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# Rank-Based Norms, Capra-Conjugacies and the Rank Function

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## Abstract

We consider the space of matrices, with given number of rows and of columns, equipped with the classic trace scalar product. With any matrix (source) norm, we associate a coupling, called Capra, between the space of matrices and itself. Then, we compute the Capra conjugate and biconjugate of the rank function. They are expressed in function of a sequence of rank-based norms, more precisely generalized  $r$ -rank and dual  $r$ -rank matrix norms associated with the matrix source norm. We deduce a lower bound of the rank function given by a variational formula which involves the generalized  $r$ -rank norms. In the case of the Frobenius norm, we show that the rank function is equal to the variational formula.

## 1 Introduction

The rank of a matrix is used in sparse optimization, either as criterion or in the constraints, to obtain matrix solutions with few independent rows or columns. However, the mathematical expression of the rank makes it difficult to handle in optimization problems. This is why one often resorts to *surrogate* expressions of the (noncontinuous and nonconvex) rank function, like norms. As it is not possible to cover all the references on such a large subject, we refer the reader to a small subset [8, 9] of the literature and to [13] which offers a kind of survey of the rank function.

In this paper, we address the question of the relation between the rank function and suitable norms. For this purpose, we introduce sequences of rank-based norms — more precisely, generalized  $r$ -rank and dual  $r$ -rank matrix norms — generated from any (source) norm. With such a source norm, we also define a coupling between the space of matrices and itself, and we compute the biconjugate of the rank function under the associated conjugacy. We deduce a lower bound variational formula for the rank function which involves generalized  $r$ -rank norms. Moreover, when the source norm is the Frobenius norm, we prove that the inequality is an equality.

The paper is organized as follows. In Sect. 2, we define and study rank-based norms. In Sect. 3, we introduce CAPRA-conjugacies and their relations with the rank function.

## 2 Rank-based norms

In §2.1, we fix notation. In §2.2, we define rank-based norms as, more precisely, generalized  $r$ -rank and dual  $r$ -rank matrix norms. In §2.3, we detail the case of unitarily invariant source matrix norms.

### 2.1 Notation

In all the paper, we consider two fixed positive integers  $m$  (number of rows) and  $n$  (number of columns), and we denote  $d = \min(m, n)$ . We use the notation  $\llbracket k, l \rrbracket = \{k, k + 1, \dots, l - 1, l\}$  for any pair of integers such

that  $k \leq l$ . We denote by  $\mathcal{M}_{m,n}$  the space of real matrices with  $m$  rows and  $n$  columns, by  $\text{rk} : \mathcal{M}_{m,n} \rightarrow \mathbb{N}$  the rank function and by  $\mathcal{M}^{\leq r}$  (resp.  $\mathcal{M}^{=r}$ ) the subset of matrices of rank less than or equal to  $r$  (resp. equal to  $r$ ). We recall that the singular values of a matrix  $M \in \mathcal{M}_{m,n}$  are the square root of the (nonnegative) eigenvalues of the square matrix  $M^T M$ , and we denote by  $s(M) = \{s_i(M)\}_{i \in \llbracket 1, d \rrbracket} \in \mathbb{R}^d$  the vector composed of the singular values of  $M$  arranged in nonincreasing order, that is,

$$s(M) \in K = \{x \in \mathbb{R}^d \mid 0 \leq x_1 \leq \dots \leq x_d\} = s(\mathcal{M}_{m,n}), \quad \forall M \in \mathcal{M}_{m,n}. \quad (1)$$

For any  $t \in \mathbb{N}^*$ , we denote by  $\mathcal{O}_t$  the group of orthogonal square  $t \times t$  matrices. It is established that, for any matrix  $M \in \mathcal{M}_{m,n}$ , there exists a *singular value decomposition* [3, p. 6]  $M = U \text{diag}(s(M)) V^T$  of the matrix  $M$ , where  $U \in \mathcal{O}_m$  and  $V \in \mathcal{O}_n$ . It is also readily proven that, for any matrix  $M \in \mathcal{M}_{m,n}$ , for any  $U \in \mathcal{O}_m$  and  $V \in \mathcal{O}_n$ , we have that  $s(M) = s(UMV)$ .

When equipped with the scalar product  $\mathcal{M}_{m,n}^2 \ni M, N \mapsto \text{Tr}(MN^T)$ ,  $\mathcal{M}_{m,n}$  is a Euclidean space which is in duality with itself. As we manipulate functions with values in  $\overline{\mathbb{R}} = [-\infty, +\infty]$ , we adopt the Moreau *lower and upper additions* [14] that extend the usual addition with  $(+\infty) \dot{+} (-\infty) = (-\infty) \dot{+} (+\infty) = -\infty$  or with  $(+\infty) \dot{+} (-\infty) = (-\infty) \dot{+} (+\infty) = +\infty$ . For any subset  $Y \subset \mathcal{M}_{m,n}$ ,  $\sigma_Y : \mathcal{M}_{m,n} \rightarrow \overline{\mathbb{R}}$  denotes the *support function of the subset Y*:

$$\sigma_Y(M) = \sup_{N \in Y} \text{Tr}(MN^T), \quad \forall M \in \mathcal{M}_{m,n}. \quad (2)$$

For any norm  $\|\cdot\|$  on the space  $\mathcal{M}_{m,n}$  of matrices, also called *matrix norm*, we denote by  $\mathbb{B}_{\|\cdot\|} \subset \mathcal{M}_{m,n}$  and  $\mathbb{S}_{\|\cdot\|} \subset \mathbb{B}_{\|\cdot\|} \subset \mathcal{M}_{m,n}$  the associated unit ball and unit sphere. The dual norm  $\|\cdot\|_\star$  of the norm  $\|\cdot\|$  is defined by  $\|\cdot\|_\star = \sigma_{\mathbb{B}_{\|\cdot\|}}$ .

## 2.2 Definition of generalized $r$ -rank and dual $r$ -rank matrix norms

To define rank-based norms, one could take inspiration from the construction of vector norms. Given a vector norm, one may define other norms as follows: for any vector, one evaluates the norms of all subvectors with dimension less than or equal to a fixed integer, and then take the maximum. Unfortunately, this procedure does not work with the rank.

Indeed, let  $\|\cdot\|$  be the  $\ell_1$ -norm on the space  $\mathcal{M}_{m,n}$  of matrices, that is,  $\|M\|$  is the sum of the modules of all the components of the matrix  $M \in \mathcal{M}_{m,n}$ . Define, for any matrix  $M \in \mathcal{M}_{m,n}$  and  $r \in \llbracket 1, d \rrbracket$ ,  $\|M\|_{(r)}^{\text{tn}} = \sup_{X \subset M, \text{rk}(X) \leq r} \|X\|$ , where  $X \subset M$  is a shorthand for matrices  $X$  of  $\mathcal{M}_{m,n}$  for which there exists  $K \subset \llbracket 1, m \rrbracket$  and  $L \subset \llbracket 1, n \rrbracket$  such that  $X$  coincides with  $M$ , except for entries  $X_{k,l} = 0$  for  $(k, l) \notin K \times L$ . We now show that the function  $\|\cdot\|_{(r)}^{\text{tn}}$  is not a norm by contradicting the triangular inequality. Indeed,

consider  $m = n = 2$  and the matrix  $M = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$ . As  $\text{rk}(M) = 1$ , we get that  $\|M\|_{(1)}^{\text{tn}} = 4$ . We can write

$M = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$  and we easily get that  $\left\| \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right\|_{(1)}^{\text{tn}} = \left\| \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right\|_{(1)}^{\text{tn}} = 1$ . However, the triangular

inequality does not hold true as we have that  $4 = \|M\|_{(1)}^{\text{tn}} > \left\| \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right\|_{(1)}^{\text{tn}} + \left\| \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right\|_{(1)}^{\text{tn}} = 1 + 1 = 2$ .

This is why we turn to the following definition, inspired by the construction of generalized coordinate- $r$  vector norms in [4, Definition 3]. This construction, for matrices, can also be found in [12] in the unitarily invariant norm case (see the discussion at the beginning of §2.3).

**Proposition 1.** *Let  $\|\cdot\|$  be a norm on the space  $\mathcal{M}_{m,n}$  of matrices. We denote by  $\mathbb{B}_{\|\cdot\|}$  and  $\mathbb{S}_{\|\cdot\|}$  the associated unit ball and unit sphere, as well as, for any  $r \in \llbracket 0, d \rrbracket$ ,*

$$\mathbb{B}_{\|\cdot\|}^{\leq r} = \mathbb{B}_{\|\cdot\|} \cap \mathcal{M}^{\leq r}, \quad \mathbb{B}_{\|\cdot\|}^{=r} = \mathbb{B}_{\|\cdot\|} \cap \mathcal{M}^{=r}, \quad \mathbb{S}_{\|\cdot\|}^{\leq r} = \mathbb{S}_{\|\cdot\|} \cap \mathcal{M}^{\leq r}, \quad \mathbb{S}_{\|\cdot\|}^{=r} = \mathbb{S}_{\|\cdot\|} \cap \mathcal{M}^{=r}. \quad (3)$$

The following expressions  $\|\cdot\|_{(r),\star}^{\text{rk}}$  define a nondecreasing sequence  $\left\{\|\cdot\|_{(r),\star}^{\text{rk}}\right\}_{r \in \llbracket 1, d \rrbracket}$  of norms on  $\mathcal{M}_{m,n}$

$$\|N\|_{(r),\star}^{\text{rk}} = \sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}}(N) = \sup_{M \in \mathbb{B}_{\|\cdot\|}^{\leq r}} \text{Tr}(MN^T), \quad \forall N \in \mathcal{M}_{m,n}, \quad \forall r \in \llbracket 1, d \rrbracket, \quad (4)$$

which satisfy

$$\|\cdot\|_{(r),\star}^{\text{rk}} = \sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \sigma_{\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}}, \quad \forall r \in \llbracket 1, d \rrbracket. \quad (5)$$

*Proof.* The sequence  $\left\{\|\cdot\|_{(r),\star}^{\text{rk}}\right\}_{r \in \llbracket 1, d \rrbracket}$  in (4) is nondecreasing since the sequence  $\left\{\mathbb{B}_{\|\cdot\|}^{\leq r}\right\}_{r \in \llbracket 1, d \rrbracket}$  of unit balls in (3) is nondecreasing, as so is the sequence  $\left\{\mathcal{M}^{\leq r}\right\}_{r \in \llbracket 1, d \rrbracket}$ .

First, we prove that  $\sigma_{\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ , for  $r \in \llbracket 1, d \rrbracket$ . For this purpose, we show that  $\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \mathbb{S}_{\|\cdot\|}^{\leq r}$ , where  $\overline{\cdot}$  denotes the topological closure. The inclusion  $\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} \subset \mathbb{S}_{\|\cdot\|}^{\leq r}$  is straightforward because it is well known [13, Theorem 2] that  $\overline{\mathcal{M}^{\leq r}} = \mathcal{M}^{\leq r}$ , from which we deduce that  $\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} \cap \overline{\mathcal{M}^{\leq r}} \subset \overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} \cap \mathcal{M}^{\leq r} = \mathbb{S}_{\|\cdot\|}^{\leq r} \cap \mathcal{M}^{\leq r}$ , the inclusion being a property of the topological closure.

To prove the reverse inclusion  $\mathbb{S}_{\|\cdot\|}^{\leq r} \cap \mathcal{M}^{\leq r} \subset \overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ , we consider  $M \in \mathbb{S}_{\|\cdot\|}^{\leq r} \cap \mathcal{M}^{\leq r}$ . As  $\overline{\mathcal{M}^{\leq r}} = \mathcal{M}^{\leq r}$ , there exists a sequence  $\{M_n\}_{n \in \mathbb{N}}$  in  $\mathcal{M}^{\leq r}$  such that  $M_n \rightarrow M$  when  $n \rightarrow +\infty$ . Since  $M \in \mathbb{S}_{\|\cdot\|}^{\leq r}$ , we can always suppose that  $M_n \neq 0$ , for all  $n \in \mathbb{N}$ . Therefore  $\frac{M_n}{\|M_n\|}$  is well defined, and when  $n \rightarrow +\infty$  we have that  $\frac{M_n}{\|M_n\|} \rightarrow \frac{M}{\|M\|} = M$  since  $M \in \mathbb{S}_{\|\cdot\|}^{\leq r}$ . Now, for all  $n \in \mathbb{N}$ , on the one hand,  $\frac{M_n}{\|M_n\|} \in \mathcal{M}^{\leq r}$  and, on the other hand,  $\frac{M_n}{\|M_n\|} \in \mathbb{S}_{\|\cdot\|}^{\leq r}$ . As a consequence, we get that the sequence  $\left\{\frac{M_n}{\|M_n\|}\right\}_{n \in \mathbb{N}} \in \mathbb{S}_{\|\cdot\|}^{\leq r} \cap \mathcal{M}^{\leq r}$ , and we conclude that the limit of the sequence  $M \in \overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ . Thus, we have proven that  $\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \mathbb{S}_{\|\cdot\|}^{\leq r}$ , hence that  $\sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \sigma_{\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$  by [2, Proposition 7.13].

Second, we prove that  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ . It is readily established that  $\mathbb{S}_{\|\cdot\|}^{\leq r} \subset \mathbb{B}_{\|\cdot\|}^{\leq r} \subset \text{co}\mathbb{S}_{\|\cdot\|}^{\leq r}$  (the convex hull of  $\mathbb{S}_{\|\cdot\|}^{\leq r}$ ) as any point in  $\mathbb{B}_{\|\cdot\|}^{\leq r} = \mathbb{B}_{\|\cdot\|} \cap \mathcal{M}^{\leq r}$  is the convex combination of a point and its opposite in  $\mathbb{S}_{\|\cdot\|}^{\leq r} = \mathbb{S}_{\|\cdot\|} \cap \mathcal{M}^{\leq r}$ . Therefore, by property [2, Proposition 7.13] of the support function (2), we get that  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ . By the same reasoning, we also obtain that  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$  which, combined with the first part, gives  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}} = \sigma_{\overline{\mathbb{S}_{\|\cdot\|}^{\leq r}}} = \sigma_{\mathbb{S}_{\|\cdot\|}^{\leq r}}$ .

Third, we prove that (4) defines norms. We consider a fixed  $r \in \llbracket 1, d \rrbracket$ . As the set  $\mathbb{B}_{\|\cdot\|}^{\leq r}$  is easily seen to be bounded and symmetric,  $\|\cdot\|_{(r),\star}^{\text{rk}} = \sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}}$  is a 1-homogeneous subadditive function with values in  $[0, +\infty[$ . It remains to prove that, for any  $N \in \mathcal{M}_{m,n}$ ,  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}}(N) = 0 \Leftrightarrow N = 0$ . For this purpose, we consider a matrix  $N \in \mathcal{M}_{m,n}$  which satisfies  $\sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}}(N) = 0$ , and we prove that  $N = 0$ . We consider the singular value decomposition  $N = U \text{diag}(s(N))V^T$  of the matrix  $N$ . Defining  $M = U \text{diag}(s_1(N), 0, \dots, 0)V^T$ , the matrix  $M$  has rank less than or equal to 1. Thus, we obtain that

$$|s_1(N)|^2 = |s_1(M)|^2 = \text{Tr}(MN^T) \leq \|M\| \sup_{M' \in \mathbb{S}_{\|\cdot\|}^{\leq r}} \text{Tr}(M'^T N) = \|M\| \sigma_{\mathbb{B}_{\|\cdot\|}^{\leq r}}(N) = 0,$$

hence that  $s_1(N) = 0$ . This implies that all the singular values of  $N$  are null because  $s_1(N)$  is the largest one. Hence, we get that  $N = 0$ .

This ends the proof. □

Now, we define rank-based norms as follows.

**Definition 2.** Let  $\|\cdot\|$  be a norm on the space  $\mathcal{M}_{m,n}$  of matrices, that we call source (matrix) norm. The matrix norms in the nondecreasing sequence  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$ , given by Proposition 1, are called generalized dual  $r$ -rank matrix norms. By taking their dual norms  $\|\cdot\|_{(r),\star}^{\text{rk}} = (\|\cdot\|_{(r),\star}^{\text{rk}})_{\star}$ , we obtain a nonincreasing sequence  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  of norms on  $\mathcal{M}_{m,n}$  called generalized  $r$ -rank matrix norms.

Notice that, by (4) for  $r = d$ , and then by taking the dual norms, we get that

$$\|\cdot\|_{(1),\star}^{\text{rk}} \leq \dots \leq \|\cdot\|_{(d),\star}^{\text{rk}} = \|\cdot\|_{\star} \quad \text{and} \quad \|\cdot\|_{(1)}^{\text{rk}} \geq \dots \geq \|\cdot\|_{(d)}^{\text{rk}} = \|\cdot\|. \quad (6)$$

## 2.3 The case of unitarily invariant source matrix norms

When the source norm is unitarily invariant, the norms in Proposition 1 have been introduced and studied in [12]. The *rank constrained dual norm* in [12, Equation (9)] is a case of generalized dual  $r$ -rank matrix norm, and the *low-rank inducing norm* in [12, Equation (10)] is a case of generalized  $r$ -rank matrix norm. Hence, the term *generalized* in Definition 2.

In §2.3.1, we provide background on unitarily invariant matrix norms. In §2.3.2, we make the link between generalized  $r$ -rank and dual  $r$ -rank matrix norms, on the one hand, and generalized coordinate and dual coordinate- $r$  norms and the  $\ell_0$  pseudonorm, on the other hand. In §2.3.3, we treat the case of Schatten and Ky Fan norms.

### 2.3.1 Background on unitarily invariant matrix norms

We recall that a *unitarily invariant norm* on  $\mathcal{M}_{m,n}$  is a matrix norm such that  $\|UMV\| = \|M\|$ , for any matrix  $M \in \mathcal{M}_{m,n}$  and orthogonal matrices  $U \in \mathcal{O}_m, V \in \mathcal{O}_n$ .

We recall that a *symmetric absolute norm* is a vector norm  $\|\cdot\|$  on  $\mathbb{R}^d$  which satisfies the following properties:  $\|\cdot\|$  is *absolute* in the sense that  $\| |x| \| = \|x\|$ , for any  $x \in \mathbb{R}^d$ , where  $|x| = (|x_1|, \dots, |x_d|)$ ;  $\|\cdot\|$  is *symmetric* (or *permutation invariant*), that is,  $\|(x_{\nu(1)}, \dots, x_{\nu(d)})\| = \|(x_1, \dots, x_d)\|$ , for any  $x \in \mathbb{R}^d$  and for any permutation  $\nu$  of the indices in  $\llbracket 1, d \rrbracket$ . In the literature, a symmetric absolute norm is also often called a *symmetric gauge function*.

These two notions are linked by the following property (a proof can be found in [12], for example).

**Proposition 3** (Von Neumann). *A norm  $\|\cdot\|$  on the space  $\mathcal{M}_{m,n}$  of matrices is unitarily invariant if and only there exists a symmetric absolute norm  $\|\cdot\|$  on  $\mathbb{R}^d$  such that*

$$\|\cdot\| = \|\cdot\| \circ s \quad \text{that is,} \quad \|M\| = \|(s_1(M), \dots, s_d(M))\|, \quad \forall M \in \mathcal{M}_{m,n}. \quad (7)$$

In that case, one has the following relation between dual norms

$$\|\cdot\|_{\star} = \|\cdot\|_{\star} \circ s. \quad (8)$$

The proof relies on the so-called *Von Neumann inequality trace theorem* [7]:

$$\sup_{U \in \mathcal{O}_m, V \in \mathcal{O}_n} \text{Tr}(UMVN^T) = \langle s(M), s(N) \rangle, \quad \forall M, N \in \mathcal{M}_{m,n}, \quad (9)$$

where  $\langle \cdot, \cdot \rangle$  is the scalar product on  $\mathbb{R}^d$ .

### 2.3.2 Links with generalized coordinate- $r$ norms and the $\ell_0$ pseudonorm

We recall that the so-called  $\ell_0$  pseudonorm on  $\mathbb{R}^d$  is the function  $\ell_0 : \mathbb{R}^d \rightarrow \llbracket 0, d \rrbracket$  defined by

$$\ell_0(x) = \text{number of nonzero components of } x, \quad \forall x \in \mathbb{R}^d. \quad (10)$$

It is clear that rank and  $\ell_0$  pseudonorm are related through the relation

$$\text{rk}(M) = \ell_0(s(M)), \quad \forall M \in \mathcal{M}_{m,n}. \quad (11)$$

In [4, Definition 3], we introduce, for any vector norm  $\|\cdot\|$  on  $\mathbb{R}^d$ , the sequence  $\left\{ \|\cdot\|_{(r)}^{\mathcal{R}} \right\}_{r \in \llbracket 1, d \rrbracket}$  of *generalized coordinate- $r$  norms* on  $\mathbb{R}^d$ , and the sequence  $\left\{ \|\cdot\|_{(r),\star}^{\mathcal{R}} \right\}_{r \in \llbracket 1, d \rrbracket}$  of *generalized dual coordinate- $r$  norms*, their dual norms. We do not detail their definition as we will only need the forthcoming characterization (13), that we now detail. The norms  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$ , for any  $r \in \llbracket 1, d \rrbracket$ , are related to the  $\ell_0$  pseudonorm by means of

$$\text{the level sets} \quad \ell_0^{\leq r} = \{x \in \mathbb{R}^d \mid \ell_0(x) \leq r\}, \quad \forall r \in \llbracket 0, d \rrbracket, \quad (12a)$$

$$\text{and the level curves} \quad \ell_0^= r = \{x \in \mathbb{R}^d \mid \ell_0(x) = r\}, \quad \forall r \in \llbracket 0, d \rrbracket. \quad (12b)$$

Indeed, it is proven in [4, Equation (16)] that, for any  $r \in \llbracket 1, d \rrbracket$ , the dual coordinate- $r$  norm satisfies

$$\|\cdot\|_{(r),\star}^{\mathcal{R}} = \sigma_{\ell_0^{\leq r} \cap \mathbb{S}_{\|\cdot\|}} = \sigma_{\ell_0^= r \cap \mathbb{S}_{\|\cdot\|}}, \quad (13)$$

where  $\mathbb{S}_{\|\cdot\|} \subset \mathbb{R}^d$  denotes the unit sphere of the norm  $\|\cdot\|$ . The expression (13) is reminiscent, using (3), of the property (5) of the generalized rank-based norms.

In [12, Lemma 3], it is shown that, when the source norm  $\|\cdot\|$  is unitarily invariant, so are the generalized  $r$ -rank matrix norms and the generalized dual  $r$ -rank matrix norms (respectively called rank constrained dual norms and low-rank inducing norms). In the coming proposition, we recover this result but we add the relation (14) which establishes links between rank-based norms and generalized coordinate and dual coordinate- $r$  norms.

**Proposition 4.** *When the source norm  $\|\cdot\|$  on  $\mathcal{M}_{m,n}$  is unitarily invariant, with associated symmetric absolute norm  $\|\cdot\|$  on  $\mathbb{R}^d$  as in Proposition 3, then both the generalized dual  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  and the generalized  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$ , given by Definition 2, are unitarily invariant, with*

$$\|\cdot\|_{(r)}^{\text{rk}} = \|\cdot\|_{(r)}^{\mathcal{R}} \circ s \quad \text{and} \quad \|\cdot\|_{(r),\star}^{\text{rk}} = \|\cdot\|_{(r),\star}^{\mathcal{R}} \circ s, \quad \forall r \in \llbracket 1, d \rrbracket. \quad (14)$$

*Proof.* We suppose that the norm  $\|\cdot\|$  is unitarily invariant on  $\mathcal{M}_{m,n}$  and that  $\|\cdot\|$  is the associated symmetric absolute norm. For any  $N \in \mathcal{M}_{m,n}$ , we have that

$$\begin{aligned} \|\cdot\|_{(r),\star}^{\text{rk}} N &= \sup_{\|M\|=1, \text{rk}(M) \leq r} \text{Tr}(MN^T) && \text{(by definition (4) and property (5))} \\ &= \sup_{\|M\|=1, \text{rk}(M) \leq r, U \in \mathcal{O}_m, V \in \mathcal{O}_n} \text{Tr}(UMVN^T) \end{aligned}$$

by change of variable  $M \rightarrow UMV$ , and using the properties that  $\|UMV\| = \|M\|$  and that  $\text{rk}(UMV) = \text{rk}(M)$

$$\begin{aligned} &= \sup_{\|M\|=1, \text{rk}(M) \leq r} \left\{ \sup_{U \in \mathcal{O}_m, V \in \mathcal{O}_n} \text{Tr}(UMVN^T) \right\} \\ &= \sup_{\|M\|=1, \text{rk}(M) \leq r} \langle s(N), s(M) \rangle && \text{(using Von Neumann inequality trace theorem (9))} \\ &= \sup_{\|s(M)\|=1, \ell_0(s(M)) \leq r} \langle s(N), s(M) \rangle && \text{(by (7) and (11))} \\ &= \sup_{\|x\|=1, \ell_0(x) \leq r, x \in K} \langle s(N), x \rangle \end{aligned}$$

as easily seen from the definition (1) of the cone  $K = s(\mathcal{M}_{m,n})$ , which is in one-to-one correspondence with the image of the singular values mapping  $s$

$$= \sup_{\|x\|=1, \ell_0(x) \leq r} \langle s(N), x \rangle$$

because  $s(N) \in K$ , hence the supremum is achieved on the cone  $K$  by the well-known Hardy-Littlewood-Pólya rearrangement inequality

$$= \sigma_{\ell_0^{\leq r} \cap \mathbb{S}_{\|\cdot\|}}(s(N))$$

by definition (12a) of the level sets  $\ell_0^{\leq r}$ , and as  $\mathbb{S}_{\|\cdot\|} \subset \mathbb{R}^d$  is the unit sphere of the norm  $\|\cdot\|$

$$= \|s(N)\|_{(r),\star}^{\mathcal{R}} \cdot \quad (\text{as } \|\cdot\|_{(r),\star}^{\mathcal{R}} = \sigma_{\ell_0^{\leq r} \cap \mathbb{S}_{\|\cdot\|}} \text{ by (13)})$$

Thus, we have proven that  $\|\cdot\|_{(r),\star}^{\text{rk}} = \|\cdot\|_{(r),\star}^{\mathcal{R}} \circ s$ , that is, the second equality in (14).

Now, it is easily established by (13) that the vector norm  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$  is a symmetric absolute norm (hence so is its dual norm  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$ ). As a consequence, the first equality in (14) easily follows by using (8) (see [3, Proposition IV.2.11]), giving

$$\|\cdot\|_{(r),\star}^{\text{rk}} = \left( \|\cdot\|_{(r),\star}^{\text{rk}} \right)_{\star} = \left( \|\cdot\|_{(r),\star}^{\mathcal{R}} \circ s \right)_{\star} = \left( \|\cdot\|_{(r),\star}^{\mathcal{R}} \right)_{\star} \circ s = \|\cdot\|_{(r),\star}^{\mathcal{R}} \circ s. \quad (15)$$

By Proposition 3, we obtain the unitarily invariance of both the generalized dual  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  and the generalized  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$ .  $\square$

Because the symmetric absolute norm  $\|\cdot\|$  in Proposition 4 is a symmetric monotonic norm [1, Theorem 2], it is an orthant-monotonic norm [10, 11]. As a consequence, by [5, Proposition 13], we get that, for any  $r \in \llbracket 1, d \rrbracket$ , the generalized  $r$ -rank matrix norm  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$  is equal to the so-called  $r$ -support dual norm  $\|\cdot\|_{\star,(r)}^{\text{sn}}$ , and the generalized dual  $r$ -rank matrix norm  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$  is equal to the  $top$ - $r$  dual norm  $\|\cdot\|_{\star,(r)}^{\text{tn}}$  as introduced in [5, Definition 3].

### 2.3.3 The case of Schatten and Ky Fan source norms

For any  $p \in [1, \infty[$ , we define the  $\ell_p$  norm on  $\mathbb{R}^d$  by  $\|x\|_{\ell_p} = \left( \sum_{i=1}^d |x_i|^p \right)^{\frac{1}{p}}$ , as well as  $\|x\|_{\ell_\infty} = \max_{i \in \llbracket 1, d \rrbracket} |x_i|$ , for any vector  $x \in \mathbb{R}^d$ . The Schatten  $p$ -norm on the space  $\mathcal{M}_{m,n}$  of matrices is defined (see [3, IV.31]) as the unitarily invariant norm

$$\|M\|_{s_p} = \|s(M)\|_{\ell_p}, \quad \forall M \in \mathcal{M}_{m,n}, \quad \forall p \in [1, \infty]. \quad (16)$$

In particular, the Schatten 1-norm is the *nuclear norm* given by

$$\|M\|_{s_1} = \|s(M)\|_{\ell_1} = \sum_{i=1}^d s_i(M), \quad \forall M \in \mathcal{M}_{m,n}, \quad (17a)$$

the Schatten 2-norm is the *Frobenius norm* given by

$$\sqrt{\text{Tr}(MM^T)} = \|M\|_{s_2} = \|s(M)\|_{\ell_2} = \sqrt{\sum_{i=1}^d s_i(M)^2}, \quad \forall M \in \mathcal{M}_{m,n}, \quad (17b)$$

and the Schatten  $\infty$ -norm is the *spectral norm* given by

$$\|M\|_{s_\infty} = \|s(M)\|_{\ell_\infty} = s_1(M), \quad \forall M \in \mathcal{M}_{m,n}. \quad (17c)$$

Now, we build upon Proposition 4 to obtain expressions for the generalized dual  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  and the generalized  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$ , given by Definition 2, when the source norm is a Schatten  $p$ -norm as follows. For this purpose, we use the following properties [5]. With the notation of §2.3.2, if  $\|\cdot\|$  is the  $\ell_p$  norm, the associated generalized coordinate- $r$  norm  $\|\cdot\|_{(r)}^{\mathcal{R}}$  is the  $(p,r)$ -support norm  $\|x\|_{p,r}^{\text{sn}}$ , and the generalized dual coordinate- $r$  norm  $\|\cdot\|_{(r),\star}^{\mathcal{R}}$  is the *top- $(q,r)$  norm*  $\|\cdot\|_{q,r}^{\text{tn}}$ , where  $1/p + 1/q = 1$ . For  $y \in \mathbb{R}^d$ , letting  $\nu$  denote a permutation of  $\{1, \dots, d\}$  such that  $|y_{\nu(1)}| \geq |y_{\nu(2)}| \geq \dots \geq |y_{\nu(d)}|$ , we have that  $\|y\|_{q,r}^{\text{tn}} = \left( \sum_{l=1}^r |y_{\nu(l)}|^q \right)^{\frac{1}{q}}$ .

source norm $\ \cdot\ $	$\ \cdot\ _{(r)}^{\text{rk}}, r \in \llbracket 1, d \rrbracket$	$\ \cdot\ _{(r),\star}^{\text{rk}}, r \in \llbracket 1, d \rrbracket$
Schatten 1-norm = nuclear norm	Schatten 1-norm for all $r \in \llbracket 1, d \rrbracket$	Schatten $\infty$ -norm for all $r \in \llbracket 1, d \rrbracket$
Schatten 2-norm = Frobenius norm	$\ s(M)\ _{2,r}^{\text{sn}}$	$\ s(N)\ _{2,r}^{\text{tn}} = \sqrt{\sum_{i=1}^r s_i(N)^2}$
Schatten $p$ -norm	$\ s(M)\ _{p,r}^{\text{sn}}$	$\ s(N)\ _{q,r}^{\text{tn}} = \left( \sum_{i=1}^r s_i(N)^q \right)^{\frac{1}{q}}$
Schatten $\infty$ -norm = spectral norm	$\ s(M)\ _{\infty,r}^{\text{sn}} = s_1(M)$ Schatten $\infty$ -norm	$\ s(N)\ _{1,r}^{\text{tn}} = \sum_{i=1}^r s_i(N)$
Ky Fan $k$ -norm $k \in \llbracket 1, d \rrbracket$	Schatten 1-norm for all $r \in \llbracket 1, k \rrbracket$	Schatten $\infty$ -norm for all $r \in \llbracket 1, k \rrbracket$

Table 1: Generalized  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  and generalized dual  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  associated with by Schatten and Ky Fan source norms  $\|\cdot\|$  (for  $p \in [1, \infty]$ , and where  $1/p + 1/q = 1$ ).

Table 1 summarizes our findings. The well-known *Ky Fan  $k$ -norms* on the space  $\mathcal{M}_{m,n}$  of matrices are defined by

$$\|s(M)\|_{1,k}^{\text{tn}} = \sum_{i=1}^k s_i(M), \quad \forall M \in \mathcal{M}_{m,n}, \quad \forall k \in \llbracket 1, d \rrbracket.$$

### 3 CAPRA-conjugacies and the rank function

In §3.1, we adapt the definition of CAPRA-couplings in [4] to the case of matrices instead of vectors. In §3.2, we provide a variational lower bound of the rank function.

#### 3.1 CAPRA-couplings and conjugacies for matrices

We adapt the definition of CAPRA-couplings in [4] to the space  $\mathcal{M}_{m,n}$  of matrices.

**Definition 5.** Let  $\|\cdot\|$  be a source matrix norm on  $\mathcal{M}_{m,n}$ . The CAPRA-coupling  $\zeta$ , between  $\mathcal{M}_{m,n}$  and  $\mathcal{M}_{m,n}$ , associated with  $\|\cdot\|$ , is defined by:

$$\forall M, N \in \mathcal{M}_{m,n}, \quad \zeta(M, N) = \begin{cases} \frac{\text{Tr}(MN^T)}{\|M\|} & \text{if } M \neq 0, \\ 0 & \text{otherwise.} \end{cases} \quad (18)$$



For any function  $F : \mathcal{M}_{m,n} \rightarrow \overline{\mathbb{R}}$ , the  $\dot{\varsigma}$ -Fenchel-Moreau conjugate, or CAPRA-conjugate, is the function  $F^{\dot{\varsigma}} : \mathcal{M}_{m,n} \rightarrow \overline{\mathbb{R}}$  defined by

$$F^{\dot{\varsigma}}(N) = \sup_{M \in \mathcal{M}_{m,n}} \left( \dot{\varsigma}(M, N) \dagger (-F(M)) \right), \quad \forall N \in \mathcal{M}_{m,n}, \quad (19)$$

and the  $\dot{\varsigma}$ -Fenchel-Moreau biconjugate, or CAPRA-biconjugate, is the function  $F^{\dot{\varsigma}\dot{\varsigma}'}$  :  $\mathcal{M}_{m,n} \rightarrow \overline{\mathbb{R}}$  defined by

$$F^{\dot{\varsigma}\dot{\varsigma}'}(M) = \sup_{N \in \mathcal{M}_{m,n}} \left( \dot{\varsigma}(M, N) \dagger (-F^{\dot{\varsigma}}(N)) \right), \quad \forall M \in \mathcal{M}_{m,n}. \quad (20)$$

Then, we show below that the CAPRA-conjugate and biconjugate of the rank function are expressed in function of the generalized dual  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r),\star}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  and the generalized  $r$ -rank matrix norms  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$ , given by Definition 2. We do not give the proof as it is a simple adaptation, to the matrix case, of the proofs of [4, Propositions 11, 12].

**Proposition 6.** *Let  $\|\cdot\|$  be a source matrix norm on  $\mathcal{M}_{m,n}$ , and  $\dot{\varsigma}$  be the associated CAPRA-coupling as in Definition 5.*

*For any function  $\varphi : \llbracket 0, d \rrbracket \rightarrow \overline{\mathbb{R}}$ , we have that (with the convention that  $\|\cdot\|_{(0),\star}^{\text{rk}} = 0$ )*

$$(\varphi \circ \text{rk})^{\dot{\varsigma}}(N) = \sup_{i \in \llbracket 0, d \rrbracket} \left\{ \|N\|_{(i),\star}^{\text{rk}} - \varphi(i) \right\}, \quad \forall N \in \mathcal{M}_{m,n}, \quad (21)$$

*and, for any function  $\varphi : \llbracket 0, d \rrbracket \rightarrow \mathbb{R}_+$  (that is, with nonnegative finite values) and such that  $\varphi(0) = 0$ , we have that*

$$(\varphi \circ \text{rk})^{\dot{\varsigma}\dot{\varsigma}'}(M) = \frac{1}{\|M\|} \min_{\substack{M^{(1)} \in \mathcal{M}_{m,n}, \dots, M^{(d)} \in \mathcal{M}_{m,n} \\ \sum_{r=1}^d \|M^{(r)}\|_{(r)}^{\text{rk}} \leq \|M\| \\ \sum_{r=1}^d M^{(r)} = M}} \sum_{r=1}^d \varphi(r) \|M^{(r)}\|_{(r)}^{\text{rk}}, \quad \forall M \in \mathcal{M}_{m,n} \setminus \{0\}. \quad (22)$$

### 3.2 Variational lower bound of the rank function

Now, thanks to Proposition 6, we obtain a variational lower bound of the rank function.

**Theorem 7.** *Let  $\|\cdot\|$  be a source norm on the space  $\mathcal{M}_{m,n}$  of matrices, with associated sequence  $\left\{ \|\cdot\|_{(r)}^{\text{rk}} \right\}_{r \in \llbracket 1, d \rrbracket}$  of generalized  $r$ -rank matrix norms as in Definition 2. Then, we have the following variational lower bound of the rank function*

$$\text{rk}(M) \geq \frac{1}{\|M\|} \min_{\substack{M^{(1)} \in \mathcal{M}_{m,n}, \dots, M^{(d)} \in \mathcal{M}_{m,n} \\ \sum_{r=1}^d \|M^{(r)}\|_{(r)}^{\text{rk}} \leq \|M\| \\ \sum_{r=1}^d M^{(r)} = M}} \sum_{r=1}^d r \|M^{(r)}\|_{(r)}^{\text{rk}}, \quad \forall M \in \mathcal{M}_{m,n} \setminus \{0\}. \quad (23)$$

*Moreover, if the source norm  $\|\cdot\|$  is the Frobenius norm (17b), the inequality in (23) is an equality.*

*Proof.* From the expression (22) of  $\text{rk}^{\dot{\varsigma}\dot{\varsigma}'}$ , with  $\varphi$  the identity function, and from the (true for any coupling) inequality  $\text{rk} \geq \text{rk}^{\dot{\varsigma}\dot{\varsigma}'}$ , we readily deduce (23).

In the rest of the proof — which follows that of [6, Theorem 11] —  $\|\cdot\|$  denotes the Frobenius norm (17b). We consider a fixed matrix  $M \in \mathcal{M}_{m,n} \setminus \{0\}$  and we are going to show that  $\text{rk}(M) = \text{rk}^{\dot{C}\dot{C}'}(M)$ . We denote by  $r = \text{rk}(M) \geq 1$  the rank of  $M$ . By Table 1, and as  $s_i(M) = 0 \iff i > r$ , we have that

$$\|M\|_{(k),\star}^{\text{rk}} = \|s(M)\|_{2,k}^{\text{tn}} = \sqrt{\sum_{i=1}^k s_i(M)^2} \begin{cases} = \sqrt{\sum_{i=1}^r s_i(M)^2} = \|M\|, & \forall k \geq r, \\ < \sqrt{\sum_{i=1}^r s_i(M)^2} = \|M\|, & \forall k < r. \end{cases} \quad (24)$$

We consider the mapping  $\phi : ]0, +\infty[ \rightarrow \mathbb{R}$  defined by

$$\phi(\lambda) = \frac{\text{Tr}(\lambda M M^T)}{\|M\|} - \sup_{k \in \llbracket 0, d \rrbracket} \left\{ \|\lambda M\|_{(k),\star}^{\text{rk}} - k \right\}, \quad \forall \lambda > 0, \quad (25)$$

and we will show that  $\lim_{\lambda \rightarrow +\infty} \phi(\lambda) = r$ . We have that

$$\phi(\lambda) = \lambda \|M\| - \sup \left( 0, \sup_{k \in \llbracket 1, d \rrbracket} \left\{ \lambda \|M\|_{(k),\star}^{\text{rk}} - k \right\} \right)$$

by definition (25) of  $\phi$ , by the convention that  $\|M\|_{(0),\star}^{\text{rk}} = 0$  and by  $\|M\|^2 = \text{Tr}(M M^T)$

$$\begin{aligned} &= \lambda \|M\|_{(r),\star}^{\text{rk}} + \inf \left\{ 0, - \sup_{k \in \llbracket 1, d \rrbracket} \left[ \lambda \|M\|_{(k),\star}^{\text{rk}} - k \right] \right\} && \text{(as } \|M\| = \|M\|_{(r),\star}^{\text{rk}} \text{ by (24))} \\ &= \inf \left\{ \lambda \|M\|_{(r),\star}^{\text{rk}}, \lambda \|M\|_{(r),\star}^{\text{rk}} + \inf_{k \in \llbracket 1, d \rrbracket} \left( - \left[ \lambda \|M\|_{(k),\star}^{\text{rk}} - k \right] \right) \right\} \\ &= \inf \left\{ \lambda \|M\|_{(r),\star}^{\text{rk}}, \inf_{k \in \llbracket 1, d \rrbracket} \left( \lambda (\|M\|_{(r),\star}^{\text{rk}} - \|M\|_{(k),\star}^{\text{rk}}) + k \right) \right\} \\ &= \inf \left\{ \lambda \|M\|_{(r),\star}^{\text{rk}}, \inf_{k \in \llbracket 1, r-1 \rrbracket} \left( \lambda (\|M\|_{(r),\star}^{\text{rk}} - \|M\|_{(k),\star}^{\text{rk}}) + k \right), \inf_{k \in \llbracket r, d \rrbracket} \left( \lambda (\|M\|_{(r),\star}^{\text{rk}} - \|M\|_{(k),\star}^{\text{rk}}) + k \right) \right\} \\ &= \inf \left\{ \lambda \|M\|_{(r),\star}^{\text{rk}}, \inf_{k \in \llbracket 1, r-1 \rrbracket} \left( \lambda (\|M\|_{(r),\star}^{\text{rk}} - \|M\|_{(k),\star}^{\text{rk}}) + k \right), r \right\} \end{aligned}$$

as  $\|M\|_{(k),\star}^{\text{rk}} = \|M\|_{(r),\star}^{\text{rk}}$  for  $k \geq r$  by (24). Let us show that the two first terms in the infimum go to  $+\infty$  when  $\lambda \rightarrow +\infty$ . The first term  $\lambda \|M\|_{(r),\star}^{\text{rk}}$  goes to  $+\infty$  because  $\|M\|_{(r),\star}^{\text{rk}} = \|M\| > 0$  by assumption ( $M \neq 0$ ). The second term  $\inf_{k \in \llbracket 1, r-1 \rrbracket} \left( \lambda (\|M\|_{(r),\star}^{\text{rk}} - \|M\|_{(k),\star}^{\text{rk}}) + k \right)$  also goes to  $+\infty$  because  $\text{rk}(M) = r$ , so that  $\|M\| = \|M\|_{(r),\star}^{\text{rk}} > \|M\|_{(k),\star}^{\text{rk}}$  for  $k \in \llbracket 1, r-1 \rrbracket$  as shown in (24). Therefore, we get that  $\lim_{\lambda \rightarrow +\infty} \phi(\lambda) = \inf\{+\infty, +\infty, r\} = r$ . This concludes the proof since

$$\begin{aligned} r &= \lim_{\lambda \rightarrow +\infty} \phi(\lambda) \leq \sup_{N \in \mathcal{M}_{m,n}} \left( \frac{\text{Tr}(M N^T)}{\|M\|} - \sup_{k \in \llbracket 0, d \rrbracket} \left\{ \|N\|_{(k),\star}^{\text{rk}} - k \right\} \right) && \text{(by definition (25) of } \phi) \\ &= \sup_{N \in \mathcal{M}_{m,n}} \left( \frac{\text{Tr}(M N^T)}{\|M\|} - \text{rk}^{\dot{C}}(N) \right) \end{aligned}$$

by the formula (21) for the conjugate  $\text{rk}^{\dot{C}}$

$$\begin{aligned} &= \text{rk}^{\dot{C}\dot{C}'}(M) && \text{(by the biconjugate formula (20))} \\ &\leq \text{rk}(M) && \text{(as } \text{rk}^{\dot{C}\dot{C}'} \leq \text{rk}) \\ &= r. && \text{(by assumption)} \end{aligned}$$

Therefore, we have obtained that  $r = \text{rk}^{\dot{C}\dot{C}'}(M) = \text{rk}(M)$ .

This ends the proof.  $\square$

## 4 Conclusion

As recalled in the Introduction, since the mathematical expression of the rank makes it difficult to handle in optimization problems, one often resorts to surrogate expressions like matrix norms. In this paper, we have shown how such surrogates can be obtained as variational lower bound of the rank function (Theorem 7). Interestingly, the formula depends on a (source) matrix norm and on the derived generalized  $r$ -rank matrix norms, that we introduce (Definition 2). This is made possible by the versatility of the CAPRA-couplings, themselves depending on a matrix norm (Definition 5). Thus, we hope to offer a general framework to derive matrix norms suitable for optimization problems involving the rank function, as well as variational formulations.

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