# A Gradient-Descent Method for Curve Fitting on Riemannian Manifolds* 

Chafik Samir ${ }^{\dagger}$ P.-A. Absil ${ }^{\dagger}$ Anuj Srivastava ${ }^{\ddagger}$ Eric Klassen ${ }^{\S}$


#### Abstract

Given data points $p_{0}, \ldots, p_{N}$ on a closed submanifold $M$ of $\mathbb{R}^{n}$ and time instants $0=t_{0}<$ $t_{1}<\ldots<t_{N}=1$, we consider the problem of finding a curve $\gamma$ on $M$ that best approximates the data points at the given instants while being as "regular" as possible. Specifically, $\gamma$ is expressed as the curve that minimizes the weighted sum of a sum-of-squares term penalizing the lack of fitting to the data points and a regularity term defined, in the first case as the mean squared velocity of the curve, and in the second case as the mean squared acceleration of the curve. In both cases, the optimization task is carried out by means of a steepest-descent algorithm on a set of curves on $M$. The steepest-descent direction, defined in the sense of the first-order and second-order Palais metric, respectively, is shown to admit analytical expressions involving parallel transport and covariant integral along curves. Illustrations are given in $\mathbb{R}^{n}$ and on the unit sphere.


Keywords: curve fitting, steepest-descent, Sobolev space, Palais metric, geodesic distance, energy minimization, splines, piecewise geodesic, smoothing, Riemannian center of mass.

## 1 Introduction

We are interested in the problem of fitting smooth curves to given finite sets of points on Riemannian manifolds. Let $p_{0}, p_{1}, \ldots, p_{N}$ be a finite set of points on a Riemannian manifold $M$, and let $0=t_{0}<t_{1}<\ldots<t_{N}=1$ be distinct and ordered instants of time. The problem of fitting a smooth curve $\gamma$ on $M$ to the given points at the given times involves two goals of conflicting nature. The first goal is that the curve should fit the data as well as possible, as measured, e.g., by the real-valued function $E_{\mathrm{d}}$ defined by:

$$
\begin{equation*}
E_{\mathrm{d}}(\gamma)=\sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right) \tag{1}
\end{equation*}
$$

where $d$ denotes the distance function on the Riemannian manifold $M$. The second goal is that the curve should be sufficiently "regular", as measured by a function $\gamma \mapsto E_{\mathrm{s}}(\gamma)$ such as (2) or (3) below. We are thus facing an optimization problem with two objective functions-a fitting function $E_{\mathrm{d}}$ and a regularity function $E_{\mathrm{s}}$-whose domain is a suitable set of curves on the Riemannian manifold $M$.

Curve fitting problems on manifolds appear in various applications. To cite but one example, let $\left(I_{i}\right)_{i \leq N}$ be a temporal sequence of images of a 2 D or 3 D object motion, in which the object can appear and disappear at arbitrary times due to obscuration and other reasons. The task is to

[^0]estimate the missing data and recover the motion of the object as well as possible. It is clear that focussing on the first goal (fitting the data) without concern for the second goal (regularity of the curve) would yield poor motion recovery, and that the result is likely to be improved if inherent regularity properties of the object motion are taken into account. The features of interest in such tracking problems are often represented as elements of nonlinear manifolds. An important feature in object tracking and recognition is the shape formed by its silhouette in an image.

### 1.1 Previous work

One possible way of tackling an optimization problem with two objective functions is to turn it into a classical optimization problem where one of the objective functions becomes the objective function and the other objective function is turned into a constraint.

Let us first discuss the case where the fitting objective function $E_{\mathrm{d}}$ is minimized under a regularity constraint. When $M=\mathbb{R}^{n}$, a classical regularity constraint is to restrict the curve $\gamma$ to the family of polynomial functions of degree not exceeding $m,(m \leq N)$. This least-squares problem cannot be straightforwardly generalized to an arbitrary Riemannian manifold $M$ because the notion of polynomial does not carry to $M$ in an obvious way. An exception is the case $m=1$; the polynomial functions in $\mathbb{R}^{n}$ are then straight lines, whose natural generalization on Riemannian manifolds are geodesics. The problem of fitting a geodesic to data on Riemannian manifold $M$ was considered in MS06 for the case where $M$ is the special orthogonal group $\mathrm{SO}(n)$ or the unit sphere $\mathbb{S}^{n}$.

The other case is when a regularity criterion $E_{\mathrm{s}}$ is optimized under a constraint on $E_{\mathrm{d}}$, in which case it is natural to impose the interpolation constraint $E_{\mathrm{d}}(\gamma)=0$. For example, when $M=\mathbb{R}^{n}$, minimizing the function $E_{\mathrm{s}}$ defined by

$$
\begin{equation*}
E_{\mathrm{s}, 1}(\gamma)=\frac{1}{2} \int_{0}^{1}\|\dot{\gamma}(t)\|^{2} \mathrm{~d} t \tag{2}
\end{equation*}
$$

yields the piecewise-linear interpolant for the given data points and time instants (this follows from Mil63, p. 70]), while minimizing

$$
E_{\mathrm{s}, 2}(\gamma)=\frac{1}{2} \int_{0}^{1}\|\ddot{\gamma}(t)\|^{2} \mathrm{~d} t
$$

yields solutions known as cubic splines. (From now on, we will frequently omit the variable $t$ in the integrand when it is clear from the context.) For the case where $M$ is a nonlinear manifold, several results on interpolation can be found in the literature. Spherical smoothing splines on the two dimensional unit sphere were originally studied by Jupp and Kent JK87. The generalization of cubic splines to more general Riemannian manifolds was pioneered by Noakes et al. [NHP89]. Cubic splines are then defined as curves that minimize the function

$$
\begin{equation*}
E_{\mathrm{s}, 2}(\gamma)=\frac{1}{2} \int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}\right\rangle_{\gamma(t)} \mathrm{d} t \tag{3}
\end{equation*}
$$

where $\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}$ denotes the (Levi-Civita) second covariant derivative of $\gamma$ and $\langle\cdot, \cdot\rangle_{p}$ stands for the Riemannian metric on $M$ at $p$. (The subscript may be omitted if there is no risk of confusion.) A necessary condition for optimality takes the form of a fourth-order differential equation. This variational approach was followed by other authors, including Crouch and Silva Leite CS91, CS95. Splines of class $C^{k}$ were generalized to Riemannian manifolds by Camarinha et al. [CSC95. Still in the context of interpolation on manifolds, but without a variational interpretation, we mention the literature on splines based on generalized Bézier curves, defined by a generalization to manifolds of the de Casteljau algorithm; see CKS99, Alt00, PN07. Recently, Jakubiak et al. JSR06] presented a geometric two-step algorithm to generate splines of an arbitrary degree of smoothness in Euclidean spaces, then extended the algorithm to matrix Lie groups and applied it to generate smooth motions of 3D objects. Another approach to interpolation on manifolds consists of mapping
the data points onto the affine tangent space at a particular point of $M$, then computing an interpolating curve in the tangent space, and finally mapping the resulting curve back to the manifold. The mapping can be defined, e.g., by a rolling procedure, see HS07, KDL07.

Another way of tackling an optimization problem with two objective functions is to optimize a weighted sum of the objective functions. In the context of curve fitting on manifolds, this approach was followed by Machado et al. MSH06] using the first-order smoothing term (2) and by Machado and Silva Leite MS06] for the second-order smoothing term (3).

Specifically, in MSH06, the objective function is defined to be

$$
E_{1} \equiv \frac{1}{2} \sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)+\frac{\lambda}{2} \int_{0}^{1}\langle\dot{\gamma}, \dot{\gamma}\rangle \mathrm{d} t
$$

over the class of all piecewise smooth curves $\gamma:[0,1] \rightarrow M$, where $\lambda(>0)$ is a smoothing parameter. Solutions to this variational problem are piecewise geodesics that best fit the given data. As shown in MSH06, when $\lambda$ goes to $+\infty$, the optimal curve converges to a single point which is shown in MLK10 to be the Riemannian mean of the data points. When $\lambda$ goes to zero, the optimal curve goes to a broken geodesic on $M$ interpolating the data points.

In MS06, the objective function is defined to be

$$
E_{2} \equiv \frac{1}{2} \sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)+\frac{\lambda}{2} \int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}\right\rangle \mathrm{d} t
$$

over a certain set of admissible $C^{2}$ curves. The authors give a necessary condition of optimality that takes the form of a fourth-order differential equation involving the covariant derivative and the curvature tensor along with certain regularity conditions at the time instants $t_{i}, i=0, \ldots, N$ MS06, Th. 4.4]. The optimal curves are approximating cubic splines: they are approximating because in general $\gamma\left(t_{i}\right)$ differs from $p_{i}$, and they are cubic splines because they are obtained by smoothly piecing together segments of cubic polynomials on $M$, where "cubic polynomial on $M$ " is understood in the sense of Noakes et al. [NHP89. It is also shown in [MS06, Prop. 4.5] that, as the smoothing parameter $\lambda$ goes to $+\infty$, the optimal curves converge to a geodesic curve on $M$ fitting the given data points at the given instants of time. When $\lambda$ goes to zero, the approximating cubic spline converges to an interpolating cubic spline MS06, Prop. 4.6].

### 1.2 Our approach

In this paper, rather than trying to solve directly the fourth-order differential equation obtained in MS06 (a feat that is not attempted there, except for $M=\mathbb{R}^{n}$ ), we propose to search for an optimizer of the objective function using a steepest-descent method in an adequate set of curves on the Riemannian manifold $M$. In this section, we present the essence of our approach, and delay the mathematical technicalities until Section 2.

As in MS06, we consider the problem of minimizing the objective function

$$
\begin{align*}
E_{2}: \Gamma_{2} \rightarrow \mathbb{R}: \gamma \mapsto E_{2}(\gamma) & =E_{\mathrm{d}}(\gamma)+\lambda E_{\mathrm{s}, 2}(\gamma) \\
& =\frac{1}{2} \sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)+\frac{\lambda}{2} \int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}\right\rangle \mathrm{d} t \tag{4}
\end{align*}
$$

where $\Gamma_{2}$ is an adequate set of curves on $M$ to be defined in Section 2. The steepest-descent direction for $E_{2}$ is defined with respect to the second-order Palais metric defined by

$$
\begin{equation*}
\langle\langle v, w\rangle\rangle_{2, \gamma}=\langle v(0), w(0)\rangle_{\gamma(0)}+\left\langle\frac{\mathrm{D} v}{\mathrm{~d} t}(0), \frac{\mathrm{D} w}{\mathrm{~d} t}(0)\right\rangle_{\gamma(0)}+\int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} v}{\mathrm{~d} t^{2}}, \frac{\mathrm{D}^{2} w}{\mathrm{~d} t^{2}}\right\rangle_{\gamma(t)} \mathrm{d} t \tag{5}
\end{equation*}
$$

where $v$ and $w$ are tangent vector fields along $\gamma$. We assume that $M$ is a closed Riemannian submanifold of $\mathbb{R}^{n}$-a mild condition in virtue of Nash's isometric embedding theorem-since the
required theory on the Palais metric is only available in this case Tro77, Prop. 6.1]. Consequently, the Levi-Civita covariant derivative $\frac{\mathrm{D}}{\mathrm{d} t}$ along $\gamma$ reduces to the classical derivative in $\mathbb{R}^{n}$ followed by the orthogonal projection onto the tangent space to $M$ at $\gamma(t)$; see, e.g., Boo03, §VII.2].

As we shall see in Section 4, the choice of the second-order Palais metric (5) ensures that the gradient of $E_{2}$ at $\gamma$, represented by a vector field $G$ along $\gamma$, admits an analytical expression involving parallel transport and covariant integral along $\gamma$. This expression makes it possible to implement a steepest-descent algorithm on $\Gamma_{2}$, where the next iterate is obtained from the current iterate $\gamma$ using a line-search procedure along the path $\tau \mapsto \gamma^{\tau}$ on $\Gamma_{2}$ defined by

$$
\gamma^{\tau}(t)=\exp _{\gamma(t)}(-\tau G(t))
$$

see Section 5. We use an Armijo backtracking procedure, but other stepsize selection methods would be suitable.

We also present a gradient-descent approach for the objective function of MSH06, namely

$$
\begin{align*}
E_{1}: \Gamma_{1} \rightarrow \mathbb{R}: \gamma \mapsto E_{1}(\gamma) & =E_{\mathrm{d}}(\gamma)+\lambda E_{\mathrm{s}, 1}(\gamma) \\
& =\frac{1}{2} \sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)+\frac{\lambda}{2} \int_{0}^{1}\langle\dot{\gamma}, \dot{\gamma}\rangle \mathrm{d} t \tag{6}
\end{align*}
$$

where $\Gamma_{1}$ is another adequate set of curves on $M$ defined in Section 2 For $E_{1}$, the steepest-descent direction is considered with respect to the first-order Palais metric defined by

$$
\begin{equation*}
\langle\langle v, w\rangle\rangle_{1, \gamma}=\langle v(0), w(0)\rangle_{\gamma(0)}+\int_{0}^{1}\left\langle\frac{\mathrm{D} v}{\mathrm{~d} t}, \frac{\mathrm{D} w}{\mathrm{~d} t}\right\rangle_{\gamma(t)} \mathrm{d} t \tag{7}
\end{equation*}
$$

where $v$ and $w$ are tangent vector fields along $\gamma$.
This choice confers a simple expression to the gradient; see Section 3
Observe that the parameter $\lambda$ makes it possible to balance between the two conflicting goals mentioned above: when $\lambda$ is large, a higher emphasis is on the regularity condition relative to the fitting condition, whereas when $\lambda$ is small, the fitting condition dominates.

The rest of the paper is organized as follows. Section 2 deals with the choice of the curve spaces $\Gamma_{1}$ and $\Gamma_{2}$. An expression for the gradient of $E_{1}$, resp. $E_{2}$, is given in Section 3 resp. 4 The steepest-descent method is presented in Section 5. Numerical illustrations are given in Section 6 for $M=\mathbb{R}^{2}$ and $M=\mathbb{S}^{2}$. Section 7 contains final remarks.

## 2 Preliminaries

In this section, we exploit results of Palais [Pal63, §13] and Tromba Tro77, §6] to define the domain $\Gamma$ of the objective function $E$ in such a way that the gradient of $E$ with respect to the Palais metric is guaranteed to exist and be unique.

### 2.1 First-order case

We first consider the objective function $E_{1}$ defined in (6). Let $I$ denote the unit interval $[0,1]$ and let $H^{0}\left(I, \mathbb{R}^{n}\right)$ denote the set of square integrable functions from $I$ to $\mathbb{R}^{n}$. The set $H^{0}\left(I, \mathbb{R}^{n}\right)$ is a Hilbert space under pointwise operations and with the inner product $\langle\langle\cdot, \cdot\rangle\rangle_{0}$ defined by

$$
\langle\langle v, w\rangle\rangle_{0}=\int_{0}^{1}\langle v(t), w(t)\rangle \mathrm{d} t
$$

where $\langle\cdot, \cdot\rangle$ is the standard inner product in $\mathbb{R}^{n}$. Let $H^{1}\left(I, \mathbb{R}^{n}\right)$ denote the set of absolutely continuous maps $\gamma: I \rightarrow \mathbb{R}^{n}$ such that $\dot{\gamma} \in H^{0}\left(I, \mathbb{R}^{n}\right)$. Note that absolute continuity is equivalent to requiring that $\dot{\gamma}(t)$ exists for almost all $t \in I$, that $\dot{\gamma}$ is summable, and that

$$
\gamma(t)=\gamma(0)+\int_{0}^{t} \dot{\gamma}(s) \mathrm{d} s
$$

Then $H^{1}\left(I, \mathbb{R}^{n}\right)$ is a Hilbert space under the inner product $\langle\langle\cdot, \cdot\rangle\rangle_{1}$ defined by

$$
\begin{equation*}
\langle\langle v, w\rangle\rangle_{1}=\langle v(0), w(0)\rangle+\int_{0}^{1}\langle\dot{v}(t), \dot{w}(t)\rangle \mathrm{d} t \tag{8}
\end{equation*}
$$

This inner product belongs to a class of Riemannian structures proposed by Linnér Lin03 §3].
Let $M$ be a closed $C^{k+4}$-submanifold of $\mathbb{R}^{n}(k \geq 1)$. Define $H^{1}(I, M)$ to be the set of all $\gamma \in H^{1}\left(I, \mathbb{R}^{n}\right)$ such that $\gamma(I) \subseteq M$. Then $H^{1}(I, M)$ is a closed $C^{k}$-submanifold of the Hilbert space $H^{1}\left(I, \mathbb{R}^{n}\right)$. We set

$$
\begin{equation*}
\Gamma_{1}=H^{1}(I, M) \tag{9}
\end{equation*}
$$

which ensures that $E_{1}$ (6) is a well defined $C^{k}$ map around each $\gamma \in \Gamma_{1}$ such that, for all $i, p_{i}$ is in the image of the domain of injectivity of the exponential mapping at $\gamma\left(t_{i}\right)$ (see Lazard and Tits [LT66] for the case where the manifold is a Lie group).

The tangent space to $H^{1}(I, M)$ at a curve $\gamma \in H^{1}(I, M)$ is given by

$$
T_{\gamma} H^{1}(I, M)=\left\{v \in H^{1}(I, T M): v(t) \in T_{\gamma(t)} M \text { for all } t \in I\right\}
$$

where $T M$ denotes the tangent bundle of $M$. Moreover, $H^{1}(I, M)$ is a complete $C^{k}$-Riemannian manifold in the Riemannian structure induced on it as a closed $C^{k}$-submanifold of $H^{1}\left(I, \mathbb{R}^{n}\right)$.

Note that the induced Riemannian structure on $H^{1}(I, M)$ induced by (8) is the "extrinsic" structure given by

$$
\langle v(0), w(0)\rangle+\int_{0}^{1}\langle\dot{v}(t), \dot{w}(t)\rangle \mathrm{d} t
$$

where $\dot{v}$ and $\dot{w}$ are the derivatives in the sense of the embedding space $\mathbb{R}^{n}$. It thus differs from the "intrinsic" first-order Palais metric defined in (77). However, the extrinsic and intrinsic Riemannian structures are equivalent on bounded sets Tro77, Prop. 6.1].

From this, it follows that, given $\gamma \in H^{1}(I, M)$, the tangent space $T_{\gamma} H^{1}(I, M)$ endowed with the inner product (7) is a Hilbert space. The gradient of $E_{1}$ at $\gamma$ is defined to be the unique $G_{\gamma} \in T_{\gamma} H^{1}(I, M)$ that satisfies, for all $w \in T_{\gamma} H^{1}(I, M)$,

$$
\left\langle\left\langle G_{\gamma}, w\right\rangle\right\rangle_{1, \gamma}=\mathrm{D} E_{1}(\gamma)[w]
$$

where $\mathrm{D} E_{1}(\gamma)[w]$ denotes the derivative of $E_{1}$ at $\gamma$ along $w$. The existence and uniqueness of $G$ are guaranteed by the Riesz representation theorem. We will use the notation $\nabla E(\gamma)$ for the gradient of a function $E$ at $\gamma$, or simply $G_{\gamma}$ when $E$ and $\gamma$ are clear from the context.

### 2.2 Second-order case

We now turn to the objective function $E_{2}$ defined in (4). Let $H^{2}\left(I, \mathbb{R}^{n}\right)$ be the set of maps $\gamma: I \rightarrow \mathbb{R}^{n}$ with $\gamma \in H^{1}\left(I, \mathbb{R}^{n}\right)$ and $\dot{\gamma} \in H^{1}\left(I, \mathbb{R}^{n}\right)$. Then $H^{2}\left(I, \mathbb{R}^{n}\right)$ is a vector space under pointwise operations, and the map

$$
\Phi: \mathbb{R}^{n} \times \mathbb{R}^{n} \times H^{0}\left(I, \mathbb{R}^{n}\right) \rightarrow H^{2}\left(I, \mathbb{R}^{n}\right):\left(\gamma_{0}, \dot{\gamma}_{0}, h\right) \mapsto \gamma
$$

defined by $\gamma(0)=\gamma_{0}, \dot{\gamma}(0)=\dot{\gamma}_{0}, \ddot{\gamma}(t)=h(t)$ for all $t \in I$, is an isomorphism. In $H^{2}\left(I, \mathbb{R}^{n}\right)$, consider the inner product $\langle\langle\cdot, \cdot\rangle\rangle$ defined by

$$
\langle\langle v, w\rangle\rangle_{2}=\langle v(0), w(0)\rangle+\langle\dot{v}(0), \dot{w}(0)\rangle+\int_{0}^{1}\langle\ddot{v}(t), \ddot{w}(t)\rangle \mathrm{d} t .
$$

Then $\Phi$ is an isometry and $H^{2}\left(I, \mathbb{R}^{n}\right)$ is a Hilbert space.
Let $M$ be a closed $C^{k+4}$-submanifold of $\mathbb{R}^{n}(k \geq 1)$. Define $H^{2}(I, M)$ to be the set of all $\gamma \in H^{2}\left(I, \mathbb{R}^{n}\right)$ such that $\gamma(I) \subseteq M$. Then, by restricting the proof of Pal63, Th. 6.6] to $H^{2}$, one obtains that $H^{2}(I, M)$ is a closed $C^{k}$-submanifold of the Hilbert space $H^{2}\left(I, \mathbb{R}^{n}\right)$. We set

$$
\begin{equation*}
\Gamma_{2}=H^{2}(I, M) \tag{10}
\end{equation*}
$$

which ensures that $E_{2}$ is well defined. The tangent space to $H^{2}(I, M)$ at a curve $\gamma \in H^{2}(I, M)$ is given by

$$
T_{\gamma} H^{2}(I, M)=\left\{v \in H^{2}(I, T M): v(t) \in T_{\gamma(t)} M \text { for all } t \in I\right\}
$$

Given $\gamma \in H^{2}(I, M)$, consider the mapping

$$
\Phi: T_{\gamma(0)} M \times T_{\gamma(0)} M \times H^{0}\left(I, T_{\gamma(0)} M\right) \rightarrow T_{\gamma} H^{2}(I, M)
$$

that maps $\left(v_{0}, \dot{v}_{0}, g\right)$ to the vector field $v$ along $\gamma$ defined by

$$
v(0)=v_{0}, \quad \frac{\mathrm{D} v}{\mathrm{~d} t}(0)=\dot{v}_{0}, \quad \frac{\mathrm{D}^{2} v}{\mathrm{~d} t^{2}}(t)=P_{\gamma}^{t \leftarrow 0} g(t),
$$

where $P_{\gamma}^{t \leftarrow 0}$ is the parallel transport along $\gamma$. Recall that the parallel transport is an isometry. The map $\Phi$ is an isomorphism of vector spaces between its domain and image, and it is an isometry with the obvious metric on the domain and the second-order Palais metric (5) on the image. Since the domain of $\Phi$ is a Hilbert space, its image is also a Hilbert space endowed with the inner product (5). Hence the Riesz representation theorem applies.

## 3 Gradient of $E_{1}$ in the first-order Palais metric

We derive an expression for the gradient of $E_{1}=E_{\mathrm{d}}+\lambda E_{\mathrm{s}, 1}$ (6) over $\Gamma_{1}$ (9) endowed with the first-order Palais metric (17). The gradient evaluated at a curve $\gamma$ involves the operations of parallel transport and covariant integral along $\gamma$.

### 3.1 Derivative of $E_{\mathrm{d}}$

We first give an expression for the derivative of the $i^{\text {th }}$ term in $E_{\mathrm{d}}$, namely,

$$
f_{i}: \Gamma_{1} \rightarrow \mathbb{R}: \gamma \mapsto \frac{1}{2} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)
$$

Let $\exp _{p}$ denote the Riemannian exponential map at $p \in M$; see, e.g., Boo03, dC92. Since $M$ is a closed Riemannian submanifold of $\mathbb{R}^{n}$, it follows that $M$ is complete (see [Pal63, p. 326]), which means that $\exp _{p} \xi$ exists for all $\xi \in T_{p} M$. If $q \in M$ is not in the cut locus of $p$, then there exists a unique minimizing geodesic $\alpha_{p q}$ with $\alpha_{p q}(0)=p$ and $\alpha_{p q}(1)=q$ (see dC92, corollary 13.2.8]), and we define $\exp _{p}^{-1}(q)=\dot{\alpha}_{p q}(0)$. Note that in this case, it also holds that $p$ is not in the cut locus of $q$ (see dC92, corollary 13.2.7]), and we have $\exp _{q}^{-1}(p)=-\dot{\alpha}_{p q}(1)$. An expression for the derivative of $f_{i}$ is readily obtained from the following result. A proof is given in Section A.

Theorem 3.1 (Karcher, 1977). Let $M$ be a complete Riemannian manifold, let $p$ be a point of $M$ and let $q$ be a point of $M$ that is not in the cut locus of $p$. Then the squared distance function to $p$ is differentiable at $q$ and we have, for all $\xi \in T_{q} M$,

$$
\frac{1}{2} \mathrm{D} d^{2}(p, \cdot)(q)[\xi]=\left\langle\xi,-\exp _{q}^{-1} p\right\rangle
$$

In view of this result, we have that the derivative of $f_{i}$ at $\gamma$ along $w \in T_{\gamma}\left(\Gamma_{1}\right)$ is

$$
\begin{equation*}
\mathrm{D} f_{i}(\gamma)[w]=\left\langle w\left(t_{i}\right), v_{i}\right\rangle \tag{11}
\end{equation*}
$$

where

$$
v_{i}=-\exp _{\gamma\left(t_{i}\right)}\left(p_{i}\right)
$$

provided that $\gamma\left(t_{i}\right)$ is not in the cut locus of $p_{i}$. This is a mild condition, since the cut locus has measure zero GHL04 lemma 3.96]. Finally, the derivative of $E_{\mathrm{d}}$ is given by

$$
\mathrm{D} E_{\mathrm{d}}(\gamma)[w]=\sum_{i=0}^{N}\left\langle w\left(t_{i}\right), v_{i}\right\rangle
$$

### 3.2 Gradient of $E_{\mathrm{d}}$

The gradient of $f_{i}$ at $\gamma$, with respect to the first-order Palais metric (7), is the unique element $g_{i}$ of $T_{\gamma} \Gamma_{1}$ such that, for all $w \in T_{\gamma} \Gamma_{1}$,

$$
\begin{equation*}
\left\langle\left\langle g_{i}, w\right\rangle\right\rangle_{1}=\mathrm{D} f_{i}(\gamma)[w] . \tag{12}
\end{equation*}
$$

The next theorem gives an expression for $g_{i}$.
Theorem 3.2. The gradient of the function $f_{i}: \Gamma_{1} \rightarrow \mathbb{R}: \gamma \mapsto \frac{1}{2} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)$ evaluated at $\gamma \in \Gamma_{1}$ is the vector field $g_{i}$ along $\gamma$ defined by

$$
g_{i}(t)=\left\{\begin{array}{cc}
(1+t) \tilde{v}_{i}(t), & 0 \leq t \leq t_{i} \\
\left(1+t_{i}\right) \tilde{v}_{i}(t), & t_{i} \leq t \leq 1
\end{array}\right.
$$

where $v_{i}=-\exp _{\gamma\left(t_{i}\right)}^{-1}\left(p_{i}\right) \in T_{\gamma\left(t_{i}\right)} M$ and $\tilde{v}_{i}$ is the parallel transport of $v_{i}$ along $\gamma$.
Proof. In view of (7), (11), and (12), $g_{i}$ is the unique element of $T_{\gamma} \Gamma_{1}$ (vector field along $\gamma$ ) that satisfies

$$
\begin{equation*}
\left\langle g_{i}(0), w(0)\right\rangle+\int_{0}^{1}\left\langle\frac{\mathrm{D} g_{i}}{\mathrm{~d} t}(t), \frac{\mathrm{D} w}{\mathrm{~d} t}(t)\right\rangle \mathrm{d} t=\left\langle v_{i}, w\left(t_{i}\right)\right\rangle \tag{13}
\end{equation*}
$$

for all $w \in T_{\gamma} \Gamma_{1}$. Let $\tilde{v}_{i}$ denote the parallel transport of $v_{i}$ along $\gamma$, and observe that $\tilde{v}_{i}\left(t_{i}\right)=v_{i}$. We have

$$
\left\langle v_{i}, w\left(t_{i}\right)\right\rangle=\left\langle\tilde{v}_{i}(0), w(0)\right\rangle+\int_{0}^{t_{i}} \frac{\mathrm{~d}}{\mathrm{~d} t}\left\langle\tilde{v}_{i}(t), w(t)\right\rangle \mathrm{d} t
$$

since $t \mapsto\left\langle\tilde{v}_{i}(t), w(t)\right\rangle$ is absolutely continuous,

$$
=\left\langle\tilde{v}_{i}(0), w(0)\right\rangle+\int_{0}^{t_{i}}\left\langle\frac{\mathrm{D} \tilde{v}_{i}}{\mathrm{~d} t}(t), w(t)\right\rangle+\left\langle\tilde{v}_{i}(t), \frac{\mathrm{D} w}{\mathrm{~d} t}(t)\right\rangle \mathrm{d} t
$$

by a defining property of the Levi-Civita covariant derivative,

$$
=\left\langle\tilde{v}_{i}(0), w(0)\right\rangle+\int_{0}^{t_{i}}\left\langle\tilde{v}_{i}(t), \frac{\mathrm{D} w}{\mathrm{~d} t}(t)\right\rangle \mathrm{d} t
$$

since $\frac{\mathrm{D}}{\mathrm{d} t} \tilde{v}_{i}=0$ by definition of parallel transport. It follows that $g_{i}$ satisfies

$$
\begin{aligned}
g_{i}(0) & =\tilde{v}_{i}(0) \\
\frac{\mathrm{D} g_{i}}{\mathrm{~d} t}(t) & = \begin{cases}\tilde{v}_{i}(t), & 0<t<t_{i} \\
0, & t_{i}<t<1\end{cases}
\end{aligned}
$$

The solution is given by

$$
g_{i}(t)= \begin{cases}(1+t) \tilde{v}_{i}(t), & 0 \leq t \leq t_{i}  \tag{14}\\ \left(1+t_{i}\right) \tilde{v}_{i}(t), & t_{i} \leq t \leq 1\end{cases}
$$

Observe that $g_{i}$ is covariantly linear from 0 to $t_{i}$, and is covariantly constant from $t_{i}$ to 1 . In other words, the covariant derivative of $g_{i}$ is covariantly constant $\left(\tilde{v}_{i}\right)$ until $t_{i}$, and it is 0 after that. Note also that $\tilde{v}_{i}\left(t_{i}\right)=v_{i}$.

Once we have the gradient for each of the terms in $E_{\mathrm{d}}$, the gradient of $E_{\mathrm{d}}$, under the first-order Palais metric, is simply their sum

$$
\begin{equation*}
G_{1}=\sum_{i=0}^{N} g_{i} \tag{15}
\end{equation*}
$$

### 3.3 Derivative of $E_{\mathrm{s}, 1}$

The derivative and gradient of $E_{\mathrm{s}, 1}$ (2) can be readily deduced, e.g., from Tro77, §6] or [KS06, Th. 1]. We give a full development here for convenience.

Recall that

$$
E_{\mathrm{s}, 1}(\gamma)=\frac{1}{2} \int_{0}^{1}\langle\dot{\gamma}(t), \dot{\gamma}(t)\rangle \mathrm{d} t
$$

Define a variation of $\gamma$ to be a smooth function $h:[0,1] \times(-\epsilon, \epsilon) \rightarrow M$ such that $h(t, 0)=\gamma(t)$ for all $t \in[0,1]$. The variational vector field corresponding to $h$ is given by $w(t)=h_{s}(t, 0)$ where $s$ denotes the second argument in $h$. Thinking of $h$ as a path of curves in $M$, we define $F(s)$ as the energy of the curve obtained by restricting $h$ to $[0,1] \times\{s\}$. That is,

$$
F(s)=\frac{1}{2} \int_{0}^{1}\left\langle h_{t}(t, s), h_{t}(t, s)\right\rangle d t
$$

We now compute,

$$
F^{\prime}(0)=\int_{0}^{1}\left\langle\frac{\mathrm{D} h_{t}}{\mathrm{~d} s}(t, 0), h_{t}(t, 0)\right\rangle \mathrm{d} t=\int_{0}^{1}\left\langle\frac{\mathrm{D} h_{s}}{\mathrm{~d} t}(t, 0), h_{t}(t, 0)\right\rangle \mathrm{d} t=\int_{0}^{1}\left\langle\frac{\mathrm{D} w}{\mathrm{~d} t}(t), \dot{\gamma}(t)\right\rangle \mathrm{d} t
$$

since $h_{t}(t, 0)$ is simply $\dot{\gamma}(t)$. Hence the derivative of $E_{\mathrm{s}, 1}$ at $\gamma$ along $w$ is given by

$$
\begin{equation*}
\mathrm{D} E_{\mathrm{s}, 1}(\gamma)[w]=\int_{0}^{1}\left\langle\frac{\mathrm{D} w}{\mathrm{~d} t}(t), \dot{\gamma}(t)\right\rangle \mathrm{d} t \tag{16}
\end{equation*}
$$

### 3.4 Gradient of $E_{\mathrm{s}, 1}$

In view of the above expression for the derivative of $E_{\mathrm{s}, 1}$, we have the following expression for gradient of $E_{\mathrm{s}, 1}$.
Theorem 3.3. The vector field $H_{1}$ along $\gamma$ that provides the gradient of the function $E_{\mathrm{s}, 1}$ (2) on $\Gamma_{1}$ (9) with respect to the first-order Palais metric (7) satisfies the equation:

$$
\begin{equation*}
\frac{\mathrm{D} H_{1}}{\mathrm{~d} t}(t)=\dot{\gamma}(t), \quad H_{1}(0)=0 \tag{17}
\end{equation*}
$$

Proof. In view of (16), $H_{1}$ is the unique vector field along $\gamma$ that satisfies

$$
\left\langle w(0), H_{1}(0)\right\rangle+\int_{0}^{1}\left\langle\frac{\mathrm{D} w}{\mathrm{~d} t}(t), \frac{\mathrm{D} H_{1}}{\mathrm{~d} t}(t)\right\rangle d t=\int_{0}^{1}\left\langle\frac{\mathrm{D} w}{\mathrm{~d} t}(t), \dot{\gamma}(t)\right\rangle \mathrm{d} t
$$

for all $w \in T_{\gamma} \Gamma_{1}$. The result follows.
In the case $M=\mathbb{R}^{n}$, the gradient vector field is simply $H_{1}(t)=\gamma(t)-\gamma(0)$.

### 3.5 Gradient of $E_{1}$

Since $E_{1}=E_{\mathrm{d}}+\lambda E_{\mathrm{s}, 1}$, the gradient of $E_{1}$ follows directly from the gradients of $E_{\mathrm{d}}$ and $E_{\mathrm{s}, 1}$ computed above. We thus have that $\nabla E_{1}=G_{1}+\lambda H_{1}$, with $G_{1}$ given by (15) and $H_{1}$ given by (17).

## 4 Gradient of $E_{2}$ in the second-order Palais metric

Recall that $E_{2}=E_{\mathrm{d}}+\lambda E_{\mathrm{s}, 2}$ is defined on $\Gamma_{2}$ (10) by

$$
\begin{equation*}
E_{2}(\gamma)=\frac{1}{2} \sum_{i=0}^{N} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)+\frac{\lambda}{2} \int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}\right\rangle \mathrm{d} t \tag{18}
\end{equation*}
$$

The purpose of this section is to obtain an expression for the gradient of $E_{2}$ with respect to the second-order Palais metric (5).

### 4.1 Gradient of $E_{\mathrm{d}}$

The derivative does not depend on the metric, in contrast to the gradient. Thus we have, as in Section 3

$$
\mathrm{D} f_{i}(\gamma)[w]=\left\langle w\left(t_{i}\right), v_{i}\right\rangle
$$

where $f_{i}$ denotes the function $\gamma \mapsto \frac{1}{2} d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)$ and $v_{i}=-\exp _{\gamma\left(t_{i}\right)}^{-1}\left(p_{i}\right)$.
Theorem 4.1. The gradient of the function $f_{i}: \Gamma_{2} \rightarrow \mathbb{R}: \gamma \rightarrow d^{2}\left(p_{i}, \gamma\left(t_{i}\right)\right)$ at $\gamma \in \Gamma_{2}$ with respect to the second-order Palais metric (5) is given by the vector field $g_{i}$ along $\gamma$ defined by

$$
g_{i}(t)=\left\{\begin{array}{cc}
\left(1+t_{i} t+\frac{1}{2} t_{i} t^{2}-\frac{1}{6} t^{3}\right) \tilde{v}_{i}(t) & 0 \leq t \leq t_{i} \\
\left(1+t t_{i}+\frac{1}{2} t t_{i}^{2}-\frac{1}{6} t_{i}^{3}\right) \tilde{v}_{i}(t) & t_{i} \leq t \leq 1,
\end{array}\right.
$$

where $\tilde{v}_{i}$ is the parallel transport of $v_{i}$ along $\gamma$.
Proof. In view of (5) and (11), $g_{i}$ is the unique tangent vector field along $\gamma$ that satisfies

$$
\left\langle g_{i}(0), w(0)\right\rangle+\left\langle\frac{\mathrm{D} g_{i}}{\mathrm{~d} t}(0), \frac{\mathrm{D} w}{\mathrm{~d} t}(0)\right\rangle+\int_{0}^{t_{i}}\left\langle\frac{\mathrm{D}^{2} g}{\mathrm{~d} t^{2}}(t), \frac{\mathrm{D}^{2} w}{\mathrm{~d} t^{2}}(t)\right\rangle \mathrm{d} t=\left\langle v_{i}, w\left(t_{i}\right)\right\rangle
$$

We have

$$
\left\langle v_{i}, w\left(t_{i}\right)\right\rangle=\left\langle\tilde{v}_{i}(0), w(0)\right\rangle+\left.t_{i} \frac{\mathrm{~d}}{\mathrm{~d} t}\left\langle\tilde{v}_{i}(t), w(t)\right\rangle\right|_{t=0}+\int_{0}^{t_{i}}\left(t_{i}-t\right) \frac{\mathrm{d}^{2}}{\mathrm{~d} t^{2}}\left\langle\tilde{v}_{i}(t), w(t)\right\rangle \mathrm{d} t
$$

by Taylor's theorem with remainder in integral form,

$$
=\left\langle\tilde{v}_{i}(0), w(0)\right\rangle+t_{i}\left\langle\tilde{v}_{i}(0), \frac{\mathrm{D} w}{\mathrm{~d} t}(0)\right\rangle+\int_{0}^{t_{i}}\left(t_{i}-t\right)\left\langle\tilde{v}_{i}(t), \frac{\mathrm{D}^{2} w}{\mathrm{~d} t^{2}}(t)\right\rangle \mathrm{d} t
$$

for reasons already given in the proof of Theorem 3.2. It follows that

$$
\begin{aligned}
g_{i}(0) & =\tilde{v}_{i}(0) \\
\frac{\mathrm{D} g_{i}}{\mathrm{~d} t}(0) & =t_{i} \tilde{v}_{i}(0) \\
\frac{\mathrm{D}^{2} g_{i}}{\mathrm{~d} t^{2}}(t) & = \begin{cases}\left(t_{i}-t\right) \tilde{v}_{i}(t), & 0<t<t_{i} \\
0, & t_{i}<t<1\end{cases}
\end{aligned}
$$

Solving for $g_{i}$, we obtain:

$$
g_{i}(t)= \begin{cases}\left(1+t_{i} t+\frac{1}{2} t_{i} t^{2}-\frac{1}{6} t^{3}\right) \tilde{v}_{i}(t), & 0 \leq t \leq t_{i}  \tag{19}\\ \left(1+t t_{i}+\frac{1}{2} t t_{i}^{2}-\frac{1}{6} t_{i}^{3}\right) \tilde{v}_{i}(t), & t_{i} \leq t \leq 1\end{cases}
$$

This gradient function is a covariantly cubic polynomial before $t_{i}$ and is a covariantly linear polynomial after $t_{i}$. The total gradient is given by $G_{2}(t)=\sum_{i=0}^{N} g_{i}(t)$. Another way of writing this summation is, for $t_{i-1} \leq t \leq t_{i}$,

$$
\begin{equation*}
G_{2}(t)=\sum_{j=0}^{i-1}\left(1+t t_{j}+\frac{1}{2} t t_{j}^{2}-\frac{1}{6} t_{j}^{3}\right) \tilde{v}_{j}(t)+\sum_{j=i}^{N}\left(1+t_{j} t+\frac{1}{2} t_{j} t^{2}-\frac{1}{6} t^{3}\right) \tilde{v}_{j}(t) \tag{20}
\end{equation*}
$$

### 4.2 Derivative of $E_{\mathrm{s}, 2}$

Let $h(t, s)$ be a collection, indexed by $s$, of elements of the curve set $\Gamma_{2}$. Hence, for a fixed $s$, we have a curve on $M$ parameterized by $t$. For $s=0$, that curve is called $\gamma$. Then $w$ defined by $w(t)=h_{s}(t, 0)$ is a generic tangent vector to $\Gamma_{2}$ at $\gamma$. We have $\mathrm{D} E_{\mathrm{s}, 2}(\gamma)[w]=\left.\frac{\mathrm{d}}{\mathrm{d} s} F(s)\right|_{s=0}$, where

$$
F(s)=\frac{1}{2} \int_{0}^{1}\left\langle\frac{\mathrm{D}}{\mathrm{~d} t}\left(h_{t}(t, s)\right), \frac{\mathrm{D}}{\mathrm{~d} t}\left(h_{t}(t, s)\right)\right\rangle \mathrm{d} t .
$$

Taking the derivative with respect to $s$ :

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{~d} s} F(s) & =\int_{0}^{1}\left\langle\frac{\mathrm{D}}{\mathrm{~d} s}\left(\frac{\mathrm{D}}{\mathrm{~d} t}\left(h_{t}(t, s)\right)\right), \frac{\mathrm{D}}{\mathrm{~d} t}\left(h_{t}(t, s)\right)\right\rangle \mathrm{d} t \\
& =\int_{0}^{1}\left\langle\left[R\left(w, h_{t}(t, s)\right)\left(h_{t}(t, s)\right)+\frac{\mathrm{D}}{\mathrm{~d} t}\left(\frac{\mathrm{D}}{\mathrm{~d} s}\left(h_{t}(t, s)\right)\right)\right], \frac{\mathrm{D}}{\mathrm{~d} t}\left(h_{t}(t, s)\right)\right\rangle \mathrm{d} t
\end{aligned}
$$

where $R$ is the Riemannian curvature tensor defined as:

$$
R\left(h_{s}, h_{t}\right)(v)=\frac{\mathrm{D}}{\mathrm{~d} s} \frac{\mathrm{D}}{\mathrm{~d} t}(v)-\frac{\mathrm{D}}{\mathrm{~d} t} \frac{\mathrm{D}}{\mathrm{~d} s}(v) .
$$

(Note that the curvature tensor is sometimes defined with the opposite sign in the literature.) Since $\frac{\mathrm{D}}{\mathrm{d} s}\left(h_{t}\right)=\frac{\mathrm{D}}{\mathrm{d} t}\left(h_{s}\right)$, the desired derivative at $s=0$ becomes:

$$
\begin{align*}
\left.\frac{\mathrm{d}}{\mathrm{~d} s} F(s)\right|_{s=0} & =\int_{0}^{1}\left\langle\left[R(w, \dot{\gamma})(\dot{\gamma})+\frac{\mathrm{D}^{2}}{\mathrm{~d} t^{2}}(w)\right], \frac{\mathrm{D}}{\mathrm{~d} t}(\dot{\gamma})\right\rangle \mathrm{d} t \\
& =\int_{0}^{1}\left\langle R(w, \dot{\gamma})(\dot{\gamma}), \frac{\mathrm{D}}{\mathrm{~d} t}(\dot{\gamma})\right\rangle \mathrm{d} t+\int_{0}^{1}\left\langle\frac{\mathrm{D}^{2}}{\mathrm{~d} t^{2}}(w), \frac{\mathrm{D}}{\mathrm{~d} t}(\dot{\gamma})\right\rangle \mathrm{d} t \tag{21}
\end{align*}
$$

This is the sought expression for $\mathrm{D} E_{\mathrm{s}, 2}(\gamma)[w]$.

### 4.3 Gradient of $E_{\mathrm{s}, 2}$

We will analyze the two terms in (21) separately.
The Riemannian curvature tensor has certain symmetries: for vector fields $a, b, c, d$ along $\gamma$,

$$
\langle R(a, b)(c), d\rangle=-\langle R(b, a)(c), d\rangle=-\langle R(a, b)(d), c\rangle=\langle R(c, d)(a), b\rangle
$$

which allows us to rewrite the first term of (21) as

$$
\int_{0}^{1}\left\langle R\left(\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}(t), \dot{\gamma}(t)\right)(\dot{\gamma}(t)), w(t)\right\rangle \mathrm{d} t=\int_{0}^{1}\langle A(t), w(t)\rangle \mathrm{d} t
$$

where $A$ denotes the vector field along the curve $\gamma$ given by $A(t)=R\left(\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}(t), \dot{\gamma}(t)\right)(\dot{\gamma}(t))$. We need a vector field $H_{2}$ along $\gamma$ with the property that

$$
\left\langle H_{2}(0), w(0)\right\rangle+\left\langle H_{2}^{\prime}(0), w^{\prime}(0)\right\rangle+\int_{0}^{1}\left\langle H_{2}^{\prime \prime}(t), w^{\prime \prime}(t)\right\rangle \mathrm{d} t=\int_{0}^{1}\langle A(t), w(t)\rangle \mathrm{d} t
$$

for all $w \in T_{\gamma} \Gamma_{2}$, where we temporarily use the prime as simplified notation for $\frac{\mathrm{D}}{\mathrm{d} t}$. We now express the right-hand side of the latter equation in a form that matches the one of the left-hand side. To this end, we let $A^{[k]}$ denote the $k$ th covariant integral of $A$ with zero conditions at $t=0$. Moreover, in keeping with previous notation, we let $\widetilde{A^{[k]}(1)}$ denote the parallel transport of $A^{[k]}(1)$ along $\gamma$. We have

$$
\left.\int_{0}^{1}\langle A(t), w(t)\rangle \mathrm{d} t=\left\langle A^{[1]}(t)-\widetilde{A^{[1]}(1)}(t), w(t)\right\rangle\right]_{0}^{1}-\int_{0}^{1}\left\langle A^{[1]}(t)-\widetilde{A^{[1]}(1)}(t), w^{\prime}(t)\right\rangle \mathrm{d} t
$$

by integration by parts, where $A^{[1]}-\widetilde{A^{[1]}(1)}$ is the primitive of $A$ that vanishes at $t=1$,

$$
=\left\langle\widetilde{A^{[1]}(1)}(0), w(0)\right\rangle-\int_{0}^{1}\left\langle A^{[1]}(t)-\widetilde{A^{[1]}(1)}(t), w^{\prime}(t)\right\rangle \mathrm{d} t
$$

since $A^{[1]}(0)=0$ by definition,

$$
\begin{aligned}
= & \left.\left\langle\widetilde{A^{[1]}(1)}(0), w(0)\right\rangle-\left\langle A^{[2]}(t)-\overparen{A^{[1]}(1)}(t)-\widetilde{A^{[2]}(1)}+\widetilde{A^{[1]}(1)}, w^{\prime}(t)\right\rangle\right]_{0}^{1} \\
& +\int_{0}^{1}\left\langle A^{[2]}(t)-t \widetilde{A^{[1]}(1)}(t)-\widetilde{A^{[2]}(1)}(t)+\widetilde{A^{[1]}(1)}(t), w^{\prime \prime}(t)\right\rangle \mathrm{d} t
\end{aligned}
$$

by integration by parts,

$$
\begin{aligned}
= & \left\langle\widetilde{A^{[1]}(1)}(0), w(0)\right\rangle+\left\langle-\widetilde{A^{[2]}(1)}(0)+\widetilde{A^{[1]}(1)}(0), w^{\prime}(0)\right\rangle \\
& +\int_{0}^{1}\left\langle A^{[2]}(t)-t \widetilde{A^{[1]}(1)}(t)-\widetilde{A^{[2]}(1)}(t)+\widetilde{A^{[1]}(1)}(t), w^{\prime \prime}(t)\right\rangle \mathrm{d} t
\end{aligned}
$$

which is the sought form. We can now conclude that

$$
\begin{aligned}
& H_{2}(0)=\widetilde{A^{[1]}(1)}(0) \\
& H_{2}^{\prime}(0)=-\widetilde{A^{[2]}(1)}(0)+\widetilde{A^{[1]}(1)}(0), \\
& H_{2}^{\prime \prime}(t)=\widetilde{A^{[2]}(t)-t \widetilde{A^{[1]}(1)}(t)-\widetilde{A^{[2]}(1)}(t)+\widetilde{A^{[1]}(1)}(t), 0 \leq t \leq 1}
\end{aligned}
$$

The solution is given by

$$
\begin{equation*}
H_{2}(t)=\hat{H}_{2}(t)-\frac{1}{6} t^{3} \tilde{S}(t)-\frac{1}{2} t^{2}(\tilde{Q}(t)-\tilde{S}(t))-t(\tilde{Q}(t)-\tilde{S}(t))+\tilde{S}(t) \tag{22}
\end{equation*}
$$

where $\hat{H}_{2}=A^{[4]}, S=A^{[1]}(1)=\hat{H}_{2}^{\prime \prime \prime}(1)$ and $Q=A^{[2]}(1)=\hat{H}_{2}^{\prime \prime}(1)$.
We now consider the second term in (21), that is, $\int_{0}^{1}\left\langle\frac{\mathrm{D}^{2} w}{\mathrm{~d} t^{2}}(t), \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}(t)\right\rangle \mathrm{d} t$. This term can be written as $\left\langle\left\langle H_{3}, w\right\rangle\right\rangle_{2}$ where $H_{3}$ satisfies

$$
\begin{equation*}
\frac{\mathrm{D}^{2} H_{3}}{\mathrm{~d} t^{2}}=\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \quad H_{3}(0)=\frac{\mathrm{D} H_{3}}{\mathrm{~d} t}(0)=0 \tag{23}
\end{equation*}
$$

that is, $H_{3}$ is two times covariant integral of $\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}$ with initial conditions $H_{3}(0)=\frac{\mathrm{D} H_{3}}{\mathrm{~d} t}(0)=0$.
In summary, we have the following result.
Theorem 4.2. The vector field along $\gamma$ that provides the gradient of the function $E_{\mathrm{s}, 2}$ (3) on $\Gamma_{2}$ (10) with respect to the second-order Palais metric (5) is given by

$$
\begin{equation*}
H_{2}(t)+H_{3}(t), \tag{24}
\end{equation*}
$$

as follows: $H_{2}$ admits the expression (222); $\hat{H}_{2}$ is given by $\frac{\mathrm{D}^{4} \hat{H}_{2}}{\mathrm{~d} t^{4}}(t)=R\left(\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}(t), \dot{\gamma}(t)\right)(\dot{\gamma}(t))$ with initial conditions $\hat{H}_{2}(0)=\frac{\mathrm{D} \hat{H}_{2}}{\mathrm{~d} t}(0)=\frac{\mathrm{D}^{2} \hat{H}_{2}}{\mathrm{~d} t^{2}}(0)=\frac{\mathrm{D}^{3} \hat{H}_{2}}{\mathrm{~d} t^{3}}(0)=0 ; \tilde{Q}$ and $\tilde{S}$ are the parallel transport along $\gamma$ of $Q=\frac{\mathrm{D}^{2} \hat{H}_{2}}{\mathrm{~d} t^{2}}(1)$ and of $S=\frac{\mathrm{D}^{3} \hat{H}_{2}}{\mathrm{~d} t^{3}}(1) ; H_{3}$ is given by $\frac{\mathrm{D}^{2} H_{3}}{\mathrm{~d} t^{2}}=\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}$ with initial conditions $H_{3}(0)=\frac{\mathrm{D} H_{3}}{\mathrm{~d} t}(0)=0$.

In case $M=\mathbb{R}^{n}$, the two terms are simply $H_{2}(t)=0$ and $H_{3}(t)=\gamma(t)-\dot{\gamma}(0) t-\gamma(0)$ for all $t \in I$.

### 4.4 Gradient of $E_{2}$

Combining the two gradient terms, we get the gradient of $E_{2}$ under the second-order Palais metric:

$$
\nabla E_{2}=G_{2}+\lambda\left(H_{2}+H_{3}\right)
$$

where $G_{2}$ is given in (20), $H_{2}$ in (22), and $H_{3}$ in (23).

## 5 Steepest-descent algorithm on the curve spaces

Let $E$ stand for $E_{1}$ (6), resp. $E_{2}$ (4), $\Gamma$ for the set $\Gamma_{1}$ (9), resp. $\Gamma_{2}$ (10), of curves on the Riemannian manifold $M$, and let $\Gamma$ be endowed with the first-order Palais metric (77), resp. second-order Palais metric (5). We propose the steepest-descent method for $E$ described in Algorithm (1)

The algorithm creates a sequence of curves $\left(\gamma_{k}\right)_{k=0,1, \ldots} \subset \Gamma$ with decreasing energy $E\left(\gamma_{k}\right)$. The initialization step consists in choosing an arbitrary curve in $\Gamma$ to be the starting curve $\gamma_{0}$. Then, given the current iterate $\gamma_{k}$, the algorithm computes the gradient $\nabla E\left(\gamma_{k}\right)$ and updates the curve to $\gamma_{k+1}$ according to

$$
\gamma_{k+1}(t)=\exp _{\gamma_{k}(t)}\left(-\hat{\rho}_{k} \nabla E\left(\gamma_{k}\right)(t)\right), \quad t \in I
$$

where $\hat{\rho}_{k}$ is a step size chosen using some step size selection rule (see, e.g., Ber95). We have chosen a modified version of Armijo backtracking procedure by imposing strong Wolfe conditions Wol69; see Algorithm 2 The algorithm is stopped when a certain pre-determined stopping criterion is satisfied. The criterion can be a threshold on the norm of $\nabla E\left(\gamma_{k}\right)$, for example.

```
Algorithm 1 Gradient descent
    Given a scalar \(\epsilon \in] 0,1\left[\right.\) and an initial curve \(\gamma_{0}\), arbitrary element of \(\Gamma\);
    \(k:=0\);
    repeat
        \(k:=k+1\);
        Compute \(E\left(\gamma_{k}\right)\) and \(\nabla E\left(\gamma_{k}\right)\);
        Find the step size \(\hat{\rho}_{k}\) using algorithm 2
        Set \(\gamma_{k}(t)=\exp _{\gamma_{k-1}(t)}\left(-\hat{\rho}_{k} \nabla E\left(\gamma_{k}\right)(t)\right)\);
    until \(\left\|\nabla E\left(\gamma_{k}\right)\right\| \leq \epsilon\)
    return \(\hat{\gamma}:=\gamma_{k}\)
```

```
Algorithm 2 Step size selection
    Given scalars \(\left.\rho_{0} \in\right] 0,1\left[, \epsilon>0\right.\) very small, \(0<\sigma_{1}<\sigma_{2}<1\), a function \(f\) and a descent
    direction \(q\) of \(f\) at \(x\);
    set \(k=0\) and set \(\beta_{k}=\rho_{0}\);
    \(\operatorname{until}\left(\beta_{k} \leq \epsilon\right)\) or \(\left(f\left(x+\beta_{k} q\right) \leq f(x)+\sigma_{1} \beta_{k}\langle\langle\nabla f(x), q\rangle\rangle\right.\) and \(\left|\left\langle\left\langle\nabla f\left(x+\beta_{k} q\right), q\right\rangle\right\rangle\right| \leq\)
    \(\left.\sigma_{2}|\langle\langle\nabla f(x), q\rangle\rangle|\right)\) do
        \(k:=k+1 ;\)
        \(\beta_{k}=\beta_{k-1} \rho_{0} ;\)
    end
    return \(\hat{\rho}:=\beta_{k}\)
```

Whereas analyzing the convergence of steepest-descent type methods on finite-dimensional manifolds is relatively simple (see AG09), the convergence analysis of steepest-descent methods on infinite-dimensional spaces is no trivial matter; see SZ04 and references therein. Analyzing the convergence of Algorithm 1 is the object of ongoing research. Nevertheless, it is reasonable to expect that the algorithm behaves like steepest-descent methods in finite dimension: the sequence of iterates $\gamma_{k}$ has a single limit (see AMA05) which, unless the initial curve is maliciously chosen, is a local minimizer of the objective function $E$. These expectations are corroborated by our numerical experiments; see Section 6

## 6 Illustration on some specific manifolds: $M=\mathbb{R}^{2}, \mathbb{S}^{2}$

In this section we present some illustrations of our gradient descent approach to finding optimal curves. In the case of Euclidean spaces, it is sometimes possible to derive expressions for the optimal curves under $E_{1}$ and $E_{2}$ directly. In those situations, we can compare our numerical solutions to the analytical expressions, and characterize the performances. In the remaining cases, where the analytical solutions are not readily available, we will simply illustrate the results obtained using our procedures. Examples involving the analytical expressions will have $M=\mathbb{R}^{n}$ and while the other cases will have $M=\mathbb{S}^{2}$.

### 6.1 Analytical solution of $E_{1}$ in $\mathbb{R}^{2}$

As the first example we will consider the problem of finding the optimal curves under $E_{1}$ when $M=\mathbb{R}^{2}$. For simplicity, we will take $\lambda=1$ in (6). This case is simple enough to seek an analytical expression as follows. Let $N=2$ and let the three data points be given by $p_{0}=(-A, 0)$, $p_{1}=(0, B), p_{2}=(A, 0)$, at the time instants $t_{0}=0, t_{1}=0.5, t_{2}=1$, where $A$ and $B$ are two real variables. Using the symmetry of the given points, and since we know that the optimal curves of $E_{1}$ are piecewise geodesics, we can restrict our search to piecewise-geodesic curves $\gamma$ connecting $q_{0}=(-a, c), q_{1}=(0, b)$, and $q_{2}=(a, c)$ at the three given time instants. Our goal is to find the values of $a, b$, and $c$ in $\mathbb{R}$ such that $\gamma$ is a minimum of $E_{1}$. By computing $E_{\mathrm{d}}$ and $E_{\mathrm{s}, 1}$ manually we get $E_{1}=(A-a)^{2}+c^{2}+\frac{1}{2}(B-b)^{2}+2\left(a^{2}+(b-c)^{2}\right)$. The critical points are given by the equation $\nabla E_{1}=0$, i.e., in terms of partial derivatives we have $\frac{\partial E_{1}}{\partial a}=\frac{\partial E_{1}}{\partial b}=\frac{\partial E_{1}}{\partial c}=0$. This system has only one solution given by $a=\frac{1}{3} A, b=\frac{3}{7} B$, and $c=\frac{2}{7} B$, and the minimum of $E_{1}$ is given by the piecewise geodesic curve connecting points $q_{1}=(-A / 3,2 B / 7), q_{2}=(0,3 B / 7)$, and $q_{3}=(A / 3,2 B / 7)$.

Shown in Figures (a) and (b)) are two optimal curves under $E_{1}$ obtained by our algorithm, for two different initial conditions. In each case, the green (dashed) curve shows the initial condition and the black (dotted) curve shows the final result obtained numerically. The red (continuous) curves show the optimal obtained using the analytical solution. The coincidence of black and red curves shows the accuracy and the stability of our algorithm. In Figures (c) and (d)) we show the variation of the step length, and the variation of the cost function $E_{1}$, respectively versus iterations, corresponding to the example shown in Figure (a).

In Figure (2) we present some additional results for $\mathbb{R}^{2}$, this time restricting only to our numerical solutions. These examples use a random set of points and different values of $\lambda$ to demonstrate the strength of the algorithm. Each of these solutions are piecewise geodesics and the end points of the geodesic segments depend on the value of $\lambda$.

### 6.2 Analytical solution of $E_{2}$ in $\mathbb{R}^{n}$

Next we derive the optimal curves under $E_{2}$ for Euclidean spaces. It is interesting to note that in this case the cost function has $n$ components, each corresponding to a coordinate in $\mathbb{R}^{n}$. In other words, the problem breaks down into $n$ independent problems, each being one-dimensional. Therefore, it is sufficient to illustrate the analytical solution for the one-dimensional case.

To derive an analytical solution to the one-dimensional problem, we will first establish a number of relations that this curve must satisfy and then use those relations to solve for the unknowns. We start with the fact that $\ddot{\gamma}(t)=\ddot{H}_{3}(t)$ for all $t$. Therefore, $\gamma$ takes the form:

$$
\gamma(t)=H_{3}(t)+r t+s
$$

where $r$ and $s$ are two constants. Next, since $\gamma$ is a critical point of $E_{2}$, we have $G_{2}(t)=-H_{3}(t)$ (assuming $\lambda=1$ ) for all $t$ which makes $\gamma(t)=-G_{2}(t)+r t+s$. Enumerating the different conditions on $\gamma$, we obtain the following constraints.


Figure 1: (a) and (b): The minimum of $E_{1}$ in $M=\mathbb{R}^{2}$ reached by the gradient descent method with respect to Palais metric using different starting curves for $\lambda=1$, (c): the step length variation, and (d): the energy evolution versus iterations for the example shown in (a).

1. Since $H_{3}(0)=0$, we have $G_{2}(0)=0$ which implies:

$$
G_{2}(0)=\sum_{j=1}^{n} v_{j}=0
$$

where $v_{j}$ is as defined in Section 4.1.
2. Also, since $\dot{H}_{3}(0)=0$, we have $\dot{G}_{2}(0)=0$ which means:

$$
\dot{G}_{2}(0)=\sum_{j=1}^{n} v_{j} t_{j}=0 .
$$

3. Finally, since we know that $\gamma\left(t_{i}\right)=v_{i}+p_{i}$, we get:

$$
-G_{2}\left(t_{i}\right)+r t_{i}+s=v_{i}+p_{i},
$$

which give us the relations: for $i=0, \ldots, N$

$$
\begin{equation*}
-\sum_{j=0}^{N}\left(1+t_{j} t_{i}+\frac{1}{2} t_{j} t_{i}^{2}-\frac{1}{6} t_{i}^{3}\right) v_{j}-\sum_{j=1}^{i-1}\left(1+t_{i} t_{j}+\frac{1}{2} t_{i} t_{j}^{2}-\frac{1}{6} t_{j}^{3}\right) v_{j}+r t_{i}+s=v_{i}+p_{i} . \tag{25}
\end{equation*}
$$

Rearranging this equation, we reach

$$
\sum_{j=1}^{n} \beta_{j, i} v_{j}+r t_{i}+s=p_{i}
$$

where

$$
\beta_{j, i}= \begin{cases}-\left[\left(1-\frac{1}{6} t_{j}^{3}\right)+\left(t_{j}+\frac{1}{2} t_{j}^{2}\right) t_{i}\right] & j<i \\ -\left[\left(2+t_{j} t_{i}+\frac{1}{2} t_{j} t_{i}^{2}-\frac{1}{6} t_{i}^{3}\right)\right] & j=i \\ -\left[\left(1+t_{j} t_{i}+\frac{1}{2} t_{j} t_{i}^{2}-\frac{1}{6} t_{i}^{3}\right)\right] & j>i\end{cases}
$$



Figure 2: The minimum of $E_{1}$ in $M=\mathbb{R}^{2}$ reached by the gradient descent method with respect to first-order Palais metric using different values of $\lambda$.


Figure 3: The panels (a) and (b) show two examples of optimal curves under $E_{2}$ obtained using our numerical approach (black curve) and the analytical solution (red curve). The panels in (c) and (d) plot the evolutions of $E_{2}$ versus iterations for the cases (a) and (b), respectively. The curves in green (dashed) are used as the initial curves for the optimization.

Taking these three types of relations, we form a linear system of equations. We have $N+3$ equations and $N+3$ unknowns:

$$
\left[\begin{array}{cccccc}
1 & 1 & \ldots & 1 & 0 & 0  \tag{26}\\
t_{0} & t_{1} & \ldots & t_{N} & 0 & 0 \\
\beta_{0,0} & \beta_{1,0} & \ldots & \beta_{N, 0} & t_{0} & 1 \\
\ldots & & & & & \\
\beta_{0, N} & \beta_{1, N} & \ldots & \beta_{N, N} & t_{N} & 1
\end{array}\right]\left[\begin{array}{c}
v_{0} \\
v_{1} \\
v_{2} \\
\ldots \\
v_{N} \\
r \\
s
\end{array}\right]=\left[\begin{array}{c}
0 \\
0 \\
p_{0} \\
p_{1} \\
\ldots \\
p_{N}
\end{array}\right]
$$

After solving for the $v_{j} \mathrm{~s}, r$ and $s$, we can evaluate the optimal curve $\gamma(t)=-G_{2}(t)+r t+s$.
We present some examples for comparing the numerical solutions with this analytical solution for $n=2$. In the panels Figure 3 (a) and (b), we present two examples with three points each and solve for the optimal curves under different $\lambda \mathrm{s}$. In each case, the green (dashed) line shows the initial curve, the black line shows the optimal curve obtained numerically, and the red (continuous) line shows the analytical solution. We have used a dotted pattern for the black (dotted) curve since the two optimal curves match perfectly and one hides the other. As predicted by the theory, the optimal solution resembles a straight line when $\lambda$ is sufficiently large, and an interpolating spline when $\lambda$ is sufficiently small. The plots in panels (c) and (d) show the corresponding evolution of $E_{2}$ versus iterations.

In Figure 4] we present some additional examples of optimal curves (obtained using our numerical method) under $E_{2}$ in $\mathbb{R}^{2}$ for a variety of data points and $\lambda \mathrm{s}$. Each panel in this figure shows the optimal $\gamma \mathrm{s}$ for different (mostly small) values of $\lambda$ but with the same data points. In each case the initial curve for the gradient process is given by the green (dashed) curve.


Figure 4: The optimal curves under $E_{2}$ for different combinations of data points and $\lambda \mathrm{s}$.


Figure 5: Optimal curves under $E_{1}$ for $M=\mathbb{S}^{2}$ obtained by our gradient descent method with respect to the first-order Palais metric. (a): $\lambda=100$, (b): $\lambda=1$, (c) and (d): $\lambda=10,1,0.1$, and 0.0001 . In each case the green curve shows the initial condition.


Figure 6: The evolution of curves under the gradient iterations for minimizing $E_{1}$. (a): $\lambda=10^{-5}$, (b): $\lambda=100$.

### 6.3 Optimal Curves on the Unit Sphere

In this section we consider the case of $M=\mathbb{S}^{2}$ where the analytical expressions for the optimal curves are not readily available, and we apply our numerical approach to find the solutions. In these experiments, we first generate $N+1$ data points $p_{0}, p_{1}, \ldots, p_{N}$ randomly on $\mathbb{S}^{2}$ and associate them with different instants of time $0=t_{0}<t_{1}<t_{2}<\ldots t_{n} \leq t_{1}=1$. Then, we initialize our algorithm by an arbitrary continuous curve $\gamma_{0} \in \Gamma$, and finally apply our gradient descent method to search for the optimal curve $\gamma_{*}$ that minimizes $E$.

1. Case 1: In the case $E=E_{1}$ we apply our algorithm as described in Section 3 and examples are shown in Figure 5 Similar to the Euclidean case, the solutions are piecewise geodesic curves. Since geodesics on $\mathbb{S}^{2}$ are arcs that lie on great circles, these optimal curves are piecewise arcs. The panels (a) and (b) show examples of optimal $\gamma$ for $N=2$ (three data points) and $N=3$ (four data points) with $\lambda$ values being 100 and 1, respectively. For $\lambda=100$, the resulting optimal curve looks like a point. The remaining two panels (c) and (d) show several optimal curves, each corresponding to different $\lambda \mathrm{s}$, for the same set of data points. As earlier, the initial condition for the gradient descent is given by the green curve.
The Figure 6 shows two examples of the actual optimization process where the iterative updates for $\gamma$ under the gradient of $E_{1}$ are shown. The process starts with the green curves as the initial conditions and the updates are shown in black. The final curves in each case are shown in red.
2. Case 2: In the case $E=E_{2}$, we need to obtain an expression for the tangent vector field


Figure 7: Optimal curves under $E_{2}$ for $M=\mathbb{S}^{2}$ obtained by our gradient descent method with respect to the second-order Palais metric. (a): $\lambda=0.01$, (b): $\lambda=10^{-8}$, (c) and (d): $\lambda=0.01,0.001,10^{-4}$, and $10^{-6}$. In each case the green curve shows the initial condition.


Figure 8: Evolutions of $\gamma$ under the gradient of $E_{2}$. The green curves are the initial conditions and the red curves are the final states.
$A$ defined in Section 4.3, which involves the Riemannian curvature tensor $R$ on $M$. Since the unit sphere has constant sectional curvature $k=1$, the curvature tensor is given by $R(X, Y) Z=k(\langle Y, Z\rangle X-\langle X, Z\rangle Y), k=1$; see, e.g., Lee07. Alternatively, this formula is easily obtained from the material in Section B. Thus, for the vector field $A$ defined in Section 4.3, we have the expression

$$
\begin{equation*}
A=\langle\dot{\gamma}, \dot{\gamma}\rangle \frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}-\left\langle\frac{\mathrm{D}^{2} \gamma}{\mathrm{~d} t^{2}}, \dot{\gamma}\right\rangle \dot{\gamma} . \tag{27}
\end{equation*}
$$

Using this expression, we first integrate $A(t)$ covariantly to determine the term $H_{2}$ of the gradient of $E_{2}$, and then use the gradient descent method of Algorithm 1 to minimize $E_{2}$. Shown in Figure 7 are some examples of our approach applied to different sets of points generated randomly on $\mathbb{S}^{2}$. The pictures in (a) and (b) show examples of optimal curves for three and five points with $\lambda \mathrm{s}$ as indicated there. The remaining two panels show examples of optimal curves obtained for fixed data points under different $\lambda$ s. Curves in different colors are obtained by using different values of $\lambda$. The values of $\lambda$ used in (c) and (d) are $10^{-2}, 10^{-3}, 10^{-4}$, and $10^{-6}$. As the value of $\lambda$ increases, we can see the optimal curves straightening and shortening into single arcs.
Figure 8 shows two examples of the iterative process by displaying the intermediate curves also. The initial curves are shown in green, the iterations are shown in black and the final curves are shown in red.

Asymptotics on $\lambda$ : Our numerical experiments corroborate the following theoretical results mentioned in Section 1.1.

- Let $\lambda$ go to zero. When $E=E_{1}$ (6), the optimal curve is the piecewise geodesic passing through the given points. When $E=E_{2}$ (4), the optimal curve is a piecewise cubic polynomial (in the sense of [NHP89]) interpolating the given set of points when $E=E_{2}$.
- Let $\lambda$ go to infinity. When $E=E_{1}$, the optimal curve shrinks to one point in $M$, precisely the Riemannian center of mass (also called Fréchet mean or Karcher mean) of the given set of points $p_{0}, p_{1}, \ldots, p_{N}$. When $E=E_{2}$, the optimal curve approaches a geodesic.


## 7 Concluding remarks

We have addressed the problem of fitting a curve to data points on a closed Riemannian submanifold $M$ of some Euclidean space by means of a Palais-based steepest-descent algorithm applied to the weighted sum of a fitting-related and a regularity-related cost function. As a proof of concept, we have used the simple regularity cost function (2) based on the first derivative. We have also considered the more challenging case of the regularity cost function (3), whose derivative involves the Riemannian curvature tensor on $M$, and for which the optimal curves are generalized cubic splines. We have illustrated the proposed method on fitting problems in $\mathbb{R}^{2}$ and $\mathbb{S}^{2}$. In future work, we will consider other nonlinear manifolds with applications in pattern recognition and image analysis.

An important feature of our approach is that the discretization takes place as late as possible in the implementation. The gradient of the cost function at a curve $\gamma$ is a (continuous-time) vector field along $\gamma$ expressed by means of the Riemannian logarithm, parallel transport, covariant differentiation, and covariant integrals. It is these operations that are approximated by discretization in the algorithm implementation. The advantage of using a continuous formulation is that tools from functional analysis become available. We are able to use the Palais metrics and, thus, simplify the gradient vector fields only because of this continuous formulation. An alternate approach would be to consider a discretization $\hat{\gamma}$ of $\gamma$ using $Q$ points and discretize the function $E$ accordingly to obtain a new objective function $\hat{E}: M^{Q} \rightarrow \mathbb{R}: \hat{\gamma} \mapsto \hat{E}(\hat{\gamma})$ that we would optimize on the finitedimensional product manifold $M^{Q}$ using, e.g., a steepest-descent method described in AMS08. The two approaches yield considerably different expressions for the gradient. In particular, in the approach on $\hat{E}$, the gradient of the fitting term $d^{2}\left(\gamma\left(t_{i}\right), p_{i}\right)$, with respect to the product Riemannian metric on $M^{Q}$, vanishes everywhere except at time $t_{i}$, whereas with the approach proposed here the influence of the $i$ th fitting term is spread along the whole curve in the expression of its gradient. Although we have not compared the results, one should expect a better performance with the approach where the discretization is delayed until the implementation step.

## A Proof of Theorem 3.1

This proof is essentially a restriction of the proof of Kar77, Th. 1.2]. Let $\alpha$ be defined by $\alpha(t)=\exp _{q}(t \xi)$. Consider the family of geodesics from $p$ to $\alpha(t): c_{p}(s, t)=\exp _{p}\left(s \exp _{p}^{-1} \alpha(t)\right)$. Since the cut locus is closed dC92, corollary 13.2.10], this expression is well defined for all $t$ in a neighborhood of 0 and all $s \in[0,1]$. Denote $c_{p}^{\prime}=\frac{\mathrm{d}}{\mathrm{d} s} c_{p}(s, t)$ and $\dot{c}_{p}=\frac{\mathrm{d}}{\mathrm{d} t} c_{p}(s, t)$. We know that $d(p, \alpha(t))=\left\|c_{p}^{\prime}(s, t)\right\|$ is independent of $s$. We have successively

$$
\frac{1}{2} \frac{\mathrm{~d}}{\mathrm{~d} t} d^{2}(p, \alpha(t))=\frac{1}{2} \frac{\mathrm{~d}}{\mathrm{~d} t}\left\langle c_{p}^{\prime}(s, t), c_{p}^{\prime}(s, t)\right\rangle
$$

which does not depend on $s$,

$$
\begin{aligned}
& =\left\langle\frac{\mathrm{D}}{\mathrm{~d} t} c_{p}^{\prime}(s, t), c_{p}^{\prime}(s, t)\right\rangle \\
& =\left\langle\frac{\mathrm{D}}{\mathrm{~d} s} \dot{c}_{p}(s, t), c_{p}^{\prime}(s, t)\right\rangle
\end{aligned}
$$

which still does not depend on $s$, thus

$$
\begin{aligned}
& =\int_{0}^{1}\left\langle\frac{\mathrm{D}}{\mathrm{~d} s} \dot{c}_{p}(s, t), c_{p}^{\prime}(s, t)\right\rangle \mathrm{d} s \\
& =\int_{0}^{1} \frac{\mathrm{~d}}{\mathrm{~d} s}\left\langle\dot{c}_{p}(s, t), c_{p}^{\prime}(s, t)\right\rangle \mathrm{d} s
\end{aligned}
$$

since $\frac{\mathrm{D}}{\mathrm{d} s} c_{p}^{\prime}(s, t)=0$ (geodesic property),

$$
=\left\langle\dot{c}_{p}(1, t), c_{p}^{\prime}(1, t)\right\rangle
$$

since $\dot{c}_{p}(0, t)=0$,

$$
=\left\langle\dot{\alpha}(t),-\exp _{\alpha(t)}^{-1} p\right\rangle .
$$

Since $\frac{1}{2} \mathrm{D} d^{2}(p, \cdot)(q)[\xi]=\left.\frac{1}{2} \frac{\mathrm{~d}}{\mathrm{~d} t} d^{2}(p, \alpha(t))\right|_{t=0}$, the result follows.

## B An extrinsic expression for the curvature tensor

The expression of the derivative of $E_{\mathrm{s}, 2}$ obtained in Section 4.2 involves the Riemannian curvature tensor of the Riemannian manifold $M$. When $M$ is a Riemannian submanifold of a Riemannian manifold $N$, the curvature tensor admits an extrinsic expression in terms of the second fundamental form and of the Weingarten map, which turns out to be handy in certain cases. In this section, we present this extrinsic expression, then we work out in detail the particular case where $N$ is a Euclidean space.

Let $\mathrm{D}_{\eta} \xi$ denote the (Levi-Civita) covariant derivative of $\xi$ along $\eta$ on the embedding manifold $M$, and let $\overline{\mathrm{D}}$ denote that derivative on $N$. The curvature tensor $R$ is defined by

$$
\begin{equation*}
R(\xi, \eta) \zeta=\mathrm{D}_{\xi} \mathrm{D}_{\eta} \zeta-\mathrm{D}_{\eta} \mathrm{D}_{\xi} \zeta-\mathrm{D}_{[\xi, \eta]} \zeta \tag{28}
\end{equation*}
$$

where $\xi, \eta, \zeta$ are tangent vector fields on $M$ and $[\xi, \eta]$ denotes the Lie bracket. Given $x \in M$, let $P_{x}: T_{x} N \rightarrow T_{x} M$ denote the orthogonal projector onto $T_{x} M$. Let $T_{x}^{\perp} M$ denote the normal space to $M$ at $x$, and let $P_{x}^{\perp}: T_{x} N \rightarrow T_{x}^{\perp} M$ denote the orthogonal projector onto the normal space $T_{x}^{\perp} M$. The shape operator (also called second fundamental form) is the object $I I$ defined as follows: for all $x \in M$ and all $\xi_{x}, \eta_{x} \in T_{x} M$,

$$
\begin{equation*}
I I\left(\eta_{x}, \xi_{x}\right):=P_{x}^{\perp} \overline{\mathrm{D}}_{\eta_{x}} \xi \tag{29}
\end{equation*}
$$

where $\xi$ is any tangent vector field that extends $\xi_{x}$. This definition can be found, e.g., in O'N83, Cha06. The Weingarten map is the object $\mathfrak{U}$ defined as follows. For all $x \in M, \eta_{x} \in T_{x} M$, $v_{x} \in T_{x}^{\perp} M$,

$$
\begin{equation*}
\mathfrak{U}_{\eta_{x}}\left(v_{x}\right):=-P_{x} \overline{\mathrm{D}}_{\eta_{x}} v, \tag{30}
\end{equation*}
$$

where $v$ is any normal vector field that extends $v_{x}$. This definition can be found, e.g., in Cha06, p. 62]. Then the curvature tensor can be expressed as follows:

$$
\begin{equation*}
R(\xi, \eta) \zeta=\mathfrak{U}_{\xi} I I(\eta, \zeta)-\mathfrak{U}_{\eta} I I(\xi, \zeta) . \tag{31}
\end{equation*}
$$

Let us now assume that $N$ is a Euclidean space. Then the projector field $P$ can be viewed as a matrix-valued function, the shape operator admits the expression

$$
\begin{equation*}
I I\left(\eta_{x}, \xi_{x}\right)=\left(\overline{\mathrm{D}}_{\eta_{x}} P\right) \xi_{x} \tag{32}
\end{equation*}
$$

where $\overline{\mathrm{D}}$ now reduces to the classical derivative, and the Weingarten map takes the form

$$
\begin{equation*}
\mathfrak{U}_{\eta_{x}}\left(v_{x}\right)=\left(\overline{\mathrm{D}}_{\eta_{x}} P\right) v_{x} . \tag{33}
\end{equation*}
$$

We refer to ATMA09 for details. These formulas are particularly useful when the projector field $P$ admits a simple expression.

## References

[AG09] P.-A. Absil and K. A. Gallivan. Accelerated line-search and trust-region methods. SIAM J. Numer. Anal., 47(2):997-1018, 2009.
[Alt00] C. Altafini. The de Casteljau algorithm on se(3). In Book chapter, Nonlinear control in the Year 2000, pages 23-34, 2000.
[AMA05] P.-A. Absil, R. Mahony, and B. Andrews. Convergence of the iterates of descent methods for analytic cost functions. SIAM J. Optim., 6(2):531-547, 2005.
[AMS08] P.-A. Absil, R. Mahony, and R. Sepulchre. Optimization Algorithms on Matrix Manifolds. Princeton University Press, 2008.
[ATMA09] P.-A. Absil, Jochen Trumpf, Robert Mahony, and Ben Andrews. All roads lead to Newton: Feasible second-order methods for equality-constrained optimization, 2009. in preparation.
[Ber95] D. P. Bertsekas. Nonlinear programming. Athena Scientific, Belmont, Massachusetts, 1995.
[Boo03] William M. Boothby. An Introduction to Differentiable Manifolds and Riemannian Geometry. Academic Press, 2003. Revised Second Edition.
[Cha06] Isaac Chavel. Riemannian geometry, volume 98 of Cambridge Studies in Advanced Mathematics. Cambridge University Press, Cambridge, second edition, 2006. A modern introduction.
[CKS99] P. Crouch, G. Kun, and F. Silva Leite. The de Casteljau algorithm on the Lie group and spheres. In Journal of Dynamical and Control Systems, volume 5, pages 397-429, 1999.
[CS91] P. Crouch and F. Silva Leite. Geometry and the dynamic interpolation problem. In Proc. Am. Control Conf., Boston, 26-29 July, 1991, pages 1131-1136, 1991.
[CS95] P. Crouch and F. Silva Leite. The dynamic interpolation problem: on Riemannian manifolds, Lie groups, and symmetric spaces. J. Dynam. Control Systems, 1(2):177-202, 1995.
[CSC95] M. Camarinha, F. Silva Leite, and P. Crouch. Splines of class $C^{k}$ on non-Euclidean spaces. IMA J. Math. Control Inform., 12(4):399-410, 1995.
[dC92] Manfredo Perdigão do Carmo. Riemannian geometry. Mathematics: Theory \& Applications. Birkhäuser Boston Inc., Boston, MA, 1992. Translated from the second Portuguese edition by Francis Flaherty.
[GHL04] Sylvestre Gallot, Dominique Hulin, and Jacques Lafontaine. Riemannian geometry. Universitext. Springer-Verlag, Berlin, third edition, 2004.
[HS07] K. Hüper and F. Silva Leite. On the geometry of rolling and interpolation curves on $S^{n}$, $\mathrm{SO}_{n}$, and Grassmann manifolds. J. Dyn. Control Syst., 13(4):467-502, 2007.
[JK87] Peter E. Jupp and John T. Kent. Fitting smooth paths to spherical data. J. Roy. Statist. Soc. Ser. C, 36(1):34-46, 1987.
[JSR06] Janusz Jakubiak, Fátima Silva Leite, and Rui C. Rodrigues. A two-step algorithm of smooth spline generation on Riemannian manifolds. J. Comput. Appl. Math., 194(2):177-191, 2006.
[Kar77] H. Karcher. Riemannian center of mass and mollifier smoothing. Comm. Pure. Appl. Math., 30(5):509541, 1977.
[KDL07] Alfred Kume, Ian L. Dryden, and Huiling Le. Shape-space smoothing splines for planar landmark data. Biometrika, 94(3):513-528, 2007.
[KS06] E. Klassen and A. Srivastava. Geodesic between 3D closed curves using path straightening . In A. Leonardis, H. Bischof, and A. Pinz, editors, European Conference on Computer Vision, pages 95-106, 2006.
[Lee07] John M. Lee. Riemannian Manifolds: An Introduction to Curvature, volume 176 of Graduate Texts in Mathematics. Springer-Verlag, New York, NY, 2007.
[Lin03] Anders Linnér. Symmetrized curve-straightening. Differential Geom. Appl., 18(2):119-146, 2003.
[LT66] Michel Lazard and Jacques Tits. Domaines d'injectivité de l'application exponentielle. Topology, 4:315322, 1965/1966.
[Mil63] J. W. Milnor. Morse Theory. Princeton University Press, New Jersey, 1963.
[MLK10] L. Machado, F. Silva Leite, and K. Krakowski. Higher-order smoothing splines versus least squares problems on Riemannian manifolds. J. Dyn. Control Syst., 16(1):121-148, 2010.
[MS06] Luís Machado and F. Silva Leite. Fitting smooth paths on Riemannian manifolds. Int. J. Appl. Math. Stat., 4(J06):25-53, 2006.
[MSH06] Luís Machado, F. Silva Leite, and Knut Hüper. Riemannian means as solutions of variational problems. LMS J. Comput. Math., 9:86-103 (electronic), 2006.
[NHP89] Lyle Noakes, Greg Heinzinger, and Brad Paden. Cubic splines on curved spaces. IMA J. Math. Control Inform., 6(4):465-473, 1989.
[O'N83] Barrett O'Neill. Semi-Riemannian Geometry, volume 103 of Pure and Applied Mathematics. Academic Press Inc. [Harcourt Brace Jovanovich Publishers], New York, 1983.
[Pal63] Richard S. Palais. Morse theory on Hilbert manifolds. Topology, 2:299-340, 1963.
[PN07] Tomasz Popiel and Lyle Noakes. Bézier curves and $C^{2}$ interpolation in Riemannian manifolds. J. Approx. Theory, 148(2):111-127, 2007.
[SZ04] G. Smyrlis and V. Zisis. Local convergence of the steepest descent method in Hilbert spaces. J. Math. Anal. Appl., 300(2):436-453, 2004.
[Tro77] A. J. Tromba. A general approach to Morse theory. J. Differential Geometry, 12(1):47-85, 1977.
[Wol69] P. Wolfe. Convergence conditions for ascent methods. SIAM Review, 11:226-235, 1969.


[^0]:    *This paper presents research results of the Belgian Network DYSCO (Dynamical Systems, Control, and Optimization), funded by the Interuniversity Attraction Poles Programme, initiated by the Belgian State, Science Policy Office. The scientific responsibility rests with its authors. This research was supported in part by AFOSR FA9550-06-1-0324 and ONR N00014-09-10664.
    ${ }^{\dagger}$ Department of Mathematical Engineering, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium (http://www.inma.ucl.ac.be/\{~samir, ~absil\}).
    ${ }^{\ddagger}$ Dept of Statistics, Florida State University, Tallahassee, FL 32306, USA (anuj@stat.fsu.edu).
    §Dept of Mathematics, Florida State University, Tallahassee, FL 32306, USA (klassen@math.fsu.edu).

