

Riemannian Proximal Gradient Methods

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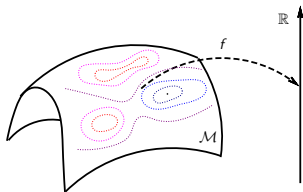
Sep. 26, 2019

This is joint work with Ke Wei at Fudan University.

Problem Statement

Optimization on Manifolds with Structure:

$$\min_{x \in \mathcal{M}} F(x) = f(x) + g(x),$$

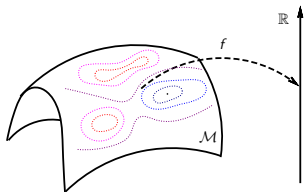


- $\mathcal{M}$ is a Riemannian manifold;
- f is Lipschitz continuously differentiable and may be nonconvex; and
- g is continuous and convex, but may be not differentiable.

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Applications: sparse PCA, sparse blind deconvolution, etc
[JTU03, GHT15, ZLK⁺17]

Existing Nonsmooth Optimization on Manifolds

$F : \mathcal{M} \rightarrow \mathbb{R}$ is Lipschitz continuous

- [Huang \(2013\)](#), Gradient sampling method without convergence analysis.
- [Grohs and Hosseini \(2015\)](#), Two ϵ -subgradient-based optimization methods using line search strategy and trust region strategy, respectively. Any limit point is a critical point.
- [Hosseini and Uschmajew \(2017\)](#), Gradient sampling method and any limit point is a critical point.
- [Hosseini and Huang and Yousefpour \(2018\)](#), Merge ϵ -subgradient-based and quasi-Newton ideas and show any limit point is a critical point.

Existing Nonsmooth Optimization on Manifolds

$F : \mathcal{M} \rightarrow \mathbb{R}$ is convex

- [Zhang and Sra \(2016\)](#), subgradient-based method and function value converges to the optimal $O(1/\sqrt{k})$.
- [Ferreira and Oliveira \(2002\)](#) and [Bento, Ferreira and Melo \(2017\)](#), proximal point method and function value converges to the optimal $O(1/k)$ on Hadamard manifold.
- [Liu, Shang, Cheng, Cheng, and Jiao \(2017\)](#), F is Lipschitz-continuously differentiable, function value converges to the optimal $O(1/k^2)$

Existing Nonsmooth Optimization on Manifolds

$F = f + g$, where f is L-con, and g is non-smooth

- [Chen, Ma, So, and Zhang \(2018\)](#), A proximal gradient method with global convergence
- [Huang and Wei \(2019\)](#), A FISTA on manifolds with global convergence
- [Huang and Wei \(2019\)](#), A Riemannian proximal gradient method and its invariant with acceleration. Convergence rate analyses are given

A Euclidean Proximal Gradient Method

Optimization with Structure: $\mathcal{M} = \mathbb{R}^{n \times m}$

$$\min_{x \in \mathbb{R}^{n \times m}} F(x) = f(x) + g(x), \quad (1)$$

Proximal gradient method is an excellent method for solving Problem (1).

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A proximal gradient method¹:

initial iterate: x_0 ,

$$\begin{cases} d_k = \arg \min_{p \in \mathbb{R}^{n \times m}} \langle \nabla f(x_k), p \rangle + \frac{L}{2} \|p\|_F^2 + g(x_k + p), & \text{(Proximal mapping)} \\ x_{k+1} = x_k + d_k. & \text{(Update iterates)} \end{cases}$$

¹The update rule: $x_{k+1} = \arg \min_x \langle \nabla f(x_k), x - x_k \rangle + \frac{L}{2} \|x - x_k\|^2 + g(x)$.

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- $g = 0$: reduce to steepest descent method;

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Convergence Rates

Assumption

$\min_{x \in \mathbb{R}^{n \times m}} F(x) = f(x) + g(x)$, with convex f ;

- $O(1/k)$ sublinear convergence rate:

$$F(x_k) - F(x_*) \leq C/k, \text{ for a constant } C;$$

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- Here, we consider FISTA [BT09]

initial iterate: x_0 and let $y_0 = x_0$, $t_0 = 1$,

$$\begin{cases} d_k = \arg \min_{p \in \mathbb{R}^{n \times m}} \langle \nabla f(y_k), p \rangle + \frac{L}{2} \|p\|_F^2 + g(y_k + p), \\ x_{k+1} = y_k + d_k, \\ t_{k+1} = \frac{1 + \sqrt{4t_k^2 + 1}}{2}, \\ y_{k+1} = x_{k+1} + \frac{t_k - 1}{t_{k+1}} (x_{k+1} - x_k). \end{cases}$$

Difficulties in the Riemannian Setting

Euclidean proximal mapping

$$d_k = \arg \min_{p \in \mathbb{R}^{n \times m}} \langle \nabla f(x_k), p \rangle + \frac{L}{2} \|p\|_F^2 + g(x_k + p)$$

In the Riemannian setting:

- How to define the proximal mapping?
- Can be solved cheaply?
- Share the same convergence rate?

A Riemannian Proximal Gradient Method in [CMSZ19]

Euclidean proximal mapping

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A Riemannian proximal mapping [CMSZ19]

$$\textcircled{1} \quad \eta_k = \arg \min_{\eta \in T_{x_k}} \mathcal{M} \langle \nabla f(x_k), \eta \rangle + \frac{L}{2} \|\eta\|_F^2 + g(x_k + \eta);$$

- Only works for embedded submanifold;

¹[CMSZ18]: S. Chen, S. Ma, M. C. So, and T. Zhang, Proximal gradient method for nonsmooth optimization over the Stiefel manifold. arXiv:1811.00980v2

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- **Convex programming;**

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ManPG [CMSZ19]

$$1 \quad \eta_k = \arg \min_{\eta \in T_{x_k} \mathcal{M}} \langle \nabla f(x_k), \eta \rangle + \frac{L}{2} \|\eta\|_F^2 + g(x_k + \eta);$$

- Only works for embedded submanifold;
- Proximal mapping is defined in tangent space;
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- Solved efficiently for the Stiefel manifold by a semi-Newton algorithm [XLWZ18];

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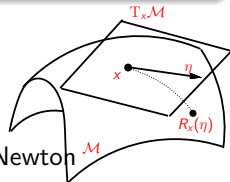
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- 2 $x_{k+1} = R_{x_k}(\alpha_k \eta_k)$ with an appropriate step size α_k ;

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- Convergence to a stationary point [HW19];

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 - 2 $x_{k+1} = R_{x_k}(\alpha_k \eta_k)$ with an appropriate step size α_k ;
- Convergence to a stationary point [HW19];
 - No convergence rate analysis (expect rate $O(1/k)$ if f is convex);

A New Riemannian Proximal Gradient Method

GOAL: Develop an accelerated Riemannian proximal gradient method with convergence rate analysis and good numerical performance

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A New Riemannian Proximal Gradient Method

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$$\textcircled{2} \quad x_{k+1} = R_{x_k}(\eta_k);$$

- General framework for Riemannian optimization;

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- General framework for Riemannian optimization;
- The tangent space may be too rough to approximate manifold for convergence analysis;
- Step size can be fixed to be 1;

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Assumption:

- 1 f is Lipschitz continuously differentiable in a Riemannian sense (L -retraction-smooth);

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Definition

A function $h : \mathcal{M} \rightarrow \mathbb{R}$ is called L -retraction-smooth with respect to a retraction R in $\mathcal{N} \subset \mathcal{M}$ if for any $x \in \mathcal{N}$ and any $\mathcal{S}_x \subset T_x \mathcal{M}$ such that $R_x(\mathcal{S}_x) \subset \mathcal{N}$, we have that $q_x = h \circ R_x$ satisfies

$$q_x(\eta) \leq q_x(\xi) + \langle \text{grad } q_x(\xi), \eta - \xi \rangle_x + \frac{L}{2} \|\eta - \xi\|_x^2 \quad \forall \eta, \xi \in \mathcal{S}_x.$$

Assumptions and Convergence Result

Assumption:

- 1 f is Lipschitz continuously differentiable in a Riemannian sense (L -retraction-smooth);

Theoretical results:

- For any accumulation point x_* of $\{x_k\}$, x_* is a stationary point, i.e., $0 \in \partial F(x_*)$.

Assumptions and Convergence Rate

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$$q_x(\eta) \geq q_x(\xi) + \langle \zeta, \eta - \xi \rangle_x \quad \forall \eta, \xi \in \mathcal{S}_x. \quad (2)$$

Note that $\zeta = \text{grad } q_x(\xi)$ if h is differentiable; otherwise, ζ is any subgradient of q_x at ξ .

Assumptions and Convergence Rate

Additional Assumptions:

- f is convex in a Riemannian sense (retraction-convex);
- Retraction approximately satisfies the triangle relation:

$$\left| \|\xi_x - \eta_x\|_x^2 - \|\zeta_y\|_y^2 \right| \leq \kappa \|\eta_x\|_x^2, \text{ for a constant } \kappa$$

where $\eta_x = R_x^{-1}(y)$, $\xi_x = R_x^{-1}(z)$, $\zeta_y = R_y^{-1}(z)$.

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Table: Exponential mapping on the Stiefel manifold with the Euclidean metric $\langle \eta_x, \xi_x \rangle_x = \text{trace}(\eta_x^T \xi_x)$. Left = $\left| \|\xi_x - \eta_x\|_x^2 - \|\zeta_y\|_y^2 \right|$

$(n, p) = (10, 1)$		$(n, p) = (10, 4)$		$(n, p) = (10, 10)$	
$\ \eta_x\ $	Left	$\ \eta_x\ $	Left	$\ \eta_x\ $	Left
5.00 ₋₂	7.83 ₋₅	5.00 ₋₂	1.83 ₋₅	5.00 ₋₂	2.14 ₋₆
2.50 ₋₂	1.80 ₋₅	2.50 ₋₂	4.27 ₋₆	2.50 ₋₂	4.72 ₋₇
1.25 ₋₂	4.25 ₋₆	1.25 ₋₂	1.01 ₋₆	1.25 ₋₂	1.11 ₋₇
6.25 ₋₃	1.03 ₋₆	6.25 ₋₃	2.46 ₋₇	6.25 ₋₃	2.68 ₋₈
3.12 ₋₃	2.54 ₋₇	3.12 ₋₃	6.05 ₋₈	3.13 ₋₃	6.61 ₋₉

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$(n, p) = (10, 2)$		$(n, p) = (10, 4)$		$(n, p) = (10, 9)$	
$\ \eta_x\ $	Left	$\ \eta_x\ $	Left	$\ \eta_x\ $	Left
5.00 ₋₂	3.55 ₋₅	5.00 ₋₂	1.15 ₋₅	5.00 ₋₂	8.39 ₋₆
2.50 ₋₂	8.06 ₋₆	2.50 ₋₂	2.58 ₋₆	2.50 ₋₂	1.89 ₋₆
1.25 ₋₂	1.90 ₋₆	1.25 ₋₂	6.08 ₋₇	1.25 ₋₂	4.45 ₋₇
6.25 ₋₃	4.61 ₋₇	6.25 ₋₃	1.47 ₋₇	6.25 ₋₃	1.08 ₋₇
3.13 ₋₃	1.13 ₋₇	3.13 ₋₃	3.63 ₋₈	3.12 ₋₃	2.66 ₋₈

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Theoretical results:

- Convergence rate $O(1/k)$:

$$F(x_k) - F(x_*) \leq \frac{1}{k} \left(\frac{L}{2} \|R_{x_0}^{-1}(x_*)\|_{x_0}^2 + \frac{L\kappa C}{2} (F(x_0) - F(x_*)) \right).$$

A Riemannian FISTA

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initial iterate: x_0 and let $y_0 = x_0$, $t_0 = 1$;

$$\textcircled{1} \quad \eta_k = \arg \min_{\eta \in T_{y_k}} \mathcal{M} \langle \text{grad } f(y_k), \eta \rangle_{y_k} + \frac{L}{2} \|\eta\|_{y_k}^2 + g(R_{y_k}(\eta));$$

$$\textcircled{2} \quad x_{k+1} = R_{y_k}(\eta_k);$$

$$\textcircled{3} \quad t_{k+1} = \frac{1 + \sqrt{4t_k^2 + 1}}{2};$$

$$\textcircled{4} \quad \text{Compute } y_{k+1} = R_{y_k} \left(\frac{t_{k+1} + t_k - 1}{t_{k+1}} \eta_{y_k} - \frac{t_k - 1}{t_{k+1}} R_{y_k}^{-1}(x_k) \right);$$

FISTA initial iterate: x_0 and let $y_0 = x_0$, $t_0 = 1$,

$$\left\{ \begin{array}{l} d_k = \arg \min_{p \in \mathbb{R}^{n \times m}} \langle \nabla f(y_k), p \rangle + \frac{L}{2} \|p\|_F^2 + g(y_k + p), \\ x_{k+1} = y_k + d_k, \\ t_{k+1} = \frac{1 + \sqrt{4t_k^2 + 1}}{2}, \\ y_{k+1} = x_{k+1} + \frac{t_k - 1}{t_{k+1}} (x_{k+1} - x_k). \end{array} \right.$$

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- 2 $x_{k+1} = R_{y_k}(\eta_k)$;
- 3 $t_{k+1} = \frac{1 + \sqrt{4t_k^2 + 1}}{2}$;
- 4 Compute $y_{k+1} = R_{y_k} \left(\frac{t_{k+1} + t_k - 1}{t_{k+1}} \eta_{y_k} - \frac{t_k - 1}{t_{k+1}} R_{y_k}^{-1}(x_k) \right)$;

A Riemannian generalization:

$$\begin{aligned} y_{k+1} &= y_k + \frac{t_{k+1} + t_k - 1}{t_{k+1}} (x_{k+1} - y_k) - \frac{t_k - 1}{t_{k+1}} (x_k - y_k) \\ &= x_{k+1} + \frac{t_k - 1}{t_{k+1}} (x_{k+1} - x_k), \end{aligned}$$

Assumptions and Convergence Rate

Additional Assumptions:

- There exists a constant $\tilde{\kappa}$ such that

$$\left| \left\| (t_{k+1} - 1)(R_{y_k}^{-1}(x_{k+1}) - R_{y_k}^{-1}(y_{k+1})) + R_{y_k}^{-1}(x_*) - R_{y_k}^{-1}(y_{k+1}) \right\|_{y_k}^2 - \left\| (t_{k+1} - 1)R_{y_{k+1}}^{-1}(x_{k+1}) + R_{y_{k+1}}^{-1}(x_*) \right\|_{y_{k+1}}^2 \right| \leq \tilde{\kappa} \|R_{y_k}^{-1}(y_{k+1})\|_{y_k}^2.$$

- $\phi(k) := \sum_{i=0}^k \|R_{y_k}^{-1}(y_{k+1})\|_{y_k}^2$ increases on the order of $O((k+1)^\theta)$ for $\theta \in [0, 1]$, i.e., $\frac{\phi(k)}{(k+1)^\theta} < C_\phi$ for all k .

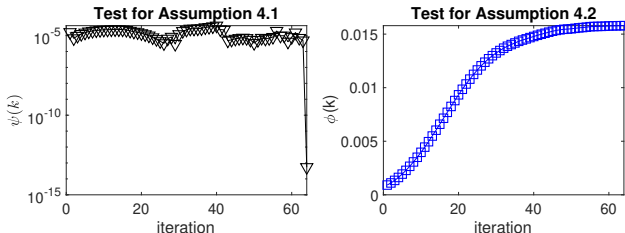
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Theoretical results:

- Convergence rate $O(1/k^2)$ if $\theta = 0$:

$$F(x_k) - F(x_*) \leq \frac{2L}{k^2} \|R_{x_0}^{-1}(x_*)\|_{x_0}^2 + \frac{2L\tilde{\kappa}C_\phi}{k^{2-\theta}} (F(x_0) - F(x_*)).$$

The Proposed Algorithm

An Accelerate Riemannian Proximal Gradient Method

initial iterate: $x_0, y_0 = z_0 = x_0, k = 0$ and $t_0 = 1$;

- ① $\eta_k = \arg \min_{\eta \in T_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2} \|\eta\|_{z_k}^2 + g(R_{z_k}(\eta));$
- ② $z_{k+1} = R_{z_k}(\eta_k);$
- ③ $\xi_k = \arg \min_{\xi \in T_{y_k}} \mathcal{M} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2} \|\xi\|_{y_k}^2 + g(R_{y_k}(\xi));$
- ④ $\tilde{x}_{k+1} = R_{y_k}(\xi_k);$
- ⑤ IF $F(\tilde{x}_{k+1}) < F(z_{k+1})$, then
 let $x_{k+1} = \tilde{x}_{k+1}$, update t_{k+1} and y_{k+1} ;
 Otherwise
 let $x_{k+1} = z_{k+1}$ and restart by setting $y_{k+1} = z_{k+1} = x_{k+1}$ and
 $t_{k+1} = 1$;
- ⑥ $k \leftarrow k + 1$ and goto Step 1;

Riemannian proximal gradient method without acceleration;

The Proposed Algorithm

An Accelerate Riemannian Proximal Gradient Method

initial iterate: $x_0, y_0 = z_0 = x_0, k = 0$ and $t_0 = 1$;

- 1 $\eta_k = \arg \min_{\eta \in T_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2} \|\eta\|_{z_k}^2 + g(R_{z_k}(\eta));$
- 2 $z_{k+1} = R_{z_k}(\eta_k);$
- 3 $\xi_k = \arg \min_{\xi \in T_{y_k}} \mathcal{M} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2} \|\xi\|_{y_k}^2 + g(R_{y_k}(\xi));$
- 4 $\tilde{x}_{k+1} = R_{y_k}(\xi_k);$
- 5 IF $F(\tilde{x}_{k+1}) < F(z_{k+1})$, then
 let $x_{k+1} = \tilde{x}_{k+1}$, update t_{k+1} and y_{k+1} ;
 Otherwise
 let $x_{k+1} = z_{k+1}$ and restart by setting $y_{k+1} = z_{k+1} = x_{k+1}$ and $t_{k+1} = 1$;
- 6 $k \leftarrow k + 1$ and goto Step 1;

Riemannian proximal gradient method with acceleration (RFISTA);

The Proposed Algorithm

An Accelerate Riemannian Proximal Gradient Method

initial iterate: $x_0, y_0 = z_0 = x_0, k = 0$ and $t_0 = 1$;

- ① $\eta_k = \arg \min_{\eta \in T_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2} \|\eta\|_{z_k}^2 + g(R_{z_k}(\eta));$
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- ④ $\tilde{x}_{k+1} = R_{y_k}(\xi_k);$
- ⑤ IF $F(\tilde{x}_{k+1}) < F(z_{k+1})$, then
 let $x_{k+1} = \tilde{x}_{k+1}$, update t_{k+1} and y_{k+1} ;
 Otherwise
 let $x_{k+1} = z_{k+1}$ and restart by setting $y_{k+1} = z_{k+1} = x_{k+1}$ and
 $t_{k+1} = 1$;
- ⑥ $k \leftarrow k + 1$ and goto Step 1;

Use the iterate with a smaller function value and use restart strategy;

The Proposed Algorithm

An Accelerate Riemannian Proximal Gradient Method

initial iterate: $x_0, y_0 = z_0 = x_0, k = 0$ and $t_0 = 1$;

$$\textcircled{1} \quad \eta_k = \arg \min_{\eta \in T_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2} \|\eta\|_{z_k}^2 + g(R_{z_k}(\eta));$$

$$\textcircled{2} \quad z_{k+1} = R_{z_k}(\eta_k);$$

$$\textcircled{3} \quad \xi_k = \arg \min_{\xi \in T_{y_k}} \mathcal{M} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2} \|\xi\|_{y_k}^2 + g(R_{y_k}(\xi));$$

$$\textcircled{4} \quad \tilde{x}_{k+1} = R_{y_k}(\xi_k);$$

$$\textcircled{5} \quad \text{IF } F(\tilde{x}_{k+1}) < F(z_{k+1}), \text{ then}$$

let $x_{k+1} = \tilde{x}_{k+1}$, update t_{k+1} and y_{k+1} ;

Otherwise

let $x_{k+1} = z_{k+1}$ and restart by setting $y_{k+1} = z_{k+1} = x_{k+1}$ and $t_{k+1} = 1$;

$$\textcircled{6} \quad k \leftarrow k + 1 \text{ and goto Step 1};$$

Not excute every iteration

Riemannian subproblem

$$\eta_u = \arg \min_{\eta \in T_u \mathcal{M}} \ell_u(\eta) := \langle \nabla f(u), \eta \rangle_u + \frac{L}{2} \|\eta\|_u^2 + g(R_u(\eta))$$

Riemannian subproblem

$$\eta_u = \arg \min_{\eta \in T_u \mathcal{M}} \ell_u(\eta) := \langle \nabla f(u), \eta \rangle_u + \frac{L}{2} \|\eta\|_u^2 + g(R_u(\eta))$$

In some cases, the subproblem can be solved by exploiting the structure of the manifold;

Riemannian subproblem

$$\eta_u = \arg \min_{\eta \in T_u \mathcal{M}} \ell_u(\eta) := \langle \nabla f(u), \eta \rangle_u + \frac{L}{2} \|\eta\|_u^2 + g(R_u(\eta))$$

Solving the Riemannian Proximal Mapping

initial iterate: $\eta_0 \in T_u \mathcal{M}$, $\sigma \in (0, 1)$, $k = 0$;

① $v_k = R_u(\eta_k)$;

② Compute

$$\xi_k^* = \arg \min_{\xi \in T_{v_k} \mathcal{M}} \langle \mathcal{T}_{R_{\eta_k}}^{-\sharp}(\text{grad } f(u) + \tilde{L}\eta_k), \xi \rangle_u + \frac{\tilde{L}}{4} \|\xi\|_F^2 + g(v_k + \xi);$$

③ Find $\alpha > 0$ such that $\ell_u(\eta_k + \alpha \mathcal{T}_{R_{\eta_k}}^{-1} \xi_k^*) < \ell_u(\eta_k) - \sigma \alpha \|\xi_k^*\|_u^2$;

④ $\eta_{k+1} = \eta_k + \alpha \mathcal{T}_{R_{\eta_k}}^{-1} \xi_k^*$, $k \leftarrow k + 1$ and goto Step 1;

Above algorithm is used if the ambient space is $\mathbb{R}^n$

Riemannian subproblem

$$\eta_u = \arg \min_{\eta \in T_u \mathcal{M}} \ell_u(\eta) := \langle \nabla f(u), \eta \rangle_u + \frac{L}{2} \|\eta\|_u^2 + g(R_u(\eta))$$

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④ $\eta_{k+1} = \eta_k + \alpha \mathcal{T}_{R_{\eta_k}}^{-1} \xi_k^*$, $k \leftarrow k + 1$ and goto Step 1;

An application of [CMSZ19] if $R_u^{-1}(\eta)$ exists.

Numerical Experiments

Sparse PCA problem [GHT15]

$$\min_{X \in OB(p, n)} \|X^T A^T A X - D^2\|_F^2 + \lambda \|X\|_1,$$

where $A \in \mathbb{R}^{m \times n}$, D is the diagonal matrix with dominant singular values of A , $OB(p, n) = \{X \in \mathbb{R}^{n \times p} \mid \text{diag}(X^T X) = I_p\}$, $p \leq m$;

Numerical Experiments

Solve the proximal mapping:

$$\eta_k = \arg \min_{\eta \in T_x \mathcal{M}} \langle \nabla f(x_k), \eta \rangle_{x_k} + \frac{L}{2} \|\eta\|_{x_k}^2 + g(R_{x_k}(\eta));$$

- Exponential mapping (each column):

$$R_x(\eta_x) = x \cos(\|\eta_x\|) + \frac{\eta_x}{\|\eta_x\|} \sin(\|\eta_x\|);$$

Numerical Experiments

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 $R_x(\eta_x) = x \cos(\|\eta_x\|) + \frac{\eta_x}{\|\eta_x\|} \sin(\|\eta_x\|);$
- Explore the fact that the following problem has a closed solution:

$$\min_{x \in OB(p,n)} \|x - y\|_F^2 + \frac{1}{2\lambda} \|x\|_1 \text{ for any } y \in \mathbb{R}^{n \times p}.$$

Numerical Experiments

Solve the proximal mapping:

$$\eta_k = \arg \min_{\eta \in T_{x_k} \mathcal{M}} \langle \nabla f(x_k), \eta \rangle_{x_k} + \frac{L}{2} \|\eta\|_{x_k}^2 + g(R_{x_k}(\eta));$$

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- A conditional gradient (Frank-Wolfe) method is used;

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Numerical Experiments

Table: An average result of 10 random tests. $n = 128$, $m = 20$, $r = 4$.
 $\delta = (L\|x_{k+1} - x_k\|)^2$. The subscript k indicates a scale of 10^k .

λ	Algo	iter	time	f	δ	spar.	navar
3	ManPG	11791	1.40	8.33 ₁	5.11 ₋₆	0.54	0.86
	RPG	11679	0.94	8.33 ₁	5.11 ₋₆	0.54	0.86
	ManPG-Ada	1398	0.30	8.33 ₁	1.67 ₋₃	0.54	0.86
	A-ManPG	273	0.09	8.33 ₁	9.19 ₋₄	0.54	0.86
	A-RPG	263	0.06	8.33 ₁	1.12 ₋₃	0.54	0.86

- **ManPG**: the method in [CMSZ19];
- **RPG**: the new Riemannian proximal gradient without acceleration;
- **A-ManPG**: Use similar technique to accelerate ManPG;
- **A-RPG**: the new Riemannian proximal gradient with acceleration;

Numerical Experiments

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ManPG-Ada:

- 1 $\eta_k = \arg \min_{\eta \in T_{x_k}} \mathcal{M} \langle \nabla f(x_k), \eta \rangle + \frac{\tilde{L}}{2} \|\eta\|_F^2 + g(x_k + \eta)$;
- 2 $x_{k+1} = R_{x_k}(\alpha_k \eta_k)$ with an appropriate step size α_k ;
- 3 Update $\tilde{L}$;

Numerical Experiments

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- **ManPG and RPG:** Stop when $\delta < 10^{-8}nr$;
- **A-ManPG and A-RPG:** Stop when F is smaller than the minimum of ManPG and RPG;

Numerical Experiments

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- **spar.**: sparsity of the solution;
- **navar**: the adjusted variance normalized by the variance from the standard PCA;

Numerical Experiments

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- PG without acceleration is slower than PG with acceleration;
- RPG is slightly faster ManPG in term of computational time;

Numerical Experiments

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- **ManPG and RPG: similarly; and A-ManPG and A-RPG: similarly;**
in term of:
 - number of iterations;
 - function values;
 - sparsity;
 - adjusted variance;

Numerical Experiments

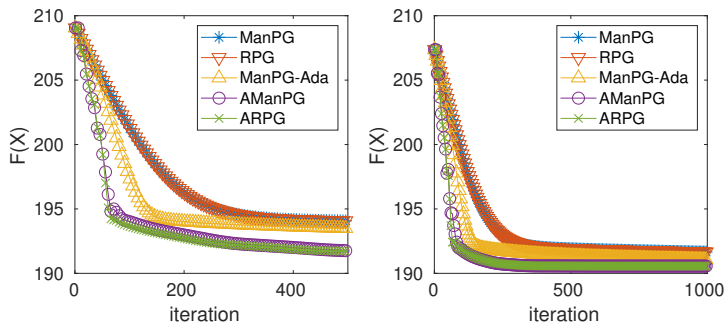


Figure: Two typical runs of ManPG, RPG, A-ManPG, and A-RPG for the Sparse PCA problem. $n = 1024$, $p = 4$, $\lambda = 2$, $m = 20$.

Numerical Experiments

Sparse PCA problem (Another model) [CMSZ19, HW19]

$$\min_{X \in \text{St}(p,n)} -\text{trace}(X^T A^T A X) + \lambda \|X\|_1,$$

where $A \in \mathbb{R}^{m \times n}$ is a data matrix.

Numerical Experiments

Solve the proximal mapping:

$$\eta_k = \arg \min_{\eta \in T_{x_k} \mathcal{M}} \langle \nabla f(x_k), \eta \rangle_{x_k} + \frac{L}{2} \|\eta\|_{x_k}^2 + g(R_{x_k}(\eta));$$

- Exponential mapping:

$$\text{Exp}_X(\eta_X) = [X \quad Q] \exp \left(\begin{bmatrix} \Omega & -R^T \\ R & 0 \end{bmatrix} \right) \begin{bmatrix} I_p \\ 0 \end{bmatrix},$$

where $\Omega = X^T \eta_X$, Q and R are from the compact QR factorization of $(I - XX^T)\eta_X$.

Numerical Experiments

Solve the proximal mapping:

$$\eta_k = \arg \min_{\eta \in T_{x_k} \mathcal{M}} \langle \nabla f(x_k), \eta \rangle_{x_k} + \frac{L}{2} \|\eta\|_{x_k}^2 + g(R_{x_k}(\eta));$$

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- **Ingredients for the algorithm on Page 17:**
 - R^{-1} by iterative methods [Zim17]
 - $\mathcal{T}_R^{-\sharp}$ by iterative methods

Numerical Experiments

Lemma

The adjoint operator of the inverse differentiated retraction is

$$\begin{aligned} \mathcal{T}_{\eta_X}^{-\sharp} \xi_X = & [X \quad Q_1] \exp \left(\begin{bmatrix} \Omega_{\eta_X} & -R_1^T \\ R_1 & 0_{p \times p} \end{bmatrix} \right) [X \quad Q_1]^T \omega_X \\ & + \left(I - [X \quad Q_1] [X \quad Q_1]^T \right) \omega_X, \end{aligned}$$

where $\omega_X = X\Omega_{\zeta_Y} + QR_2$, $Y = \text{Exp}_X(\eta_X)$, $Q_1R_1 = (I - XX^T)\eta_X$ and $Q_2\tilde{R}_2 = (I - [XQ_1][XQ_1]^T)\xi_X$ are qr decompositions, $Q = [Q_1 \quad Q_2]$,

$$\tilde{M}_1 = \begin{bmatrix} \Omega_{\eta_X} & -R_1^T & 0_{p \times p} \\ R_1 & 0_{p \times p} & 0_{p \times p} \\ 0_{p \times p} & 0_{p \times p} & 0_{p \times p} \end{bmatrix}, \quad \tilde{Z}\tilde{\Lambda}\tilde{Z}^H = \tilde{M}_1, \text{ and } \Omega_{\zeta_Y} \text{ and } R_2 \text{ are}$$

solutions of $\tilde{Z}^H [X \quad Q]^T \xi_X =$

$$\left(\left(\tilde{Z}^H \text{Exp}_X(\tilde{M}_1) \begin{bmatrix} \Omega_{\zeta_Y} & -R_2^T \\ R_2 & 0_{2p \times 2p} \end{bmatrix} \tilde{Z} \right) \odot \overline{\Phi} \right) \tilde{Z}^H \begin{bmatrix} I_p \\ 0_{2p \times p} \end{bmatrix}.$$

Numerical Experiments

Table: An average result of 10 random tests. $n = 1024$, $m = 20$, $r = 4$.
 $\delta = (L\|x_{k+1} - x_k\|)^2$. The subscript k indicates a scale of 10^k .

λ	Algo	iter	time	f	δ	spar.	navar
3	ManPG	1572	0.92	-7.28	4.76 ₋₅	0.64	0.74
	RPG	1464	5.46	-7.28	4.06 ₋₅	0.64	0.74
	ManPG-Ada	376	0.22	-7.28	3.99 ₋₄	0.64	0.74
	A-ManPG	110	0.20	-7.28	1.06 ₋₃	0.64	0.74
	A-RPG	88	1.61	-7.28	2.05 ₋₄	0.64	0.74

- Same notation, same stopping criterion, same parameter setting;
- New approaches take more time due to excessive cost on R^{-1} and $\mathcal{T}^{-\#}$;
- New approaches take less iterations;

Numerical Experiments

Table: An average result of 10 random tests. $n = 1024$, $m = 20$, $r = 4$.
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Numerical Experiments

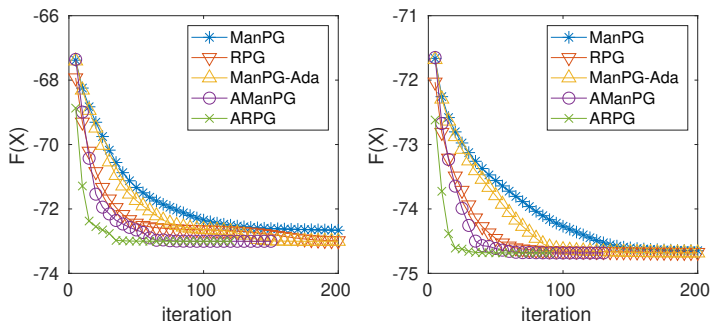


Figure: Two typical runs of ManPG, RPG, A-ManPG, and A-RPG for the Sparse PCA problem. $n = 1024$, $p = 4$, $\lambda = 2$, $m = 20$.

Summary

- Propose first Riemannian proximal gradient methods with convergence rate analyses;
- Apply this method to sparse PCA problems on the oblique manifold and the Stiefel manifold;
- Compare the new proximal gradient method with the existing proximal gradient method;

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