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Geodesics on Shape Spaces with Bounded Variation and Sobolev Metrics

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Abstract

This paper studies the space of BV^2 planar curves endowed with the BV^2 Finsler metric over its tangent space of displacement vector fields. Such a space is of interest for applications in image processing and computer vision because it enables piecewise regular curves that undergo piecewise regular deformations, such as articulations. The main contribution of this paper is the proof of the existence of a shortest path between any two BV^2 curves for this Finsler metric. The method of proof relies on the construction of a martingale on a space satisfying the Radon-Nikodym property and on the invariance under reparametrization of the Finsler metric. This method applies more generally to similar cases such as the space of curves with H^k metrics for $k \geq 2$ integer. This space has a strong Riemannian structure and is geodesically complete. Thus, our result shows that the exponential map is surjective, which is complementary to geodesic completeness in infinite dimensions. We propose a finite element discretization of the minimal geodesic problem, and use a gradient descent method to compute a stationary point of a regularized energy. Numerical illustrations show the qualitative difference between BV^2 and H^2 geodesics.

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1 Introduction

This paper addresses the problem of the existence of minimal geodesics in spaces of planar curves endowed with several metrics over the tangent spaces. Given two initial curves we prove the existence of a minimizing geodesic joining them. Such a result is proved by the direct methods of calculus of variations.

We treat the case of BV^2 -curves and H^k -curves ($k \geq 2$ integer). Although the proof's strategy is the same, the BV^2 and H^k cases are slightly different and the proof in the H^k case is simpler. This difference is essentially due to the inherent geometric structures (Riemannian or Finslerian) of each space.

We also propose a finite element discretization of the minimal geodesic problem. We further relax the problem to obtain a smooth non-convex minimization problem. This enables the use of a

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gradient descent algorithm to compute a stationary point of the corresponding functional. Although these stationary points are not in general global minimizers of the energy, they can be used to explore numerically the geometry of the corresponding spaces of curves, and to illustrate the differences between the Sobolev and BV^2 metrics.

1.1 Previous Works

Shape spaces as Riemannian spaces. The mathematical study of spaces of curves has been largely investigated in the last years, see for instance [38, 21]. The set of curves is naturally modeled over a Riemannian manifold [23]. This corresponds to using a Hilbertian metric on each tangent plane of the space of curves, i.e. the set of vector fields which deform infinitesimally a given curve. Several recent works [23, 13, 37, 36] point out that the choice of the metric notably affects the results of gradient descent algorithms for the numerical minimization of functionals. Carefully designing the metric is thus crucial to reach better local minima of the energy and also to compute descent flows with specific behaviors. These issues are important for applications in image processing (e.g. image segmentation) and computer vision (e.g. shape registration). Typical examples of such a Riemannian metrics are Sobolev-type metrics [30, 28, 32, 31] which lead to smooth curve evolutions.

Shape spaces as Finslerian spaces. It is possible to extend this Riemannian framework by considering more general metrics on the tangent planes of the space of curves. Finsler spaces make use of Banach norms instead of Hilbertian norms [6]. A few recent works [21, 37, 14] have studied the theoretical properties of Finslerian spaces of curves.

Finsler metrics are used in [14] to perform curve evolution in the space of BV^2 -curves. The authors make use of a generalized gradient which is the steepest descent direction according to the Finsler metric. The corresponding gradient flow enables piecewise regular evolutions, which is useful for applications such as registration of articulated shapes. The present work naturally follows [14]. Instead of considering gradient flows to minimize smooth functionals, we consider the minimal geodesic problem. The existence of solutions to this problem is important to understand the underlying space of curves. This problem is also useful to perform registration of two shapes in computer vision applications.

Geodesics in shape spaces. The computation of geodesics over Riemannian spaces is now routinely used in many imaging applications. Typical examples of applications include shape registration [29, 35, 33], tracking [29] and shape deformation [20]. Geodesic computations also serve as the basis to perform statistics on shape spaces, see for instance [35, 2] and to generalize standard tools from Euclidean geometry such as averages [3], linear regression [27] and cubic splines [33], to name a few. However, due to the infinite dimensional nature of shape spaces, not all Riemannian structures lead to well-posed length-minimizing problems. For instance, a striking result [23, 36, 37] is that the natural L^2 -metric on the space of curves is degenerate, despite its widespread use in computer vision applications. Indeed, the geodesic distance between any pair of curves is equal to zero.

The study of the geodesic distance over shape spaces (modeled as curves, surfaces or diffeomorphisms) has been widely developed in the past ten years [24, 9, 8]. We refer the reader to [7] for a review of this field of research. These authors typically address the questions of existence of the

exponential map, geodesic completeness (the exponential map is defined for all time) and the computation of the curvature. In some situations of interest, the shape space has a strong Riemannian metric so that the exponential map is a local diffeomorphism. In [22] the authors describe geodesic equations for Sobolev metrics. They show in Section 4.3 the local existence and uniqueness of a geodesic with prescribed initial conditions. This result is improved in [11], where the authors prove the existence for all time. Both previous results are proved by techniques from ordinary differential equations. In contrast, local existence (and uniqueness) of minimizing geodesics with prescribed boundary conditions (i.e. between a pair of curves) is typically obtained using the exponential map. In finite dimension, existence of minimizing geodesics between any two points (global existence) is obtained by the Hopf-Rinow theorem [25]. Indeed, if the exponential map is defined for all times (i.e. the space is geodesically complete) then global existence holds. This however is not true in infinite dimensions, and a counter example of non-existence of a geodesic between two points over a manifold is given in see [19]. An even more pathological case is described in [4] where an example is given where the exponential map is not surjective although the manifold is geodesically complete. Some positive results exist for infinite dimensional manifold (see in particular Theorem B in [16] and Theorem 1.3.36 in [21]) but the surjectivity of the exponential map still needs to be checked directly on a case-by-case basis.

In the case of a Finsler structure on the shape space, the situation is more complicated since the norm over the tangent plane is often non-differentiable. This non-differentiability is indeed crucial to deal with curves and evolutions that are not smooth. This implies that geodesic equations need to be understood in a weak sense. More precisely, the minimal geodesic problem can be seen as a Bolza problem on the trajectories $H^1([0, 1], BV^2(\mathbb{S}^1, \mathbb{R}^2))$. In [26] several necessary conditions for existence of solutions to Bolza problems in Banach spaces are proved within the framework of differential inclusions. Unfortunately, these results require some hypotheses on the Banach space (for instance the Radon-Nikodym property for the dual space) that are not satisfied by the space of functions with bounded variation we consider in this paper. We thus tackle these issues in the present work and prove local and global existence of minimal geodesics in the space of BV^2 curves. We also show how similar techniques can be applied to the case of Sobolev metrics.

1.2 Contributions

Section 2 deals with the Finsler space of BV^2 -curves. Our main contribution is Theorems 2.15 proving the existence of a minimizing geodesic between two BV^2 -curves. We also explain how this result can be generalized to the setting of geometric curves (i.e. up to reparameterizations).

Section 3 extends these results to H^k -curves with $k \geq 2$ integer, which gives rise to Theorem 3.2 and Theorem 3.5. Our results are complementary to those presented in [22] and [11] where the authors show the geodesic completeness of curves endowed with the H^k -metrics with $k \geq 2$ integer. We indeed show that the exponential map is surjective.

Section 4 proposes a discretized minimal geodesic problem for BV^2 and Sobolev curves. We show numerical simulations for the calculation of stationary points of a regularized energy, which is smooth and thus allows one to use gradient descent schemes.

2 Geodesics in the Space of BV^2 -Curves

In this section we define immersed parameterized BV^2 -curves and prove useful properties (Section 2.1). We also define a geodesic Finsler distance on that space and prove results of existence (Sections 2.2). Finally, we extend this framework to the case of geometric curves (Section 2.3).

The strategy is as follows: we first prove that the geodesic distance is locally equivalent to the distance defined by the ambient Banach norm and then prove existence using a convergent martingale to a minimum. Lastly, existence of geodesics between geometric curves is obtained thanks to a similar argument on the quotient space.

2.1 The Finsler Space of Parameterized BV^2 -curves

The following definition defines the space of immersed parameterized BV^2 -curves. This is the obvious generalization of the space of smooth immersed curves

$$\text{Imm}(\mathbb{S}^1, \mathbb{R}^2) = \{c \in C^\infty(\mathbb{S}^1, \mathbb{R}^2) : c'(x) \neq 0 \quad \forall x \in \mathbb{S}^1\}$$

to the space of $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ curves, which are not necessarily smooth. We remind that $f \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$ (we identify $\mathbb{S}^1$ with $[0, 1]$) if $f \in W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$ and its second variation is finite:

$$|D^2 f|(\mathbb{S}^1) = \sup \left\{ \int_{\mathbb{S}^1} f(s) \cdot g''(s) \, d\gamma(s) : g \in C_c^\infty(\mathbb{S}^1, \mathbb{R}^2), \|g\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq 1 \right\} < \infty.$$

Then, the BV^2 -norm is defined as

$$\|f\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} = \|f\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} + |D^2 f|(\mathbb{S}^1).$$

We also remind that $BV^2(\mathbb{S}^1, \mathbb{R}^2) \subset W^{1,\infty}(\mathbb{S}^1, \mathbb{R}^2)$ and, in particular, BV^2 -functions are continuous.

Definition 2.1 (BV^2 immersed curves). We consider the Banach space $BV^2(\mathbb{S}^1, \mathbb{R}^2)$, where $\mathbb{S}^1$ is the unit circle. For every $\gamma \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$ we consider the following property

$$0 \notin \text{Conv}(\gamma'(s^+), \gamma'(s^-)) \quad \forall s \in \mathbb{S}^1 \tag{2.1}$$

where Conv denotes the convex envelope (a line segment) of the right and left limits $(\gamma'(s^-), \gamma'(s^+))$ of the derivative of γ at s .

In the following we define the space $\mathcal{B}$ of immersed BV^2 parameterized curves as the set of counterclockwise oriented curves belonging to the following set:

$$\mathcal{B} = \{\gamma \in BV^2(\mathbb{S}^1, \mathbb{R}^2) : \gamma \text{ satisfies (2.1)}\}. \tag{2.2}$$

Note that due to the existence of both clockwise and counter-clockwise parametrizations, the open set (see Proposition 2.5) defined in (2.2) is not connected.

Remark 2.2 (Unit speed parameterization). Property (2.1) allows one to define the unit speed parameterization for γ :

$$s_\gamma : \mathbb{S}^1 \rightarrow \mathbb{S}^1$$

$$s_\gamma(s) = \frac{1}{\mathcal{L}(\gamma)} \int_{s_0}^s |\gamma'(t)| dt, \quad s_0 \in \mathbb{S}^1$$

where $\mathcal{L}(\gamma)$ denotes the length of γ defined as

$$\mathcal{L}(\gamma) = \int_{\mathbb{S}^1} |\gamma'(s)| ds.$$

Finally we point out that for every curve γ its unit speed parameterization is given by $\gamma \circ \varphi_\gamma$ where $\varphi_\gamma = s_\gamma^{-1}$.

Remark 2.3 (Reparameterizations). In the following we denote by $\text{Diff}(\mathbb{S}^1)$ the set of homeomorphisms $\varphi \in BV^2(\mathbb{S}^1, \mathbb{S}^1)$ such that $\varphi^{-1} \in BV^2(\mathbb{S}^1, \mathbb{S}^1)$.

Note that any $\varphi \in \text{Diff}(\mathbb{S}^1)$ can be lifted (see [18]) to a diffeomorphism $\tilde{\varphi}$ of $\mathbb{R}$. Therefore, $\text{Diff}(\mathbb{S}^1)$ can be interpreted as a subset of $BV^2(\mathbb{S}^1, \mathbb{S}^1)$. Since the reparametrization can be chosen up to the choice of a basepoint, we can assume that lifts of reparametrizations can be written as $\text{Id} + (\tilde{\varphi} - \text{Id})$ with $\tilde{\varphi} - \text{Id} \in BV^2(\mathbb{S}^1, \mathbb{R})$. This implies in particular that the weak topologies on reparametrizations correspond to the weak topologies on $BV^2(\mathbb{S}^1, \mathbb{S}^1)$.

Remark 2.4. By Claim 3 p.218 in [17], we have the continuous embedding of BV in $L^\infty(\mathbb{S}^1, \mathbb{R}^2)$:

$$\forall u \in BV(\mathbb{S}^1, \mathbb{R}^2), \quad \|u\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq \|u\|_{BV(\mathbb{S}^1, \mathbb{R}^2)}. \quad (2.3)$$

We use this continuous embedding to prove in the following proposition that $\mathcal{B}$ is an open set of $BV^2(\mathbb{S}^1, \mathbb{R}^2)$.

Proposition 2.5. Let $\gamma_0 \in \mathcal{B}$ be parameterized by the unit speed parameterization. We have

$$\left\{ \gamma \in BV^2(\mathbb{S}^1, \mathbb{R}^2) : \|\gamma - \gamma_0\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} \leq \frac{\mathcal{L}(\gamma_0)}{2} \right\} \subset \mathcal{B}, \quad (2.4)$$

which proves that $\mathcal{B}$ is an open set of $BV^2(\mathbb{S}^1, \mathbb{R}^2)$.

Proof. As $\gamma_0 \in \mathcal{B}$ is parameterized by the unit speed parameterization we have $|\gamma'_0(s)| = \mathcal{L}(\gamma_0)$ for every $s \in \mathbb{S}^1$, so that we have

$$\mathcal{L}(\gamma_0) = \min_{s \in \mathbb{S}^1} |\gamma'_0(s)|.$$

Now, by (2.3), we have $\|u\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq \|u\|_{BV(\mathbb{S}^1, \mathbb{R}^2)}$ for every $u \in BV(\mathbb{S}^1, \mathbb{R}^2)$, so every curve $\gamma \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$ such that

$$\|\gamma - \gamma_0\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} \leq \frac{\mathcal{L}(\gamma_0)}{2}$$

satisfies (2.1). □

Property (2.1) allows to generalize standard properties from the setting of smooth curves to BV^2 -curves. Note also that this condition implies that the support of the curve has no cusp points.

We can now generalize to BV^2 curves the usual properties of smooth curves.

Proposition 2.6. For every $\gamma \in \mathcal{B}$ the set $[\gamma] = \gamma(\mathbb{S}^1)$ can be locally represented as the graph of a BV^2 -function. For every $\gamma_1, \gamma_2 \in \mathcal{B}$ such that $[\gamma_1] = [\gamma_2]$, there exists a homeomorphism $\varphi \in BV^2(\mathbb{S}^1, \mathbb{S}^1)$ such that

$$\gamma_1 = \gamma_2 \circ \varphi. \quad (2.5)$$

Proof. See [14], Proposition 3.7. $\square$

Note that the diffeomorphism φ appearing in (2.5) is not unique.

Definition 2.7 (Tangent space). For any $\gamma \in \mathcal{B}$, we set $T_\gamma \mathcal{B} = BV^2(\gamma)$ the space $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ equipped with the measure $d\gamma(s) = |\gamma'(s)|ds$. In $BV^2(\gamma)$, integration and differentiation is done with respect to $d\gamma(s)$. Namely, the notation $\frac{dg}{d\gamma(s)}(s)$ stands for $\frac{1}{|\gamma'(s)|} \frac{dg}{ds}$.

Moreover, for every $f \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$, its first and second variations with respect to the measure $d\gamma$ are defined respectively by

$$TV_\gamma(f) = \sup \left\{ \int_{\mathbb{S}^1} f(s) \cdot \frac{dg}{d\gamma(s)}(s) d\gamma(s) : g \in C_c^\infty(\mathbb{S}^1, \mathbb{R}^2), \|g\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq 1 \right\} \quad (2.6)$$

and

$$TV_\gamma^2(f) = \sup \left\{ \int_{\mathbb{S}^1} f(s) \cdot \frac{d^2g}{d\gamma(s)^2}(s) d\gamma(s) : g \in C_c^\infty(\mathbb{S}^1, \mathbb{R}^2), \|g\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq 1 \right\}. \quad (2.7)$$

We also remark that

$$\|f'\|_{L^1(\mathbb{S}^1, \mathbb{R}^2)} = \left\| \frac{df}{d\gamma} \right\|_{L^1(\gamma)}.$$

Then the $BV^2(\gamma)$ -norm is defined as it follows

$$\|f\|_{BV^2(\gamma)} = \int_{\mathbb{S}^1} |f| |\gamma'| ds + \int_{\mathbb{S}^1} |f'| ds + TV_\gamma^2(f) \quad \forall f \in BV^2(\gamma).$$

Finally, we remind that

$$\begin{aligned} \|f\|_{BV^2(\gamma)} &= \|f \circ \varphi_\gamma\|_{BV^2(\mathbb{S}^1, \mathbb{R})}^w, \\ \|f\|_{BV^2(\mathbb{S}^1, \mathbb{R})}^w &= \mathcal{L}(\gamma) \|f\|_{L^1(\mathbb{S}^1, \mathbb{R})} + \|f'\|_{L^1(\mathbb{S}^1, \mathbb{R})} + \frac{1}{\mathcal{L}(\gamma)} |Df|(\mathbb{S}^1) \quad \forall f \in BV^2(\mathbb{S}^1, \mathbb{R}). \end{aligned} \quad (2.8)$$

Moreover, analogously to Lemma 2.13 in [11], we have the following Poincaré inequality

$$\|f\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq \frac{1}{\mathcal{L}(\gamma)} \int_{\mathbb{S}^1} f d\gamma + TV_\gamma \left(\frac{df}{d\gamma} \right) \quad \forall f \in BV(\gamma). \quad (2.9)$$

Remark 2.8 (Weighted norms). Similarly to [11], we could consider some weighted BV^2 -norms, defined as

$$\|f\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} = a_0 \|f\|_{L^1(\mathbb{S}^1, \mathbb{R}^2)} + a_1 \|f'\|_{L^1(\mathbb{S}^1, \mathbb{R}^2)} + a_2 |D^2 f|(\mathbb{S}^1)$$

where $a_i > 0$ for $i = 1, 2, 3$. We can define the norm on the tangent space by the same constants.

One can easily verify that our results can be generalized to such a framework. In fact, previous norm is equivalent to the classic-one and the positive constants do not affect the bounds and the convergences properties that we prove in this work.

The following proposition proves that the tangent space to a given curve in $\mathcal{B}$ and $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ represent the same space of functions with equivalent norms.

Proposition 2.9. Let $\gamma \in \mathcal{B}$. The following properties hold:

1. The sets $BV^2(\gamma)$ and $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ coincide and their norm are equivalent. More precisely, there exist two positive constants M_γ, m_γ such that, for all $f \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$

$$m_\gamma \|f\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} \leq \|f\|_{BV^2(\gamma)} \leq M_\gamma \|f\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}. \quad (2.10)$$

2. We have

$$\|f\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} = \|f\|_{L^\infty(\gamma)}. \quad (2.11)$$

Proof. (Proof of (2.10)) We suppose that f is not equal to zero. In the case of the L^1 -norm on f , the result follows from (2.1) and the compactness of $\mathbb{S}^1$. The constants are given respectively by

$$M_\gamma^0 = \|\gamma'\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \quad m_\gamma^0 = \min_{s \in \mathbb{S}^1} |\gamma'(s)|.$$

Moreover by a straightforward calculation one can easily see that the $L^1(\gamma)$ and $L^1(\mathbb{S}^1, \mathbb{R}^2)$ -norms of the first derivative coincide. So it is sufficient to obtain the result for the second variation of $f \in BV^2(\gamma)$.

By integration by part, we have

$$\int_{\mathbb{S}^1} f(s) \cdot \frac{d^2 g}{d\gamma^2(s)}(s) d\gamma(s) = \int_{\mathbb{S}^1} \frac{f'}{|\gamma'|} g'(s) ds$$

where we used the fact that $\frac{dg}{d\gamma(s)} = \frac{g'}{|\gamma'|}$. This implies in particular that

$$TV_\gamma^2(f) = \left| D \frac{f'}{|\gamma'|} \right|(\mathbb{S}^1).$$

Since $\frac{1}{|\gamma'|} \in BV(\mathbb{S}^1, \mathbb{R}^2)$ and $BV(\mathbb{S}^1, \mathbb{R}^2)$ is a Banach algebra, we get

$$\left| D \frac{f'}{|\gamma'|} \right|(\mathbb{S}^1) \leq |Df'|(\mathbb{S}^1) \left| D \frac{1}{|\gamma'|} \right|(\mathbb{S}^1).$$

Now, as $|Df'|(\mathbb{S}^1) \leq |D^2 f|(\mathbb{S}^1)$, we get the upper bound taking the constant

$$M_\gamma^2 = \left| D \frac{1}{|\gamma'|} \right|(\mathbb{S}^1).$$

On the other hand, we have

$$\int_{\mathbb{S}^1} f' g'(s) ds = \int_{\mathbb{S}^1} \frac{df}{d\gamma(s)}(s) \frac{dg}{d\gamma(s)}(s) |\gamma'| d\gamma(s)$$

so that

$$|Df'|(\mathbb{S}^1) = TV_\gamma \left(\frac{df}{d\gamma(s)} |\gamma'| \right),$$

which implies that

$$|D^2 f|(\mathbb{S}^1) \leq TV_\gamma(|\gamma'|)TV_\gamma^2(f) \leq \|\gamma'\|_{BV(\mathbb{S}^1, \mathbb{R})}TV_\gamma^2(f). \quad (2.12)$$

Therefore, the result is proved by taking the constant

$$m_\gamma^2 = \frac{1}{\|\gamma'\|_{BV(\mathbb{S}^1, \mathbb{R}^2)}}.$$

The lemma ensues setting

$$\begin{aligned} M_\gamma &= \max \{M_\gamma^0, M_\gamma^2\} = \max \left\{ \|\gamma'\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)}, \left| D \frac{1}{|\gamma'|} \right|(\mathbb{S}^1) \right\}, \\ m_\gamma &= \min \{m_\gamma^0, m_\gamma^2\} = \min \left\{ \min_{s \in \mathbb{S}^1} |\gamma'(s)|, 1/\|\gamma'(\cdot)\|_{BV(\mathbb{S}^1, \mathbb{R}^2)} \right\}. \end{aligned} \quad (2.13)$$

(*Proof of (2.11)*) It follows straightforwardly from (2.1) that the two measures are equivalent, i.e.

$$\int_A ds = 0 \Leftrightarrow \int_A d\Gamma(s) = 0$$

for every open set A of the circle. $\square$

2.2 Existence of Geodesics

In this section, we prove that geodesics for the induced Finsler metric exist for any given couple of curves in the same homotopy class.

Definition 2.10 (Paths in $\mathcal{B}$). For every $\gamma_0, \gamma_1 \in \mathcal{B}$, we define a path in $\mathcal{B}$ joining γ_0 and γ_1 as a function

$$\Gamma : t \in [0, 1] \mapsto \Gamma(t) \in \mathcal{B}$$

such that

$$\Gamma(0) = \gamma_0 \quad \Gamma(1) = \gamma_1. \quad (2.14)$$

For every $\gamma_0, \gamma_1 \in \mathcal{B}$, we denote $\mathcal{P}(\gamma_0, \gamma_1)$ the class of all paths joining γ_0, γ_1 and belonging to $H^1([0, 1], \mathcal{B})$. It holds in particular

$$\forall a.e. s \in \mathbb{S}^1, \quad \int_0^1 \Gamma_t(t)(s) dt = \gamma_1(s) - \gamma_0(s) \quad (2.15)$$

where Γ_t denotes the derivative of Γ with respect to t . In the following $\Gamma'(t)$ denotes the derivative of the curves $\Gamma(t) \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$ with respect to s .

Definition 2.11 (Geodesic paths in $\mathcal{B}$). For every path Γ we consider the following energy

$$E(\Gamma) = \int_0^1 \|\Gamma_t(t)\|_{BV^2(\Gamma(t))}^2 dt. \quad (2.16)$$

The geodesic distance between γ_0 and γ_1 is denoted by $d(\gamma_0, \gamma_1)$ and defined by

$$d^2(\gamma_0, \gamma_1) = \inf \{E(\Gamma) : \Gamma \in \mathcal{P}(\gamma_0, \gamma_1)\}. \quad (2.17)$$

A geodesic between γ_0 and γ_1 is a path $\tilde{\Gamma} \in \mathcal{P}(\gamma_0, \gamma_1)$ such that

$$E(\tilde{\Gamma}) = d^2(\gamma_0, \gamma_1).$$

Note that because of the lack of smoothness of the BV^2 norm over the tangent space, it is not possible to define an exponential map. Geodesics should thus be understood as minimal geodesics, and are thus homotopies defined using the variational problem (2.17). Recall that the existence of (minimizing) geodesics is not granted in infinite dimension. When the metric is Riemannian and even if the manifold is geodesically complete, the existence of minimizers is not guaranteed since the Hopf-Rinow theorem does not hold in infinite dimension, see Section 1.1.

Remark 2.12 (Time-reparameterization and geodesic energy). We point out that analogously to Remark 2.2 we can reparameterize every non-trivial homotopy Γ (i.e. satisfying $E(\Gamma) \neq 0$) with respect to the time-unit speed parameterization, defined as the inverse of the following parameter:

$$t_\Gamma : [0, 1] \rightarrow [0, 1]$$

$$\forall t \in [0, 1], \quad t_\Gamma(t) = \frac{1}{E_1(\Gamma)} \int_0^t \|\Gamma_\tau(\tau)\|_{BV^2(\Gamma(\tau))} d\tau,$$

where

$$E_1(\Gamma) = \int_0^1 \|\Gamma_\tau(\tau)\|_{BV^2(\Gamma(\tau))} d\tau.$$

In particular, if $\|\Gamma_\tau(\tau)\|_{BV^2(\Gamma(\tau))} \neq 0$ for every t , by reparameterizing the homotopy with respect to previous parameter we obtain a parameterization with constant velocity

$$\|\Gamma_t(t)\|_{BV^2(\Gamma(t))} = E_1(\Gamma) \quad \forall t \in [0, 1]. \quad (2.18)$$

In the general case, for every $\varepsilon > 0$, we can always prove the existence of a time-parameterization such that

$$\|\Gamma_t(t)\|_{BV^2(\Gamma(t))} \leq E_1(\Gamma) + \varepsilon \quad \forall t \in [0, 1].$$

This implies in particular that

$$E_1(\Gamma) = E(\Gamma \circ t_\Gamma^{-1})$$

for every path Γ . Then, the minimizers of E_1 coincide with the minimizers of E reparameterized with respect to the parameter t_Γ . This justifies the definition of the geodesic energy E by a L^2 -norm. We refer to [39] (see Theorem 8.18 and Corollary 8.19, p.175) for more details.

We prove now that constants $m_{\Gamma(t)}$ and $M_{\Gamma(t)}$ defined in (2.13) are uniformly bounded on minimizing paths.

To this end we need the following lemma.

Lemma 2.13. Let $\Gamma \in \mathcal{P}(\gamma_0, \gamma_1)$. Then the following properties hold:

1. The function

$$t \mapsto g(t) = \|\Gamma'(t)\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)}$$

belongs to $C([0, 1], \mathcal{B})$, so in particular it admits a maximum and a positive minimum on $[0, 1]$. Moreover

$$\min_{t \in [0, 1]} \min_{s \in \mathbb{S}^1} |\Gamma'(t)(s)| > 0.$$

2. For every $t \in [0, 1]$ we have

$$\mathcal{L}(\gamma_0)e^{-E(\Gamma)} \leq \mathcal{L}(\Gamma(t)) \leq \mathcal{L}(\gamma_0)e^{E(\Gamma)} \quad (2.19)$$

and for all $s \in \mathbb{S}^1$,

$$\left(\min_{s \in \mathbb{S}^1} |\gamma'_0(s)|\right)e^{-E(\Gamma)} \leq |\Gamma'(t)(s)| \leq \|\gamma'_0\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} e^{E(\Gamma)}. \quad (2.20)$$

Proof. 1. By Definition 2.11, every $\Gamma \in \mathcal{P}(\gamma_0, \gamma_1)$ belongs to $H^1([0, 1], \mathcal{B})$ so in particular to $C([0, 1], \mathcal{B})$. Now, as $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ is embedded in $L^\infty(\mathbb{S}^1, \mathbb{R}^2)$, we get the continuity of g . Moreover, from (2.1) and the compactness of $\mathbb{S}^1$, it follows that

$$\min_{s \in \mathbb{S}^1} |\Gamma'(t)(s)| > 0, \quad \forall t \in [0, 1]$$

which implies that $\min_{t \in [0, 1]} g(t) > 0$. The second statement is a straightforward consequence of (2.1) and the compactness of $[0, 1]$.

This implies in particular that functions $t \mapsto \mathcal{L}(\Gamma(t))$ and $t \mapsto |\Gamma'(t)(s)|$ (for every $s \in \mathbb{S}^1$) are continuous.

2. By Remark 2.12 we can suppose that the time-velocity is constant. We have

$$\frac{\partial \mathcal{L}(\Gamma(t))}{\partial t} = \int_{\mathbb{S}^1} \left\langle \frac{\Gamma'_t(t)}{|\Gamma'(t)|}, \Gamma'(t) \right\rangle ds \leq \left\| \frac{d\Gamma_t(t)}{d\Gamma(t)} \right\|_{L^1(\Gamma(t))} \mathcal{L}(\Gamma(t)),$$

and, as $\frac{d\Gamma_t(t)}{d\Gamma(t)}$ has null average, by (2.9), we have

$$\left\| \frac{d\Gamma_t(t)}{d\Gamma(t)} \right\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq E(\Gamma).$$

This implies

$$\frac{\partial \log(\mathcal{L}(\Gamma(t)))}{\partial t} \leq E(\Gamma) \quad \forall t \in [0, 1],$$

and, by integrating in time between 0 and t , we get

$$\mathcal{L}(\gamma_0)e^{-E(\Gamma)} \leq \mathcal{L}(\Gamma(t)) \leq \mathcal{L}(\gamma_0)e^{E(\Gamma)}.$$

Similarly we have

$$\frac{\partial |\Gamma'(t)(s)|}{\partial t} = \left\langle \frac{\Gamma'_t(t)}{|\Gamma'(t)|}, \Gamma'(t)(s) \right\rangle \leq \left\| \frac{d\Gamma_t(t)(s)}{d\Gamma(t)} \right\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} |\Gamma'(t)(s)|$$

and, as above, we get

$$\frac{\partial \log(|\Gamma'(t)(s)|)}{\partial t} \leq E(\Gamma), \quad \forall s \in \mathbb{S}^1 \quad \forall t \in [0, 1].$$

The result follows by integrating in time. □

Proposition 2.14. Let $\gamma_0 \in \mathcal{B}$ and we consider the geodesic ball

$$B_d(\gamma_0, r) = \{\gamma \in \mathcal{B} \mid d(\gamma_0, \gamma) < r\}.$$

Then constants m_γ and M_γ defined in (2.13) verify

$$C_1 e^{-C_0 r^2} \leq m_\gamma \leq M_\gamma \leq C_2 e^{C_0 r^2} \quad \forall \gamma \in B_d(\gamma_0, r) \quad (2.21)$$

where C_0, C_1, C_2 are three positive constants depending on γ_0 (see (2.24) and (2.27)).

Proof. Given $\gamma \in \mathcal{B}$, we show that

$$C_1 e^{-C_0 E(\Gamma)} \leq m_{\Gamma(t)} \leq M_{\Gamma(t)} \leq C_2 e^{C_0 E(\Gamma)} \quad \forall t \in [0, 1]$$

for every $\Gamma \in \mathcal{P}(\gamma_0, \gamma)$. Then, for every $\gamma \in B_d(\gamma_0, r)$, the result follows from previous inequality by considering a path $\Gamma \in \mathcal{P}(\gamma_0, \gamma)$ such that $E(\Gamma) \leq r^2$ and setting $t = 1$.

Because of (2.20), we have

$$\begin{aligned} (\min_{s \in \mathbb{S}^1} |\gamma'_0(s)|) e^{-E(\Gamma)} &\leq \min_{s \in \mathbb{S}^1} |\Gamma'(t)(s)| \\ |||\Gamma'(t)|||_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} &\leq \|\gamma'_0\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} e^{E(\Gamma)}. \end{aligned} \quad (2.22)$$

for every $t \in [0, 1]$. By setting $f(t) = \Gamma'(t)$ in (2.12) and by a time-reparameterization, we get

$$|D^2 \Gamma'(t)|(\mathbb{S}^1) \leq |||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} E(\Gamma). \quad (2.23)$$

Thus

$$\|\Gamma'(t) - \gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} \leq \int_0^t \|\Gamma'_\tau\|_{BV(\mathbb{S}^1, \mathbb{R})} d\tau = \int_0^t [|||\Gamma'_\tau|||_{L^1(\mathbb{S}^1, \mathbb{R}^2)} + |D^2 \Gamma_\tau|(\mathbb{S}^1)] d\tau$$

and, by (2.23) and (2.18), we have

$$\|\Gamma'(t) - \gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} \leq E(\Gamma) + \int_0^t |||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} E(\Gamma) d\tau.$$

In particular, by the chain rule for BV -functions ([1]: Theorem 3.96 p. 189), we have

$$|||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} \leq C_0 \|\Gamma'(t)\|_{BV(\mathbb{S}^1, \mathbb{R})}$$

where

$$C_0 = \max \left\{ 1, \frac{1}{\min_{s \in \mathbb{S}^1} |\gamma'_0(s)|} \right\}. \quad (2.24)$$

Then

$$|||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} \leq C_0 \left(\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma) + \int_0^t |||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} E(\Gamma) d\tau \right)$$

and by the Gronwall's inequality we get

$$|||\Gamma'(t)|||_{BV(\mathbb{S}^1, \mathbb{R})} \leq C_0 (\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma)) e^{C_0 E(\Gamma)}. \quad (2.25)$$

From previous relationship implies that

$$\begin{aligned} \frac{e^{-C_0 E(\Gamma)}}{C_0(\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma))} &\leq \frac{1}{\|\Gamma'(t)\|_{BV(\mathbb{S}^1, \mathbb{R}^2)}} \\ \left| D \frac{1}{|\Gamma'(t)|} \right|(\mathbb{S}^1) &\leq \frac{C_0(\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma))}{\min_{s \in \mathbb{S}^1} |\gamma'_0(s)|^2} e^{C_0 E(\Gamma)} \end{aligned} \quad (2.26)$$

where we used the chain rule for BV -functions to prove the second inequality. The result follows from (2.22) and (2.26) by setting

$$\begin{aligned} C_1 &= \min \left\{ \min_{s \in \mathbb{S}^1} |\gamma'_0(s)|, \frac{1}{C_0(\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma))} \right\}, \\ C_2 &= \max \left\{ \|\gamma'_0\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)}, \frac{C_0(\|\gamma'_0\|_{BV(\mathbb{S}^1, \mathbb{R})} + E(\Gamma))}{\min_{s \in \mathbb{S}^1} |\gamma'_0(s)|^2} \right\}. \end{aligned} \quad (2.27)$$

□

We can now prove an existence result for geodesics.

Theorem 2.15 (Existence). Let $\gamma_0, \gamma_1 \in \mathcal{B}$ such that $d(\gamma_0, \gamma_1) < \infty$. Then, there exists a geodesic between γ_0 and γ_1 .

Proof. Let $\{\Gamma^h\}_h \subset \mathcal{P}(\gamma_0, \gamma_1)$ be a minimizing sequence for E . Without loss of generality we can suppose $\sup_h E(\Gamma^h) < +\infty$. We also remark that, from the previous lemma, it follows

$$0 < \inf_h \inf_{t \in [0,1]} m_{\Gamma^h(t)} < \sup_h \sup_{t \in [0,1]} M_{\Gamma^h(t)} < +\infty.$$

Step 1: Definition of a limit path. For every $n > 1$ we consider the dyadic decomposition of $[0, 1]$ given by the intervals

$$I_{n,k} = \left[\frac{k}{2^n}, \frac{k+1}{2^n} \right[\quad \text{for } k \in [0, 2^n - 1] \quad (2.28)$$

and, for every $t \in [0, 1]$ we define

$$f_n^h(t) = 2^n \int_{I_{n,k}} \Gamma_\tau^h(\tau) d\tau,$$

where $I_{n,k}$ is the interval containing t . Remark that, for every n and h , $f_n^h : [0, 1] \rightarrow BV^2(\mathbb{S}^1, \mathbb{R}^2)$ is piecewise-constant and

$$\int_0^1 f_n^h(\tau) d\tau = \int_0^1 \Gamma_t^h(t) dt = \Gamma(1) - \Gamma(0). \quad (2.29)$$

Now, we have $m = \inf_h \min_{t \in [0,1]} m_{\Gamma^h(t)} > 0$ and, by (2.10), we get

$$\|f_n^h(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 \leq 2^n \int_0^1 \frac{\|\Gamma_t^h(t)\|_{BV^2(\Gamma(t))}^2}{m_{\Gamma(t)}} \leq \frac{2^n}{m} E(\Gamma^h) \quad \forall t \in [0, 1]. \quad (2.30)$$

So, by a diagonal extraction, we can take a subsequence (not relabeled) and a piecewise-constant function $f_n^\infty : [0, 1] \rightarrow BV^2(\mathbb{S}^1, \mathbb{R}^2)$ such that

$$\forall (n, k), \quad f_n^h(t) \xrightarrow{*BV^2} f_n^\infty(t), \quad \forall t \in [0, 1]$$

and

$$\int_0^1 \|f_n^\infty(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 dt \leq \liminf_{h \rightarrow \infty} \int_0^1 \|f_n^h(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 dt.$$

Moreover we can write $I_{n,k} = [k2^{-n}, (2k+1)2^{-n-1}[\cup [(2k+1)2^{-n-1}, (k+1)2^{-n}[$ and

$$f_{n+1}^h(t) = 2^{n+1} \int_{I_{n+1,2k}} \Gamma_t^h(t) dt \quad \forall t \in [k2^{-n}, (2k+1)2^{-n-1}[$$

$$f_{n+1}^h(t) = 2^{n+1} \int_{I_{n+1,2k+1}} \Gamma_t^h(t) dt \quad \forall t \in [(2k+1)2^{-n-1}, (k+1)2^{-n}[$$

therefore

$$\begin{aligned} \int_{I_{n,k}} f_{n+1}^h(t) dt &= \int_{I_{n,k}} \Gamma_t^h(t) dt \\ f_n^h(t) &= 2^n \int_{I_{n,k}} f_{n+1}^h(t) dt \quad \forall t \in I_{n,k}. \end{aligned}$$

Then, by the Dominated Convergence Theorem, we get

$$f_n^\infty(t) = 2^n \int_{I_{n,k}} f_{n+1}^\infty(t) dt \tag{2.31}$$

which implies that $\{f_n^\infty\}$ is a $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ -valued martingale ([15]: Section 5.2, p. 198).

Moreover, by Fatou's Lemma and (2.30), we get

$$\begin{aligned} \int_0^1 \|f_n^\infty(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 dt &\leq \liminf_{h \rightarrow \infty} \int_0^1 \|f_n^h(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 dt \\ &\leq \liminf_{h \rightarrow \infty} \frac{E(\Gamma^h)}{m}. \end{aligned}$$

Now, as $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ is embedded in $H^1(\mathbb{S}^1, \mathbb{R}^2)$, this implies that $\{f_n^\infty\}$ is a bounded martingale in $L^2([0, 1], H^1(\mathbb{S}^1, \mathbb{R}^2))$ so, by the Convergence Theorem for Martingales ([15]: Theorem 5.4.5, p. 215), $f_n^\infty(t) \rightarrow f(t)$ in $H^1(\mathbb{S}^1, \mathbb{R}^2)$ for almost every t . Note also that, as $f_n^\infty \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$ and the second variation is lower semicontinuous with respect to the $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$ -convergence, we actually get $f \in L^2([0, 1], BV^2(\mathbb{S}^1, \mathbb{R}^2))$.

We can now define a candidate to be a minimum of E by setting

$$\Gamma^\infty(t) = \int_0^t f(\tau) d\tau + \Gamma(0), \quad \forall t \in [0, 1]. \tag{2.32}$$

We can easily verify that $\Gamma^\infty \in H^1([0, 1], BV^2(\mathbb{S}^1, \mathbb{R}^2))$ and that Γ^∞ verifies (2.15). In fact, by the Dominated Convergence Theorem and (2.29), we have

$$\int_0^1 f(\tau) d\tau = \lim_{n \rightarrow \infty} \int_0^1 f_n^\infty(\tau) d\tau = \lim_{n \rightarrow \infty} \lim_{h \rightarrow \infty} \int_0^1 f_n^h(\tau) d\tau = \Gamma(1, \cdot) - \Gamma(0, \cdot).$$

This implies in particular that Γ^∞ verifies (2.14). So we get $\Gamma^\infty \in \mathcal{P}(\gamma_0, \gamma_1)$.

Step 2: Γ^∞ is a geodesic path. We now prove that $\Gamma^h(t) \rightarrow \Gamma^\infty(t)$ in $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$ for every t . For that we denote by Γ_n^∞ and Γ_n^h the paths defined by f_n^∞ and f_n^h through (2.32). Now, by definition of f_n^h and a straightforward calculation, we get that $\|\Gamma^h(t) - \Gamma_n^h(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)}$ is small for n large enough. Moreover, as $f_n^h(t) \xrightarrow{*BV^2} f_n^\infty(t)$ for every t and $f_n^\infty \rightarrow f$ in $L^2([0, 1], BV^2(\mathbb{S}^1, \mathbb{R}^2))$ we have $\|\Gamma_n^\infty(t) - \Gamma_n^h(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \rightarrow 0$, as $h \rightarrow \infty$ and that $\|\Gamma_n^\infty(t) - \Gamma^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)}$ is small for n large enough. This implies that

$$\|\Gamma^h(t) - \Gamma^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \rightarrow 0. \quad (2.33)$$

By the same arguments we can show that

$$\|\Gamma_t^h(t) - \Gamma_t^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \rightarrow 0, \quad \forall t \in [0, 1], \quad (2.34)$$

which implies in particular that $\{\Gamma_t^h(t)\}_h$ is bounded in $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ for almost every t .

Now, as $\Gamma^h(t)$ converges in $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$ towards $\Gamma^\infty(t) \in BV^2(\mathbb{S}^1, \mathbb{R}^2)$, the unit speed parameterizations at the time t , denoted respectively by $\varphi^h(t)$ and $\varphi^\infty(t)$, also converge in $W^{1,1}(\mathbb{S}^1, \mathbb{S}^1)$. Moreover, for a fixed time t , we have $\|\Gamma_t^h(t)\|_{BV^2(\Gamma^h(t))}^2 = \|\Gamma_t^h \circ \varphi^h(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2$. Since $\{\Gamma_t^h(t)\}_h$ is bounded in $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ and the two terms involved in the composition converge in $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$, we have

$$\begin{aligned} \|\Gamma_t^h \circ \varphi^h(t) - \Gamma_t^h \circ \varphi^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} &\leq \|\Gamma_t^h\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)} \|\varphi^h(t) - \varphi^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \\ \|\Gamma_t^h \circ \varphi^\infty(t) - \Gamma_t^\infty \circ \varphi^\infty(t)\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} &\leq C \|\Gamma_t^h - \Gamma_t^\infty\|_{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \end{aligned}$$

where

$$C = \max \{1, \|(\varphi^\infty)^{-1}\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)}\}.$$

This implies in particular that

$$\Gamma_t^h \circ \varphi^h(t) \xrightarrow{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \Gamma_t^\infty \circ \varphi^\infty(t). \quad (2.35)$$

Now we remark that, because of the $W^{1,1}$ -convergence, we have $\mathcal{L}(\Gamma^h(t)) \rightarrow \mathcal{L}(\Gamma(t))$. Moreover, the second variation is lower semi-continuous with respect to the $W^{1,1}$ -convergence.

Then, by (2.8), for every t we get

$$\begin{aligned} \|\Gamma_t^\infty(t)\|_{BV^2(\Gamma^\infty(t))} &= \|\Gamma_t^\infty \circ \varphi^\infty(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^w \\ &\leq \liminf_{h \rightarrow \infty} \|\Gamma_t^h \circ \varphi^h(t)\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^w = \liminf_{h \rightarrow \infty} \|\Gamma_t^h(t)\|_{BV^2(\Gamma^h(t))}. \end{aligned} \quad (2.36)$$

By integrating the previous inequality and using Fatou's Lemma we get that Γ^∞ minimizes E , which ends the proof. $\square$

Remark 2.16. In order to get the semicontinuity's inequality (2.36), we actually just would need the convergence in (2.35) with respect to the BV^2 -weak topology. We point out that it is very difficult to characterize such a topology, which explains the choice of the weak-* topology (i.e. we look at $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ as a dual Banach space) in the previous proof.

Moreover, the martingale approach allows one to get strong convergence in $W^{1,1}$ without applying any strong-compactness criterion for Sobolev spaces. This is a key point of the proof because the BV^2 -norm is semicontinuous with respect to the strong $W^{1,1}$ -topology.

Inspired by the previous proof we can define the following topology on $H^1([0, 1], \mathcal{B})$:

Definition 2.17 (σ -topology). Let $\{\Gamma^h\}_h \subset H^1([0, 1], \mathcal{B})$ and $\Gamma \in H^1([0, 1], \mathcal{B})$. We say that Γ_h converges to Γ with respect to the σ -topology (denoted by $\Gamma^h \xrightarrow{\sigma} \Gamma$) if there exists a sequence of piecewise constant functions $\{f_n^\infty\}$ such that:

- (i) (**BV^2 -* weak convergence**). Let $\{I_{n,k}\}_{n,k}$ the collection of the intervals giving the dyadic decomposition of $[0, 1]$ defined in (2.28), then the sequence

$$f_n^h(t) = 2^n \int_{I_{n,k}} \Gamma_\tau^h(\tau) d\tau$$

verifies

$$\forall (n, k) \quad f_n^h(t) \xrightarrow{*BV^2} f_n^\infty(t) \quad \forall t \in [0, 1]$$

as $h \rightarrow \infty$;

- (ii) (**Martingale convergence**). We have

$$\lim_{n \rightarrow \infty} \|f_n^\infty - \Gamma_t\|_{L^2([0,1], H^1(\mathbb{S}^1, \mathbb{R}^2))} = 0.$$

Then, the proof of Theorem 2.15 proves actually the following result:

Theorem 2.18. The following properties hold:

- (i) Every bounded set of $H^1([0, 1], \mathcal{B})$ is sequentially compact with respect to σ -topology and the σ -convergence implies the strong convergence in $H^1([0, 1], W^{1,1}(\mathbb{S}^1, \mathbb{R}^2))$;
- (ii) The energy E is lower semicontinuous with respect to the σ -topology.

Remark 2.19. The proof of Theorem 2.15 can now be presented as it follows. We can suppose that $\{\Gamma^h\} \subset H^1([0, 1], \mathcal{B})$ with $\sup_h E(\Gamma^h) < \infty$. Then $\{\Gamma^h\}$ is uniformly bounded in $H^1([0, 1], \mathcal{B})$ and, by points (i) and (ii) of previous theorem, energy E reaches its minimum on $H^1([0, 1], \mathcal{B})$.

2.3 Geodesic Distance Between Geometric Curves

Theorem 2.15 shows the existence of a geodesic between any two parameterized curves in $\mathcal{B}$. We are interested now in defining a geometric distance between geometric curves (i.e., up to parameterization).

The space of geometric curves is defined as $\mathcal{B}/\text{Diff}(\mathbb{S}^1)$. For every $\gamma \in \mathcal{B}$ its equivalence class (called also geometric curve) is denoted by $[\gamma]$.

Next proposition defines a distance on the set of curves belonging to $\mathcal{B}$ up to reparameterization.

Proposition 2.20. The Procrustean dissimilarity measure defined by

$$\mathcal{D}([\gamma_0], [\gamma_1]) = \inf \{d(\gamma_0 \circ \varphi, \gamma_1 \circ \psi) : \varphi, \psi \in \text{Diff}(\mathbb{S}^1)\} \quad (2.37)$$

is a distance on the set of $\mathcal{B}$ -curves up to reparameterization.

Proof. The function $\mathcal{D}$ is symmetric, non-negative and it is equal to zero if $[\gamma_0] = [\gamma_1]$.

Remark also that, the distance d is invariant under reparameterization, so that

$$d(\gamma_0, \gamma_1) = d(\gamma_0 \circ \varphi, \gamma_1 \circ \varphi), \quad \forall \varphi \in \text{Diff}(\mathbb{S}^1). \quad (2.38)$$

Then from the invariance (2.38) it follows that for every $\varphi_1, \varphi_2, \varphi_3 \in \text{Diff}(\mathbb{S}^1)$ and $\gamma_1, \gamma_2, \gamma_3 \in \mathcal{B}$ we have

$$\begin{aligned} d(\gamma_1 \circ \varphi_1, \gamma_2 \circ \varphi_2) &\leq d(\gamma_1 \circ \varphi_1, \gamma_3 \circ \varphi_3) + d(\gamma_3 \circ \varphi_3, \gamma_2 \circ \varphi_2) \\ &= d(\gamma_1 \circ \varphi_1 \circ \varphi_3^{-1}, \gamma_3) + d(\gamma_3, \gamma_2 \circ \varphi_2 \circ \varphi_3^{-1}) \end{aligned}$$

which implies that the triangle inequality is satisfied for $\mathcal{D}$.

We prove now that $\mathcal{D}([\gamma_0], [\gamma_1]) = 0$ implies that $[\gamma_0] = [\gamma_1]$. We assume that γ_0 is parameterized by the unit speed parameterization (this is possible because of the invariance of d under reparameterization). So there exists a sequence φ_h of reparameterizations such that

$$d(\gamma_0, \gamma_1 \circ \varphi_h) \leq \frac{1}{h}.$$

By Lemma 2.14, minimal energies $E(\Gamma^h)$ are uniformly bounded and $C = \inf_h \inf_t m_{\Gamma^h(t)} > 0$.

Then, similarly to (2.30), we get

$$\|\gamma_0 - \gamma_1 \circ \varphi_h\|_{BV^2(\mathbb{S}^1, \mathbb{R}^2)}^2 \leq \frac{1}{Ch^2}$$

for h large enough. Thus, the support of γ_0 and γ_1 coincide which implies, by Proposition 2.6, that there exists $\varphi \in \text{Diff}(\mathbb{S}^1)$ such that $\gamma_0 = \gamma_1 \circ \varphi$. $\square$

Next theorem proves a existence result for geodesics.

Theorem 2.21 (Geometric existence). Let $\gamma_0, \gamma_1 \in \mathcal{B}$ such that $\mathcal{D}([\gamma_0], [\gamma_1]) < \infty$. Then there exists a minimizer of $\mathcal{D}([\gamma_0], [\gamma_1])$.

Proof. In the following we denoted by γ_0 and γ_1 the parameterizations by the unit speed parameterization. Because of the invariance (2.38) we can write

$$\mathcal{D}([\gamma_0], [\gamma_1]) = \inf \{d(\gamma_0, \gamma_1 \circ \psi) : \psi \in \text{Diff}(\mathbb{S}^1)\}.$$

We consider a sequence $\{\psi_h\}_h \subset \text{Diff}(\mathbb{S}^1)$ such that $d(\gamma_0, \gamma_1 \circ \psi_h) \rightarrow \mathcal{D}([\gamma_0], [\gamma_1])$ and we suppose that $\sup_h d(\gamma_0, \gamma_1 \circ \psi_h) < \infty$. By Theorem 2.15, for every h , there exists a geodesic Γ^h between γ_0 and $\gamma_1 \circ \psi_h$ and $d^2(\gamma_0, \gamma_1 \circ \psi_h) = E(\Gamma^h)$. We show that there exists $\psi_\infty \in \text{Diff}(\mathbb{S}^1)$ such that $\mathcal{D}([\gamma_0], [\gamma_1]) = d(\gamma_0, \gamma_1 \circ \psi_\infty)$.

By the same arguments used in the proof of Theorem 2.15, we can define (see Step 1) a path $\Gamma^\infty \in H^1([0, 1], BV^2(\mathbb{S}^1, \mathbb{R}^2))$ such that

$$\int_0^1 \Gamma_t^h(s) ds \rightarrow \int_0^1 \Gamma_t^\infty(s) ds, \quad (2.39)$$

and (see Step 2)

$$\Gamma^h(t) \xrightarrow{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \Gamma^\infty(t), \quad \forall t \in [0, 1] \quad (2.40)$$

$$\Gamma_t^h(t) \xrightarrow{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \Gamma_t^\infty(t), \quad \forall t \in [0, 1]. \quad (2.41)$$

Now, because of (2.15), we have

$$\int_0^1 \Gamma_t^h(t)(s) dt = \gamma_1 \circ \psi_h(s) - \gamma_0(s) \quad \forall s \in \mathbb{S}^1. \quad (2.42)$$

As $\{\gamma_1 \circ \psi_h\}$ is bounded in $BV^2(\mathbb{S}^1, \mathbb{R}^2)$ there exists a subsequence (not relabeled) converging BV^{2-*} weakly towards some curve having the same support that γ_1 . So, by Proposition 2.6, there exists $\psi_\infty \in \text{Diff}(\mathbb{S}^1)$ such that

$$\gamma_1 \circ \psi_h \xrightarrow{*BV^2(\mathbb{S}^1, \mathbb{R}^2)} \gamma_1 \circ \psi_\infty.$$

Now, as $\Gamma^h(0) = \gamma_0$ and $\Gamma^h(1) = \gamma_1 \circ \psi_h$, from (2.40), it follows

$$\Gamma^\infty(0) = \gamma_0 \quad \Gamma^\infty(1) = \gamma_1 \circ \psi_\infty$$

which implies that $\Gamma^\infty \in \mathcal{P}(\gamma_0, \gamma_1 \circ \psi_\infty)$. Moreover, denoting by φ^h and φ^∞ the unit speed parameterization of $\Gamma^h(t)$ and $\Gamma^\infty(t)$ respectively, by (2.40) we have $\varphi^h \rightarrow \varphi^\infty$ in $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$. Then, similarly to (2.36), we get

$$\|\Gamma_t^\infty(t)\|_{BV^2(\Gamma^\infty(t))} \leq \liminf_{h \rightarrow \infty} \|\Gamma_t^h(t)\|_{BV^2(\Gamma^h(t))}.$$

By integrating the previous inequality and using Fatou's Lemma we get

$$E(\Gamma^\infty) \leq \lim_{h \rightarrow \infty} E(\Gamma^h) = \lim_{h \rightarrow \infty} d^2(\gamma_0, \gamma_1 \circ \psi_h) = \mathcal{D}^2([\gamma_0], [\gamma_1]),$$

which implies that $\mathcal{D}^2([\gamma_0], [\gamma_1]) = d^2(\gamma_0, \gamma_1 \circ \psi_\infty) = E(\Gamma^\infty)$. □

3 Geodesics in the Space of Sobolev Curves

In this section, we study the geodesic boundary value problem in the class of curves belonging to $H^k(\mathbb{S}^1, \mathbb{R}^2)$ with $k \geq 2$ integer.

We remind that

$$H^k(\mathbb{S}^1, \mathbb{R}^2) \subset C^1(\mathbb{S}^1, \mathbb{R}^2), \quad \forall k \geq 2. \quad (3.1)$$

In this framework, the proof of existence of geodesics is simpler, since $H^k(\mathbb{S}^1, \mathbb{R}^2)$ being a Hilbert space, the weak topology can be used instead of the BV^{2-*} -weak one.

We define the class of the parameterized H^k -curves as follows.

Definition 3.1 (H^k -curves). We define $\mathcal{H}_k$ as the class of counterclockwise oriented curves belonging to $H^k(\mathbb{S}^1, \mathbb{R}^2)$ ($k \geq 2$ integer) and verifying (2.1).

For every $\gamma \in \mathcal{H}_k$ the unit speed parameterization φ_γ can be defined as in Remark 2.2.

From (3.1) it follows that there exists a constant C such that

$$\|\gamma'\|_{L^\infty(\mathbb{S}^1, \mathbb{R}^2)} \leq C \|\gamma\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}, \quad \forall \gamma \in \mathcal{H}_k. \quad (3.2)$$

Moreover, it is easy to verify that $\mathcal{H}_k$ is an open set of $H^k(\mathbb{S}^1, \mathbb{R}^2)$. In fact, similarly to the BV^2 -case, for every $\gamma_0 \in \mathcal{H}_k$, which is parameterized by the unit speed parameterization, (3.2) implies that

$$\left\{ \gamma \in \mathcal{H}_k : \|\gamma - \gamma_0\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)} \leq \frac{\mathcal{L}(\gamma_0)}{2C} \right\} \subset \mathcal{H}_k. \quad (3.3)$$

We point out that local properties of reparameterization proved in Proposition 2.6 can be easily generalized to H^k -curves.

As in the previous section we define the space $H^k(\gamma)$ as the space $H^k(\mathbb{S}^1, \mathbb{R}^2)$, where integration and derivation are performed with respect to the measure $d\gamma = |\gamma'|ds$. Concerning the tangent space, for any $\gamma \in \mathcal{H}_k$, we set $T_\gamma \mathcal{H}_k = H^k(\gamma)$.

As in the previous section, for every $\gamma_0, \gamma_1 \in \mathcal{H}_k$ we consider the class of paths $\Gamma \in H^1([0, 1], \mathcal{H}_k)$ such that $\Gamma(0) = \gamma_0$ and $\Gamma(1) = \gamma_1$. The energy of a path is defined as

$$E(\Gamma) = \int_0^1 \|\Gamma_t(t)\|_{H^k(\Gamma(t))}^2 dt$$

and the geodesic distance $d(\gamma_0, \gamma_1)$ is defined accordingly (see Definition 2.11).

Moreover, Lemma 5.1 in [11] proves the equivalence of the norms of $H^k(\mathbb{S}^1, \mathbb{R}^2)$ and $H^k(\gamma)$. Such a result states that, for every $\gamma_0 \in \mathcal{H}_k$, there exists a constant $C = C(\gamma_0, D) > 0$ such that

$$\frac{1}{C} \|f\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)} \leq \|f\|_{H^k(\gamma)} \leq C \|f\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)} \quad (3.4)$$

for every $\gamma \in \mathcal{H}_k$ such that $d(\gamma_0, \gamma) < D$. This proves in particular that the constant C is uniformly bounded on every geodesic ball.

Finally, in order to compare the H^k -norm after reparameterization, we remark that

$$\begin{aligned} \|f\|_{H^k(\gamma)} &= \|f \circ \varphi_\gamma\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^w \\ (\|f\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^w)^2 &= \mathcal{L}(\gamma)^2 \|f\|_{L^2(\mathbb{S}^1, \mathbb{R}^2)}^2 + \mathcal{L}(\gamma)^{2(1-k)} \|f^{(k)}\|_{L^2(\mathbb{S}^1, \mathbb{R}^2)}^2, \quad \forall f \in H^k(\mathbb{S}^1, \mathbb{R}^2). \end{aligned} \quad (3.5)$$

We prove now an existence result for geodesics in the Sobolev framework.

Theorem 3.2 (Existence). Let $\gamma_0, \gamma_1 \in \mathcal{H}_k$ such that $d(\gamma_0, \gamma_1) < \infty$. Then, there exists a geodesic between γ_0 and γ_1 .

Proof. Because of (3.4) there exists a constant $M > 0$ such that

$$\int_0^1 \|\Gamma_t^h(t)\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^2 dt \leq \int_0^1 M \|\Gamma_t^h(t)\|_{H^k(\Gamma(t))}^2 dt \leq M E(\Gamma). \quad (3.6)$$

This implies that Γ_t^h is uniformly bounded in $L^2([0, 1], H^k(\mathbb{S}^1, \mathbb{R}^2))$ and, because of the boundary conditions, that Γ^h is uniformly bounded in $H^1([0, 1], H^k(\mathbb{S}^1, \mathbb{R}^2))$.

Therefore there exists a subsequence of Γ^h that weakly converges in $H^1([0, 1], H^k(\mathbb{S}^1, \mathbb{R}^2))$. Since the embedding

$$H^1([0, 1], H^k(\mathbb{S}^1, \mathbb{R}^2)) \subset C([0, 1], H^{k-1}(\mathbb{S}^1, \mathbb{R}^2))$$

is compact, this subsequence (not relabeled) converges to a path $\Gamma^\infty \in L^2([0, 1], C(\mathbb{S}^1, \mathbb{R}^2))$,

$$\Gamma^h \rightarrow \Gamma^\infty \quad \text{in} \quad C([0, 1], H^{k-1}(\mathbb{S}^1, \mathbb{R}^2)).$$

This proves in particular that

$$\Gamma^h(t) \xrightarrow{W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)} \Gamma^\infty(t), \quad \forall t \in [0, 1] \quad \text{and} \quad \Gamma_t^h(t) \xrightarrow{H^k(\mathbb{S}^1, \mathbb{R}^2)} \Gamma_t^\infty(t), \quad \forall t \in [0, 1].$$

Now, as $\Gamma^h(t)$ converges in $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$ towards $\Gamma^\infty(t)$, the unit speed parameterizations at the time t , denoted respectively by $\varphi^h(t)$ and $\varphi^\infty(t)$, also converge in $W^{1,1}(\mathbb{S}^1, \mathbb{S}^1)$.

Thus, by the same arguments used for (2.35) ($\Gamma_t^h \circ \varphi^h(t)$ being bounded in $H^s(\mathbb{S}^1, \mathbb{R}^2)$), we have

$$\Gamma_t^h \circ \varphi^h(t) \xrightarrow{H^k(\mathbb{S}^1, \mathbb{R}^2)} \Gamma_t^\infty \circ \varphi^\infty(t), \quad \forall t \in [0, 1].$$

Now, because of (3.5), we have $\|\Gamma_t^h(t)\|_{H^k(\Gamma(t))} = \|\Gamma_t^h \circ \varphi^h(t)\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^w$. Moreover, because of the strong convergence of the unit speed parameterizations we get $\mathcal{L}(\Gamma^h(t)) \rightarrow \mathcal{L}(\Gamma^\infty(t))$ for every t . Then, for every t , we get

$$\|\Gamma_t^\infty(t)\|_{H^k(\Gamma(t))}^w = \|\Gamma_t^\infty \circ \varphi^\infty(t)\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^w \leq \liminf_{h \rightarrow \infty} \|\Gamma_t^h \circ \varphi^h(t)\|_{H^k(\mathbb{S}^1, \mathbb{R}^2)}^w = \liminf_{h \rightarrow \infty} \|\Gamma_t^h(t)\|_{H^k(\Gamma(t))}.$$

By integrating the previous inequality and using Fatou's Lemma we get that Γ^∞ minimizes E and the theorem ensues. $\square$

In [11], the authors prove (Theorem 1.1) that the space of immersed curves is geodesically complete with respect to the H^k -metrics ($k \geq 2$ integer). Since H^k -metrics ($k \geq 2$ integer) are smooth Riemannian metrics, minimizing geodesics are given locally by the exponential map. Moreover, from Theorem 3.2, we have the existence of minimal geodesics (in our variational sense) between any two points. Therefore, the minimizing curve found by our variational approach coincides with an exponential ray. Thus, we have the following corollary.

Corollary 3.3 (Surjectivity of the exponential map). The exponential map on $\mathcal{H}_k$ for $k \geq 2$ integer is defined for all time and is surjective.

The so-called Fréchet or Kärcher means often used in imaging are a particular case of minimizers of the distance to a closed subset. The surjectivity of the exponential map enables the use of [5, Theorem 3.5] which proves that the projection onto a closed subset is unique on a dense subset. A direct theoretical consequence of this surjectivity result is the following result.

Proposition 3.4. Let $k \geq 2$ be an integer. For any integer $n \geq 1$, there exists a dense subset $D \subset \mathcal{H}_k^n$, such that the Kärcher mean associated with any $(\gamma_1, \dots, \gamma_n) \in D$, defined as a minimizer of

$$\min_{\gamma \in \mathcal{H}_k} \sum_{i=1}^n d(\gamma, \gamma_i)^2, \tag{3.7}$$

is unique.

Proof. Let S be the diagonal in $\mathcal{H}_k^n$. The set S is a closed subset of $\underbrace{\mathcal{H}_k \times \dots \times \mathcal{H}_k}_{n \text{ times}}$. In [5, Theorem 3.5] the authors prove that the set of minimizers of $\arg \min_{y \in S} d(x, y)$ is a singleton for a dense subset in $\mathcal{H}_k^n$. $\square$

Analogously to the BV^2 -case we can define a distance $\mathcal{D}$ between two geometric curves (see Proposition 2.20). By the same arguments used to prove Theorem 2.21 (it suffices to use the H^k -weak convergence instead of the BV^2 -weak* one) we obtain the following result:

Theorem 3.5 (Geometric existence). Let $\gamma_0, \gamma_1 \in \mathcal{H}_k$ such that $\mathcal{D}([\gamma_0], [\gamma_1]) < \infty$. Then there exists a minimizer of $\mathcal{D}([\gamma_0], [\gamma_1])$.

4 Numerical Computations of Geodesics

In this section we discretize and relax Problem (2.17) in order to approximate numerically geodesic paths. Note that since we use a gradient descent to minimize a discretized and relaxed energy, the resulting optimal discrete homotopy aims at approximating stationary points of the geodesic energy, and that these homotopies cannot be guaranteed to be globally minimizing geodesics.

4.1 Penalized Boundary Condition at $t = 1$

To obtain a simple numerical scheme, we first relax the constraint $\Gamma(1) = \gamma_1$ by adding at the energy E a data fidelity term $H(\Gamma(1), \gamma_1)$ taking into account the deviation between $\Gamma(1)$ and γ_1 . In the following we make use of the H functional defined in [14] (equation 5.4).

Such a functional is defined as the following distance between two curves

$$H(\gamma, \lambda)^2 = T(\gamma, \gamma) + T(\lambda, \lambda) - 2T(\gamma, \lambda), \quad \forall \gamma, \lambda \in \mathcal{B}$$

where

$$T(\gamma, \lambda) = \int_{\mathbb{S}^1} \int_{\mathbb{S}^1} \mathbf{n}_\gamma(s) \cdot \mathbf{n}_\lambda(t) k(\gamma(s), \lambda(t)) d\gamma(s) d\lambda(t)$$

with

$$k(v, w) = e^{-\frac{\|v-w\|^2}{2\sigma^2}} + e^{-\frac{\|v-w\|^2}{2\delta^2}}, \quad \forall v, w \in \mathbb{R}^2.$$

Here (σ, δ) are positive constant that should adapted depending on the targeted application.

This functional H was initially proposed in [34] as a norm on a reproducing Hilbert space of currents. It can be shown to be a metric on the space of geometric curves, which explains why it is a good candidate to enforce approximately the boundary constraint at time $t = 1$. We remind that H is continuous with respect to strong topology of $W^{1,1}(\mathbb{S}^1, \mathbb{R}^2)$. We refer to [14] for its properties and its discretization using finite elements.

Then, given two curves $\gamma_0, \gamma_1 \in \mathcal{B}$, we consider the following problem

$$\begin{aligned} \min \{ F(\Gamma) : \Gamma \in H^1([0, 1], \mathcal{B}), \Gamma(0) = \gamma_0 \} \\ F(\Gamma) = H(\Gamma(1), \gamma_1) + E(\Gamma). \end{aligned} \tag{4.1}$$

To allow for more flexibility in the numerical experiments, we introduce a weighted BV^2 norm in the definition (2.16) of the energy E . Given some positive weights $(\lambda_0, \lambda_1, \lambda_2) \in (\mathbb{R}^+)^3$, we consider in this section

$$E(\Gamma) = \int_0^1 \|\Gamma_t(t)\|_{BV^2(\Gamma(t))} dt, \quad (4.2)$$

where, for all $\gamma \in \mathcal{B}$ and $v \in T_\gamma \mathcal{B}$,

$$\|v\|_{BV^2(\gamma)} = \int_{\mathbb{S}^1} \left(\lambda_0 |v(s)| + \lambda_1 \left| \frac{dv}{d\gamma}(s) \right| + \lambda_2 \left| \frac{d^2v}{d\gamma^2}(s) \right| \right) d\gamma(s).$$

4.2 Regularized Problem and Γ -convergence

The energy minimized in (4.1) is both non-smooth and non-convex. In order to compute stationary points using a gradient descent scheme, we further relax this problem by smoothing the $\mathbb{R}^2$ -norm used to calculate the BV^2 -norm. This approach is justified by a Γ -convergence result in Theorem 4.1.

The energy E is regularized as

$$E_\varepsilon(\Gamma) = \int_0^1 \|\Gamma_t(t)\|_{BV^2(\Gamma(t))}^\varepsilon dt. \quad (4.3)$$

where $\varepsilon > 0$ controls the amount of smoothing, and the smoothed BV^2 -norm is defined, for $\gamma \in \mathcal{B}$ and $v \in T_\gamma \mathcal{B}$, as

$$\|v\|_{BV^2(\gamma)}^\varepsilon = \int_{\mathbb{S}^1} \left(\lambda_0 |v(s)|_\varepsilon + \lambda_1 \left| \frac{dv}{d\gamma}(s) \right|_\varepsilon \right) |\gamma'(s)|_\varepsilon ds + \lambda_2 TV_\gamma^2(v),$$

where

$$\forall x \in \mathbb{R}^2, \quad |x|_\varepsilon = \sqrt{|x|^2 + \varepsilon^2}.$$

A regularization of the second total variation is given by (4.10) in the case of the finite element space. The initial problem (4.1) is then replaced by

$$\begin{aligned} \min \{ F_\varepsilon(\Gamma) : \Gamma \in H^1([0, 1], \mathcal{B}), \Gamma(0) = \gamma_0 \} \\ F_\varepsilon(\Gamma) = H(\Gamma(1), \gamma_1) + E_\varepsilon(\Gamma) \end{aligned} \quad (4.4)$$

This smoothing approach is justified by the following theorem

Theorem 4.1. Let $\gamma_0 \in \mathcal{B}$ and $X = \{\Gamma \in H^1([0, 1], \mathcal{B} \cap B_r(\gamma_0)) : \Gamma(0) = \gamma_0\}$, where $B_r(\gamma_0)$ is defined as in the point (iii) of Theorem 2.18. Then

$$\lim_{\varepsilon \rightarrow 0} \min_{\Gamma \in X} F_\varepsilon(\Gamma) = \min_{\Gamma \in X} F(\Gamma).$$

Moreover if $\{\Gamma_\varepsilon\}_\varepsilon$ is a sequence of minimizers of F_ε then there exists a subsequence (not relabelled) such that $\Gamma_\varepsilon \xrightarrow{\sigma} \Gamma$ as $\varepsilon \rightarrow 0$ (see Definition 2.17) and Γ is a minimizer of F .

Proof. Remark that F and F_ε are not equal to infinity. Then, by Theorem 2.18 (iii), F and F_ε reach their minima on X .

As $\{F_\varepsilon\}_\varepsilon$ is a decreasing sequence converging to F pointwise, we get

$$\lim_{\varepsilon \rightarrow 0} \min_{\Gamma \in X} F_\varepsilon(\Gamma) = \inf_{\varepsilon > 0} \min_{\Gamma \in X} F_\varepsilon(\Gamma) = \min_{\Gamma \in X} \inf_{\varepsilon > 0} F_\varepsilon(\Gamma) = \min_{\Gamma \in X} F(\Gamma). \quad (4.5)$$

Thus, if $\{\Gamma_\varepsilon\}$ is a sequence of minimizers of F_ε we have $F(\Gamma_\varepsilon) \leq F_\varepsilon(\Gamma_\varepsilon)$ so that $\{\Gamma_\varepsilon\}$ is a minimizing sequence for F . Then, by Theorem 2.18, there exists $\Gamma \in X$ and a subsequence (not relabelled) such that $\Gamma_\varepsilon \xrightarrow{\sigma} \Gamma$ as $\varepsilon \rightarrow 0$. As F is lower semicontinuous with respect to the σ convergence, from (4.5), it follows that Γ is a minimizer of F . $\square$

4.3 Finite Element Space

In the following, to ease the notation, we identify $\mathbb{R}^2$ with $\mathbb{C}$ and $\mathbb{S}^1$ with $[0, 1]$ using periodic boundary conditions.

To approximate numerically stationary points of (4.4), we discretize this problem by using finite element approximations of the homotopies, which are piecewise linear along the s variable and piecewise constant along the t variable. This choice of elements is justified by the fact that the evaluation of the energy requires the use of two derivatives along the s variable, and a single derivative along the t variable.

Finite elements curves. A piecewise affine curve with n node is defined as

$$\forall s \in [0, 1], \quad \gamma(s) = \sum_{j=1}^n \tilde{\gamma}_j \xi_j(s)$$

where we used piecewise affine finite elements

$$\begin{aligned} \xi_j(s) &= \max \left\{ 0, 1 - n \left| s - \frac{j}{n} \right| \right\} \quad s \in [0, 1], \quad \forall j = 1, \dots, n-1 \\ \xi_n(s) &= \max \{0, 1 - n |s|\} + \max \{0, 1 - n |s - 1|\}, \quad s \in [0, 1]. \end{aligned}$$

Here, $\tilde{\gamma} \in \mathbb{C}^n$ denotes the coordinates of γ and we denote $\gamma = P_1(\tilde{\gamma})$ the corresponding bijection.

Finite elements homotopies. We consider the finite dimensional space of homotopies of the form

$$\forall (t, s) \in [0, 1]^2, \quad \Gamma(t)(s) = \sum_{i=1}^N \sum_{j=1}^n \tilde{\Gamma}_{i,j} \zeta_i(t) \xi_j(s) \quad (4.6)$$

where we used piecewise constant finite elements

$$\zeta_i(t) = \mathbb{I}_{[\frac{i}{N}, \frac{i+1}{N}]}(t) \quad \forall i = 1, \dots, N-1, \quad \zeta_N(t) = \mathbb{I}_{[0, \frac{1}{N}]}(t),$$

Here, $\tilde{\Gamma} \in \mathbb{C}^{N \times n}$ denotes the coordinates of Γ and we denote $\Gamma = P_{0,1}(\tilde{\Gamma})$ the corresponding bijection.

4.4 Discretized Energies

The initial infinite dimensional optimization problem (4.4) is discretized by restricting the minimization to the finite element space described by (4.6) as follow

$$\min \left\{ \mathcal{F}_\varepsilon(\tilde{\Gamma}) : \tilde{\Gamma} \in \mathbb{C}^{N \times n}, \tilde{\Gamma}_{1,\cdot} = \tilde{\gamma}_0 \right\} \quad \text{where} \quad \mathcal{F}_\varepsilon(\tilde{\Gamma}) = F_\varepsilon(\Gamma) \quad (4.7)$$

where $\Gamma = P_{0,1}(\tilde{\Gamma})$ and where the input boundary curves are $\gamma_0 = P_1(\tilde{\gamma}_0)$, $\gamma_1 = P_1(\tilde{\gamma}_1)$, which are assumed to be piecewise affine finite elements. We have denoted here $\Gamma_{i,\cdot} = (\Gamma_{i,j})_{j=1}^n \in \mathbb{R}^n$.

In order to ease the computation of gradients, we note that the energy $\mathcal{F}_\varepsilon$ can be decomposed as

$$\mathcal{F}_\varepsilon(\tilde{\Gamma}) = H(P_1(\tilde{\Gamma}_{N,\cdot}), \gamma_1) + \mathcal{E}_\varepsilon(\tilde{\Gamma}) \quad \text{where} \quad \mathcal{E}_\varepsilon(\tilde{\Gamma}) = \frac{1}{N-1} \sum_{i=1}^{N-1} J(\tilde{\Gamma}_{i,\cdot}, \tilde{v}_i) \quad (4.8)$$

where we denoted the discrete time derivative vector field as

$$\tilde{v}_i = \frac{\tilde{\Gamma}_{i+1,\cdot} - \tilde{\Gamma}_{i,\cdot}}{N-1} \in \mathbb{C}^n.$$

For $\tilde{\gamma} \in \mathbb{C}^n$ and $\tilde{v} \in \mathbb{C}^n$, we used the notation

$$J(\tilde{\gamma}, \tilde{v}) = \sum_{\ell=0}^2 \lambda_\ell J_\ell(\tilde{\gamma}, \tilde{v}).$$

and we define bellow the explicit computation of the terms $J_\ell(\tilde{\gamma}, \tilde{v})$ for $\ell = 0, 1, 2$.

Zero order energy term ($\ell = 0$). The L^1 norm of a piecewise affine field $v = P_1(\tilde{v})$ tangent to a piecewise affine curve $\gamma = P_1(\tilde{\gamma})$ can be computed as

$$\int_{\mathbb{S}^1} |v(s)|_\varepsilon |\gamma'(s)|_\varepsilon ds = \sum_{i=1}^n n |\Delta^+(\tilde{\gamma})_i|_{\frac{\varepsilon}{n}} \int_{\frac{i}{n}}^{\frac{i+1}{n}} |\tilde{v}_i \xi_i(s) + \tilde{v}_{i+1} \xi_{i+1}(s)|_\varepsilon ds.$$

This quantity cannot be evaluated in closed form. For numerical simplicity, we thus approximate the integral by the trapezoidal rule. With a slight abuse of notation (this is only an approximate equality), we define the discrete L^1 -norm as

$$J_0(\tilde{\gamma}, \tilde{v}) = \frac{1}{2} \sum_{i=1}^n |\Delta^+(\tilde{\gamma})_i|_{\frac{\varepsilon}{n}} \left(|\tilde{v}_i|_\varepsilon + |\tilde{v}_{i+1}|_\varepsilon \right),$$

where we used the following forward finite difference operator

$$\Delta^+ : \mathbb{C}^n \rightarrow \mathbb{C}^n, \quad \Delta^+(\tilde{\gamma})_i = \tilde{\gamma}_{i+1} - \tilde{\gamma}_i.$$

First order energy term ($\ell = 1$). We point out that

$$\frac{dv}{d\gamma} = \sum_{i=1}^n \frac{\Delta^+(\tilde{v})_i}{|\Delta^+(\tilde{\gamma})_i|_{\frac{\varepsilon}{n}}} \zeta_i \quad (4.9)$$

which implies that

$$\int_{\mathbb{S}^1} \left| \frac{dv}{d\gamma(s)} \right|_{\varepsilon} |\gamma'(s)|_{\varepsilon} ds = \sum_{i=1}^n \int_{\frac{i}{n}}^{\frac{i+1}{n}} n |\Delta^+(\tilde{v})_i|_{\frac{\varepsilon}{n}} ds.$$

Then the discretized L^1 -norm of the first derivative is defined by

$$J_1(\tilde{\gamma}, \tilde{v}) = \sum_{i=1}^n |\Delta^+(\tilde{v})_i|_{\frac{\varepsilon}{n}}.$$

Second order energy term ($\ell = 2$). As the first derivative is piecewise constant, the second variation coincides with the sum of the jumps of the first derivative. In fact, for every $g \in C_c^1(\mathbb{S}^1, \mathbb{R}^2)$, we have

$$\begin{aligned} \int_{\mathbb{S}^1} \left\langle \frac{dv}{d\gamma(s)}, \frac{dg}{d\gamma(s)} \right\rangle d\gamma(s) &= \sum_{i=1}^n \int_{\frac{i}{n}}^{\frac{i+1}{n}} \left\langle \frac{dv}{d\gamma(s)}, g'(s) \right\rangle ds = \\ &= \sum_{i=1}^n \left\langle \frac{dv}{d\gamma} \left(\frac{i-1}{n} \right) - \frac{dv}{d\gamma} \left(\frac{i}{n} \right), g \left(\frac{i}{n} \right) \right\rangle. \end{aligned}$$

Then, by (4.9), the second variation $TV_{\gamma}^2(v)$ can be defined as

$$J_2(\tilde{\gamma}, \tilde{v}) = \sum_{i=1}^n \left| \frac{\Delta^+(\tilde{v})_{i+1}}{|\Delta^+(\tilde{\gamma})_{i+1}|_{\frac{\varepsilon}{n}}} - \frac{\Delta^+(\tilde{v})_i}{|\Delta^+(\tilde{\gamma})_i|_{\frac{\varepsilon}{n}}} \right|_{\varepsilon}. \quad (4.10)$$

We point out that J_2 represents a regularized definition of the second total variation because we evaluate the jumps by the smoothed norm $|\cdot|_{\varepsilon}$.

4.5 Minimization with Gradient Descent

The finite problem (4.7) is an unconstrained optimization on the variable $(\tilde{\Gamma}_{2,\cdot}, \dots, \tilde{\Gamma}_{N,\cdot})$, since $\tilde{\Gamma}_{1,\cdot} = \tilde{\gamma}_0$ is fixed. The function $\mathcal{F}_{\varepsilon}$ being minimized is C^1 with a Lipschitz gradient, and we thus make use of a gradient descent method. In the following, we compute gradient for the canonical inner product in $\mathbb{C}^{N \times n}$.

Starting from some $\tilde{\Gamma}^{(0)} \in \mathbb{C}^{N \times n}$, we iterate

$$\tilde{\Gamma}^{(k+1)} = \tilde{\Gamma}^{(k)} - \tau_k \nabla \mathcal{F}_{\varepsilon}(\tilde{\Gamma}^{(k)}) \quad (4.11)$$

where $\tau_k > 0$ is the descent step. A small enough gradient step size (or an adaptive line search strategy) ensures that the iterates converge toward a stationary point $\Gamma^{(\infty)}$ of $\mathcal{F}_{\varepsilon}$.

The gradient $\nabla \mathcal{F}_{\varepsilon}(\tilde{\Gamma})$ is given by its partial derivatives as, for $i = 2, \dots, N-1$,

$$\partial_{\tilde{\Gamma}_i} \mathcal{F}_{\varepsilon}(\tilde{\Gamma}) = \frac{1}{N-1} \left(\partial_1 J(\tilde{\Gamma}_i, \tilde{v}_i) - \frac{1}{N-1} \partial_2 J(\tilde{\Gamma}_{i+1}, \tilde{v}_{i+1}) + \frac{1}{N-1} \partial_2 J(\tilde{\Gamma}_{i-1}, \tilde{v}_{i-1}) \right)$$

where $\partial_1 J$ (resp. $\partial_2 J$) is the derivative of J with respect to the first (resp. second) variable and

$$\partial_{\tilde{\Gamma}_N} \mathcal{F}_\varepsilon = \delta + \frac{1}{(N-1)^2} \partial_1 J(\tilde{\Gamma}_{N-1}, \tilde{v}_{N-1}),$$

where δ is the gradient of the map $\tilde{\gamma} \mapsto H(P_1(\tilde{\gamma}), \gamma_1)$ at $\tilde{\gamma} = \tilde{\Gamma}_{N,\cdot}$. This gradient can be computed as detailed in [14].

4.6 Numerical Results

In this section we show some numerical examples of computations of a stationary points $\tilde{\Gamma}^{(\infty)}$ of the problem (4.7) that is intended to approximate geodesics for the BV^2 metric. We use a similar approach to approximate geodesic for the H^k metric, for $k = 2$, by replacing E in (4.2) by

$$E(\Gamma) = \int_0^1 \|\Gamma_t(t)\|_{H^s(\Gamma(t))} dt \quad (4.12)$$

where, for all $\gamma \in H^s(\mathbb{S}^1, \mathbb{R}^2)$ and $v \in H^s(\gamma)$,

$$\|v\|_{H^s(\gamma)} = \int_{\mathbb{S}^1} \left(\mu_0 |v(s)|^2 + \mu_1 \left| \frac{dv}{d\gamma}(s) \right|^2 + \mu_2 \left| \frac{d^2 v}{d\gamma^2}(s) \right|^2 \right) d\gamma(s),$$

where the parameter $(\mu_0, \mu_1, \mu_2) \in (\mathbb{R}^+)^3$ can be tuned for each particular application. Note that, on contrast to the BV^2 case, this Sobolev energy is a smooth functional, and one thus does not need to perform a regularization (4.3), or equivalently, one can use $\varepsilon = 0$ in this case. We do not detail the computation of the gradient of the discretized version of the functional (4.12), since these computations are very similar to the BV^2 case.

In the following experiments, we use a discretization grid of size $(N, n) = (10, 256)$. The weights are set to $(\lambda_0, \lambda_1, \lambda_2) = (1, 0, 1)$ and $(\mu_0, \mu_1, \mu_2) = (1, 0, 1)$ (the curves are normalized to fit in $[0, 1]^2$). These experiments can be seen as toy models illustrations for the shape registration problem, where one seeks for a meaningful bijection between two geometric curves parameterized by γ_0 and γ_1 . Note that the energies being minimized are highly non-convex, so that the initialization $\Gamma^{(0)}$ of the gradient descent (4.11) plays a crucial role.

Figure 1, top row, shows a simple test case, for which using a trivial constant initialization $\tilde{\Gamma}_i^{(0)} = \tilde{\gamma}_0$, for both BV^2 and H^2 metric, produces a valid homotopy $\Gamma^{(\infty)}$ between γ_0 and γ_1 . One can observe that while both homotopies are similar, the Sobolev metric produces a slightly smoother regular evolution of curves. This is to be expected, since piecewise affine curves are not in the Sobolev space $H^2(\mathbb{S}^1, \mathbb{R}^2)$.

Figure 1, bottom row, shows a more complicated case, where using a trivial initialization $\tilde{\Gamma}^{(0)}$ fails to give a correct result $\tilde{\Gamma}^{(\infty)}$, because the gradient descent is trapped in a poor local minimum. We thus use as initialization the natural bijection $\tilde{\Gamma}^{(0)}$ which is piecewise affine and correctly links the singular points of the curves γ_0 and γ_1 . It turns out that this homotopy is a stationary point of the energy (4.7), which can be checked on the numerical results obtained by the gradient descent. On the contrary, the Sobolev metric finds a slightly different homotopy, which leads to smoother intermediate curves.

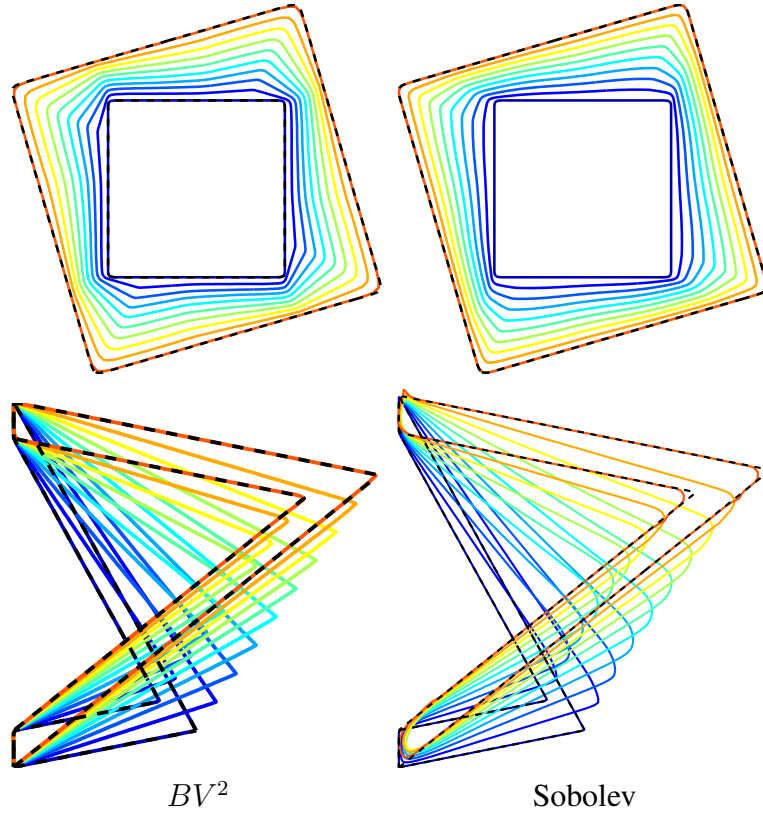


Figure 1: Homotopies $\Gamma^{(\infty)}$ obtained for BV^2 -Finsler energy (left) and Sobolev metric (right). Each image displays the initial curve γ_0 (black one) and γ_1 (dash line) and the optimal $\{\tilde{\Gamma}_{i,\cdot}\}_i$ where the index $1 \leq i \leq N$ is indicated by color variations between blue ($i = 1$) and red ($i = N$).

5 Conclusion

The variational approach defined in this work represents a general strategy to prove existence of minimal geodesics with respect to Finslerian metrics. The uniqueness is at the moment an open question.

In order to generalize previous results to more general Banach spaces, we point out the main properties which must be satisfied by the Banach topology:

- (i) the two constants m_γ, M_γ appearing in Proposition 2.9 must be bounded on geodesic balls;
- (ii) the topology of the space must imply a suitable convergence of the reparameterizations in order to get semi-continuity of the norm of $\{\Gamma_t^h \circ \varphi^h(t)\}_h$; in the BV^2 -case such a topology is the $W^{1,1}$ -strong topology.

For the BV^2 metric, the major difficulty concerns the characterization of the weak topology of the space of the paths. The usual characterization of the dual of Boncher spaces $H^1([0, 1], B)$ (B is a Banach space) requires that the dual of B verifies the Radon-Nikodym property ([10], [12]). We point out that the martingale argument used to prove Theorem 2.15 avoids this problem and allows one to define a suitable topology in such a space guaranteeing the lower semi-continuity of the geodesic energy.

Moreover, as pointed out in the introduction, the necessary conditions proved in [26] are not valid in our case. This represents an interesting direction of research because optimality conditions allow one to study regularity properties of minimal geodesics. It is an open question if the generalized Euler-Lagrange equations in [26] can be generalized to our case and give the Hamiltonian geodesic equations. Strongly linked to this question is the issue of convergence of the numerical method. Indeed, the convergence of the sequence of discretized problems would imply the existence of geodesic equations.

From a numerical point of view, as we pointed out, the minimal geodesic energy suffers from many poor local minima. To avoid some of these poor local minima, it is possible to modify the metric to take into account some prior on the set of deformations. For instance, in the spirit of [14], a Finsler metric can be designed to favor piecewise rigid motions.

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