Riemannian Proximal Gradient Methods

Wen Huang

Xiamen University

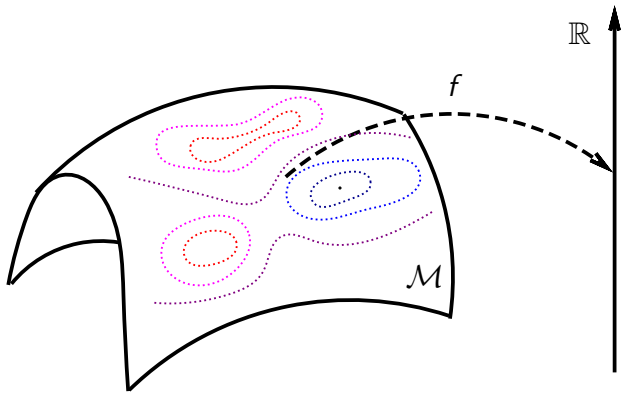
Oct. 25, 2019

This is joint work with Ke Wei at Fudan University.

Problem Statement

Optimization on Manifolds with Structure:

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



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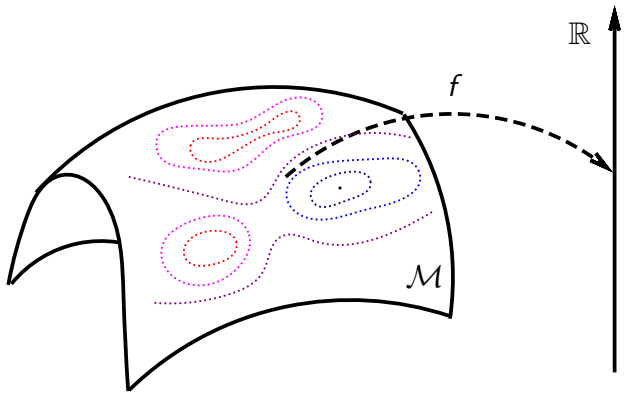

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Applications: sparse PCA, sparse blind deconvolution, etc [JTU03, GHT15, ZLK+17]

Existing Nonsmooth Optimization on Manifolds

$F : \mathcal{M} \to \mathbb{R}$ 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

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

- 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: $\mathcal{M} = \mathbb{R}^{n\times m}$

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

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

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A proximal gradient method[1]:

initial iterate:x_0,

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

[1] The 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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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]

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

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]

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

- 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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- Solved efficiently for the Stiefel manifold by a semi-Newton algorithm [XLWZ18];

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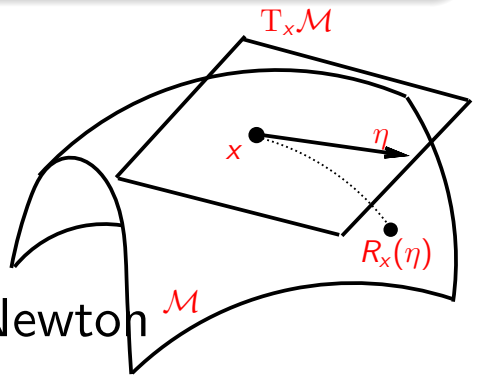

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- Convergence to a stationary point [HW19];
- No convergence rate analysis (expect rate $O(1/k)$ if f is convex);

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- General framework for Riemannian optimization;
- The tangent space may be too rough to approximate manifold for convergence analysis;
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Definition

A function $h : \mathcal{M} \to \mathbb{R}$ 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 $\mathcal{S}_x \subset \mathrm{T}_x \mathcal{M}$ such that $R_x(\mathcal{S}_x) \subset \mathcal{N}$, we have that $q_x = h \circ R_x$ satisfies

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

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Theoretical results:

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

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

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

Assumptions and Convergence Rate

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- 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 Stifel manifold with the Euclidean metric $\langle \eta_x, \xi_x \rangle_x = \mathrm{trace}(\eta_x^T \xi_x)$. 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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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}
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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 $y_0 = x_0,\ t_0 = 1$;

1. $\eta_k = \arg\min_{\eta \in \mathrm{T}_{y_k}\mathcal{M}} \langle \operatorname{grad} f(y_k), \eta \rangle_{y_k} + \frac{L}{2}\|\eta\|^2_{y_k} + g(R_{y_k}(\eta))$;
2. $x_{k+1} = R_{y_k}(\eta_k)$;
3. $t_{k+1} = \frac{1+\sqrt{4t_k^2+1}}{2}$;
4. Compute $y_{k+1} = R_{y_k}\left(\frac{t_{k+1}+t_k-1}{t_{k+1}}\eta_{y_k} - \frac{t_k-1}{t_{k+1}}R^{-1}_{y_k}(x_k)\right)$;

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

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

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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

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

- $\phi(k) := \sum_{i=0}^{k} \|R_{y_k}^{-1}(y_{k+1})\|_{y_k}^2$ 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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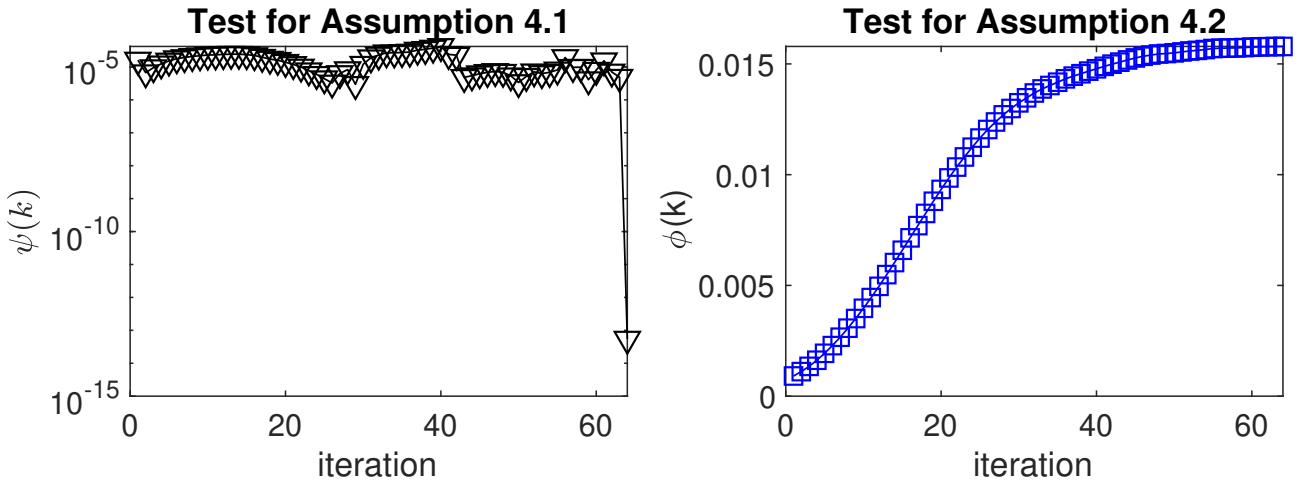

Assumptions and Convergence Rate

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

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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. $\eta_k = \arg\min_{\eta \in \mathrm{T}_{z_k}\mathcal{M}} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2}\|\eta\|^2_{z_k} + g(R_{z_k}(\eta))$;
2. $z_{k+1} = R_{z_k}(\eta_k)$;
3. $\xi_k = \arg\min_{\xi \in \mathrm{T}_{y_k}\mathcal{M}} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2}\|\xi\|^2_{y_k} + g(R_{y_k}(\xi))$;
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. $\eta_k = \arg\min_{\eta \in \mathrm{T}_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2}\|\eta\|_{z_k}^2 + g(R_{z_k}(\eta))$;
2. $z_{k+1} = R_{z_k}(\eta_k)$;
3. $\xi_k = \arg\min_{\xi \in \mathrm{T}_{y_k}} \mathcal{M} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2}\|\xi\|_{y_k}^2 + g(R_{y_k}(\xi))$;
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. $\eta_k = \arg\min_{\eta \in \mathrm{T}_{z_k}\mathcal{M}} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2}\|\eta\|^2_{z_k} + g(R_{z_k}(\eta))$;
2. $z_{k+1} = R_{z_k}(\eta_k)$;
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   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 $t_0 = 1$;

1. $\eta_k = \arg\min_{\eta \in \mathrm{T}_{z_k}} \mathcal{M} \langle \nabla f(z_k), \eta \rangle_{z_k} + \frac{L}{2} \|\eta\|_{z_k}^2 + g(R_{z_k}(\eta))$;
2. $z_{k+1} = R_{z_k}(\eta_k)$;
3. $\xi_k = \arg\min_{\xi \in \mathrm{T}_{y_k}} \mathcal{M} \langle \nabla f(y_k), \xi \rangle_{y_k} + \frac{L}{2} \|\xi\|_{y_k}^2 + g(R_{y_k}(\xi))$;
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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;

Not excute every iteration

Riemannian subproblem

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

Riemannian subproblem

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

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

Riemannian subproblem

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

Solving the Riemannian Proximal Mapping

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

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

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

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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, $OB(p,n) = \{X \in \mathbb{R}^{n \times p} \mid \operatorname{diag}(X^T X) = I_p\}$, $p \leq m$;

Numerical Experiments

Solve the proximal mapping:

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

- Exponential mapping (each column):
  $R_x(\eta_x) = x \cos(\|\eta_x\|) + \frac{\eta_x}{\|\eta_x\|} \sin(\|\eta_x\|);$

Numerical Experiments

Solve the proximal mapping:

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

- Exponential mapping (each column):
  $R_x(\eta_x) = x\cos(\|\eta_x\|) + \frac{\eta_x}{\|\eta_x\|}\sin(\|\eta_x\|)$;
- 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:

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

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

Numerical Experiments

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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

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.

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ManPG-Ada:

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

Numerical Experiments

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.

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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

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.

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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

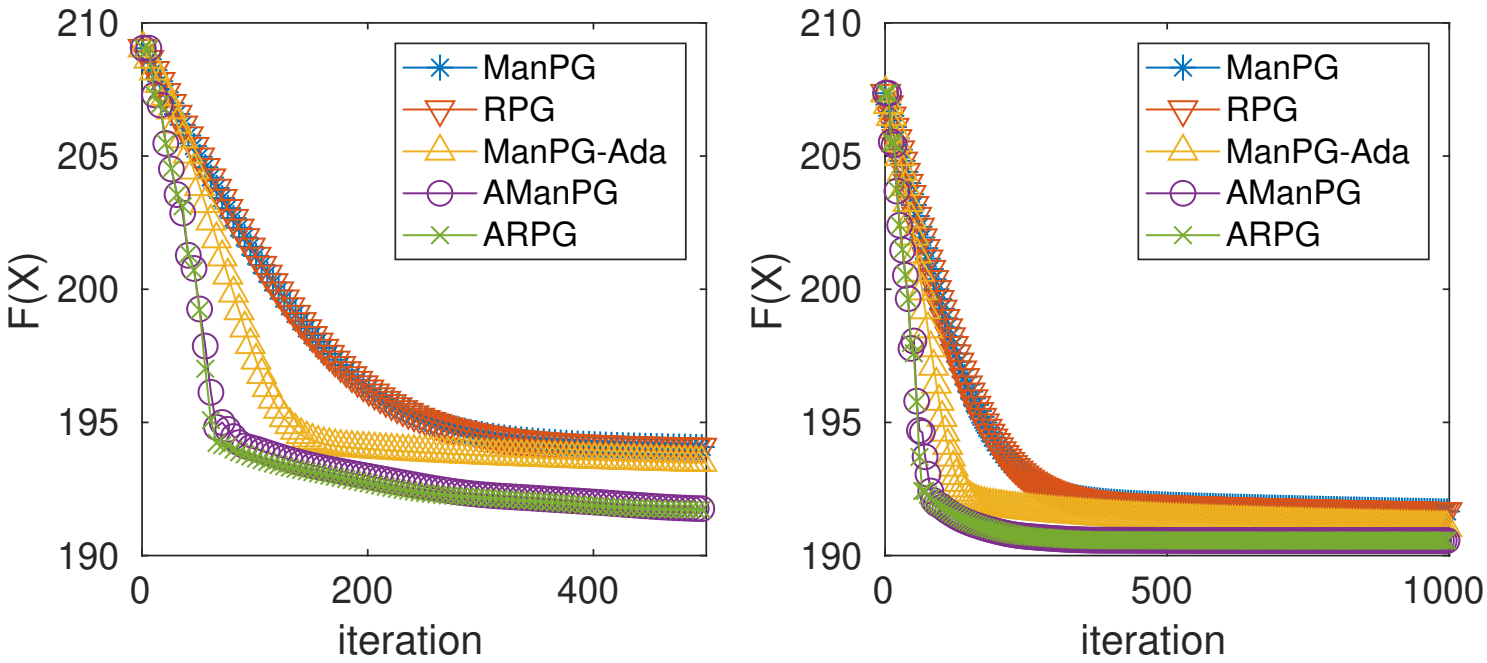

Figure: Two typical runs of ManPG, RPG, A-ManPG, and A-RPG for the Sparse PCA problem. $n = 1024$, $p = 4$, $\lambda = 2$, $m = 20$.

Numerical Experiments

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

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

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

Numerical Experiments

Solve the proximal mapping:

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

- Exponential mapping:

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

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

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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

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

where $\omega_X = X\Omega_{\zeta_Y} + QR_2$, $Y = \operatorname{Exp}_X(\eta_X)$, $Q_1R_1 = (I - XX^T)\eta_X$ *and* $Q_2\tilde{R}_2 = (I - [XQ_1][XQ_1]^T)\xi_X$ *are qr decompositions,* $Q = \begin{bmatrix} Q_1 & Q_2 \end{bmatrix}$, $\tilde{M}_1 = \begin{bmatrix} \Omega_{\eta_X} & -R_1^T & 0_{p\times p} \\ R_1 & 0_{p\times p} & 0_{p\times p} \\ 0_{p\times p} & 0_{p\times p} & 0_{p\times p} \end{bmatrix}$, $\tilde{Z}\tilde{\Lambda}\tilde{Z}^H = \tilde{M}_1$, *and* Ω_{ζ_Y} *and* R_2 *are solutions of* $\tilde{Z}^H \begin{bmatrix} X & Q \end{bmatrix}^T \xi_X =$

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

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 $\mathcal{T}^{-\sharp}$;
- New approaches take less iterations;

Numerical Experiments

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Numerical Experiments

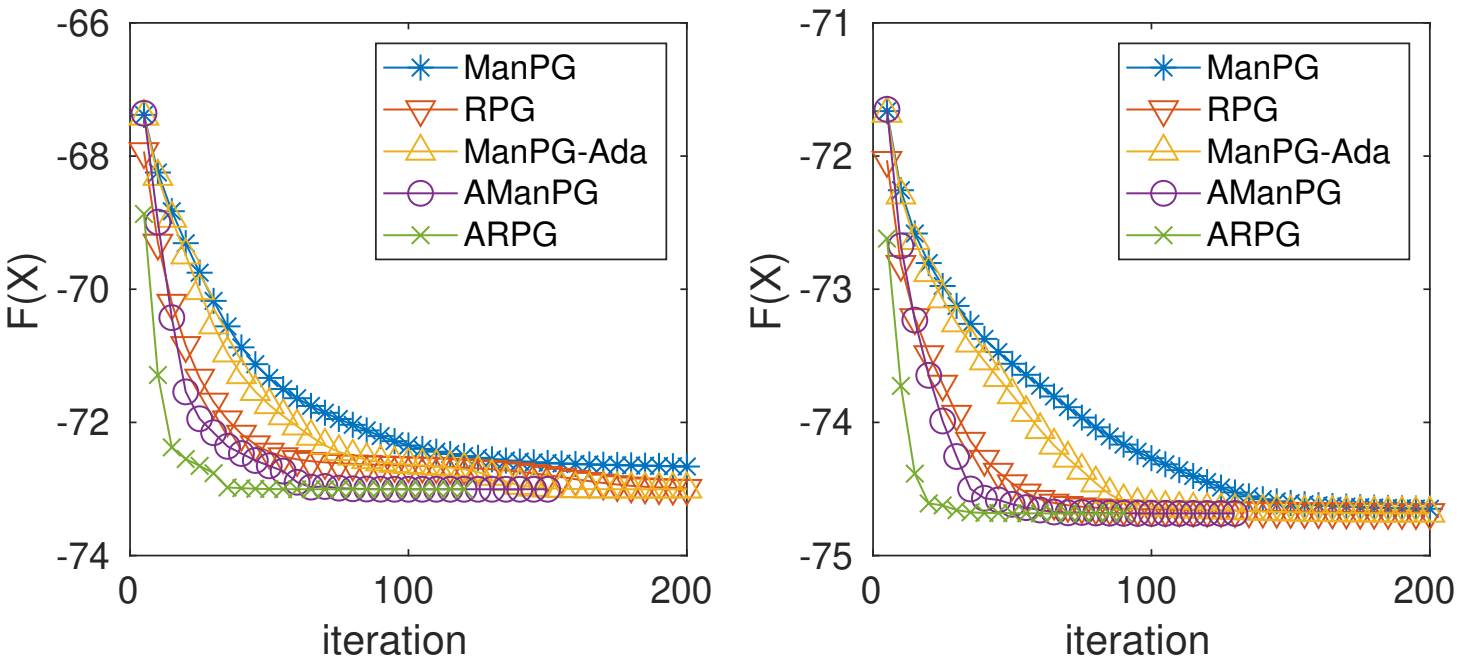

Figure: Two typical runs of ManPG, RPG, A-ManPG, and A-RPG for the Sparse PCA problem. $n = 1024$, $p = 4$, $\lambda = 2$, $m = 20$.

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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