The first property links the parameter  $\delta$  of a LTB curve with the diameter of the curve.

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<sup>2</sup>About these properties, the reader can find in [26] some comments and more precise references.

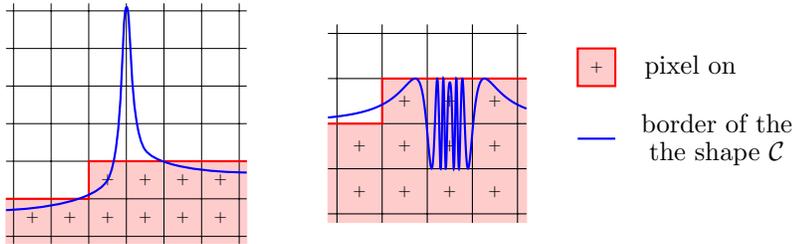


Figure 3: The curve on the left has a thin spike avoiding all the centers of pixels. Alike, we can build curves having arcs arbitrarily far from their Gauss digitization. Even if the curve stay close to its digitization, it can oscillate a lot around its digitization. Such artifacts can induce for instance an arbitrarily big difference between the length of the curve and the length of its digitization.

**Property 2** ([26], Lemma 3). *Let  $\mathcal{C}$  be a  $\delta$ -LTB Jordan curve. Then,  $\delta \leq \text{diam}(\mathcal{C})$ , where  $\text{diam}$  denotes the diameter.*

Notice that two distinct points of a Jordan curve delimit two arcs of the curve. To distinguish these two arcs, we introduced in [1] the notion of *straightest arc*.

**Property 3** ([26], Definition 6 and Proposition 4). *Let  $a, b$  be two distinct points of a  $\delta$ -LTB Jordan curve  $\mathcal{C}$ . If  $\|b - a\| < \delta$ , then there exists a unique arc of  $\mathcal{C}$  between  $a$  and  $b$  whose turn is less than or equal to  $\pi/2$ . This arc noted  $\mathcal{C}_{a,b}$  is included in the closed disk with diameter  $[a, b]$  and is called the straightest arc between  $a$  and  $b$ .*

Local turn-boundedness can be understood as a constraint on the thickness of the interior of the curve  $\mathcal{C}$ . Indeed, the intersection of  $\mathcal{C}$  with any open disk centered in a point of  $\mathcal{C}$  and of radius less than or equal to  $\delta$  is path-connected.

**Property 4** ([26], Proposition 5). *Let  $\mathcal{C}$  be a  $\delta$ -LTB Jordan curve and  $a \in \mathcal{C}$ . Then, for any  $\epsilon \leq \delta$ , the intersection of  $\mathcal{C}$  with the open disk  $B(a, \epsilon)$  is path-connected and is therefore an arc of  $\mathcal{C}$ .*

From Property 4, we derive that LTB curves have no local U-turns.

**Property 5** ([26]). *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve. Let  $\gamma: [0, t_M) \rightarrow \mathcal{C}$  be an injective parametrization of the curve  $\mathcal{C}$  and  $t_m \in (0, t_M)$  be such that the arc  $\gamma([0, t_m])$  is included in  $B(\gamma(0), \frac{\delta}{2})$ . Then, the restriction of the function  $t \mapsto \|\gamma(t) - \gamma(0)\|$  to  $[0, t_m]$  is increasing.*

The preservation by the digitization process of topological properties as connectedness, or manifoldness, requires to discretize continuous objects with sufficiently tight grids. In the framework of LTB curves, this is expressed by the notion of grid *compatible with* a (LTB) curve presented here (Definition 2).

**Definition 2** ([26], Definition 9). *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve. A grid with step  $h$ , or a square of side length  $h$ , is said to be *compatible* (with the curve  $\mathcal{C}$ ) if  $h$  is strictly smaller than  $\min(\frac{\sqrt{2}}{2}\delta, \frac{1}{2}\text{diam}(\mathcal{C}))$ .*

215 Any  $\delta$ -LTB curve yields 4-connected and well-composed discretizations on compatible grids.

**Property 6** ([26]). *Let  $\mathcal{C}$  be  $\delta$ -LTB curve. Then, the Gauss digitization of  $\mathcal{C}$  on any compatible grid is 4-connected and well-composed.*

220 The constraint on the curvature of a LTB curve makes it possible to describe with accuracy the behavior of such a curve with respect to compatible grid pixels. This was expressed in [26] through the notion of “arc passing through” a pixel.

**Definition 3** ([26], Definition 8 and Proposition 7). Given a LTB curve  $\mathcal{C}$  and a compatible square  $T$ , there exists a maximal (for the inclusion) straightest arc of  $\mathcal{C}$  with endpoints in  $T$ . It is called the  $T$ -straightest arc of  $\mathcal{C}$  and it is denoted by  $\mathcal{C}_T$ .

Be aware that we have changed the designation of the arc passing through  $T$  from [26] into  $T$ -straightest arc .

The  $T$ -straightest arc has the following localization property.

230 **Property 7** ([26], Proposition 6). *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve and  $T$  be a compatible square. Then, the  $T$ -straightest arc of  $\mathcal{C}$  is included in the swelling of  $T$  which is the union of the four disks whose diameters are the sides of  $T$ . Furthermore, the complement of  $\mathcal{C}_T$  in  $\mathcal{C}$ , the open arc  $\mathcal{C} \setminus \mathcal{C}_T$ , does not intersect  $T$ .*

235 Thanks to the notion of  $T$ -straightest arc, we are able to locally distinguish exterior points from interior points. The notion of swelling of  $T$  corresponds to the swollen set of  $T$  defined in [26], we change the designation in this article.

240 **Property 8** ([26]). *Let  $\mathcal{C}$  be  $\delta$ -LTB Jordan curve and  $T$  be a compatible square. Let  $a, b$  be the endpoints of the  $T$ -straightest arc of  $\mathcal{C}$ . Two vertices of  $T$  are in the same connected component of  $\mathbb{R}^2 \setminus \mathcal{C}$  if and only if they are in the same connected component of  $T \setminus [a, b]$  and they do not lie on  $\mathcal{C}$ .*

The following property considers the case when the  $T$ -straightest arc contains a vertex of the square  $T$ .

245 **Property 9** ([26]). *Let  $\mathcal{C}$  be a  $\delta$ -LTB Jordan curve and  $T$  be a compatible square. Suppose that the square  $T$  has a vertex  $v$  lying on  $\mathcal{C}$ . Then, either this vertex  $v$  is an endpoint of the  $T$ -straightest arc of  $\mathcal{C}$ , or the  $T$ -straightest arc is wholly included in the two sides of  $T$  having  $v$  for endpoint.*

250 We end this section about local turn boundedness by two new results. The first one is just a set of technical improvements of some of the properties mentioned above. These new statements are used in Section 3. The second one is a complement about regularity that gives meaning to turn usage in discrete geometry.

**Lemma 1.** *Let  $C_{a,b}$  be a subarc of a  $\delta$ -LTB Jordan curve such that  $d(a, b) < \delta$ .*

(a) The arc  $C_{a,b}$  is the straightest arc between  $a$  and  $b$  if and only if it is included in the disk whose diameter is the straight segment  $[a, b]$ .

255 (b) If the arc  $C_{a,b}$  is the straightest arc between  $a$  and  $b$ , then,

$$\langle e_l(a), e_r(a) \rangle + \kappa(C_{a,b}) + \langle e_l(b), e_r(b) \rangle \leq \frac{\pi}{2}.$$

*Proof.*

(a) The “only if” part of the assertion is stated in Property 3. The “if” part results from Property 2. Indeed, if  $C_{a,b}$  is included in the disk  $D$  whose diameter is  $[a, b]$  where  $d(a, b) < \delta$ , by Property 2, the other arc between  
260  $a$  and  $b$ , say  $C_{b,a}$ , is not included in  $D$ . Thus, from the “only if” part,  $C_{b,a}$  is not the straightest arc from  $a$  to  $b$ . As, according to Property 3, the straightest arc exists, it is  $C_{a,b}$ .

(b) The idea is to slightly extend the arc  $C_{a,b}$  on both sides so as to include the points  $a$  and  $b$  in its interior while keeping the distance between the  
265 extremities under the threshold value  $\delta$ . Nevertheless, we have to justify that the extended arc is still a straightest arc.

So, let  $a'$  and  $b'$  be the extremities of the extended arc  $C_{a',b'}$ :  $a' \neq a$ ,  $b' \neq b$ ,  $C_{a',b'} \supset C_{a,b}$ . Let  $\varepsilon = \min((\delta - d(a, b))/4, d(a, b)/2)$ . We choose  $a'$  and  $b'$  such that  $d(a, a') < \varepsilon$  and  $d(b, b') < \varepsilon$ . Then,  $d(a', b') < \delta - 2\varepsilon$ .  
270 Furthermore, it can be proved that the distance between the center of the disk  $D$  whose diameter is  $[a, b]$  and the disk  $D'$  whose diameter is  $[a', b']$  is less than  $\varepsilon$ . Thanks to the triangle inequality, we derive that  $D'$  is included in the interior of the disk  $D_+$  whose center is the midpoint of  $[a, b]$  and whose diameter is  $\delta$ . Furthermore, the straightest arcs  $C_{a',a}$   
275 and  $C_{b,b'}$  are included in  $D_+$  by the choice of  $\varepsilon$  and Property 3. Then,  $C_{a',a} \cup C_{a,b} \cup C_{b,b'} \subset D_+$ ,  $D' \subset D_+$  but the whole curve  $\mathcal{C}$  is not included in  $D_+$  (by Property 2). It comes that  $\mathcal{C} \setminus (C_{a',a} \cup C_{a,b} \cup C_{b,b'})$  is not included in  $D'$  and for this reason cannot be the straightest arc from  $a'$  to  $b'$ . Hence  $C_{a',a} \cup C_{a,b} \cup C_{b,b'}$  is the straightest arc between  $a'$  and  $b'$ .

280 □

The classical notions of (having) *positive reach* [28], *par-regularity* [19], which are equivalent to  $C^{1,1}$  regularity ( $C^1$ -curve with Lipschitz derivative), can be expressed very easily in the framework of LTB curves as stated by the following theorem.

285 **Theorem 1.** *A  $\delta$ -LTB curve is of class  $C^{1,1}$  if and only if it has a Lipschitz turn:  $\kappa(\mathcal{A}) \leq k\mathcal{L}(\mathcal{A})$  for some  $k \geq 0$  and for any subarc  $\mathcal{A}$  of  $\mathcal{C}$ .*

The only if part of Theorem 1 was proved in [26]. We give in Appendix A the proof of the converse part.

### 3. Digitization based partition of a LTB curve

290 One main objective of this article is to map the boundary of a discretized object onto the continuous original object thanks to small displacements of the discrete boundary while keeping the order on the boundary of the discrete object. This is the purpose of this section.

Note that the proofs given in Section 3 rely on the properties of LTB curves 295 recalled in Section 2.2.

#### 3.1. Back-digitization

We begin by some vocabulary and notations that will be used throughout Section 3.

Let  $p \in \mathbb{R}^2$  and  $h \in (0, +\infty)$ . We denote by  $P_p$  the square  $p \oplus P$  where 300  $P = [-h/2, h/2]$ . When  $p \in h\mathbb{Z}^2$ , we say that  $P_p$  is a *pixel* and when  $p \in (h/2, h/2) + h\mathbb{Z}^2$ , we say that  $P_p$  is a *dual pixel*. Observe that the vertices of a dual pixel all have integer coordinates.

Given a Jordan curve  $\mathcal{C}$  surrounding a shape  $S$  and a grid step  $h$ , we recall that a *bel* (for “boundary element”) is an ordered pair of 4-adjacent grid points, 305 the first point lying inside the shape, or on its boundary and the second point lying outside the shape. By abuse of language, a bel is identified with the segment linking its two points. The set of all the bels obtained from  $\text{Dig}_h(S)$  is denoted  $\text{Bel}_h(\mathcal{C})$ .

A dual pixel containing a bel is called a *boundary dual pixel*, or BDP for 310 short. Obviously, a bel always belongs to two BDPS. Conversely, it is plain that in a well-composed digitization, a BDP contains exactly two bels (see Figure 4). That way, the graph whose vertex set is  $\text{Bel}_h(\mathcal{C})$  and whose edges are the pairs of bels belonging to a same dual pixel is regular with degree 2. If  $\text{Bel}_h(\mathcal{C})$  is 4-connected,  $\text{Bel}_h(\mathcal{C})$  may be equipped with a cyclic order and when we need 315 to consider this cyclic order, we put  $\text{Bel}_h(\mathcal{C}) = (b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ . We derive from Property 6 that if the grid is compatible with  $\mathcal{C}$ ,  $\text{Bel}_h(\mathcal{C})$  is equipped with a cyclic order.

From Jordan’s Curve Theorem, we derive that each segment in  $\text{Bel}_h(\mathcal{C})$  intersects the curve  $\mathcal{C}$ . The notion of *back-digitization* defined hereafter corresponds 320 to a mapping from bels to such intersection points. Since we want our mapping to preserve the bel order but we cannot impose injectivity (see Figure 5), we have to relax the notion of chain (see Section 2.1) to sequences of curve points having several consecutive occurrences of the same point.

**Definition 4** (semi-chain). Let  $N \geq 1$ . A sequence  $(\xi_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  of points of a 325 simple closed curve  $\mathcal{C}$  forms a *semi-chain* if for each pair  $(i, j)$ , the intersections of the two closed arcs of  $\mathcal{C}$  between  $\xi_i$  and  $\xi_j$  with the set  $\{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}}$  are the subsets  $\{\xi_k\}_{k \in [i, j]}$  and  $\{\xi_k\}_{k \in [j, i]}$  (see Figure 6 a). Given a  $\delta$ -LTB curve  $\mathcal{C}$ , a semi-chain  $(\xi_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  of  $\mathcal{C}$  is a *sampling semi-chain* if, for any  $k \in \mathbb{Z}/N\mathbb{Z}$ ,  $d(\xi_k, \xi_{k+1}) < \delta$  and the open straightest arc of  $\mathcal{C}$  between  $\xi_k$  and  $\xi_{k+1}$  330 does not intersect  $\{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}}$ .

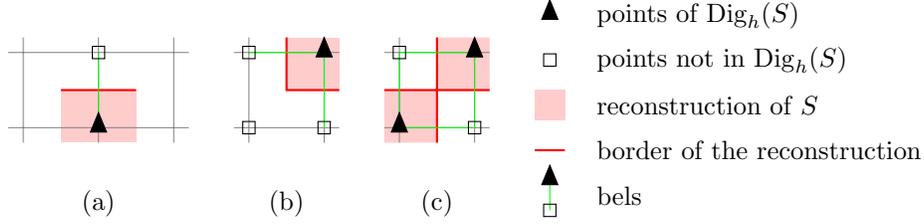


Figure 4: Let  $S$  be a shape homeomorphic to a closed disk. Its boundary is a Jordan curve, we call it  $\mathcal{C}$ . (a) Each edge of the boundary of the reconstruction of the shape  $S$  separates a grid point outside  $S$  and one adjacent grid point in  $S$ . Then the bels of  $\text{Dig}_h(S)$  and the edges of the reconstruction are in one-to-one correspondence. (b) and (c): When the digitization of  $S$  is well-composed, no BDP contains the cross configuration (c). Then each BDP contains exactly two bels (b).

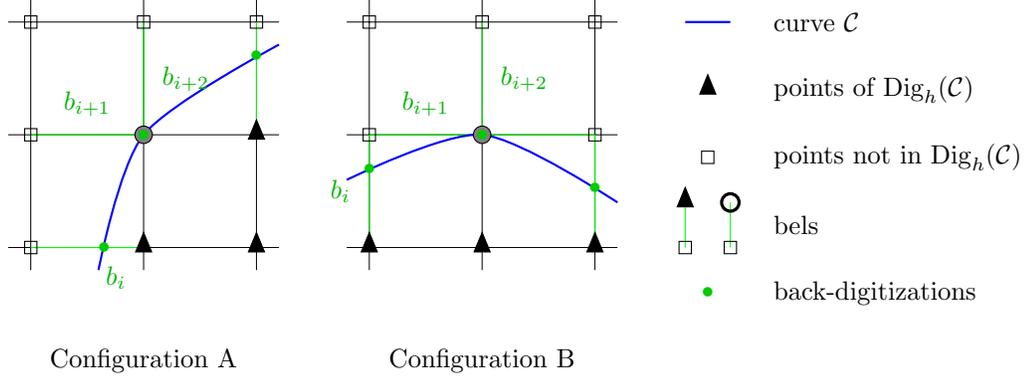


Figure 5: Consecutive bels (left: 2 bels, right: 3 bels) have to be back-digitized on the same point of the curve.

An example of a semi-chain not being a sampling semi-chain is given in Figure 6 b. Observe that any Jordan-curve point sequence whose cardinal is less than 4 is a semi-chain.

The two following lemmas give some properties of (sampling) semi-chains.

335 **Lemma 2.** *Let  $\mathcal{C}$  be  $\delta$ -LTB curve and  $(\xi_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  be a semi-chain of  $\mathcal{C}$ . If  $\xi_i = \xi_j$  for some  $i, j \in \mathbb{Z}/N\mathbb{Z}$  then  $\{\xi_k\}_{k \in \llbracket i, j \rrbracket}$  or  $\{\xi_k\}_{k \in \llbracket j, i \rrbracket}$  is a singleton.*

*Proof.* This is a direct consequence of the definition of a semi-chain applied to the arcs between  $\xi_i$  and  $\xi_j$ .  $\square$

340 In the following lemma, the standard notation  $A \sqcup B$  denotes the disjoint union.

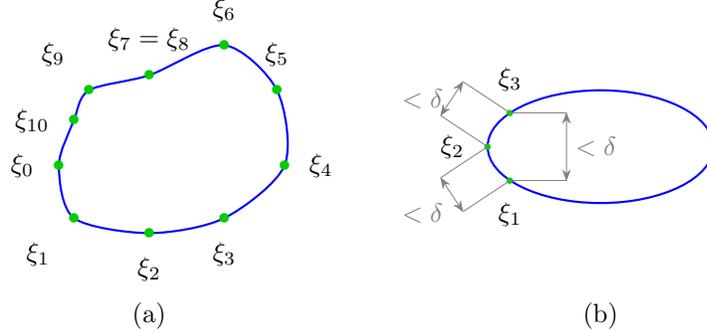


Figure 6: a) The sequence  $(\xi_k)_{k=0}^{10}$  is a semi-chain of the blue Jordan curve. For instance, the intersections of the set  $\{\xi_k\}_{k \in \mathbb{Z}/11\mathbb{Z}}$  with the two arcs of the blue curve between  $\xi_3$  and  $\xi_8$  are the subsets  $\{\xi_8, \xi_9, \xi_{10}, \xi_0, \xi_1, \xi_2, \xi_3\}$  and  $\{\xi_3, \xi_4, \xi_5, \xi_6, \xi_7, \xi_8\}$  (since  $\xi_7 = \xi_8$ ). b) Example of a semi-chain not being a sampling semi-chain. Two points in  $\{\xi_1, \xi_2, \xi_3\}$  are always strictly less than  $\delta$ , but the open straightest arc between  $\xi_1$  and  $\xi_3$  contains  $\xi_2$ .

**Lemma 3.** *Let  $\mathcal{C}$  be  $\delta$ -LTB curve and  $(\xi_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  be a sampling semi-chain of  $\mathcal{C}$  such that the cardinal of the set  $\{\xi_k\}$  is greater than 2. Then,*

$$\mathcal{C} = \{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}} \sqcup \bigsqcup_{k \in \mathbb{Z}/N\mathbb{Z}} \mathring{\mathcal{C}}_{\xi_k, \xi_{k+1}} .$$

In particular, for any  $(i, j) \in \mathbb{Z}/N\mathbb{Z}$ , the arcs of  $\mathcal{C}$  from  $\xi_i$  to  $\xi_j$  are

$$\{\xi_k\}_{k \in [i, j]} \sqcup \bigsqcup_{k \in [i, j]} \mathring{\mathcal{C}}_{\xi_k, \xi_{k+1}} \quad \text{and} \quad \{\xi_k\}_{k \in [j, i]} \sqcup \bigsqcup_{k \in [j, i]} \mathring{\mathcal{C}}_{\xi_k, \xi_{k+1}} .$$

*Proof.* Firstly, observe that, thanks to the assumption  $d(\xi_k, \xi_{k+1}) < \delta$ , the arc  $\mathring{\mathcal{C}}_{\xi_k, \xi_{k+1}}$  is well-defined.

- First, let us prove that the sets  $\mathring{\mathcal{C}}_{\xi_i, \xi_{i+1}}$ ,  $\mathring{\mathcal{C}}_{\xi_{i'}, \xi_{i'+1}}$  and  $\{x_k\}_{k \in \mathbb{Z}/N\mathbb{Z}}$  are disjoint whenever  $i \neq i'$ . Let  $i$  and  $i'$  be two different classes in  $\mathbb{Z}/N\mathbb{Z}$ . Since the sequence  $(\xi_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  is a sampling semi-chain of  $\mathcal{C}$ , the open arc  $\mathring{\mathcal{C}}_{\xi_i, \xi_{i+1}}$  does not contain any  $\xi_k$ ,  $k \in \mathbb{Z}/N\mathbb{Z}$ . Therefore,  $\mathring{\mathcal{C}}_{\xi_i, \xi_{i+1}} \cap \{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}} = \emptyset$  and  $\mathring{\mathcal{C}}_{\xi_i, \xi_{i+1}} \cap \mathring{\mathcal{C}}_{\xi_{i'}, \xi_{i'+1}} = \emptyset$  if  $\{\xi_i, \xi_{i+1}\} \neq \{\xi_{i'}, \xi_{i'+1}\}$ . Assume that  $\{\xi_i, \xi_{i+1}\} = \{\xi_{i'}, \xi_{i'+1}\}$ . If  $\xi_i = \xi_{i+1}$ , then we immediately have  $\mathring{\mathcal{C}}_{\xi_i, \xi_{i+1}} \cap \mathring{\mathcal{C}}_{\xi_{i'}, \xi_{i'+1}} = \emptyset$ . Now, by contradiction, assume that  $\xi_i \neq \xi_{i+1}$  (and thus,  $\xi_{i'} \neq \xi_{i'+1}$ ). Two cases are possible : either  $\xi_i = \xi_{i'}$  and  $\xi_{i+1} = \xi_{i'+1}$ , or  $\xi_i = \xi_{i'+1}$  and  $\xi_{i+1} = \xi_{i'}$ .

- In the first case,  $\mathcal{C}$  is the union of the two closed arcs between  $\xi_i$  and  $\xi_{i'}$ . As  $\xi_i = \xi_{i'}$ , the two arcs are  $\{\xi_i\}$  and  $\mathcal{C}$ . Since  $i + 1 \in [i, i']$  and  $i' + 1 \in [i', i]$ , by definition of a semi-chain, one of the two points  $\xi_{i+1}$  and  $\xi_{i'+1}$  belongs to the arc between  $\xi_i$  and  $\xi_{i'}$  reduced to  $\{\xi_i\}$ . Since  $\xi_{i+1} = \xi_{i'+1}$ ,  $\{\xi_i, \xi_{i+1}\}$  is a singleton. Contradiction !

– In the second case ( $\xi_i = \xi_{i'+1}$  and  $\xi_{i+1} = \xi_{i'}$ ), by Lemma 2, we derive that either  $\{\xi_k\}_{k \in [i, i'+1]}$  or  $\{\xi_k\}_{k \in [i'+1, i]}$  is a singleton and either  $\{\xi_k\}_{k \in [i', i+1]}$  or  $\{\xi_k\}_{k \in [i+1, i']}$  is a singleton. There are four possibilities which can be reduced to two thanks to the symmetry swapping  $i$  and  $i'$ . If  $\{\xi_k\}_{k \in [i, i'+1]}$  and  $\{\xi_k\}_{k \in [i', i+1]}$  are singletons, we derive that  $i = i' + 1$  and  $i + 1 = i'$  (for we assumed  $\xi_{i+1} \neq \xi_i$  and  $\xi_{i'+1} \neq \xi_{i'}$ ). It comes that  $i = i + 2$  in  $\mathbb{Z}/N\mathbb{Z}$ . That is,  $N = 2$ : a contradiction. If  $\{\xi_k\}_{k \in [i, i'+1]}$  and  $\{\xi_k\}_{k \in [i+1, i']}$  are singletons, we derive that  $i = i' + 1$  and the set  $\{\xi_k\}_{k \in [i+1, i'+1]} = \{\xi_k\}_{k \in [i+1, i]}$  is a pair. Since,  $\{\xi_k\}_{k \in [i, i+1]}$  is also a pair, we get again  $N = 2$ .

- The arc  $\bigsqcup_{k \in \mathbb{Z}/N\mathbb{Z}} \overset{\circ}{C}_{\xi_k, \xi_{k+1}} \sqcup \{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}}$ , which can be written as  $\{\xi_0\} \sqcup \overset{\circ}{C}_{\xi_0, \xi_1} \sqcup \{\xi_1\} \sqcup \dots \sqcup \overset{\circ}{C}_{\xi_{-1}, \xi_0}$ , is a simple closed arc of  $\mathcal{C}$  that is not reduced to a singleton for the cardinal of the semi-chain  $(\xi_k)$  is greater than 1. Then,  $\bigsqcup_{k \in \mathbb{Z}/N\mathbb{Z}} \overset{\circ}{C}_{\xi_k, \xi_{k+1}} \sqcup \{\xi_k\}_{k \in \mathbb{Z}/N\mathbb{Z}}$  is equal to  $\mathcal{C}$ .
- Alike, the arcs  $\bigsqcup_{k \in [i, j]} \overset{\circ}{C}_{\xi_k, \xi_{k+1}} \sqcup \{\xi_k\}_{k \in [i, j]}$  and  $\bigsqcup_{k \in [j, i]} \overset{\circ}{C}_{\xi_k, \xi_{k+1}} \sqcup \{\xi_k\}_{k \in [j, i]}$  are simple arcs of  $\mathcal{C}$  between  $\xi_i$  and  $\xi_j$  and they are not equal if  $\{\xi_k\}_{k \in [i, j]} \neq \{\xi_k\}_{k \in [j, i]}$ . So, by contradiction, assume that  $\{\xi_k\}_{k \in [i, j]} = \{\xi_k\}_{k \in [j, i]}$ . Since  $\#\{\xi_k\} > 2$ , there exist  $\ell \in [i, j]$  and  $\ell' \in [j, i]$  such that  $\xi_\ell = \xi_{\ell'}$  and  $\xi_\ell \notin \{\xi_i, \xi_j\}$ . Finally, applying Lemma 2 to  $\xi_\ell$  and  $\xi_{\ell'}$ , we get  $\xi_i = \xi_\ell$  or  $\xi_j = \xi_\ell$ : a contradiction.  $\square$

Lemma 3 explains the designation “sampling” semi-chain. Indeed, given a sampling semi-chain  $(\xi_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ , each point  $p$  of the curve  $\mathcal{C}$  is on a straightest arc between two consecutive points of this semi-chain (Lemma 3). Thereby, and because the straightest arc between two points  $a$  and  $b$  is included in the disk whose diameter is  $[a, b]$  (Property 3), each point  $p$  of the curve  $\mathcal{C}$  is at distance less than  $\delta$  of a point of  $(\xi_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ .

We can now define the main notion provided by this article.

**Definition 5** (Back-digitization). Let  $\mathcal{C}$  be a Jordan curve and  $h > 0$ .

- A map  $\xi: \text{Bel}_h(\mathcal{C}) \rightarrow \mathcal{C}$  is called a *back-digitization* if for every segment  $p \in \text{Bel}_h(\mathcal{C})$ ,  $\xi(p) \in p$ .
- A back-digitization  $\xi: (b_i)_{i \in \mathbb{Z}/N\mathbb{Z}} \rightarrow \mathcal{C}$  is *monotonic* if  $(\xi(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  is a semi-chain of  $\mathcal{C}$ .
- If  $\mathcal{C}$  is a LTB curve, a back-digitization  $\xi: (b_i)_{i \in \mathbb{Z}/N\mathbb{Z}} \rightarrow \mathcal{C}$  is a *monotonically sampling* back-digitization if  $(\xi(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  is a sampling semi-chain of  $\mathcal{C}$ .

As shown in Figure 7, there are curves with non-monotonic back-digitization or even, with no monotonic back-digitization. Nevertheless, in the sequel of

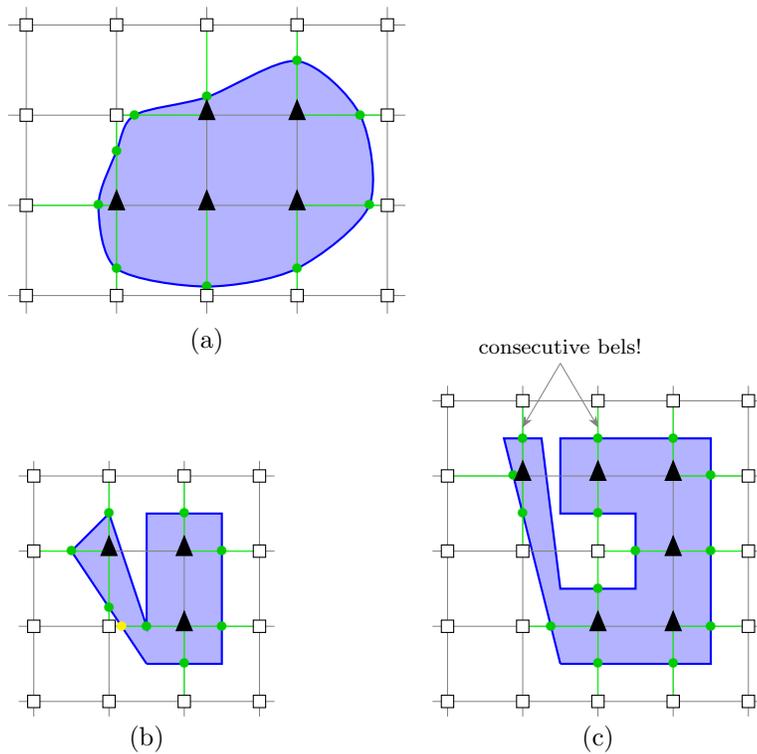


Figure 7: Light blue: a shape bounded by a Jordan curve (thick blue line). Black points: digitization of  $S$ . White points: grid points outside  $S$ . Green segments represent bels. Green points: intersection points. Example (a): a simple case: there is a unique mapping linking bels to their green points and it is injective and well-ordered. Example (b): There are several mappings and some of them are not well-ordered. Example (c): There is a unique mapping and it is not well-ordered.

Section 3, we prove the Proposition 2 according to which, assuming a LTB-  
 395 curve, any back-digitization is monotonically sampling.

The proof of this latter statement is split into four steps. In the first step,  
 we prove that some configurations cannot appear in the digitization of a LTB  
 curve (Subsection 3.2). In the second step, we define a specific back-digitization  
 called the *canonical back-digitization* and prove it to be a monotonically sam-  
 400 pling back-digitization (Subsection 3.3 ). In the third step, we prove that any  
 back-digitization of a LTB curve is a monotonically sampling back-digitization  
 (Subsection 3.4 ). In the fourth step, given a back-digitization  $\xi$ , we prove that  
 tight enough subsequences of  $(\xi(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  are also sampling semi-chains (Sub-  
 section 3.5).

### 405 3.2. Impossible configurations

The first step of the proof of the back-digitization monotonicity consists in  
 excluding local configurations in the digitization of a LTB curve on a compatible  
 grid (Lemma 5). In order to exclude these configurations, we use geometrical  
 arguments based on the turn and, in particular, results about the  $T$ -straightest  
 410 arc (Properties 7, 8, 9) and introduce Lemma 4 that precises Property 9 in the  
 case where the square  $T$  is a BDP. Figure 8 illustrates the proof.

**Lemma 4.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB Jordan curve. Let  $T$  be a BDP compatible with  $\mathcal{C}$   
 and having a vertex  $v$  lying on  $\mathcal{C}$ . If  $v$  belongs to a bel of  $T$ , then the vertex  $v$  is  
 an endpoint of the  $T$ -straightest arc of  $\mathcal{C}$ .*

415 *Proof.* By contradiction, assume that  $v$  is not an end of  $\mathcal{C}_T$ . Then, by Property  
 9, the arc  $\mathcal{C}_T$  is included in  $[a, v, b]$  and its turn is equal to  $\pi/2$  (see Figure 8).  
 Let  $p, q$  be the ends of  $\mathcal{C}_T$ ,  $p \in (a, v)$  and  $q \in (v, b]$ . Since, by the compatibility  
 hypothesis, the diameter of  $T$  is smaller than  $\delta$ , there exist points close to  $p$   
 in  $\mathcal{C} \setminus T$  at distance from  $q$  less than  $\delta$ . Let  $p'$  be such a point (see Figure 8).  
 420 On the one hand, the turn of the arc between  $p'$  and  $q$  including the arc  $\mathcal{C}_T$  is  
 greater than  $\pi/2$ . Thus, it is distinct from the straightest arc between  $p'$  and  $q$ .  
 On the other hand, the straightest arc between  $p'$  and  $q$  is included in the disk  
 whose diameter is  $[p', q]$  (Property 3). Then, the diameter of the curve  $\mathcal{C}$  is less  
 than  $\delta$  which contradicts Property 2.  $\square$

425 The purpose of the next lemma is to show that configurations depicted in  
 Figure 9 cannot appear in the digitization of a LTB curve on a compatible grid.  
 Notice that other configurations are already excluded by the well-composedness  
 (Property 6).

**Lemma 5** (Impossible configurations). *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve. Given a grid  
 430 compatible with  $\mathcal{C}$ , the configurations depicted in Figure 9 cannot appear in the  
 digitization of  $\mathcal{C}$ .*

*Proof.* For the first three configurations, let  $V$  be the square which is the union of  
 the four BDP of the configuration. We define an orthonormal coordinate system  
 by letting the center of  $V$  be the point  $(0,0)$  and the two exterior points be

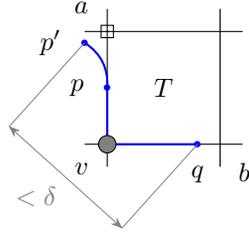


Figure 8: Grid square with an exterior vertex (square) and a border vertex (circle). The configuration is described up to a rigid transformation preserving  $h\mathbb{Z}^2$ . Any arc containing the arc  $C_T$  passing through  $T$  without having  $p$  for end has its turn greater than  $\frac{\pi}{2}$ .

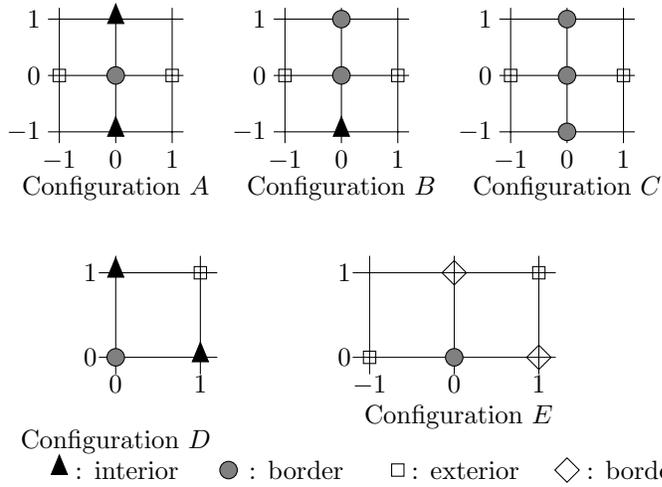


Figure 9: The configurations are defined up to a rigid transformation preserving  $h\mathbb{Z}^2$ .

435 the points  $(1, 0)$  and  $(-1, 0)$ . Notice that the border point  $(0, 0)$  is an endpoint of each  $T$ -straightest arc of a dual pixel included in  $V$  (Lemma 4). Then, the union of the arcs passing through the four BDP is path connected.

440 • *Configuration A.* Let  $P$  be one of the four BDP included in  $V$  and  $p$  be the endpoint of  $\mathcal{C}_P$  distinct from  $(0, 0)$ . The point  $p$  lies in the boundary of  $V$  for the segment  $[(0, 0), p]$  separates the exterior vertex of  $P$  from the interior vertex of  $P$  (Property 8). Notice that the point  $p$  does not belong to the swelling of another BDP of  $V$ , since the arc passing through a BDP is included in the swelling of the BDP. Thereby,  $\mathcal{C}_P$  is not included in another arc passing through a BDP of  $V$ . Then, four distinct arcs of  $\mathcal{C}$  meet in  $(0, 0)$  which contradicts the simplicity of the curve  $\mathcal{C}$ . Thus, on a LTB curve, Configuration  $A$  is impossible.

450 • *Configuration B.* Assume that the interior point has  $(0, -1)$  for coordinates. On the one hand, the same arguments as in the first Configuration hold for the dual pixels  $P_{(-0.5, -0.5)}$  and  $P_{(0.5, -0.5)}$ . On the other hand, the  $T$ -straightest arc of the dual pixel  $P_{(-0.5, 0.5)}$  is included in the swollen set of  $P_{(-0.5, 0.5)}$  and contains the vertex  $(0, 1)$ . Hence, it is distinct from the arcs passing through  $P_{(-0.5, -0.5)}$  and  $P_{(0.5, -0.5)}$ . Thus, three distinct arcs of  $\mathcal{C}$  meet in  $(0, 0)$ : on a LTB curve, Configuration  $B$  is impossible.

455 • *Configuration C.* From Properties 3, 9 and Lemma 4, the union  $\mathcal{C}_{P_{(-0.5, 0.5)}} \cup \mathcal{C}_{P_{(0.5, 0.5)}}$  of the arcs passing through  $P_{(-0.5, 0.5)}$  and  $P_{(0.5, 0.5)}$  is an arc of  $\mathcal{C}$  containing the points  $(0, 1)$  and  $(0, 0)$ , and included in the union of the disk of diameter  $[(0, 1), (0, 0)]$  with the segment  $[(-1, 1), (1, 1)]$ . Moreover, by Property 7, the intersection of  $\mathcal{C}$  with  $P_{(-0.5, 0.5)} \cup P_{(0.5, 0.5)}$  is included in  $\mathcal{C}_{P_{(-0.5, 0.5)}} \cup \mathcal{C}_{P_{(0.5, 0.5)}}$ . Alike,  $\mathcal{C} \cap (P_{(-0.5, -0.5)} \cup P_{(0.5, -0.5)}) \subseteq \mathcal{C}_{P_{(-0.5, -0.5)}} \cup \mathcal{C}_{P_{(0.5, -0.5)}}$  is an arc of  $\mathcal{C}$  passing through the points  $(0, -1)$  and  $(0, 0)$ , and included in the union of the disk of diameter  $[(0, -1), (0, 0)]$  with the segment  $[(-1, -1), (1, -1)]$ . Then,  $\mathcal{C} \cap V$  is an arc of  $\mathcal{C}$  that separates two exterior points in two distinct connected components of  $\mathbb{R}^2 \setminus \mathcal{C}$ : on a LTB curve, the configuration  $C$  is impossible.

465 • *Configuration D.* We define an orthonormal coordinate system by letting the border point having the coordinates  $(0, 0)$  and letting the exterior point having the coordinates  $(1, 1)$ . By Property 8, one end of the  $P_{(0.5, 0.5)}$ -straightest arc is on the open bel  $((0, 1), (1, 1))$  and the other on the open bel  $((1, 0), (1, 1))$ . This contradicts Property 9. Thus, Configuration  $D$  never occurs on a LTB curve.

470 • *Configuration E.* We define an orthonormal coordinate system by letting the border point having the coordinates  $(0, 0)$ , the border or interior points having the coordinates  $(0, 1)$  and  $(1, 0)$  and the two exterior points having coordinates  $(-1, 0)$  and  $(1, 1)$ . Since Configuration  $D$  cannot occur,  $(0, 1)$  or  $(1, 0)$  is a border point. Let us show by contradiction that actually both points are border points. Assume for instance that  $(1, 0)$  is

an interior point (exactly the same arguments hold for  $(0, 1)$ ). Then the curve  $\mathcal{C}$  intersects the open bel  $((1, 0), (1, 1))$  at a point  $f$ . By Lemma 4  $(0, 1)$  is an end of the  $P_{(0.5, 0.5)}$ -straightest arc. Then either  $[(0, 1), f, (0, 0)]$  or  $[(0, 1), (0, 0), f]$  is a chain of  $\mathcal{C}$  included in the  $P_{(0.5, 0.5)}$ -straightest arc. We derive that the  $P_{(0.5, 0.5)}$ -straightest arc has its turn greater than  $\frac{\pi}{2}$  which is absurd. Hence,  $(0, 1)$  and  $(1, 0)$  are both border points and, by Lemma 4 and Property 9,  $\mathcal{C}_{P_{(0.5, 0.5)}} = [(0, 1), (0, 0), (1, 0)]$ . Moreover, from Property 4, the intersection of the Jordan curve  $\mathcal{C}$  with the closed set  $B((0, 0), h)$  equals the polygonal line  $[(0, 1), (0, 0), (1, 0)]$ . Then the intersection of the Jordan curve  $\mathcal{C}$  with the closed set  $P_{(0.5, 0.5)} \cup B((0, 0), h)$  also equals the polygonal line  $[(0, 1), (0, 0), (1, 0)]$ . We derive that the two exterior points shown in Configuration  $E$  lie in two different connected components of  $P_{(0.5, 0.5)} \cup B((0, 0), h) \setminus [(0, 1), (0, 0), (1, 0)]$ . Thereby, the two exterior points shown in Configuration  $E$  lie in two distinct components of  $\mathbb{R}^2 \setminus \mathcal{C}$  (Property 9) which contradicts the Jordan curve theorem. Hence, Configuration  $E$  cannot occur on a LTB curve.  $\square$

### 3.3. The canonical back-digitization

Firstly, let us show two technical results linking the notions of  $T$ -straightest arc and BDP.

**Lemma 6.** *Let  $\mathcal{C}$  be  $\delta$ -LTB curve. We assume a grid compatible with  $\mathcal{C}$ .*

- *Let  $T$  be a BDP. The endpoints of the  $T$ -straightest arc lie on the bels of  $T$  and conversely each bel of  $T$  contains an endpoint of  $\mathcal{C}_T$ .*
- *Let  $b$  be a bel and  $T_1, T_2$  be the two BDPs containing  $b$ . The straightest arcs of  $\mathcal{C}$  between any endpoints of  $\mathcal{C}_{T_1}$  and  $\mathcal{C}_{T_2}$  lying on  $b$  are included in  $\mathcal{C}_{T_1} \cap \mathcal{C}_{T_2}$ .*

*Proof.*

- Let  $b$  be a bel of  $T$  and  $p_{\text{in}}$  be its inner-or-border point. If  $p_{\text{in}}$  is interior, then, from Property 8,  $b$  contains an end-point of  $\mathcal{C}_T$ . If  $p_{\text{in}}$  lies on  $\mathcal{C}$ , from Lemma 4,  $p_{\text{in}}$  is an end-point of  $\mathcal{C}_T$ . In the case where the two bels share their inner-or-border point which is an end-point of  $\mathcal{C}_T$ , Property 8 shows that no end-point of  $\mathcal{C}_T$  lies on the two edges of  $T$  that are not bels.
- From the first assertion of this lemma, there is an end-point  $e_1$  of the arc  $\mathcal{C}_{T_1}$  lying on  $b$  and there is an end-point  $e_2$  of the arc  $\mathcal{C}_{T_2}$  lying on  $b$ . Since the grid step is compatible with  $\mathcal{C}$ , the distance between  $e_1$  and  $e_2$  is less than  $\delta$ . Then, the straightest arc between  $e_1$  and  $e_2$  is well-defined and is included in both  $\mathcal{C}_{T_1}$  and  $\mathcal{C}_{T_2}$  by Definition 3.  $\square$

Let us now define a particular back-digitization that will be proved to be  
 515 a monotonically sampling back-digitization. Notice a point that is used in the  
 forthcoming definition: if the  $T_i$ -straightest arc has two endpoints on the bel  $b_i$ ,  
 then, by Lemma 6, one of them is shared with  $b_{i+1}$  and therefore is a grid point.

**Definition 6** (canonical back-digitization). Let  $\mathcal{C}$  be a LTB curve and  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$   
 be a cyclically ordered set of its bels on a compatible grid. Denoting by  $T_i$  the  
 520 BDP containing both  $b_i$  and  $b_{i+1}$ , the *canonical back-digitization*  $\xi_c$  associates  
 to each  $b_i$  either the unique  $T_i$ -straightest arc endpoint lying on  $b_i$  or the one  
 which is not a grid point.

Observe that, since the digitization is well-composed, the mapping  $b_i \mapsto T_i$   
 is a one-to-one correspondence between the bels and the BDPS. Nevertheless,  
 525 the canonical back-digitization may not be one-to-one since consecutive images  
 of  $\xi_c$  can be equal. For instance, a point of the curve lying on a grid point may  
 yield three consecutive identical images (see Figure 5).

**Proposition 1.** *Let  $\mathcal{C}$  be a LTB curve and  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$  be a cyclically ordered  
 set of its bels on a compatible grid. Then, if for some  $i$  and  $j$  in  $\mathbb{Z}/N\mathbb{Z}$ ,  $\xi_c(b_j)$   
 530 lies on the straightest arc linking  $\xi_c(b_i)$  and  $\xi_c(b_{i+1})$ , then either  $j \in \llbracket i - 2, i \rrbracket$   
 and  $\xi_c(b_j) = \xi_c(b_i)$  or  $j \in \llbracket i + 1, i + 3 \rrbracket$  and  $\xi_c(b_j) = \xi_c(b_{i+1})$ .*

*Proof.* Let  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$  be the cyclically ordered set of bels. Assume that  $\xi_c(b_j)$   
 lies on the straightest arc linking  $\xi_c(b_i)$  and  $\xi_c(b_{i+1})$  for some  $j \notin \{i, i + 1\}$ .  
 Then,  $\xi_c(b_j)$  belongs to the  $T_i$ -straightest arc where  $T_i$  is the BDP containing  
 535  $b_i$  and  $b_{i+1}$ . Hence, it belongs to the swelling of  $T_i$ . Since  $\xi_c(b_j)$  lies on a bel,  
 that is on an edge of the grid, actually,  $\xi_c(b_j) \in T_i$ . Since  $T_i$  is a BDP,  $T_i$  has an  
 exterior point and the border point  $\xi_c(b_j)$  for vertices (the intersection of a bel  
 $b_j \notin \{b_i, b_{i+1}\}$  with the BDP  $T_i$  is necessarily a vertex of the grid). One of the  
 540 bels  $b_i$  or  $b_{i+1}$  has  $\xi_c(b_j)$  for end. Indeed if it was not the case,  $\xi_c(b_j)$  and the  
 exterior point would be diagonally opposed and Configuration  $E$  would occur,  
 which is impossible by Lemma 5. Then the border point  $\xi_c(b_j)$  is a vertex of an  
 edge of  $T_i$  having an exterior point for the other end, that is a vertex of  $b_i$  or  
 $b_{i+1}$ . We assume that  $\xi_c(b_j) \in b_i$  (the case  $\xi_c(b_j) \in b_{i+1}$  is similar). We derive  
 from Lemma 4, that  $\xi_c(b_j)$  is an endpoint of  $\mathcal{C}_{T_i}$ . Then, either  $\xi_c(b_i) = \xi_c(b_j)$   
 545 or  $\xi_c(b_j)$  is the second endpoint of the  $T_i$ -straightest arc (by definition of  $\xi_c$ ). In  
 the latter case, both endpoints of the  $T_i$ -straightest arc belong to  $b_i$  and  $\mathcal{C}_{T_i}$  is  
 included in the disk with diameter  $b_i$  (Property 3). Therefore,  $\xi_c(b_{i+1})$ , which  
 lies in both  $b_{i+1}$  and the  $T_i$ -straightest arc is the intersection of  $b_{i+1}$  and the  
 550 disk with diameter  $b_i$  which is the grid point  $\xi_c(b_j)$  since the other endpoint of  
 $b_i$  is an exterior point. At this stage, we have proved that

1. either  $\xi_c(b_j) = \xi_c(b_i)$  or  $\xi_c(b_j) = \xi_c(b_{i+1})$ .
2.  $\xi_c(b_j)$  is a grid point.

Let  $b_k$  be one of the bels such that  $\xi_c(b_k) = \xi_c(b_j)$  with  $k \in \{i, i + 1\}$ . There  
 are two possibilities: either  $b_k$  and  $b_j$  are orthogonal (Figure 10-a) or they are  
 555 aligned (Figure 10-b).

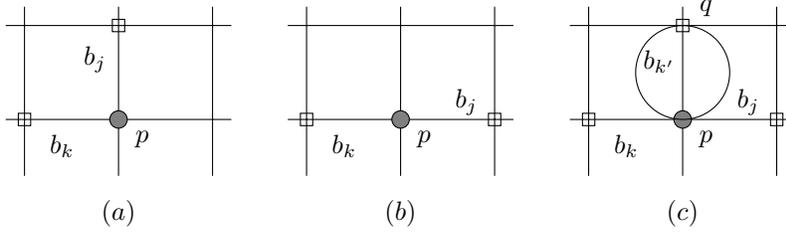


Figure 10: (Proof of Proposition 1) The bels  $b_j$  and  $b_k$  share the same image  $p$  by the canonical back-digitization  $\xi_c$ .

In the first case,  $b_k$  and  $b_j$  are two orthogonal bels sharing a vertex, thus they share a BDP. Since there are exactly two bels per BDP,  $|k - i| = 1$ , moreover  $j \notin \{i, i + 1\}$ , then either  $k = i$  and  $j = i - 1$  or  $k = i + 1$  and  $j = i + 2$ .

In the second case  $b_k$  and  $b_j$  are aligned. We derive from Lemma 5 (Configurations  $A, B, C$ ) that there is a third bel  $b_{k'}$  having  $\xi_c(b_j)$  as extremity. Then  $|k - j| = 2$ . Thus  $j \in \llbracket i - 2, i + 3 \rrbracket$ . If  $(k, j) = (i, i - 2)$  or  $(k, j) = (i + 1, i + 3)$ , there is nothing left to prove since  $\xi_c(b_k) = \xi_c(b_j)$ . Otherwise,  $(k, j) = (i, i + 2)$  or  $(k, j) = (i + 1, i - 1)$ . It remains to prove that  $\xi_c(b_{i+2}) = \xi_c(b_{i+1})$  or  $\xi_c(b_{i-1}) = \xi_c(b_i)$ . Assume that  $(k, j) = (i, i + 2)$  (the case  $(k, j) = (i + 1, i - 1)$  is similar) and, by contradiction, that  $\xi_c(b_{i+1}) \neq \xi_c(b_j)$ . By Lemma 4,  $\xi_c(b_j)$  is an endpoint of the  $T_{i+1}$ -straightest arc. Therefore, from the assumptions and the definition of  $\xi_c$ , all the endpoints of the  $T_i$ -straightest arc and the  $T_{i+1}$ -straightest arc are in  $b_{i+1}$ . Then, by Property 3,  $\mathcal{C}_{T_i} \cup \mathcal{C}_{T_{i+1}}$  is included in the disk  $D$  with diameter  $[\xi_c(b_j), q]$  where  $q$  is the exterior point of the bel  $b_{i+1}$  (see Figure 10-c). We have a contradiction with the simplicity of  $\mathcal{C}$  and the fact that the arc  $\mathcal{C} \setminus (\mathcal{C}_{T_i} \cup \mathcal{C}_{T_{i+1}})$  does not intersect  $T_i \cup T_{i+1}$  (Property 7).  $\square$

Proposition 1 is the heart of the proof of the monotonicity of the canonical back-digitization. Corollary 1 is only a formal verification that the result of Proposition 1 coincides with the definition of the monotonicity.

**Corollary 1.** *Let  $\mathcal{C}$  be a LTB curve and  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$  be a cyclically ordered set of its bels on a compatible grid. The canonical back-digitization is a monotonically sampling back-digitization.*

*Proof.* In this proof, the cardinal of a subsequence  $(\xi_c(b_k))_{k \in \llbracket i, j \rrbracket}$  of  $(\xi_c(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  ( $i, j \in \mathbb{Z}/N\mathbb{Z}$ ), is the cardinal of the set  $\{\xi_c(b_k)\}_{k \in \llbracket i, j \rrbracket}$  and we set  $M = \#\xi_c(\text{Bel}_h(\mathcal{C}))$ . We assume  $M \geq 3$  (otherwise, the result is obvious).

Let us firstly prove that  $(\xi_c(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  is a semi-chain. For any  $n \in [2, M/2 + 1] \cap \mathbb{N}$ , let  $H_n$  be the induction hypothesis: “for any  $i, j \in \mathbb{Z}/N\mathbb{Z}$  and any subsequence  $(\xi_c(b_k))_{k \in \llbracket i, j \rrbracket}$  of  $(\xi_c(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  whose cardinal is less than  $n$ , the two sets resulting from the intersection of the closed arcs from  $\xi_c(b_i)$  to  $\xi_c(b_j)$  with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  are equal to  $\{\xi_c(b_k)\}_{k \in \llbracket i, j \rrbracket}$  and  $\{\xi_c(b_k)\}_{k \in \llbracket j, i \rrbracket}$ ”. Notice that between any two terms of the sequence  $(\xi_c(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  there is an arc containing at most  $\lfloor M/2 + 1 \rfloor$  terms of the sequence. Hence  $H_{\lfloor M/2 + 1 \rfloor}$  states that

$(\xi_c(b_i))_{i \in \mathbb{Z}/N\mathbb{Z}}$  is a semi-chain.

590 • From Proposition 1, we get that, for any  $i \in \mathbb{Z}/N\mathbb{Z}$ , the intersections of the closed arcs from  $\xi_c(b_i)$  to  $\xi_c(b_{i+1})$  with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  are equal to  $\{\xi_c(b_k)\}_{k \in \llbracket i, i+1 \rrbracket}$  (for the straightest arc) and  $\{\xi_c(b_k)\}_{k \in \llbracket i+1, i \rrbracket}$  (for the complementary arc). It is plain that we can extend this property to closed arcs from  $\xi_c(b_i)$  to  $\xi_c(b_j)$  provided that either  $\#\{\xi_k\}_{k \in \llbracket i, j \rrbracket} \leq 2$  or  $\#\{\xi_k\}_{k \in \llbracket j, i \rrbracket} \leq 2$ . Then  $H_2$ .

595 • Let  $n \geq 3$ . Assume  $H_{n-1}$ . We consider two integers  $i$  and  $j$  in  $\mathbb{Z}/N\mathbb{Z}$  such that  $\#\{\xi_c(b_k)\}_{k \in \llbracket i, j \rrbracket} = n$ . There exists  $\ell \in \llbracket i, j \rrbracket$  such that  $\#\{\xi_c(b_k)\}_{k \in \llbracket i, \ell \rrbracket} = n - 1$  and  $\#\{\xi_c(b_k)\}_{k \in \llbracket i, \ell+1 \rrbracket} = n$ . We write  $C_{i, \ell}$ , resp.  $C_{\ell, i}$ , for the arc between  $\xi_c(b_i)$  and  $\xi_c(b_\ell)$  whose intersection with  $\text{Bel}_h(\mathcal{C})$  is equal to  $\{\xi_c(b_k)\}_{k \in \llbracket i, \ell \rrbracket}$ , resp.  $\{\xi_c(b_k)\}_{k \in \llbracket \ell, i \rrbracket}$  (we use the induction hypothesis  $H_{n-1}$ ). Since  $\xi_c(b_{\ell+1}) \notin \{\xi_c(b_k)\}_{k \in \llbracket i, \ell \rrbracket}$  (by definition of  $\ell$ ),  $\xi_c(b_{\ell+1})$  lies in the interior of  $C_{\ell, i}$ . Furthermore, by Proposition 1, the open straightest arc  $\overset{\circ}{C}_{\xi_c(b_\ell), \xi_c(b_{\ell+1})}$  from  $\xi_c(b_\ell)$  to  $\xi_c(b_{\ell+1})$  does not contain any point of  $\xi_c(\text{Bel}_h(\mathcal{C}))$ . Then,  $C_{i, \ell+1} := C_{i, \ell} \sqcup \overset{\circ}{C}_{\xi_c(b_\ell), \xi_c(b_{\ell+1})} \sqcup \{\xi_c(b_{\ell+1})\}$  is an arc from  $\xi_c(b_i)$  to  $\xi_c(b_{\ell+1})$  whose intersection with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is  $\{\xi_c(b_k)\}_{k \in \llbracket i, \ell+1 \rrbracket}$ .

600 Alike, the arc  $C_{\ell, i} \setminus (\{\xi_c(b_\ell)\} \sqcup \overset{\circ}{C}_{\xi_c(b_\ell), \xi_c(b_{\ell+1})})$  is an arc from  $\xi_c(b_i)$  to  $\xi_c(b_{\ell+1})$  whose intersection with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is  $\{\xi_c(b_k)\}_{k \in \llbracket \ell+1, i \rrbracket}$ . It remains to show that the points  $\xi_c(b_k)$ ,  $k \in \llbracket \ell+1, j \rrbracket$ , are all equal to  $\xi_c(b_{\ell+1})$ . For any  $k \in \llbracket \ell+1, j \rrbracket$ , let  $P_k$  be the induction hypothesis : “  
610  $\xi(b_k) = \xi(b_{\ell+1})$ ”.

–  $P_{\ell+1}$  is obvious.

– Let  $k \in \llbracket \ell+2, j \rrbracket$ , assume  $P_{\ell+1}, \dots, P_{k-1}$ , i.e.  $\xi_c(b_{\ell+1}) = \xi_c(b_{\ell+2}) = \dots = \xi_c(b_{k-1})$ .

\* By definition of  $\ell$ ,  $\xi_c(b_k) \in C_{i, \ell+1}$  and  $\xi_c(b_k) \in C_{\ell, i}$ . Then,

$$\begin{aligned} \xi_c(b_k) &\in C_{i, \ell+1} \cap C_{\ell, i} \cap \xi_c(\text{Bel}_h(\mathcal{C})), \\ &= (C_{i, \ell} \sqcup \overset{\circ}{C}_{\xi_c(b_\ell), \xi_c(b_{\ell+1})} \sqcup \{\xi_c(b_{\ell+1})\}) \cap C_{\ell, i} \cap \xi_c(\text{Bel}_h(\mathcal{C})), \\ &= (C_{i, \ell} \cap C_{\ell, i} \cap \xi_c(\text{Bel}_h(\mathcal{C}))) \sqcup \{\xi_c(b_{\ell+1})\}, \\ &= \{\xi(b_i), \xi(b_\ell), \xi(b_{\ell+1})\}. \end{aligned}$$

615 \* By contradiction assume that  $\xi_c(b_k) = \xi_c(b_\ell)$ . Then, on the one hand, one of the arc between  $\xi_c(b_\ell)$  and  $\xi_c(b_k)$  is a singleton while the other arc is  $\mathcal{C}$ . On the other hand, by the induction hypothesis  $H_{n-1}$ , one of the arcs between  $\xi_c(b_\ell)$  and  $\xi_c(b_k)$  contains exactly two points of  $\xi_c(\text{Bel}_h(\mathcal{C}))$ ,  $\xi_c(b_\ell)$  and  $\xi_c(b_{\ell+1})$ . It follows that the cardinal of  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is 2 which contradicts the  
620 assumption  $M \geq 3$ . Thus,  $\xi_c(b_k) \neq \xi_c(b_\ell)$ .

\* By contradiction assume that  $\xi_c(b_k) = \xi_c(b_i)$ . Then, on the one hand, one of the arcs between  $\xi_c(b_{\ell+1})$  and  $\xi_c(b_k)$  is  $C_{i,\ell+1}$ . By definition of  $l$ , this arc contains exactly  $n$  points of  $\xi_c(\text{Bel}_h(\mathcal{C}))$  where  $n \geq 3$ . On the other hand, by the induction hypothesis  $P_{k-1}$ , one of the arcs between  $\xi_c(b_{\ell+1})$  and  $\xi_c(b_k)$  contains at most two points of  $\xi_c(\text{Bel}_h(\mathcal{C}))$  while the other arc contains all the points of  $\xi_c(\text{Bel}_h(\mathcal{C}))$ . It follows that the cardinal of  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is  $n$  which contradicts the assumptions  $n \leq M/2 + 1$  and  $M \geq 3$ . Then,  $\xi_c(b_k) \neq \xi_c(b_i)$ . Since  $\xi_c(b_k) \in \{\xi_c(b_i), \xi_c(b_l), \xi_c(b_{l+1})\}$ ,  $P_k$ .

Finally, we derive that  $\xi_c(b_{\ell+1}) = \xi_c(b_{\ell+2}) = \dots = \xi_c(b_j)$ .

Then,  $C_{i,\ell+1}$  is an arc from  $\xi_c(b_i)$  to  $\xi_c(b_j)$  whose intersection with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is  $\{\xi_c(b_k)\}_{k \in \llbracket i,j \rrbracket}$ . Alike, the arc  $C_{\ell,i} \setminus (\{\xi_c(b_\ell)\} \sqcup \dot{C}_{\xi_c(b_\ell), \xi_c(b_{\ell+1})})$  is an arc from  $\xi_c(b_i)$  to  $\xi_c(b_j)$  whose intersection with  $\xi_c(\text{Bel}_h(\mathcal{C}))$  is  $\{\xi_c(b_k)\}_{k \in \llbracket j,i \rrbracket}$ . Then  $H_n$ .

Eventually, observe that the sequence  $(\xi_c(b_k))_{k \in \mathbb{Z}/N\mathbb{Z}}$  is a sampling semi-chain. Indeed,  $d(b_k, b_{k+1}) < \delta$  for any  $k$  because the grid is compatible with  $\mathcal{C}$  and the straightest arc between  $\xi_c(b_k)$  and  $\xi_c(b_{k+1})$  does not contain any point of  $\xi_c(\text{Bel}_h(\mathcal{C}))$  by Proposition 1.  $\square$

#### 3.4. Monotony of any back-digitization

We now show that any back-digitization defined on the bels of a LTB curve is a monotonically sampling back-digitization. The heart of this result is brought by the following lemma.

**Lemma 7.** *Let  $\mathcal{C}$  be a LTB curve and  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$  be a cyclically ordered set of its bels on a compatible grid. Let  $\xi$  be a back-digitization. Then, for any  $i \in \mathbb{Z}/N\mathbb{Z}$ ,  $\xi(b_i)$  lies on the straightest arc between  $\xi_c(b_i)$  and  $\xi_c(b_{i+1})$ .*

*Proof.* Let  $T_i$ , resp.  $T_{i+1}$ , be the BDP containing both  $b_i$  and  $b_{i+1}$ , resp.  $b_{i+1}$  and  $b_{i+2}$ . By definition of a back-digitization,  $\xi(b_i) \in b_i$  and  $\xi_c(b_{i+1}) \in b_{i+1}$ . Then,  $\xi(b_i)$  and  $\xi_c(b_{i+1})$  lie on  $\mathcal{C}_{T_i}$ , the  $T_i$ -straightest arc. Recall that, by definition of  $\xi_c$ ,  $\xi_c(b_i)$  is an endpoint of  $\mathcal{C}_{T_i}$ . Let  $e_i$  be the other end-point of  $\mathcal{C}_{T_i}$ . By contradiction assume that  $\xi(b_i)$  does not belong to the straightest arc between  $\xi_c(b_i)$  and  $\xi_c(b_{i+1})$ . Then  $\xi(b_i)$  belongs to the straightest arc between  $\xi_c(b_{i+1})$  and  $e_i$ , then  $\xi(b_i) \in \mathcal{C}_{T_i} \cap \mathcal{C}_{T_{i+1}}$  (Lemma 6). Since  $\mathcal{C}_{T_i} \cap \mathcal{C}_{T_{i+1}}$  is included in the disk with diameter  $b_{i+1}$  which intersects  $b_i$  in a grid point  $p$ ,  $\xi(b_i)$  is a grid point and, by Lemma 4, it is an end-point of  $\mathcal{C}_{T_i}$ . Since  $\xi(b_i) \neq \xi_c(b_i)$ ,  $\mathcal{C}_{T_i}$  is included in the disk with diameter  $b_i$  and  $\xi_c(b_{i+1}) = \xi(b_i)$ . Contradiction! Then  $\xi(b_i)$  is in the straightest arc between  $\xi_c(b_i)$  and  $\xi_c(b_{i+1})$ .  $\square$

Establishing the monotony of a back-digitization needs further tedious calculations that will be carried out in Proposition 2. But before that, we still have to give a technical lemma about subsequences of semi-chains. This lemma is also of primary importance for the next subsection dealing with sparse samplings of a curve.

**Lemma 8.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve.*

- 665 (a) *Let  $a, b, c$  be three points of  $\mathcal{C}$  such that  $d(a, b) < \delta$  and  $d(b, c) < \delta$ . Let consider the three arcs such that  $\mathcal{C} \setminus \{a, b, c\}$  is a disjoint union of these three arcs. Then one of them has its turn greater than  $\frac{\pi}{2}$ .*
- (b) *Let  $(a_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$ ,  $N \geq 3$ , be a semi-chain of  $\mathcal{C}$  such that, for any  $i, j \in \mathbb{Z}/N\mathbb{Z}$ ,  $d(a_i, a_j) < \delta$  and, for any  $k \in \mathbb{Z}/N\mathbb{Z} \setminus \{0\}$ , the arc from  $a_{k-1}$  to  $a_k$  whose intersection with the semi-chain is  $\{a_{k-1}, a_k\}$  is a straightest arc.*
- 670 *Then, the arc from  $a_0$  to  $a_N$  passing through  $a_1, \dots, a_{N-1}$  is a straightest arc.*

*Proof.*

- (a) Let  $A$  be the arc of  $\mathcal{C}$  between the points  $a$  and  $b$  and not containing the point  $c$ . If  $A$  is not a straightest arc, then by applying Fenchel's Theorem (the turn of closed curve is bounded from below by  $2\pi$ ) and the additivity of turns, both stated in Property 1, one has

$$\kappa(A) + \langle e_l(a), e_r(a) \rangle + \kappa(\mathbf{A}') + \langle e_l(b), e_r(b) \rangle \geq 2\pi,$$

where  $\mathbf{A}'$  is the straightest arc between  $a$  and  $b$  ( $\mathbf{A}'$  exists for  $d(a, b) < \delta$ ). Moreover, from Lemma 1-b, we have

$$\langle e_l(a), e_r(a) \rangle + \kappa(\mathbf{A}') + \langle e_l(b), e_r(b) \rangle \leq \frac{\pi}{2}.$$

Then  $\kappa(A) \geq 2\pi - \pi/2 > \pi/2$  and we are done. The same arguments hold for the arc  $B$  between the points  $b$  and  $c$  and not containing the point  $a$ . Finally, if  $A$  and  $B$  are straightest arcs, we denote by  $C$  the arc of  $\mathcal{C}$  between the points  $a$  and  $c$  and not containing the point  $b$ . Using as above Fenchel's Theorem, the additivity of turns and Lemma 1-b, we get

$$\begin{aligned} \kappa(C) &\geq 2\pi - (\langle e_l(a), e_r(a) \rangle + \kappa(A) + \langle e_l(b), e_r(b) \rangle + \kappa(B) \\ &\quad + \langle e_l(c), e_r(c) \rangle) \\ &\geq 2\pi - (\langle e_l(a), e_r(a) \rangle + \kappa(A) + \langle e_l(b), e_r(b) \rangle) \\ &\quad - (\langle e_l(b), e_r(b) \rangle + \kappa(B) + \langle e_l(c), e_r(c) \rangle) \\ &\geq 2\pi - \pi/2 - \pi/2 \\ &\geq \pi. \end{aligned}$$

So, the result holds.

- (b) The proof is done by finite induction on  $N$ .

675 If  $N = 3$ , we derive from the first statement of this lemma that the arc of  $\mathcal{C}$  between  $a_0$  and  $a_2$  and not containing  $a_1$  has a turn greater than  $\pi/2$ . Then, the straightest arc between  $a_0$  and  $a_2$ , which exists for  $d(a_0, a_2) < \delta$ , is the arc between  $a_0$  and  $a_2$  and containing  $a_1$ .

680 Assume that the result holds for the semi-chain  $(a_k)_{k \in [0, n]}$  where  $3 \leq n \leq N - 1$ . On the one hand, from the induction hypothesis, the arc

$C_n$  between  $a_0$  and  $a_n$  not containing  $a_N$  is a straightest arc. On the other hand, from the general hypothesis, the arc from  $a_n$  to  $a_{n+1}$  not containing  $a_0$  is a straightest arc. Then, from the previous result of this lemma (Lemma 1(c)), the arc from  $a_{n+1}$  to  $a_0$  not containing the points  $a_i$ ,  $1 \leq i \leq n$ , has a turn greater than  $\pi/2$ . Thus, this arc cannot be a straightest arc though such a straightest arc between  $a_0$  and  $a_{n+1}$  exists (for  $d(a_0, a_{n+1}) < \delta$ ). We conclude that the arc from  $a_0$  to  $a_{n+1}$  passing through  $a_i, \dots, a_n$  is a straightest arc. This achieves the induction  $\square$

**Proposition 2.** *Let  $\mathcal{C}$  a  $\delta$ -LTB curve. Any back-digitization defined on a compatible grid is a monotonically sampling back-digitization.*

*Proof.* Let  $(b_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$  be a cyclically ordered set of the bels associated to  $\mathcal{C}$  on a compatible grid and  $\xi$  be a back-digitization. Let  $i, j \in \mathbb{Z}/N\mathbb{Z}$ . We consider the following sets:

$$C_1 = \{\xi_c(b_k)\}_{k \in \llbracket i, j+1 \rrbracket} \sqcup \bigsqcup_{k \in \llbracket i, j \rrbracket} \overset{\circ}{C}_{\xi_c(b_k), \xi_c(b_{k+1})},$$

and

$$C_2 = \{\xi_c(b_k)\}_{k \in \llbracket j, i+1 \rrbracket} \sqcup \bigsqcup_{k \in \llbracket j, i \rrbracket} \overset{\circ}{C}_{\xi_c(b_k), \xi_c(b_{k+1})}.$$

From Lemma 3,  $C_1$  is an arc between  $\xi_c(b_i)$  and  $\xi_c(b_{j+1})$  and  $C_2$  is an arc between  $\xi_c(b_j)$  and  $\xi_c(b_{i+1})$ . From Lemma 7, we derive that

$$C_1 = \bigsqcup_{k \in \llbracket i, j \rrbracket} \left( \overset{\circ}{C}_{\xi_c(b_k), \xi(b_k)} \sqcup \overset{\circ}{C}_{\xi(b_k), \xi_c(b_{k+1})} \right) \sqcup \{\xi(b_k)\}_{k \in \llbracket i, j \rrbracket} \sqcup \left( \{\xi_c(b_k)\}_{k \in \llbracket i, j+1 \rrbracket} \setminus \{\xi(b_k)\}_{k \in \llbracket i, j \rrbracket} \right), \quad (1)$$

and

$$C_2 = \bigsqcup_{k \in \llbracket j, i \rrbracket} \left( \overset{\circ}{C}_{\xi_c(b_k), \xi(b_k)} \sqcup \overset{\circ}{C}_{\xi(b_k), \xi_c(b_{k+1})} \right) \sqcup \{\xi(b_k)\}_{k \in \llbracket j, i \rrbracket} \sqcup \left( \{\xi_c(b_k)\}_{k \in \llbracket j, i+1 \rrbracket} \setminus \{\xi(b_k)\}_{k \in \llbracket j, i \rrbracket} \right). \quad (2)$$

Lemma 8-c, applied to the semi-chains  $(\xi(b_k), \xi_c(b_{k+1}), \xi(b_{k+1}))$ , shows that the arcs  $\overset{\circ}{C}_{\xi(b_k), \xi_c(b_{k+1})} \sqcup \{\xi_c(b_{k+1})\} \sqcup \overset{\circ}{C}_{\xi_c(b_{k+1}), \xi(b_{k+1})}$  are straightest arcs of  $\mathcal{C}$ , that is,  $\overset{\circ}{C}_{\xi(b_k), \xi(b_{k+1})} = \overset{\circ}{C}_{\xi(b_k), \xi_c(b_{k+1})} \sqcup \{\xi_c(b_{k+1})\} \sqcup \overset{\circ}{C}_{\xi_c(b_{k+1}), \xi(b_{k+1})}$ . Observe that, if for some  $k$ ,  $\xi_c(b_{k+1}) \notin \{\xi_c(b_m)\}_{m \in \llbracket i, j+1 \rrbracket} \setminus \{\xi(b_m)\}_{m \in \llbracket i, j \rrbracket}$ , then  $\xi_c(b_{k+1}) = \xi(b_k)$  or  $\xi_c(b_{k+1}) = \xi(b_{k+1})$  and  $\overset{\circ}{C}_{\xi(b_k), \xi(b_{k+1})} = \overset{\circ}{C}_{\xi_c(b_{k+1}), \xi(b_{k+1})}$  or  $\overset{\circ}{C}_{\xi(b_k), \xi(b_{k+1})} = \overset{\circ}{C}_{\xi_c(b_k), \xi(b_{k+1})}$ . The same reasoning holds if  $\xi_c(b_{k+1}) \notin \{\xi_c(b_m)\}_{m \in \llbracket j, i+1 \rrbracket} \setminus \{\xi(b_m)\}_{m \in \llbracket j, i \rrbracket}$ .

Then, Equations (1), (2) can be rewritten as

$$C_1 = \{\xi_c(b_i)\} \sqcup \mathring{C}_{\xi_c(b_i), \xi(b_i)} \sqcup \left( \{\xi(b_k)\}_{k \in \llbracket i, j \rrbracket} \sqcup \bigsqcup_{k \in \llbracket i, j-1 \rrbracket} \mathring{C}_{\xi(b_k), \xi(b_{k+1})} \right) \sqcup \mathring{C}_{\xi(b_j), \xi_c(b_{j+1})} \sqcup \{\xi_c(b_{j+1})\}$$

and

$$C_2 = \{\xi_c(b_j)\} \sqcup \mathring{C}_{\xi_c(b_j), \xi(b_j)} \sqcup \left( \{\xi_c(b_k)\}_{k \in \llbracket j, i \rrbracket} \sqcup \bigsqcup_{k \in \llbracket j, i-1 \rrbracket} \mathring{C}_{\xi(b_k), \xi(b_{k+1})} \right) \sqcup \mathring{C}_{\xi(b_i), \xi_c(b_{i+1})} \sqcup \{\xi_c(b_{i+1})\}.$$

Eventually, the latter equalities show that the arcs of  $\mathcal{C}$  from  $\xi(b_i)$  to  $\xi(b_j)$  are

$$C'_1 = \bigsqcup_{k \in \llbracket i, j-1 \rrbracket} \mathring{C}_{\xi(b_k), \xi(b_{k+1})} \sqcup \{\xi(b_k)\}_{k \in \llbracket i, j \rrbracket} \quad (3)$$

and

$$C'_2 = \bigsqcup_{k \in \llbracket j, i-1 \rrbracket} \mathring{C}_{\xi(b_k), \xi(b_{k+1})} \sqcup \{\xi_c(b_k)\}_{k \in \llbracket j, i \rrbracket}. \quad (4)$$

Since  $C'_1$  and  $C'_2$  are complementary arcs, it can be seen that these two arcs intersect  $\xi(\text{Bel}_h(\mathcal{C}))$  respectively in  $\{\xi(b_k)\}_{k \in \llbracket i, j \rrbracket}$  and  $\{\xi(b_k)\}_{k \in \llbracket j, i \rrbracket}$ . In particular, taking  $j = i + 1$ , we see that the straightest between  $\xi(b_i)$  and  $\xi(b_{i+1})$  does not contain any point of  $\xi(\text{Bel}_h(\mathcal{C}))$  in its interior. Besides, by definition of a back-digitization, and since the grid is compatible with the curve  $\mathcal{C}$ , we have  $d(\xi(b_k), \xi(b_{k+1})) < \delta$  for any  $k \in \mathbb{Z}/N\mathbb{Z}$ .  $\square$

### 3.5. Monotonically sampling subsequences of $\text{Bel}_h(\mathcal{C})$

In this subsection, we extend Proposition 2 to subsequences of  $\text{Bel}_h(\mathcal{C})$ . This is of interest for the length estimation where estimators should only use sparse subsequences of  $\text{Bel}_h(\mathcal{C})$  to be convergent (see Section Introduction).

**Theorem 2.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve on a compatible grid  $h\mathbb{Z}^2$ . Let  $\xi : \text{Bel}_h(\mathcal{C}) \rightarrow \mathcal{C}$  be a back-digitization. Denoting by  $(a_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  the cyclically ordered set  $\text{Bel}_h(\mathcal{C})$  and assuming  $N \geq 3$ , let  $(a_{\sigma(i)})_{i \in \mathbb{Z}/N_\sigma\mathbb{Z}}$  be a subsequence of  $(a_k)$  such that  $h\#\llbracket \sigma(i), \sigma(i+1) \rrbracket < \delta$ . Then,*

$$\mathcal{C} = \bigcup_{i \in \mathbb{Z}/N_\sigma\mathbb{Z}} \mathcal{C}'_i,$$

where  $\mathcal{C}'_i$  is the straightest arc between  $\xi(a_{\sigma(i)})$  and  $\xi(a_{\sigma(i+1)})$ , and the intersection between  $\mathcal{C}'_i$  and  $\mathcal{C}'_j$  with  $i \neq j$  is either empty or reduced to a point.

*Proof.* In this proof, we write  $m_i$  for the middle of the bel  $a_i$ . For any  $i \in \mathbb{Z}/N\mathbb{Z}$ , let  $\mathcal{C}_i$  be the straightest arc between  $\xi(a_i)$  and  $\xi(a_{i+1})$ . From Proposition 2, we have  $\mathcal{C} = \bigcup_{i \in \mathbb{Z}/N\mathbb{Z}} \mathcal{C}_i$  with  $\mathcal{C}_i \cap \mathcal{C}_j = \emptyset$  if  $j - i \notin \{-1, 0, 1\}$  and  $\mathcal{C}_i \cap \mathcal{C}_j$  is a singleton if  $j - i \in \{-1, 1\}$ .

710 Thus,  $\mathcal{C} = \bigcup_{i \in \mathbb{Z}/N_\sigma\mathbb{Z}} \mathcal{C}'_i$  where  $\mathcal{C}'_i$  is defined by  $\mathcal{C}'_i = \bigcup_{j=\sigma(i)}^{\sigma(i+1)-1} \mathcal{C}_j$ . Therefore, it is sufficient to prove that, for any  $i \in \mathbb{Z}/N_\sigma\mathbb{Z}$ ,  $\mathcal{C}'_i$  is a straightest arc. So, let  $i \in \mathbb{Z}/N_\sigma\mathbb{Z}$ . As  $\#\llbracket\sigma(i), \sigma(i+1)\rrbracket < \delta/h$  and the distance  $d_1$  between two consecutive middles  $m_i$  and  $m_{i+1}$  is equal to  $h$ , the distance  $d_1$  between any points  $m_i$  and  $m_j$  where  $\sigma(i) \leq i < j \leq \sigma(i+1)$  is bounded from above by  
715  $\delta - h$ . Moreover, by definition of a back-digitization,  $|\xi(a_j) - m_j| \leq h/2$  for any  $j \in \llbracket\sigma(i), \sigma(i+1)\rrbracket$ . Hence,  $d_1(\xi(a_j), \xi(a_k)) < \delta$  if  $\sigma(i) \leq j < k \leq \sigma(i+1)$ . Then, the Euclidean distance between  $\xi(a_i)$  and  $\xi(a_k)$  is also bounded from above by  $\delta$ . All the assumptions of Lemma 8-(b) are then satisfied. Thereby, thanks to this lemma, we conclude that  $\mathcal{C}'_i$  is a straightest arc and we are done.  $\square$

720 In Theorem 2, the expression  $h\#\llbracket\sigma(i), \sigma(i+1)\rrbracket$  can be viewed as the  $d_1$  length of the boundary polyline associated to the dual representation of the bels  $a_k$ ,  $k \in \llbracket\sigma(i), \sigma(i+1)\rrbracket$  (see Figure 11).

In the sequel, given a LTB curve  $\mathcal{C}$  and a grid step  $h$  compatible with  $\mathcal{C}$ , any subsequence  $(a_{\sigma(i)})_{i \in \mathbb{Z}/N_\sigma\mathbb{Z}}$  of the cyclically ordered sequence  $(a_k)_{k \in \mathbb{Z}/N\mathbb{Z}}$  of the  
725 bels of the digitization of  $\mathcal{C}$  is called a *normal subsequence of  $\text{Bel}_h(\mathcal{C})$*  if, for any  $i \in \mathbb{Z}/N_\sigma\mathbb{Z}$ ,  $(\#\llbracket\sigma(i+1), \sigma(i)\rrbracket)h < \delta$ .

#### 4. Application to length estimation

It is well-known that the length of a rectifiable curve can be approximated with any arbitrary precision by the length of an inscribed polygonal line provided  
730 the polygonal edge lengths are small enough. This is no more true when the vertices of the polygonal line are rounded as explained in the introduction of this article. Thanks to the notion of monotonically sampling back-digitization introduced in Section 3, we can now study the conditions under which the lengths of a grid polygon sequence converge towards the length of a LTB curve and with  
735 what speed.

In this section, given a positive integer  $n$  and a polygon  $P$ , we denote by  $M_n(P)$  the mean, relying on the  $L_n$  norm, of the edge lengths of  $P$ :

$$M_n(P) = \left( \sum_k x_k^n \right)^{\frac{1}{n}} \quad \text{if } n < \infty \quad \text{and} \quad M_\infty(P) = \sup_k (|x_k|),$$

where the reals  $x_k$  are the edge lengths of  $P$ .

##### 4.1. LTB curve length estimation using inscribed polygon

According to Jordan's definition of curve length, we compare the length of a LTB curve with the length of an inscribed polygon (without any rounding).

740 More specifically, we focus on the convergence of the length of polygons inscribed in a LTB curve.

Given a LTB curve  $\mathcal{C}$ , we say that a polygon inscribed in  $\mathcal{C}$  *splits  $\mathcal{C}$  into straightest arcs* if the sequence of the vertices of the polygon is a sampling semi-chain of  $\mathcal{C}$ .

745 *4.1.1. Turn and length*

Intuitively, the more a curve of fixed length turns, the less it moves away from its origin. This is quantified in the following property.

**Property 10** ([29], Theorem 5.8.1 p. 151). *Let  $\mathcal{C}$  be a curve such that  $\kappa(\mathcal{C}) < \pi$  and let  $d$  be the distance between the ends of  $\mathcal{C}$ . Then,*

$$\cos\left(\frac{\kappa(\mathcal{C})}{2}\right) \times \mathcal{L}(\mathcal{C}) \leq d.$$

Notice that this bound is sharp and the equality case only holds for a polygonal line of two sides of same length [29].

750 *4.1.2. General case*

Here, we study the general case of a LTB-curve without smoothness assumption.

**Proposition 3.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve with  $\delta > 0$ . Let  $(L_k)$  be a sequence of polygons splitting the curve into straightest arcs and let  $\mu \in (0, 1)$  such that  $M_\infty(L_k)^{4\mu} = o(M_1(L_k))$  as  $k \rightarrow +\infty$ . Then*

$$\lim_{k \rightarrow +\infty} \mathcal{L}(L_k) = \mathcal{L}(\mathcal{C}).$$

*More precisely,*

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_k)| = O\left(\frac{M_\infty(L_k)^{2\mu}}{M_1(L_k)^{1/2}}\right) + O(M_\infty(L_k)^{1-\mu}).$$

*Proof.* From the hypothesis, we derive that  $\lim_{k \rightarrow +\infty} M_\infty(L_k)^{2\mu} = 0$ . Then, there exists  $k_0$  such that for any  $k > k_0$ ,  $M_\infty(L_k) < 1$ . We consider such a  $k > k_0$  and we denote by  $(\xi_i)_{i \in \mathbb{Z}/N_k\mathbb{Z}}$ ,  $N_k \in \mathbb{N}$ , an ordered sequence of the vertices of the polygon  $L_k$ . Since  $M_\infty(L_k) < \delta$ , for any  $i \in \mathbb{Z}/N_k\mathbb{Z}$  the straightest arc  $\mathcal{C}_i$  between  $\xi_{i-1}$  and  $\xi_i$  is well defined and  $\kappa(\mathcal{C}_i) \leq \pi/2$ .

Let  $I_0$  and  $I_1$  be two subsets of integers defined by:

$$I_0 := \left\{ i \mid \kappa(\mathcal{C}_i) \leq \frac{\pi}{2} M_\infty(L_k)^\mu \right\},$$

$$I_1 := \mathbb{Z}/N_k\mathbb{Z} \setminus I_0.$$

By definition of length and Property 10,

$$\sum_{i=0}^{N_k-1} \|\xi_{i+1} - \xi_i\| \leq \mathcal{L}(\mathcal{C}) \leq \sum_{i=0}^{N_k-1} \frac{\|\xi_{i+1} - \xi_i\|}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)}.$$

Hence,

$$\begin{aligned}
\left| \mathcal{L}(\mathcal{C}) - \sum_{i=0}^{N_k-1} \|\xi_{i+1} - \xi_i\| \right| &\leq \left| \sum_{i=0}^{N_k-1} \frac{\|\xi_{i+1} - \xi_i\|}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - \sum_{i=0}^{N_k-1} \|\xi_{i+1} - \xi_i\| \right| \\
&\leq \sum_{i=0}^{N_k-1} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\|, \\
&\leq \sum_{i \in I_0} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\| \\
&\quad + \sum_{i \in I_1} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\|.
\end{aligned}$$

On the one hand, since there is at most  $\lfloor mM_\infty(L_k)^{-\mu} \rfloor$  arcs  $\mathcal{C}_i$  of turn greater than  $M_\infty(L_k)^\mu \pi/2$  in  $\mathcal{C}$  where  $m := \frac{\kappa(\mathcal{C})}{\pi/2}$  (otherwise, the turn of  $\mathcal{C}$  would be greater than  $\kappa(\mathcal{C})$ ), the cardinal of  $I_1$  is such that

$$\#I_1 \leq mM_\infty(L_k)^{-\mu}.$$

Then,

$$\begin{aligned}
\sum_{i \in I_1} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i^k)}{2}\right)} - 1 \right) \|\xi_{i+1}^k - \xi_i^k\| &\leq \left( \frac{1}{\cos\left(\frac{\pi/2}{2}\right)} - 1 \right) mM_\infty(L_k)^{1-\mu} \quad (5) \\
&= O(M_\infty(L_k)^{1-\mu}).
\end{aligned}$$

On the other hand, by Titu's Lemma,

$$\begin{aligned}
\sum_{i \in I_0} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i^k)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\| &\leq \\
&\sqrt{N_k} \left( \frac{1}{\cos\left(\frac{M_\infty(L_k)^\mu \pi/2}{2}\right)} - 1 \right) \sqrt{\sum_{i \in I_0} \|\xi_{i+1} - \xi_i\|^2}.
\end{aligned}$$

Thus, since  $M_\infty(L_k) \leq 1$ ,

$$\begin{aligned}
\sum_{i \in I_0} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\| &\leq \\
&\sqrt{N_k} \left( \frac{1}{\cos\left(\frac{M_\infty(L_k)^\mu \pi/2}{2}\right)} - 1 \right) \sqrt{\sum_{i \in I_0} \|\xi_{i+1} - \xi_i\|^2},
\end{aligned}$$

$$\begin{aligned} &\leq \sqrt{N_k} \left( \frac{1}{\cos\left(\frac{M_\infty(L_k)^\mu \pi/2}{2}\right)} - 1 \right) \sqrt{\mathcal{L}(L_k)}. \\ &\leq \sqrt{N_k} \left( \frac{1}{\cos\left(\frac{M_\infty(L_k)^\mu \pi/2}{2}\right)} - 1 \right) \sqrt{\mathcal{L}(\mathcal{C})}. \end{aligned}$$

Moreover,

$$\frac{1}{\cos(y/2)} - 1 = O(y^2).$$

760 Hence

$$\sum_{i \in I_0} \left( \frac{1}{\cos\left(\frac{\kappa(\mathcal{C}_i)}{2}\right)} - 1 \right) \|\xi_{i+1} - \xi_i\| = O(\sqrt{N_k} M_\infty(L_k)^{2\mu}). \quad (6)$$

Finally, by the equations (5) and (6),

$$\begin{aligned} \left| \mathcal{L}(\mathcal{C}) - \sum_{i=0}^{N_k} \|\xi_{i+1} - \xi_i\| \right| &= O(\sqrt{N_k} M_\infty(L_k)^{2\mu}) + O(M_\infty(L_k)^{1-\mu}) \\ &= O\left(\frac{M_\infty(L_k)^{2\mu}}{M_1(L_k)^{1/2}}\right) + O(M_\infty(L_k)^{1-\mu}). \quad \square \end{aligned}$$

In order to use Proposition 3, the parameter  $\mu$  has to be chosen. Since the speed of convergence is the slowest of  $\frac{M_\infty(L_k)^{2\mu}}{M_1(L_k)^{1/2}}$  and  $M_\infty(L_k)^{1-\mu}$ , the best choice of the parameter is such that

$$M_1(L_k) \sim M_\infty(L_k)^{6\mu-2}.$$

That is,  $\mu = 1/2$  for a uniform partition giving an error in  $O(M_\infty(L_k)^{1/2})$  (in comparison, a polygonal LTB curve randomly sampled provides a linear error).

765 Nevertheless, before going further in the determination of the convergence speed, it is necessary to study the weight of the error due to the use of discrete chords instead of Euclidean chords.

#### 4.1.3. Regular case

In this section, we deal with the case of a LTB-curve whose turn is Lipschitz, that is the curve is of class  $C^{1,1}$ .

**Proposition 4.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve having a  $\frac{1}{r}$ -Lipschitz turn. Let  $(L_k)$  be a sequence of inscribed polygons splitting the curve  $\mathcal{C}$  into straightest arcs such that  $\lim_{k \rightarrow +\infty} M_\infty(L_k) = 0$ . Then*

$$\lim_{k \rightarrow +\infty} \mathcal{L}(L_k) = \mathcal{L}(\mathcal{C}).$$

Let  $r_1 = \min(r, \delta/2)$  and  $(\xi_i^k)_{i \in \mathbb{Z}/N_k\mathbb{Z}}$  be a cyclically ordered sequence of all the vertices of  $L_k$  in  $\mathcal{C}$ . For any  $k$  such that  $M_\infty(L_k) < 2r_1$ ,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_k)| \leq \sum_{i=0}^{N_k-1} \left| 2r_1 \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r_1} \right) - \|\xi_i^k - \xi_{i-1}^k\| \right|.$$

Moreover

$$\sum_{i=0}^{N_k-1} \left| 2r \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r} \right) - \|\xi_i^k - \xi_{i-1}^k\| \right| = O \left( \frac{(M_3^k(L_k))^3}{M_1^k(L_k)} \right).$$

*Proof.* For any  $k$ , let  $(\xi_i^k)_{i \in \mathbb{Z}/N_k\mathbb{Z}}$  be a cyclically ordered sequence of the vertices of  $L_k$  in  $\mathcal{C}$ . There exists  $k_0$ , such that for any  $k > k_0$ ,  $M_\infty(L_k) < 2r_1$ . By Lemma 9, for any  $i \in \mathbb{Z}/N_k\mathbb{Z}$ , the straightest arc  $\mathcal{C}_{\xi_{i-1}^k, \xi_i^k}$  between  $\xi_{i-1}^k$  and  $\xi_i^k$  is such that

$$\mathcal{L}(\mathcal{C}_{\xi_{i-1}^k, \xi_i^k}) \leq 2r_1 \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r_1} \right).$$

Since the function  $x \mapsto 2r_1 \arcsin(\frac{x}{2r_1}) - x$  is increasing on  $[0, 2r_1)$ , for any  $k$  such that  $M_\infty(L_k) < 2r_1$ ,

$$\begin{aligned} |\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_k)| &\leq \sum_{i=0}^{N_k-1} \left| 2r_1 \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r_1} \right) - \|\xi_i^k - \xi_{i-1}^k\| \right|, \\ &\leq N_k \left( 2r_1 \arcsin \left( \frac{M_\infty(L_k)}{2r_1} \right) - M_\infty(L_k) \right). \end{aligned}$$

Moreover,

$$\arcsin(x) = x + O(x^3) \quad \text{as } x \rightarrow 0.$$

Then,

$$\begin{aligned} |\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_k)| &\leq \sum_{i=0}^{N_k-1} \left| 2r_1 \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r_1} \right) - \|\xi_i^k - \xi_{i-1}^k\| \right|, \\ &\leq N_k O((M_3^k)^3) \\ &\leq \frac{\mathcal{L}(\mathcal{C})}{M_1^k} O((M_3^k)^3), \\ &\leq O \left( \frac{(M_3^k)^3}{M_1^k} \right). \end{aligned} \quad \square$$

The bound of Proposition 4 is sharp. Indeed, for a circle of radius  $r$  and a uniform and tight enough partition of the circle, one has:

$$\begin{aligned} |\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_k)| &= \sum_{i=0}^{N_k-1} \left| 2r \arcsin \left( \frac{\|\xi_i^k - \xi_{i-1}^k\|}{2r} \right) - \|\xi_i^k - \xi_{i-1}^k\| \right|, \\ &= N_k \left( 2r \arcsin \left( \frac{M_\infty(L_k)}{2r} \right) - M_\infty(L_k) \right) \\ &= O \left( \frac{(M_3^k)^3}{M_1^k} \right). \end{aligned}$$

Proposition 4 can be compared to [4, Proposition 3]. We get the same rate of convergence replacing the convexity hypothesis by the local turn boundedness hypothesis.

#### 4.2. LTB curve length estimation by means of polygons inscribed in the curve digitization

Given a LTB curve  $\mathcal{C}$  and the family of its Gauss digitizations  $\{\text{Dig}_h(\mathcal{C})\}_{h>0}$ , the results obtained in Sections 3 and 4.1 make it possible to build a convergent estimator of the curve length  $\mathcal{L}(\mathcal{C})$  using polygons  $\mathcal{A}_h$  inscribed in the reconstructions  $\partial_h(\mathcal{C})$  under some assumptions on their edge lengths. At a fixed resolution, the estimated length is the length  $\mathcal{L}(\mathcal{A}_h)$ . The two following theorems specify these assumptions, and give the convergence rate, in the general case then in the regular case.

##### 4.2.1. General case

The length estimator studied in Theorem 3 is based on a partition of the border of the digitization  $\partial_h(\mathcal{C})$  into arcs. To each arc corresponds an edge of the inscribed polygon  $\mathcal{A}_h$  (see Figure 11). Theorem 3 states that the length estimator  $\mathcal{L}(\mathcal{A}_h)$  is convergent provided that it ensures that each edge  $\mathcal{D}$  of  $\mathcal{A}_h$  verifies the 4 following conditions.

1. For a sufficiently small grid step  $h$ , the true length of  $\mathcal{D}$  (that is, the Euclidean distance between its endpoints) is bounded from above by  $\delta$ .
2. The relative size of  $\mathcal{D}$  (that is the number of bels it is built from) tends towards infinity as  $h \rightarrow 0$ .
3. The mean true size of the edges of  $\mathcal{A}_h$  at step  $h$  tends towards 0 as  $h \rightarrow 0$ .
4. The range of the edge length family (for a given grid step  $h$ ) is bounded from above by some power of the mean length as  $h \rightarrow 0$ .

**Theorem 3.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve with  $\delta > 0$ . Let  $\mu \in (\frac{1}{4}, 1)$  and  $\{\mathcal{A}_h\}_{h>0}$  be a family of polygons such that*

- for any  $h$  compatible with  $\mathcal{C}$ , the vertices of  $\mathcal{A}_h$  are the bel middles of a normal subsequence of the cyclically ordered bels  $(\xi_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ ,
- $h = o(M_1(\mathcal{A}_h))$  as  $h \rightarrow 0$ ,

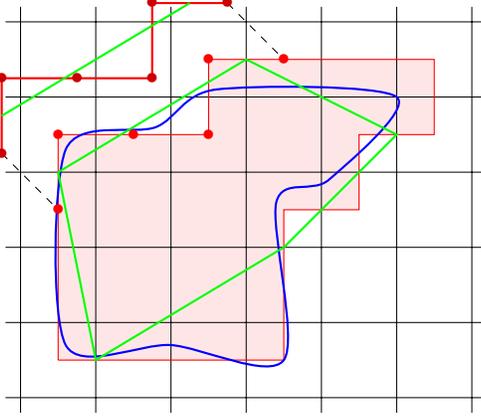


Figure 11: In blue, a LTB curve  $\mathcal{C}$ . The reconstruction of  $\mathcal{C}$  (red border) is partitionned into subarcs (as the one emphasized in the figure). To each subarc corresponds an edge whose ends are on the ending bels of the subarc. The union of all these edges forms a polygon  $\mathcal{A}_h$  (green) inscribed in  $\partial_h(\mathcal{C})$ . The length of the curve  $\mathcal{C}$  is estimated by the length of  $\mathcal{A}_h$ .

- $M_\infty(\mathcal{A}_h)^{4\mu} = o(M_1(\mathcal{A}_h)) = o(1)$  as  $h \rightarrow 0$ .

Then,

$$\lim_{h \rightarrow 0} \mathcal{L}(\mathcal{A}_h) = \mathcal{L}(\mathcal{C}).$$

More precisely,

$$\begin{aligned} \|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)\| = \\ O_{h \rightarrow 0} \left( M_\infty(\mathcal{A}_h)^{2\mu} M_1(\mathcal{A}_h)^{-1/2} + M_\infty(\mathcal{A}_h)^{1-\mu} + h M_1(\mathcal{A}_h)^{-1} \right). \end{aligned}$$

*Proof.* Let  $\xi : \text{Bel}_h(\mathcal{C}) \rightarrow \mathcal{C}$  be a back-digitization and  $(a_i^h)_{i \in \mathbb{Z}/N_h\mathbb{Z}}$  be a normal subsequence of the bel sequence  $(\xi_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ , defining the polygon  $\mathcal{A}_h$ . Write  $m_i^h$  for the middle of  $a_i^h$  and let  $L_h$  be the polygon whose ordered set of vertices is  $\xi((a_i^h)_{i \in \mathbb{Z}/N_h\mathbb{Z}})$ . Then,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| \leq |\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_h)| + |\mathcal{L}(L_h) - \mathcal{L}(\mathcal{A}_h)|.$$

By definition of a back-digitization,  $d(m_{\sigma(i)}, \xi(a_{\sigma(i)})) < h/2$  for any  $i$ , so  $|\mathcal{L}(L_h) - \mathcal{L}(\mathcal{A}_h)|$  is bounded from above by  $N_h \times h$ , that is by  $h/M_1(\mathcal{A}_h) \times \mathcal{L}(\mathcal{A}_h)$ . Since  $\mathcal{L}(L_h) < \mathcal{L}(\mathcal{C})$  and we assume  $\lim_{h \rightarrow 0} h/M_1(\mathcal{A}_h) = 0$ , using the triangle inequality, we can bound from above  $\mathcal{L}(\mathcal{A}_h)$  by some constant (for instance  $2\mathcal{L}(\mathcal{C})$  for  $h/M_1(\mathcal{A}_h) \leq 1/2$ ). We derive that

$$|\mathcal{L}(L_h) - \mathcal{L}(\mathcal{A}_h)| = O_{h \rightarrow 0} \left( \frac{h}{M_1(\mathcal{A}_h)} \right).$$

By Theorem 2,  $(a_i^h)$  delimits straightest arcs of  $\mathcal{C}$ . Hence, thanks to Proposition 3, we get

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| = O_{h \rightarrow 0} \left( \frac{M_\infty(L_h)^{2\mu}}{M_1(L_h)^{1/2}} + M_\infty(L_h)^{1-\mu} + \frac{h}{M_1(\mathcal{A}_h)} \right).$$

Moreover,  $M_\infty(L_h) \leq M_\infty(\mathcal{A}_h) + h$ . Then,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| = O_{h \rightarrow 0} \left( \frac{(M_\infty(\mathcal{A}_h) + h)^{2\mu}}{M_1(\mathcal{A}_h)^{1/2}} + (M_\infty(\mathcal{A}_h) + h)^{1-\mu} + \frac{h}{M_1(\mathcal{A}_h)} \right).$$

Finally, since  $h$  is dominated asymptotically by  $M_1(\mathcal{A}_h)$  which is less than  $M_\infty(\mathcal{A}_h)$ ,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| = O_{h \rightarrow 0} \left( \frac{M_\infty(\mathcal{A}_h)^{2\mu}}{M_1(\mathcal{A}_h)^{1/2}} + M_\infty(\mathcal{A}_h)^{1-\mu} + \frac{h}{M_1(\mathcal{A}_h)} \right). \quad \square$$

Theorem 3 gives indication in order to choose the best sampling of the curve.  
 805 For a fixed  $M_\infty(\mathcal{A}_h)$ , the best rate of convergence for an unknown curve  $\mathcal{C}$  is reached when  $M_1(\mathcal{A}_h)$  is maximum, that is when  $M_1(\mathcal{A}_h) = M_\infty(\mathcal{A}_h)$ : the inscribed polygons associated with the family  $\{\mathcal{A}_h\}$  have equal edges. In this latter case the rate of convergence is  $O(M_\infty(\mathcal{A}_h)^{1/2} + hM_\infty(\mathcal{A}_h)^{-1})$  (by choosing  $\mu = \frac{1}{2} = \max_{\mu \in (0,1)} \min(2\mu - 1/2, 1 - \mu)$ ). Since  $h^{2/3} = \operatorname{argmin}_{x>0} \max(\sqrt{x}, h/x)$ ,  
 810 the best rate of convergence,  $h^{1/3}$ , is achieved for  $M_\infty(\mathcal{A}_h) \sim h^{2/3}$ .

#### 4.2.2. Regular case

**Theorem 4.** Let  $\mathcal{C}$  be a  $\delta$ -LTB curve having a  $\frac{1}{r}$ -Lipschitz turn ( $r > 0$ ). Let  $\{\mathcal{A}_h\}_{h>0}$  be a family of polygons such that

- for any  $h$  compatible with  $\mathcal{C}$ , the vertices of  $\mathcal{A}_h$  are the bel middles of a  
 815 normal subsequence of the cyclically ordered bels  $(\xi_i)_{i \in \mathbb{Z}/N\mathbb{Z}}$ ,
- $h = o_{h \rightarrow 0}(M_1(\mathcal{A}_h))$ ,
- $\lim_{h \rightarrow 0} M_\infty(\mathcal{A}_h) = 0$ .

Then,

$$\lim_{h \rightarrow 0} \mathcal{L}(\mathcal{A}_h) = \mathcal{L}(\mathcal{C})$$

and,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| = O_{h \rightarrow 0} \left( \frac{M_3(\mathcal{A}_h)^3}{M_1(\mathcal{A}_h)} \right).$$

Moreover, for any  $h$  compatible with  $\mathcal{C}$  such that  $h + M_\infty(\mathcal{A}_h) < 2r_1$  with  $r_1 = \min(r, \delta/2)$ , we have

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| \leq N_h \left( 2r_1 \arcsin \left( \frac{M_\infty(\mathcal{A}_h) + h}{2r_1} \right) - M_\infty(\mathcal{A}_h) \right),$$

*Proof.* Let  $h$  be compatible with  $\mathcal{C}$  and  $\xi : \text{Bel}_h(\mathcal{C}) \rightarrow \mathcal{C}$  be a back-digitization. As in the proof of Theorem 3, we have

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| \leq |\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_h)| + hN_h,$$

where  $L_h$  is the polygon whose vertices are the images by  $\xi$  of the bels defining  $\mathcal{A}_h$ . By Theorem 2, the vertices of  $L_h$  delimit straightest arcs of  $\mathcal{C}$ . Let  $(\xi_i^h)_{i \in \mathbb{Z}/N_h\mathbb{Z}}$  be a cyclically ordered sequence of vertices of  $L_h$  in  $\mathcal{C}$ . Assuming  $h + M_\infty(\mathcal{A}_h) < 2r_1$ , we derive from Proposition 4 that,

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(L_h)| \leq \sum_{i=0}^{N_h-1} \left| 2r_1 \arcsin \left( \frac{\|\xi_i^h - \xi_{i-1}^h\|}{2r_1} \right) - \|\xi_i^h - \xi_{i-1}^h\| \right| \quad (7)$$

Since the function  $x \mapsto 2r_1 \arcsin \left( \frac{x}{2r_1} \right) - x$  is non-negative and increasing on  $[0, 2r_1)$ ,

$$\begin{aligned} |\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| &\leq \sum_{i=0}^{N_h-1} \left( 2r_1 \arcsin \left( \frac{\|\xi_i^h - \xi_{i-1}^h\| + h}{2r_1} \right) - \|\xi_i^h - \xi_{i-1}^h\| - h \right) \\ &\quad + hN_h \\ &\leq \sum_{i=0}^{N_h-1} \left( 2r_1 \arcsin \left( \frac{\|\xi_i^h - \xi_{i-1}^h\| + h}{2r_1} \right) - \|\xi_i^h - \xi_{i-1}^h\| \right) \\ &\leq N_h \left( 2r_1 \arcsin \left( \frac{M_\infty(\mathcal{A}_h) + h}{2r_1} \right) - M_\infty(\mathcal{A}_h) \right). \end{aligned}$$

Moreover,

$$\arcsin(x) = x + O(x^3) \quad \text{as } x \rightarrow 0.$$

Then, from Equation 7, we derive

$$\begin{aligned} |\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| &\leq \sum_{i=0}^{N_h-1} \left( 2r_1 \arcsin \left( \frac{\|\xi_i^h - \xi_{i-1}^h\|}{2r_1} \right) - \|\xi_i^h - \xi_{i-1}^h\| \right) + hN_h, \\ &\leq N_h (O(M_3(\mathcal{A}_h)^3) + h) \\ &\leq \frac{\mathcal{L}(\mathcal{C})}{M_1^h(\mathcal{A}_h)} O(M_3(\mathcal{A}_h)^3 + h), \\ &\leq O \left( \frac{M_3(\mathcal{A}_h)^3 + h}{M_1^h} \right). \end{aligned}$$

Since  $h = o(M_1(\mathcal{A}_h))$  and  $M_1(\mathcal{A}_h) \leq M_3(\mathcal{A}_h)$ , we obtain the result:

$$|\mathcal{L}(\mathcal{C}) - \mathcal{L}(\mathcal{A}_h)| = O \left( \frac{M_3^3(\mathcal{A}_h)}{M_1^h} \right). \quad \square$$

Observe that, by [26, Theorem 2], any  $\text{par}(r)$ -regular curve  $\mathcal{C}$  is  $\sqrt{2}r$ -LTB and by [26, Lemma 6], its turn is  $\frac{1}{r}$  Lipschitz. Thus, Theorem 4 applies to  
825  $\text{par}(r)$ -regular curves taking  $r_1 = \min(r, \delta/2) = \min(r, r/\sqrt{2}) = r/\sqrt{2}$ .

Application of theorems 3 and 4 on classical estimators requires some more work and will be detailed in future works.

## 5. Conclusion

The starting point of the study presented in this paper is the couple of articles [4, 9] about convergence of length estimators. The main idea in these  
830 articles, originally stated in [16], is that—a contrary to length estimation in a pure Euclidean context—estimating a length from a digital sample cannot be performed by just picking more and more points on the boundary of the digitization. The picking has to be sparse relative to the grid step. In the cited  
835 articles, the result was established for graphs of functions and we thought at the time that it could be straightforwardly adapted on Jordan curves. The content of this paper shows that it is far to be the case. It is easy to project the OBQ digitization of a graph of function on this graph even for non-regular curves. Getting a well-ordered sample on a Jordan curve from its digitization is another  
840 challenge as shown in Figure 7. A first step in this direction was done in [27]. Nevertheless, it assumes  $C^{1,1}$  regularity and, though the size of the defective regions is quantified, the well-ordering is not guaranteed. This has led us to introduce the notion of LTB curve in [26]. The LTB class encompasses the  $C^{1,1}$  curves since we show that  $C^{1,1}$  regularity is equivalent to be LTB with a Lipschitzian turn. Then we formally establish in this paper that the LTB class of  
845 curves is sufficiently constrained to permit ordered projections (though the class contains non-regular curves). Once a reliable kind of projection—the monotonically sampling back-digitization—is found, proving the multigrid convergence of non-local perimeter estimators does not give rise to great difficulties.

850 Nevertheless, it remains to study in a future work whether the error bounds exhibited in this article are tight or not. Indeed, for a particular Jordan curve, the worst case considered in the upper bound calculus is only reached at a given resolution. Then, it may be possible to improve the error upper bound.

In the perimeter estimation, the convexity hypothesis is often used to obtain  
855 upper bounds, e.g. for Non-Local estimation, the convexity hypothesis makes it possible to approach experimental convergence speed. As the turn can be seen as a measure of the convexity loss, it can be interesting to see if the results obtained in the convex case in the literature can be generalized to LTB curves.

Another direction to continue the work done in this paper is to use the back-digitization to prove the multigrid convergence of the MDSS based perimeter  
860 estimators on LTB curves.

The back-digitization could also be used for the estimation of other geometric features. In particular, since the definition of the back-digitization rely on the notion of turn, it should be well-suited for curvature estimation. A last  
865 perspective concerns the generalization of the LTB notion to 3D curves and surfaces.

# Appendix

## Appendix A. Lipschitz turn

In this section, we show how the notion of LTB curve is linked to the well-known concepts of curve with positive reach [28] and par-regular curve [19], that is to the  $C^{1,1}$  regularity class (curves with Lipschitz unit tangents). The relationship between the four notions of  $C^{1,1}$  curves, curves having a positive reach, par-regular curves and LTB curves with Lipschitz turn are described in the graph of Figure A.12. The aim of this subsection is to prove (Theorem 1) that any LTB curve with Lipschitz turn has a positive reach (blue arrow Figure A.12). Let us first recall the definition of the reach, of par-regularity, and curves with Lipschitz turn.

**Definition 7** (reach). The *medial axis* of a compact set  $K$  is the set of points having at least two nearest neighbour in  $K$ . The *reach* is the minimal distance between  $K$  and its medial axis.

Having positive reach is equivalent to be of class  $C^{1,1}$  (the class of curves parameterized by a  $C^1$  function whose derivative is Lipschitz) [28].

Regarding par-regularity, we choose the same definition as in [21] and [27].

**Definition 8** ( $\text{par}(r)$ -regularity). Let  $\mathcal{C}$  be a Jordan curve of interior  $K$ .

- A closed ball  $\bar{B}(c_i, r)$  is an *inside osculating ball* of radius  $r$  at point  $a \in \mathcal{C}$  if  $\mathcal{C} \cap \bar{B}(c_i, r) = \{a\}$  and  $\bar{B}(c_i, r) \subset K \cup \{a\}$ .
- A closed ball  $\bar{B}(c_e, r)$  is an *outside osculating ball* of radius  $r$  at point  $a \in \mathcal{C}$  if  $\mathcal{C} \cap \bar{B}(c_e, r) = \{a\}$  and  $\bar{B}(c_e, r) \subset (\mathbb{R}^2 \setminus (\mathcal{C} \cup K)) \cup \{a\}$ .
- A curve  $\mathcal{C}$  is *par( $r$ )-regular* if there exist inside and outside osculating balls of radius  $r$  at each  $a \in \mathcal{C}$ .

Par-regularity is equivalent to having a positive reach [27].

In the framework of LTB curves, smoothness can be expressed by a Lipschitz behavior of the turn.

**Definition 9.** A curve  $\mathcal{C}$  has a  $k$ -Lipschitz turn if for every subarc  $\mathcal{A}$  of  $\mathcal{C}$ ,

$$\kappa(\mathcal{A}) \leq k\mathcal{L}(\mathcal{A}).$$

Observe that a curve  $\mathcal{C}$  has a  $k$ -Lipschitz turn if and only if the turn of any subarc of  $\mathcal{C}$  is upper bounded by the turn of an arc of circle of radius  $\frac{1}{k}$  and same length. That is why the constant  $k$  will often be noted by  $\frac{1}{r}$ . In particular, there is no spike in a curve with a  $k$ -Lipschitz turn.

The following theorem links LTB curves with Lipschitz turn and curves with positive reach (and so, with par-regular curves).

**Theorem 1.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve with  $\theta \in (0, \frac{\pi}{2}]$ . Then, the curve  $\mathcal{C}$  has a positive reach if and only if its has a Lipschitz turn.*

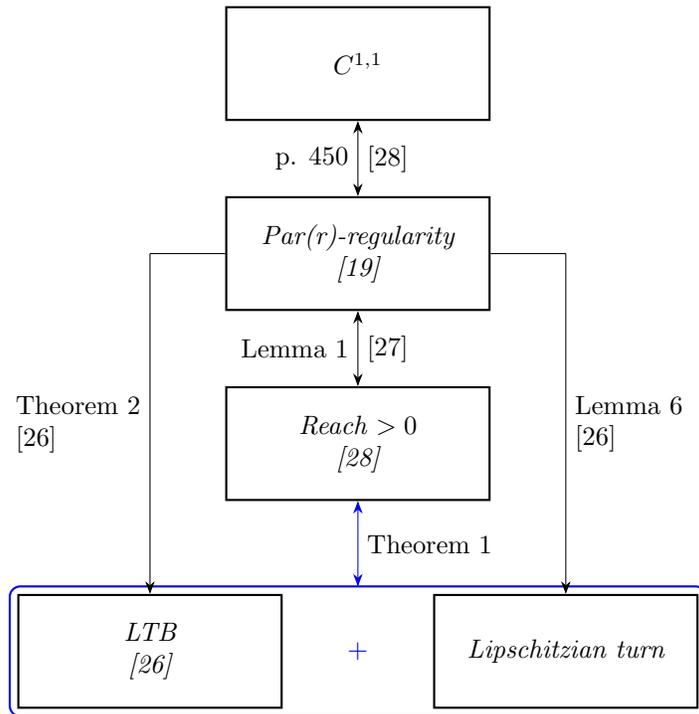


Figure A.12: Each rectangle corresponds to a notion. An arrow from a notion to another one means that if a curve has the first property then it has the second one. Notice that we lost quantitative information when using the implication from curve with positive reach to  $C^{1,1}$  curve.

The proof of Theorem 1 needs 3 lemmata. The following lemma bounds the length of a straightest arc of a LTB curve having a  $\frac{1}{k}$  Lipschitz turn. The proof of the lemma is similar to the one of Proposition 11 in [26]. Its main argument is a theorem due to Schur [31].

**Lemma 9.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve having a  $\frac{1}{r}$ -Lipschitz turn with  $\delta \geq 2r$ . Given two points  $a, b$  in  $\mathcal{C}$  such that  $\|b - a\| < 2r$ , the straightest arc  $\mathcal{C}_{a,b}$  from  $a$  to  $b$  has its length smaller than  $2r \arcsin\left(\frac{\|b-a\|}{2r}\right)$ .*

*Proof.* By Property 4, the intersection of the open disk  $B(a, 2r)$  and  $\mathcal{C}$  is path connected. Let  $\gamma$  be the parametrization by arc length of the arc of  $\mathcal{C}$  from  $a$  to  $b$  in  $B(a, 2r)$ . Then,  $\gamma(0) = a$  and  $\gamma(s_1) = b$  for some  $s_1 > 0$ . By contradiction, assume that  $s_1 > s_0$  where  $s_0 = 2r \arcsin\left(\frac{\|b-a\|}{2r}\right)$  and put  $c = \gamma(s_0)$ . Let  $\bar{\gamma}$  be the parametrization by arc length of some circle of radius  $r$ . By hypothesis, for any subinterval  $I$  of  $[0, s_0]$ ,

$$\kappa(\gamma(I)) \leq \frac{1}{r} |I| .$$

In other words, for any subinterval  $I$  of  $[0, s_0]$ ,

$$\kappa(\gamma(I)) \leq \kappa(\bar{\gamma}(I)) .$$

Hence, Schur's Comparison Theorem [31] applies:

$$\begin{aligned} \|c - a\| &\geq \|\bar{\gamma}(s_0) - \bar{\gamma}(0)\| \\ &\geq \|b - a\| \quad \text{by definition of } s_0 \text{ and } \bar{\gamma}. \end{aligned}$$

The last inequality contradicts the quasi-convexity of  $s \mapsto \|\gamma(s) - \gamma(0)\|$  (Property 5).  $\square$

Observe that the bound of the inequality in Lemma 9 is sharp: the equality case holds for a circle arc.

The second lemma is a technical lemma about turns which is a slight improvement of [26, Lemma 2]. This version is nevertheless necessary to get the result. The proof remains essentially the same.

**Lemma 10.** *Let  $\mathcal{C}$  be a curve with endpoints  $a, b$  such that the straight segment  $(a, b)$  does not intersect the curve  $\mathcal{C}$ . Let  $\mathcal{C}'$  be a simple curve from  $a$  to  $b$  such that  $\mathcal{C}'$  lies in the closure of the interior of the Jordan curve  $\mathcal{C} \cup [a, b]$  and  $\mathcal{C}' \cup [a, b]$  is convex. Then  $\kappa(\mathcal{C}) \geq \kappa(\mathcal{C}')$ .*

Since the set  $\mathcal{C}' \cup [a, b]$  is convex, Fenchel's theorem gives  $\kappa(\mathcal{C} \cup [a, b]) \geq \kappa(\mathcal{C}' \cup [a, b])$ . The interest of the lemma comes from the fact that  $\mathcal{C}$  and  $\mathcal{C}'$  are open curves. In the proof, the turn control at the extremities  $a$  and  $b$  is the key point.

*Proof.* Throughout the proof, the half-line with initial point  $a$  and passing through  $b$  will be noted  $\overrightarrow{ab}$ . Firstly, assume that  $\mathcal{C}'$  is a polygonal line. We set  $\mathcal{C}' = [a, p_1, \dots, p_m, b]$ . Let  $c$  be any point in  $(a, b)$ . For any  $i \in \llbracket 1, m \rrbracket$ , let  $q_i$  be the first intersection between the half-line  $\overrightarrow{cp_i}$  and  $\mathcal{C}$ . Let  $Q$  be the polygonal line  $[a, q_1, \dots, q_m, b]$ . Let us show that  $Q$  is inscribed in  $\mathcal{C}$ , i.e. by definition that the sequence of its vertices is a chain. Assume by contradiction that  $(a, q_1, \dots, q_m, b)$  is not a chain of  $\mathcal{C}$ . Then there exists  $(i, j, k)$  such that  $i < j < k$  and  $(q_i, q_j, q_k)$  is not a chain of  $\mathcal{C}$  or equivalently  $(q_i, q_k, q_j)$  is a chain of  $\mathcal{C}$  (up to consider  $q_0 := a$  and  $q_{m+1} := b$ ). Observe that this assumption in particular implies that  $\mathcal{C}'$  has more than two vertices:  $\mathcal{C}' \neq [a, b]$ . Therefore, the interior of  $\mathcal{C}' \cup [a, b]$  is not empty. Let  $C_{q_i, q_k}$  be the closed arc of  $\mathcal{C}$  delimited by  $q_i$  and  $q_k$ . Let  $T$  be the closed angular sector delimited by the half-lines  $\overrightarrow{cp_i}$  and  $\overrightarrow{cp_k}$  and containing the segment  $[p_i, p_k]$ . Since  $T$  contains points inside and other points outside the Jordan curve  $\mathcal{C} \cup [a, b]$ , the set  $T \setminus \mathcal{C}$  has at least two connected components. Let  $S$  be the topological closure of the connected component of  $T \setminus \mathcal{C}$  containing  $c$ . Notice that  $\partial S \subset [c, q_i] \cup C_{q_i, q_k} \cup [q_k, c]$  since  $\mathcal{C}$  does not intersect  $[c, q_i]$  nor  $[c, q_k]$ . Let us show that  $p_j \in S$ . Since  $(c, p_i, p_j, p_k)$  is a chain of the convex curve  $\mathcal{C}' \cup [a, b]$ , it defines a convex polygon. Then the point  $p_j$  belongs to the angular sector  $T$ . Therefore,  $p_j$  belongs to  $S$ . Let  $q'$  be a point in the intersection between the half-line  $\overrightarrow{cp_j}$  and the curve arc  $C_{q_i, q_k}$ . By its definition, the point  $q_j$  belongs to  $[c, q']$  and since  $[c, q_j]$  does not intersect  $\mathcal{C}$ ,  $q_j$  belongs to  $S$ . Let  $C_{q_j, b}$  be the arc of  $\mathcal{C}$  between  $q_j$  and  $b$ . Since the curve  $\mathcal{C}$  is simple, the arc  $C_{q_j, b}$  does not intersect  $C_{q_i, q_k}$ . Moreover, the arc  $C_{q_j, b}$  does not intersect the half-open segments  $[c, q_i)$  and  $[c, q_k)$  by definition of  $q_i$  and  $q_k$ . Then, the arc  $C_{q_j, b}$  has its end  $q_j$  in  $S$ , its other end  $b$  outside  $S$  but does not intersect  $\partial S$ . Contradiction! Then  $(a, q_1, \dots, q_m, b)$  is a chain of  $\mathcal{C}$ .

Then,  $\kappa(\mathcal{C}) \geq \kappa(Q)$  by definition of  $\kappa(\mathcal{C})$ ,  $\kappa(Q \cup [b, a]) \geq \kappa(\mathcal{C}' \cup [b, a])$  by Fenchel's Theorem (Property 1) and

$$\begin{aligned} \angle(a - b, p_1 - a) &\geq \angle(a - b, q_1 - a) \\ \angle(b - a, p_m - b) &\geq \angle(b - a, q_m - b) \end{aligned}$$

for  $\mathcal{C}'$  is inside  $Q \cup [a, b]$ . Since

$$\kappa(\mathcal{C}' \cup [b, a]) = \kappa(\mathcal{C}') + \angle(a - b, p_1 - a) + \angle(a - b, b - p_m)$$

and

$$\kappa(Q \cup [b, a]) = \kappa(Q) + \angle(a - b, q_1 - a) + \angle(a - b, b - q_m)$$

by definition of the turn of a polygon, the result holds if  $\mathcal{C}'$  is a polygonal line. If  $\mathcal{C}'$  is not a polygonal line, then, from the first part of the proof,  $\kappa(P) \leq \kappa(\mathcal{C})$  for any  $P$  inscribed in  $\mathcal{C}'$ . By definition of the turn and since the supremum is the smallest upper bound,

$$\kappa(\mathcal{C}') \leq \kappa(\mathcal{C}).$$

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□

From Lemmae 9 and 10, we derive in Lemma 11 the “if” part of Theorem 1.

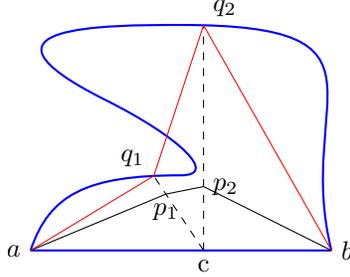


Figure A.13: Blue: the curve  $\mathcal{C}$  and the line segment  $[a, b]$ . Black: the polygonal line  $\mathcal{C}' = [a, p_1, p_2, b]$ . Black, dashed: the projection of  $p_1$  and  $p_2$  on  $\mathcal{C}$  yields the points  $q_1$  and  $q_2$ . Red: the polygonal line  $Q = [a, q_1, q_2, b]$ .

**Lemma 11.** *Let  $\mathcal{C}$  be a  $\delta$ -LTB curve having a  $\frac{1}{r}$ -Lipschitz turn with  $\delta > 0$ . Then the reach of  $\mathcal{C}$  is greater than or equal to  $\min(\frac{\delta}{2}, r)$ .*

*Proof.* By contradiction assume that  $\text{reach}(\mathcal{C}) < r_1 = \min(\frac{\delta}{2}, r)$ . Then there exist a point  $o$  on the medial axis of  $\mathcal{C}$  and two points  $a$  and  $b$  on  $\mathcal{C}$  such that  $d(o, a) = d(o, b) = d(o, \mathcal{C}) < r_1$ . Thus,  $\|a - b\| < 2r_1$ . Let  $\mathcal{C}_{a,b}$  be the straightest arc of  $\mathcal{C}$  between  $a$  and  $b$ . On the one hand, by Lemma 9 (noting that  $\mathcal{C}$  is  $(1/r_1)$ -Lipschitz for  $r_1 \leq r$ ),

$$\mathcal{L}(\mathcal{C}_{a,b}) \leq 2r_1 \arcsin\left(\frac{\|b - a\|}{2r_1}\right).$$

In other words, since the sine function is increasing on  $[0, \pi/2]$ ,

$$\|b - a\| \geq 2r_1 \sin\left(\frac{\mathcal{L}(\mathcal{C}_{a,b})}{2r_1}\right). \quad (\text{A.1})$$

On the other hand, let  $r' = d(o, a)$  ( $r' < r$ ). By definition of  $o$ ,  $a$  and  $b$ , the curve  $\mathcal{C}$  does not intersect the interior of the circle of center  $o$  and radius  $r'$ . So, let  $\bar{C}$  be the arc of this last circle bounded by  $\mathcal{C}_{a,b} \cup [oa] \cup [ob]$ . Since  $\bar{C} \cup [a, b]$  is convex, by Lemma 10 we have,

$$\kappa(\bar{C}) \leq \kappa(\mathcal{C}_{a,b}).$$

955 Hence,

$$\begin{aligned} \|b - a\| &= 2r' \sin\left(\frac{\kappa(\bar{C})}{2}\right) \\ &\leq 2r' \sin\left(\frac{\kappa(\mathcal{C}_{a,b})}{2}\right). \end{aligned} \quad (\text{A.2})$$

The last inequality holds for the sine function is increasing on  $[0, \pi/2]$  and  $\kappa(\mathcal{C}_{a,b}) \leq \pi$  because  $\mathcal{C}_{a,b}$  is the straightest arc between  $a$  and  $b$ .

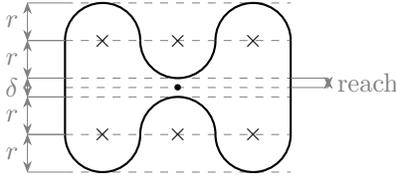


Figure A.14: The black curve —made of half-circles and straight segments— is  $\delta$ -LTB. Its reach is got at the point represented by a bullet and is equal to  $\frac{\delta}{2}$ .

By Inequality A.1 and Inequality A.2,

$$2r_1 \sin\left(\frac{\mathcal{L}(\mathcal{C}_{a,b})}{2r_1}\right) \leq 2r' \sin\left(\frac{\kappa(\mathcal{C}_{a,b})}{2}\right) < 2r_1 \sin\left(\frac{\kappa(\mathcal{C}_{a,b})}{2}\right).$$

Thus,

$$\frac{1}{r} \mathcal{L}(\mathcal{C}_{a,b}) \leq \frac{1}{r_1} \mathcal{L}(\mathcal{C}_{a,b}) < \kappa(\mathcal{C}_{a,b}),$$

which contradicts the Lipschitz hypothesis.  $\square$

The bound of Lemma 11 is sharp. Indeed, if  $\mathcal{C}$  is a circle of radius  $r$  then  
 960 the reach is exactly  $r$  and the reach of the  $\delta$ -LTB curve depicted in Figure A.14  
 is exactly  $\delta/2$ .

*Proof of Theorem 1.* The ‘if’ part of the proof is given by Lemma 11 while the  
 ‘only if’ part comes from [26, Theorem 2 and Lemma 6] where we stated that a  
 $\text{par}(r)$ -regular curve is  $(\theta, 2r \sin(\theta/2))$ -locally turn-bounded for  $\theta \leq \frac{\pi}{2}$ .  $\square$

965 Notice that we have proved a “qualitative equivalence” between the notions  
 of positive reach and LTB curve with Lipschitz turn but we failed to obtain a  
 “quantitative equivalence”. Indeed, starting from a  $\text{par}(r)$ -regular curve  $\mathcal{C}$  and  
 applying [26, Theorem 2 and Lemma 6], we derive that, for any  $0 \leq \theta \leq \pi/2$ ,  $\mathcal{C}$  is  
 a  $(\theta, 2r \sin(\frac{\theta}{2}))$ -LTB curve having a  $(1/r)$ -Lipschitz turn. Then, from Lemma 11,  
 970 we get that  $\mathcal{C}$  is a  $\text{par}(r \sin(\frac{\theta}{2}))$ -regular curve with  $\theta \leq \frac{\pi}{2}$ . Hence, at best  $\mathcal{C}$  is  
 $\text{par}((\sqrt{2}/2)r)$ -regular. We do not retrieve the starting parameter.

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