A Riemannian Optimization technique for rank inequality constraints

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Problem and Applications

This study considers combining rank inequality constraints with a matrix manifold constraint in a problem of the form

$$\min_{x \in \mathcal{M}_{\leq k}} f(x), \qquad (1)$$

where $\mathcal{M}_{\leq k} = \{x \in \mathcal{M} | \operatorname{rank}(x) \leq k\}$ and $\mathcal{M}$ is a submanifold of $\mathbb{R}^{m\times n}$. Numerous applications exist, e.g., [ZW03, FHB04, MLP+06, JHSX11].

Background

Riemannian optimization methods play important roles:

- $\mathcal{M} = \mathbb{R}^{m\times n}$ in most of applications;
- $\mathbb{R}_r^{m\times n} := \{x \in \mathbb{R}^{m\times n} | \operatorname{rank}(x) = r\}$ is a Riemannian manifold.

Existing methods choose the k in (1) a priori. However, it is not easy to choose a suitable k.

- The solution with too small k may be unacceptable;
- The computational time may be unacceptable with too large k.

Contribution

- Generalize the admissible set from $\mathbb{R}_{\leq k}^{m\times n}$ to $\mathcal{M}_{\leq k}$;
- Define an algorithm solving a rank inequality constrained problem while finding a suitable rank for approximation;
- Prove theoretical convergence results;
- Implementations based on Riemannian optimization methods.

Basic Idea

Apply Riemannian optimization methods on a fixed rank manifold $\mathcal{M}_r$ while efficiently and effectively updating the rank r.

Update Rank

Increase rank if next two conditions hold.

- Condition I (angle threshold θ_0):

$$\angle(\operatorname{grad} f_{\mathrm{F}}(x_r), \operatorname{grad} f_r(x_r)) = \theta > \theta_0,$$

- Condition II (difference threshold, ϵ_2):

$$\|\operatorname{grad} f_{\mathrm{F}}(x_r) - \operatorname{grad} f_r(x_r)\| \geq \epsilon_2,$$

where $x_r \in \mathcal{M}_r$, $\operatorname{grad} f_{\mathrm{F}}(x)$ and $\operatorname{grad} f_r(x)$ are the Riemannian gradients with respect to $\mathcal{M}$ and $\mathcal{M}_r$ respectively.

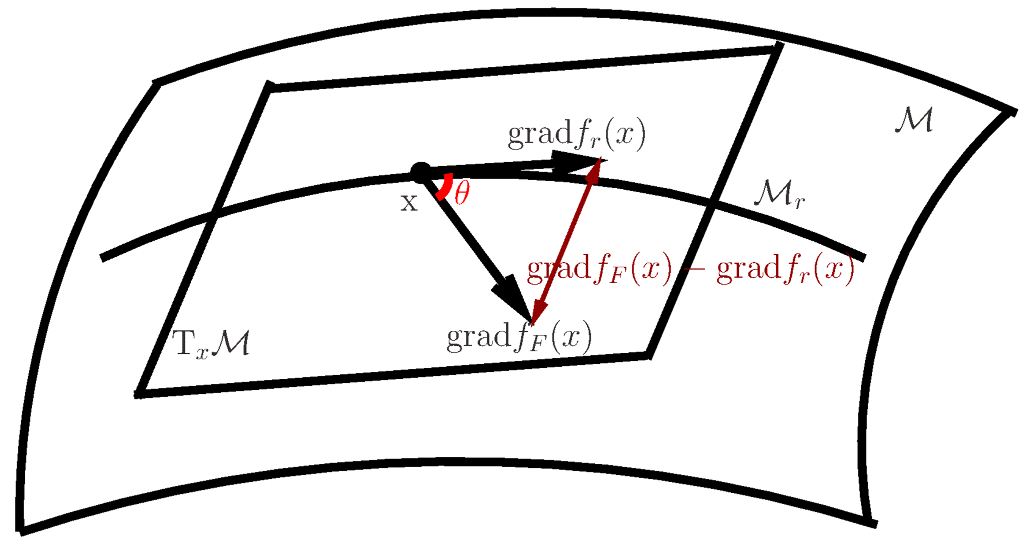

Figure 1. Strategy of increasing the rank.

Rank-Related Objects

The new concepts of rank-related vector and rank-related retraction play an important role in updating the rank and avoiding increasing it excessively.

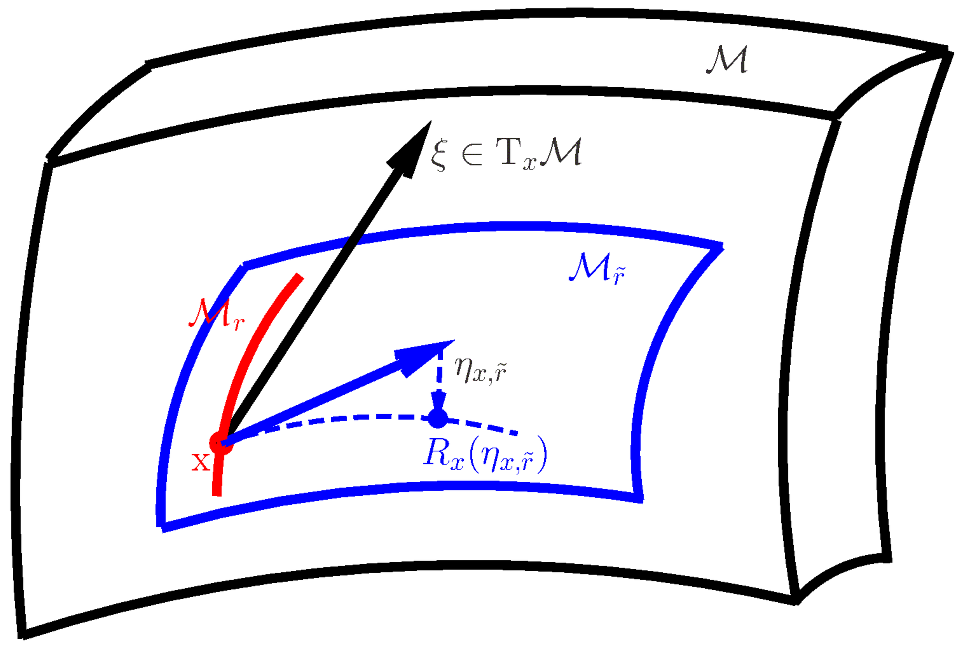

Figure 2. $x \in \mathcal{M}_r$; $r < \tilde r$; $\eta_{x,\tilde r}$ is a rank-$\tilde r$-related vector, i.e., there exists a curve $\gamma(t)$ such that $\gamma(0) = x$, $\dot\gamma(0) = \eta_{x,\tilde r}$ and $\operatorname{rank}(\gamma(t)) = \tilde r$; R is a rank-related retraction, i.e., $\operatorname{rank}(R_x(t\eta_{x,\tilde r})) = \tilde r$ for $t \in (0, \delta)$, $\delta > 0$.

Algorithm

Algorithm 1

for n = 0,1, 2,. . . **do**
  Approximately optimize f over $\mathcal{M}_r$ with initial point x_n and obtain $\tilde x_n$;
  if $\tilde x_n$ is not close to a set of lower rank matrices **then**
    if Both Conditions I and II are satisfied **then**
      Find a $\tilde r \in [r, k]$ and obtain a rank-$\tilde r$-related vector.
      Obtain x_{n+1} by applying a line search algorithm along the rank-related vector using a rank-related retraction;
    else
      If x_{n+1} is accurate enough, stop.
    end if
  else
    Reduce the rank of $\tilde x_n$ if the function value at a lower rank point is nonincreasing; Update r; Obtain next iterate x_{n+1};
  end if
end for

Main Theoretical Results

Suppose some reasonable assumptions hold:

- (Global Result) The sequence $\{x_n\}$ generated by Algorithm 1 satisfies $\liminf_{n\to\infty} \|P_{\mathrm{T}_{x_n}\mathcal{M}_{\leq k}}(\operatorname{grad} f_{\mathrm{F}}(x_n))\| \leq \left(\sqrt{1 + \frac{1}{\epsilon_1^2}}\right)\epsilon_2$, where $\epsilon_1 = \tan(\theta_0)$.
- (Local Result) The sequence $\{x_n\}$ enters a neighborhood $\mathcal{U}_*$ of a minimizer x_* and remains in $\mathcal{U}_*$. The distance $\operatorname{dist}(x_n, x_*)$ is bounded based on ϵ_1, ϵ_2 and $\operatorname{Hess} f_{\mathrm{F}}(x_*)$. The ranks of $\{x_n\}$ are fixed eventually.

Weighted Low Rank Problem

Weighted low rank problem concerns solving

$$\min_{X \in \mathcal{M}_{\leq k}} \|A - X\|_W^2$$

where $\mathcal{M} = \mathbb{R}^{m\times n}$, A is given, $W \in \mathbb{R}^{mn\times mn}$ is symmetric positive definite and $\|A - X\|_W^2 = \operatorname{vec}(A - X)^T W \operatorname{vec}(A - X)$.

Experiments

Algorithm 1 is compared with the state-of-the-art methods for weighted low rank approximation problems.

The matrix A is generated by $A_1 A_2^T \in \mathbb{R}^{10\times 80}$, where $A_1 \in \mathbb{R}^{10\times 4}$, $A_2 \in \mathbb{R}^{80\times 4}$. W is a block diagonal matrix and each block of W is $W_i = U_i \Sigma_i U_i^T \in \mathbb{R}^{10\times 10}$, where U_i is given by matlab's ORTH and RAND and Σ_i is given by randomly scaling elements from matlab's LOGSPACE.

	k	f	R_err	err	time(s)
(1)	3	2.93_{-01}	8.54_{-02}	2.53_{+00}	1.26_{-1}
	4	3.56_{-29}	9.42_{-16}	2.02_{-14}	1.05_{-2}
	5	7.02_{-29}	1.32_{-15}	2.55_{-14}	9.77_{-3}
(2)	3	2.93_{-01}	8.54_{-02}	2.53_{+00}	8.57_{-1}
	4	3.56_{-29}	9.42_{-16}	2.02_{-14}	2.52_{-2}
	5	4.27_{-29}	1.03_{-15}	2.84_{-14}	2.47_{-2}
(3)	3	2.93_{-01}	8.54_{-02}	2.53_{+00}	8.39_{-1}
	4	3.74_{-26}	3.05_{-14}	1.32_{-12}	3.19_{-2}
	5	1.36_{-22}	1.84_{-12}	1.04_{-10}	3.17_{-2}
(4)	3	2.93_{-01}	8.54_{-02}	2.53_{+00}	6.61_{-1}
	4	4.35_{-29}	1.04_{-15}	2.29_{-14}	5.58_{-2}
	5	6.27_{-29}	1.25_{-15}	2.68_{-14}	7.52_{-2}

Table 1. (1), (2), (3) and (4) denote Algorithm 1, SULS [SU14], EW-TLS [MLP+06] and APM [LPW97] respectively. R_err denotes $\|A - X\|_W / \|A\|_W$ and err denotes $\|A - X\|_F$. The subscript $\pm k$ indicates a scale of $10^{\pm k}$.

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