

Primal-dual path-following algorithms for circular programming

Baha Alzalg^{1*} and Mohammad Pirhaji²

¹Department of Mathematics, The University of Jordan, Amman 11942, Jordan
b.alzalg@ju.edu.jo

²Department of Applied Mathematics, Shahrekord University, Shahrekord, Iran
mojtabapirhaji@yahoo.com

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Abstract: Circular programming problems are a new class of convex optimization problems that include second-order cone programming problems as a special case. Alzadeh and Goldfarb [Math. Program. Ser. A 95 (2003) 3–51] introduced primal-dual path-following algorithms for solving second-order cone programming problems. In this paper, we generalize their work by using the machinery of Euclidean Jordan algebras associated with the circular cones to derive primal-dual path-following interior point algorithms for circular programming problems. We prove polynomial convergence of the proposed algorithms by showing that the circular logarithmic barrier is a strongly self-concordant barrier. The numerical examples show the path-following algorithms are simple and efficient.

Keywords: Circular cone programming, Interior point methods, Euclidean Jordan algebra, Self-concordance

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1. Introduction

We introduce and study the primal-dual pair of *circular programming* (CP) problems:

$$\begin{aligned} \min \quad & \langle c, x \rangle_{\theta} & \max \quad & b^{\top} y \\ \text{s.t.} \quad & [Ax]_{\theta} =, & \text{s.t.} \quad & A^{\top} y + s = c, \\ & x \in \mathcal{Q}_{\theta}^n, & & s \in \mathcal{Q}_{\theta}^n, y \in \mathbb{R}^m, \end{aligned} \tag{1}$$

* Corresponding Author

where $\theta \in (0, \pi/2)$ is a given angle, the inner product $\langle c, x \rangle_\theta$ denotes the *circular inner product* between c and x , which we define as $\langle c, x \rangle_\theta := c^\top I_n^2(\theta)x$, the matrix-vector product $[Ax]_\theta$ denotes the *circular matrix-vector product* between A and x , which we define as $[Ax]_\theta := AI_n^2(\theta)x$, the matrix $I_n(\theta)$ is called the *circular identity matrix*, which we define as

$$I_n(\theta) := \begin{bmatrix} 1 & 0^\top \\ 0 & \cot \theta I_{n-1} \end{bmatrix} \in \mathbb{R}^{n \times n}$$

to act as a generalization of the (standard) identity matrix $I_n = I_n(\frac{\pi}{4})$, the cone \mathcal{Q}_θ^n denotes the *circular cone* [4, 26–28] of dimension n , which is defined as

$$\mathcal{Q}_\theta^n := \left\{ \begin{bmatrix} x_0 \\ \bar{x} \end{bmatrix} \in \mathbb{R} \times \mathbb{R}^{n-1} : x_0 \geq \cot \theta \|\bar{x}\| \right\}, \quad (2)$$

and, finally, the norm $\|\cdot\|$ denotes the standard Euclidean norm.

An important special case of circular cone is that in which $\theta = \frac{\pi}{4}$. In this case, the circular cone \mathcal{Q}_θ^n reduces to the well-known second-order cone \mathcal{Q}^n , which is defined as

$$\mathcal{Q}^n := \left\{ \begin{bmatrix} x_0 \\ \bar{x} \end{bmatrix} \in \mathbb{R} \times \mathbb{R}^{n-1} : x_0 \geq \|\bar{x}\| \right\} = \mathcal{Q}_{\frac{\pi}{4}}^n,$$

the circular identity matrix $I_n(\theta)$ reduces to the identity matrix I_n , the circular inner product between c and x (i.e., $\langle c, x \rangle_\theta = c^\top I_n^2(\theta)x$) reduces to the standard inner product between c and x (i.e., $c^\top x$), the circular matrix-vector product between A and x (i.e., $AI_n^2(\theta)x$) reduces to the (standard) matrix-vector product between A and x (i.e., Ax), and, therefore, the CP problems (1) reduces to second-order cone programming problems [1]. So, CP includes second-order cone programming as a special case. We will also see that the CP is a special case of semidefinite programming [24].

It is known that circular cone is a closed, convex, pointed, solid cone. It was also popularly known (see for example [6, Theorem 3.3.6]) that the dual of the circular cone (2), denoted by \mathcal{Q}_θ^{n*} , is the circular cone

$$\mathcal{Q}_{\frac{\pi}{2}-\theta}^n = \left\{ \begin{bmatrix} x_0 \\ \bar{x} \end{bmatrix} \in \mathbb{R} \times \mathbb{R}^{n-1} : x_0 \geq \tan \theta \|\bar{x}\| \right\}.$$

In [4], Alzalg has shown that, under the circular inner product, the circular cone \mathcal{Q}_θ^n is indeed self-dual (i.e., $\mathcal{Q}_\theta^{n*} = \mathcal{Q}_\theta^n$; see Lemma 1) and homogeneous, hence it becomes a symmetric cone. In fact, there is a one-to-one correspondence between Euclidean Jordan algebras and symmetric cones. As a result, the circular cone is indeed the cone of squares of some Euclidean Jordan algebra. This motivates us to establish a Euclidean Jordan algebra associated with the circular cone. In [4], Alzalg has set up the Jordan algebra associated with the circular cone by establishing a new spectral decomposition (different and much more efficient than what has been established

in [26]) associated with this cone and establishing a circular Jordan multiplication associated with its algebra. We have also demonstrated that this algebra forms a Euclidean Jordan algebra with the circular inner product.

Being a symmetric cone, circular programming becomes one of the special cases of symmetric programming [23]. In fact, linear programming, second-order cone programming, circular programming and semidefinite programming are considered the most important subclasses of symmetric programming. The applications of the circular cone lie in various real-world engineering problems, for example the optimal grasping manipulation problems for multi-fingered robots [8, 16, 18]. In addition, CP is applied in the perturbation analysis of second-order cone programming problems [7].

Interior point methods are one of the efficient methods for conic optimization problems in general (see for example [12, 13, 19, 20, 25]) and for CP problems in particular [9, 14, 15]. Monteiro [19] introduced primal-dual path-following algorithms for solving semidefinite programming (see also Zhang [25]). Alizadeh and Goldfarb [1] introduced primal-dual path-following algorithms for solving second-order cone programs. These primal-dual interior point algorithms and their analysis have been extended by Schmieta and Alizadeh [23] for solving optimization problems over all symmetric cones. The purpose of this paper is to utilize the work of Monteiro [19], Alizadeh and Goldfarb [1] and Schmieta and Alizadeh [23] to derive primal-dual path-following algorithms for the primal-dual pair of CP problems (1). We prove the polynomial convergence results of the proposed algorithms by showing that the logarithmic barrier in the circular case is a strongly self-concordant barrier [20]. The numerical examples show the path-following algorithms are efficient.

This paper is organized as follows. The Euclidean Jordan algebra of the circular cones mentioned above is the substance of Section 2. In Section 3, we introduce the logarithmic barrier in the circular case for our problem formulation, and then state the self-concordance property of this barrier. Based on this property, we write the optimality conditions for the CP problems (1) and describe the commutative class of directions for the central path in Section 4, then we present short-, semi-long-, and long-step variants of the path-following algorithm for CP in Section 5. Section 6 is devoted to prove the self-concordance property stated in Section 3. In Section 7, we show by numerical examples that the path-following algorithms are simple and efficient. The last section contains some concluding remarks.

We end this section by introducing some notations that will be used in the sequel, and then proving the self-duality of the circular cone.

We use “,” for adjoining vectors and matrices in a row, and use “;” for adjoining them in a column. So, for example, if x, y , and z are vectors, we have

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = (x^\top, y^\top, z^\top)^\top = (x; y; z).$$

We use \mathbb{R} to denote the field of real numbers. For each vector $x \in \mathbb{R}^n$ whose first

entry is indexed with 0, we write \bar{x} for the subvector consisting of entries 1, through $n - 1$ (therefore $x = (x_0; \bar{x}) \in \mathbb{R} \times \mathbb{R}^{n-1}$). We let \mathcal{E}^n denote the n dimensional real vector space $\mathbb{R} \times \mathbb{R}^{n-1}$ whose elements x are indexed with 0. For a vector $x \in \mathcal{E}^n$ and a matrix $A \in \mathbb{R}^{m \times n}$, we let

$$\begin{aligned} x_\theta &:= (x_0; \cot \theta \bar{x}) = I_n(\theta)x, & A_\theta &:= AI_n(\theta), \\ x_{\theta^2} &:= (x_0; \cot^2 \theta \bar{x}) = I_n^2(\theta)x, & A_{\theta^2} &:= AI_n^2(\theta). \end{aligned} \quad (3)$$

Hence $\bar{x}_\theta = \cot \theta \bar{x}$, and $\|\bar{x}_\theta\| = \cot \theta \|\bar{x}\|$. Therefore, we can now rewrite the circular cone \mathcal{Q}_θ^n as follows

$$\mathcal{Q}_\theta^n = \{x \in \mathcal{E}^n : x_0 \geq \|\bar{x}_\theta\|\}.$$

As a result,

$$x \in \mathcal{Q}_\theta^n \quad \text{if and only if} \quad x_\theta \in \mathcal{Q}^n. \quad (4)$$

We can also rewrite the circular inner product between two vectors $x, y \in \mathcal{E}^n$ as follows:

$$\langle x, y \rangle_\theta := x^\top I_n^2(\theta)y = x_\theta^\top y_\theta = x_\theta^\top y_\theta = x_0 y_0 + \cot^2 \theta \bar{x}^\top \bar{y}, \quad (5)$$

and rewrite the circular matrix-vector product between a matrix $A \in \mathbb{R}^{n \times n}$ and a vector $x \in \mathcal{E}^n$ as follows:

$$[Ax]_\theta := AI_n^2(\theta)x = A_\theta x_\theta = A_{\theta^2} x. \quad (6)$$

In general, we define the *circular matrix product* between two matrices $A, B \in \mathbb{R}^{n \times n}$ as follows:

$$[AB]_\theta := AI_n^2(\theta)B = A_{\theta^2} B.$$

As we mentioned above, under the standard inner product, the circular cone \mathcal{Q}_θ^n is not self-dual, and the dual of \mathcal{Q}_θ^n is $\mathcal{Q}_{\frac{n}{2}-\theta}^n$. In fact, the inner product that should be considered with the circular cones is the circular inner product defined in (5). Under the circular inner product, the dual of \mathcal{Q}_θ^n is defined as

$$\mathcal{Q}_\theta^{n*} := \{x \in \mathcal{E}^n : x_\theta^\top y_\theta \geq 0, \forall y \in \mathcal{Q}_\theta^n\}.$$

The proof of the following lemma can be found in [4, Section 3]. We prefer to present a shorter and more direct proof because it takes the advantage of using our notations.

Lemma 1. Under the circular inner product, the circular cone \mathcal{Q}_θ^n is self-dual. That is, $\mathcal{Q}_\theta^{n*} = \mathcal{Q}_\theta^n$.

Proof. The proof follows from the following equivalences:

$$\begin{aligned} x \in \mathcal{Q}_\theta^n &\iff x_\theta \in \mathcal{Q}^n && \text{(by (4))} \\ &\iff x_\theta \in \mathcal{Q}^{n*} && \text{(as } \mathcal{Q}^n = \mathcal{Q}^{n*}\text{)} \\ &\iff x_\theta^\top y_\theta \geq 0, \forall y_\theta \in \mathcal{Q}^n && \text{(by definition of } \mathcal{Q}^{n*}\text{)} \\ &\iff x_\theta^\top y_\theta \geq 0, \forall y \in \mathcal{Q}_\theta^n && \text{(by (4))} \\ &\iff x_\theta \in \mathcal{Q}_\theta^{n*} && \text{(by definition of } \mathcal{Q}_\theta^{n*}\text{)}. \end{aligned}$$

□

2. The Euclidean Jordan algebra of the circular cone

Let $x \in \mathcal{E}^n$. The *circular spectral decomposition* of x with respect to the angle $\theta \in (0, \pi/2)$ is obtained as follows [4]

$$\begin{aligned} x &= (x_0 + \cot \theta \|\bar{x}\|) \left(\frac{1}{2}\right) \begin{bmatrix} 1 \\ \frac{\tan \theta \bar{x}}{\|\bar{x}\|} \end{bmatrix} + (x_0 - \cot \theta \|\bar{x}\|) \left(\frac{1}{2}\right) \begin{bmatrix} 1 \\ -\frac{\tan \theta \bar{x}}{\|\bar{x}\|} \end{bmatrix} \\ &= \underbrace{(x_0 + \|\bar{x}_\theta\|)}_{\lambda_{\theta,1}(x)} \underbrace{\left(\frac{1}{2}\right) \begin{bmatrix} \frac{1}{\bar{x}} \\ \frac{1}{\|\bar{x}_\theta\|} \end{bmatrix}}_{c_{\theta,1}(x)} + \underbrace{(x_0 - \|\bar{x}_\theta\|)}_{\lambda_{\theta,2}(x)} \underbrace{\left(\frac{1}{2}\right) \begin{bmatrix} \frac{1}{\bar{x}} \\ -\frac{1}{\|\bar{x}_\theta\|} \end{bmatrix}}_{c_{\theta,2}(x)}, \end{aligned} \quad (7)$$

where x_θ is defined in (3). The spectral decomposition (7) is associated with the circular cone, and it is viewed as a generalization of the spectral decomposition in [1, Section 4] which is associated with the second-order cone. Under the circular spectral decomposition (7), we have that

$$\text{trace}(x) := \lambda_{\theta,1}(x) + \lambda_{\theta,2}(x) = 2x_0, \quad \det_\theta(x) := \lambda_{\theta,1}(x)\lambda_{\theta,2}(x) = x_0^2 - \|\bar{x}_\theta\|^2,$$

and that $c_{\theta,1} + c_{\theta,2} = e := (1; 0)$ which is the *identity* element of \mathcal{E}^n . It is quite easy to see that $\text{trace}(e) = 2$, $\det(e) = 1$, $\lambda_{\theta,1}(c_{\theta,1}) = \lambda_{\theta,1}(c_{\theta,2}) = 1$, $\lambda_{\theta,2}(c_{\theta,1}) = \lambda_{\theta,2}(c_{\theta,2}) = 0$, $c_{\theta,1} = Rc_{\theta,2}$, and $c_{\theta,2} = Rc_{\theta,1}$, where R is the reflection matrix

$$R := \begin{bmatrix} 1 & 0^\top \\ 0 & -I_{n-1} \end{bmatrix}. \quad (8)$$

For any real valued continuous function f_θ , we define the image of x under f_θ with respect to θ as

$$f_\theta(x) := f_\theta(\lambda_{\theta,1}(x))c_{\theta,1}(x) + f_\theta(\lambda_{\theta,2}(x))c_{\theta,2}(x).$$

For instance, for $p \in \mathbb{R}$, $x^p := \lambda_{\theta,1}^p(x)c_{\theta,1}(x) + \lambda_{\theta,2}^p(x)c_{\theta,2}(x)$. In particular, with a little calculation, we can obtain

$$x^{-1} := \frac{1}{\lambda_{\theta,1}(x)}c_{\theta,1}(x) + \frac{1}{\lambda_{\theta,2}(x)}c_{\theta,2}(x) = \frac{1}{\det_\theta(x)} \begin{bmatrix} x_0 \\ -\bar{x} \end{bmatrix} = \frac{R}{\det_\theta(x)} x,$$

which is called the *inverse* of x (provided that x is invertible, i.e., $\det_\theta(x) \neq 0$).

The *Frobenius norm* with respect to θ of x is defined as $\|x\|_{\theta,F} := \sqrt{\lambda_{\theta,1}^2(x) + \lambda_{\theta,2}^2(x)}$, and the *2-norm* of x with respect to θ is defined as $\|x\|_{\theta,2} := \max\{|\lambda_{\theta,1}(x)|, |\lambda_{\theta,2}(x)|\}$. It is clear that $\|x\|_{\theta,2} \leq \|x\|_{\theta,F}$.

We call $x \in \mathcal{E}^n$ positive semidefinite if $x \in \mathcal{Q}_\theta^n$ (i.e., $\lambda_{1,2}(x) \geq 0$), and positive definite if $x \in \text{Int}(\mathcal{Q}_\theta^n)$ (i.e., $\lambda_{1,2}(x) > 0$). We write $x \succeq_\theta 0$ to mean that x is positive semidefinite, and $x \succ_\theta 0$ to mean that x is positive definite. We also write $x \succeq_\theta y$ or $y \preceq_\theta x$ to mean that $x - y \succeq_\theta 0$, and $x \succ_\theta y$ or $y \prec_\theta x$ to mean that $x - y \succ_\theta 0$. For real symmetric matrices of order n , X and Y , we write $X \succeq 0$ ($X \succ 0$) to mean that X is positive semidefinite (X is positive definite), and $X \succeq Y$ ($X \succ Y$) or $Y \preceq X$ ($Y \prec X$) to mean that $X - Y \succeq 0$ ($X - Y \succ 0$).

We define the *arrow-shaped matrix* $\text{Arw}_\theta(x)$ associated with $x \in \mathcal{E}^n$ with respect to θ as

$$\text{Arw}_\theta(x) := \begin{bmatrix} x_0 & \cot \theta \bar{x}^\top \\ \cot \theta \bar{x} & x_0 I_{n-1} \end{bmatrix} = \begin{bmatrix} x_0 & \bar{x}\theta^\top \\ \bar{x}\theta & x_0 I_{n-1} \end{bmatrix}. \quad (9)$$

Note that $\text{Arw}_\theta(x)e = x_\theta$, $\text{Arw}_\theta(x)x_\theta = x_\theta^2$ and $\text{Arw}(e) = I_n$. Note also that $x \succeq_\theta 0$ ($x \succ_\theta 0$) if and only if the matrix $\text{Arw}_\theta(x) \succeq 0$ ($\text{Arw}_\theta(x) \succ 0$). This explains why circular programming is a special case of semidefinite programming.

The *Jordan multiplication* between two vectors x and y with respect to θ is defined as

$$(x \circ y)_\theta := \begin{bmatrix} x_\theta^\top y_\theta \\ x_0 \bar{y}_\theta + y_0 \bar{x}_\theta \end{bmatrix} = \begin{bmatrix} x_\theta^\top y_\theta \\ x_0 \bar{y}_\theta + y_0 \bar{x}_\theta \end{bmatrix} = \text{Arw}_\theta(x)y_\theta = \text{Arw}_\theta(x)\text{Arw}_\theta(y)e. \quad (10)$$

It is clear that the definitions of the circular arrow-shaped matrix in (9) and the circular Jordan multiplication in (10) generalize the corresponding ones in [1, Section 4] associated with the second-order cone.

Observe that $c_{\theta,1}^2 = (c_{\theta,1} \circ c_{\theta,1})_\theta = c_{\theta,1}$, $c_{\theta,2}^2 = (c_{\theta,2} \circ c_{\theta,2})_\theta = c_{\theta,2}$, $(c_{\theta,1} \circ c_{\theta,2})_\theta = 0$. Therefore, $\{c_{\theta,1}, c_{\theta,2}\}$ is a Jordan frame. The vectors x and y of \mathcal{E}^n are *simultaneously decomposed* if they share a Jordan frame, i.e., $x = \lambda_{\theta,1}(x)c_{\theta,1}(x) + \lambda_{\theta,2}(x)c_{\theta,2}(x)$ and $y = \omega_{\theta,1}(x)c_{\theta,1}(x) + \omega_{\theta,2}(x)c_{\theta,2}(x)$ for a Jordan frame $\{c_{\theta,1}, c_{\theta,2}\}$. We say x and y *operator commute* with respect to θ if for all $z \in \mathcal{E}^n$, we have that $(x \circ (y \circ z))_\theta = (y \circ (x \circ z))_\theta$. Two vectors in \mathcal{E}^n operator commute if and only if they are simultaneously decomposed (see [23, Theorem 27]).

One can easily see that, for any $\alpha, \beta \in \mathbb{R}$, $(x \circ (\alpha y + \beta z))_\theta = \alpha(x \circ y)_\theta + \beta(x \circ z)_\theta$ and $((\alpha y + \beta z) \circ x)_\theta = \alpha(y \circ x)_\theta + \beta(z \circ x)_\theta$. Note that $(x \circ e)_\theta = x$, $(x \circ x^{-1})_\theta = e$, $x^p = (x^{p-1} \circ x)_\theta$ for any nonnegative integer $p \geq 1$, and $(x^p \circ x^q)_\theta = x^{p+q}$ for any nonnegative integer $p, q \geq 1$. Therefore, the algebra $(\mathcal{E}^n, \theta, \circ)$ is power associative (it is not associative though). In fact, one can also see that

$$x \circ y)_\theta = (y \circ x)_\theta \quad (\text{commutativity})$$

and

$$(x \circ (x^2 \circ y))_\theta = (x^2 \circ (x \circ y))_\theta \quad (\text{Jordan's axiom}).$$

This shows that the algebra $(\mathcal{E}^n, \theta, \circ)$ is a Jordan algebra with the circular Jordan multiplication $(\cdot \circ \cdot)_\theta$ defined in (10). Moreover, we can also show that the Jordan algebra $(\mathcal{E}^n, \theta, \circ)$ is a Euclidean Jordan algebra under the circular inner product $\langle \cdot, \cdot \rangle_\theta$ defined in (5). We have the following theorem [4].

Theorem 1. *The cone of squares of the Euclidean Jordan algebra $(\mathcal{E}^n, \theta, \circ)$ is the circular cone \mathcal{Q}_θ^n .*

The quadratic operator $Q_{\theta,x,z} : \mathcal{E}^n \times \mathcal{E}^n \rightarrow \mathcal{E}^n$ associated with the pair $(x, z) \in \mathcal{E}^n \times \mathcal{E}^n$ with respect to θ is given by

$$\begin{aligned} Q_{\theta,x,z} &:= \text{Arw}_\theta(x)\text{Arw}_\theta(z) + \text{Arw}_\theta(z)\text{Arw}_\theta(x) - \text{Arw}_\theta(x \circ z) \\ &= \begin{bmatrix} x_\theta^\top z_\theta & \cot \theta (x_0 \bar{z}^\top + z_0 \bar{x}^\top) \\ \cot \theta (x_0 \bar{z} + z_0 \bar{x}) & x_0 z_0 I_{n-1} + (\bar{x}_\theta \bar{z}_\theta^\top + \bar{z}_\theta \bar{x}_\theta^\top - \bar{x}_\theta^\top \bar{z}_\theta I_{n-1}) \end{bmatrix}. \end{aligned}$$

The quadratic representation $Q_{\theta,x} : \mathcal{E}^n \rightarrow \mathcal{E}^n$ associated with $x \in \mathcal{E}^n$ with respect to θ is given by

$$\begin{aligned} Q_{\theta,x} &:= 2\text{Arw}_\theta^2(x) - \text{Arw}_\theta(x^2) \\ &= \begin{bmatrix} \|x_\theta\|^2 & 2 \cot \theta x_0 \bar{x}^\top \\ 2 \cot \theta x_0 \bar{x} & \det_\theta(x) I_{n-1} + 2\bar{x}_\theta \bar{x}_\theta^\top \end{bmatrix} \\ &= 2x_\theta x_\theta^\top I_n(\theta) - \det_\theta(x) R, \end{aligned}$$

where R is the reflection matrix defined in (8). Note that $Q_{\theta,x}e = x_\theta^2$, $Q_{\theta,x}x_\theta^{-1} = x_\theta$, and $Q_{\theta,e} = I_n$.

We finally present some handy tools needed for our computations.

Lemma 2. [4, Theorem 7] *Let $x, u \in \mathcal{E}^n$, and $y = y(x)$ be a function of x in \mathcal{J} . Then*

1. *The gradient $\nabla_x \ln \det_\theta x = 2I_n^2(\theta)x^{-1} = 2(x^{-1})_{\theta^2}$, provided that $\det_\theta(x)$ is positive (so x is invertible). More generally, $\nabla_x \ln \det_\theta y = 2(\nabla_x y)_{\theta^2}^\top y^{-1} = 2(\nabla_x y)^\top (y^{-1})_{\theta^2}$, provided that $\det_\theta y$ is positive.*
2. *The Hessian $\nabla_{xx}^2 \ln \det_\theta x = -2I_n^2(\theta)Q_{\theta,x^{-1}}$. Hence the gradient $\nabla_x x^{-1} = -Q_{\theta,x^{-1}}$, provided that x is invertible. More generally, $\nabla_x y^{-1} = -Q_{\theta,y^{-1}} \nabla_x y$ provided that y is invertible.*

3. Problem formulation and self-concordance properties

In CP problems, we minimize a linear function over the intersection of an affine linear manifold with the Cartesian product of circular cones:

$$\mathcal{Q}_{(\theta_1, \theta_2, \dots, \theta_r)}^n := \mathcal{Q}_{\theta_1}^{n_1} \times \mathcal{Q}_{\theta_2}^{n_2} \times \dots \times \mathcal{Q}_{\theta_r}^{n_r},$$

where $n = n_1 + n_2 + \dots + n_r$. In this paper, without loss of generality, we assume that $r = 1$, hence

$$\mathcal{Q}_{\theta_1, \dots, \theta_r}^{n_1, \dots, n_r} = \mathcal{Q}_{\theta_1}^{n_1} = \mathcal{Q}_\theta^n.$$

We use the Euclidean Jordan algebraic characterization of circular cones to define the primal-dual pair of the CP problems. Let $\theta \in (0, \pi/2)$ be a given angle, by using the notations introduced in Subsection 1.1, we define the CP problem and its dual as

$$\begin{aligned} \min \quad & c_{\theta^2}^\top x & \max \quad & b^\top y \\ \text{s.t.} \quad & a_{\theta^2}^{(i)\top} x = b_i, i = 1, 2, \dots, m, & \text{s.t.} \quad & \sum_{i=1}^m y_i a^{(i)} + s = c, \\ & x \succeq_{\theta} 0, & & s \succeq_{\theta} 0, y \in \mathbb{R}^m, \end{aligned} \quad (11)$$

where $c, a^{(i)} \in \mathcal{E}^n$ for $i = 1, 2, \dots, m$, $b \in \mathbb{R}^m$, x is the primal variable, and y and s are the dual variables. The pair (11) can be compactly rewritten as

$$\begin{aligned} \min \quad & c_{\theta^2}^\top x & \max \quad & b^\top y \\ \text{s.t.} \quad & A_{\theta^2} x = b, & \text{s.t.} \quad & A^\top y + s = c, \\ & x \succeq_{\theta} 0, & & s \succeq_{\theta} 0, y \in \mathbb{R}^m, \end{aligned} \quad (12)$$

where $A := (a^{(1)\top}; a^{(2)\top}; \dots; a^{(m)\top})$ is a matrix that maps \mathcal{E}^n into \mathbb{R}^m , and A^\top is its transpose. We call $x \in \mathcal{E}^n$ primal feasible if $A_{\theta^2} x = b$ and $x \succeq_{\theta} 0$. Similarly, $(s, y) \in \mathcal{E}^n \times \mathbb{R}^m$ is called dual feasible if $A^\top y + s = c$ and $s \succeq_{\theta} 0$.

Now, we consider the self-concordance properties for CP. First, we define the logarithmic barrier for the circular case and compute the partial derivatives of this barrier. We then state and prove our self-concordance result.

We define the following strictly feasibility sets:

$$\begin{aligned} \mathcal{F}_{\theta}^0(P) &:= \{x \in \mathcal{E}^n : A_{\theta^2} x = b, x \succ_{\theta} 0\}; \\ \mathcal{F}_{\theta}^0(D) &:= \{(s, y) \in \mathcal{E}^n \times \mathbb{R}^m : A^\top y + s = c, s \succ_{\theta} 0\}; \\ \mathcal{F}_{\theta} &:= \mathcal{F}_{\theta}^0(P) \cap \mathcal{F}_{\theta}^0(D). \end{aligned}$$

Now, we make two assumptions.

Assumption 1. *The matrix A has a full row rank.*

Assumption 2. *\mathcal{F}_{θ} is not empty.*

Assumption 1 is for convenience. Assumption 2 requires that both primal and dual CP problems (12) contain strictly feasible solutions (i.e., positive definite feasible points), which guarantees strong duality for CPs and therefore implies that the CP problems (12) have unique solutions.

We define the logarithmic barrier [20] on the interior of the feasible set of the dual CP problem (12):

$$\begin{aligned} \max \quad & b^\top y \\ \text{s.t.} \quad & s(y) := A^\top y - c \succeq_{\theta} 0. \end{aligned}$$

Let

$$\mathcal{H}_\theta := \left\{ y \in \mathbb{R}^m : s(y) \succeq_\theta 0 \right\}, \text{ hence } \text{Int}(\mathcal{H}_\theta) = \left\{ y \in \mathbb{R}^m : s(y) \succ_\theta 0 \right\}.$$

Under Assumption 2, the set $\text{Int}(\mathcal{H}_\theta)$ is nonempty. The *circular logarithmic barrier* for $\text{Int}(\mathcal{H}_\theta)$ is the function $f_\theta : \text{Int}(\mathcal{H}_\theta) \rightarrow \mathbb{R}$ defined as

$$f_\theta(y) := -\ln \det_\theta(s(y)), \quad \forall y \in \text{Int}(\mathcal{H}_\theta).$$

To state the result on the self-concordance of the logarithmic barrier $f_\theta(\cdot)$ for CP, we need the following definition.

Definition 1. [20, Definition 2.1.1] Let E be a finite-dimensional real vector space, G be an open nonempty convex subset of E , and let g be a \mathcal{C}^3 , convex mapping from G to \mathbb{R} . Then g is called α -*self-concordant* on G with the parameter $\alpha > 0$ if for every $y \in G$ and $h \in E$, the following inequality holds:

$$|\nabla_{yyy}^3 g(y)[h, h, h]| \leq 2\alpha^{-1/2} (\nabla_{yy}^2 g(y)[h, h])^{3/2}.$$

An α -self-concordant function g on G is called *strongly α -self-concordant* if g tends to infinity for any sequence approaching a boundary point of G .

We note that in the above definition the set G is assumed to be open. However, relative openness would be sufficient to apply the definition. See also [20, Item A, Page 57].

We now present the following important result in the self-concordance of the circular logarithmic barrier.

Theorem 2. *The logarithmic barrier function $f_\theta(\cdot)$ is a strongly 1-self-concordant barrier for \mathcal{H}_θ .*

Theorem 2 implies the existence of polynomial-time interior-point algorithms for circular programming [20]. This is the substance of Sections 4 and 5. We prove Theorem 2 in Section 6. Proving Theorem 2 establishes the polynomial convergence results of the proposed algorithms.

4. Newton's method and commutative directions

In the primal dual pair of CP problems (12), the matrix A is defined to map \mathcal{E}^n into \mathbb{R}^m , and its transpose, A^\top , is defined to map \mathbb{R}^m into \mathcal{E}^n such that $x^\top (A_{\theta^2}^\top y) = (A_{\theta^2} x)^\top y$. Indeed, we can prove weak and strong duality properties for the pair (12) as justification for referring to them as a primal dual pair. The following lemma generalizes [1, Lemma 15].

Lemma 3. (Complementarity conditions) *Suppose that $x, s \succeq_\theta 0$. Then*

$$x_\theta^\top s_\theta = x^\top s_{\theta^2} = 0 \text{ if and only if } (x \circ s)_\theta = 0.$$

Proof. Since

$$(x \circ s)_\theta = \begin{bmatrix} x_\theta^\top s_\theta \\ x_0 \bar{s} + s_0 \bar{x} \end{bmatrix} = \begin{bmatrix} x_0 s_0 + \cot^2 \theta \bar{x}^\top \bar{s} \\ x_0 \bar{s} + s_0 \bar{x} \end{bmatrix},$$

it is enough to prove that $x_\theta^\top s_\theta = x_0 s_0 + \cot^2 \theta \bar{x}^\top \bar{s} = 0$ implies that $x_0 \bar{s} + s_0 \bar{x} = 0$. If $x_0 = 0$ or $s_0 = 0$, then $x = 0$ or $s = 0$ and hence result is trivial. Therefore, we need only to consider the case where x_0 and s_0 are strictly greater than zero. By Cauchy-Schwartz inequality and the assumption that $x \succeq_\theta 0$ and $s \succeq_\theta 0$, we have

$$\cot^2 \theta \bar{x}^\top \bar{s} \geq -\cot^2 \theta |\bar{x}^\top \bar{s}| \geq -\cot^2 \theta \|\bar{x}\| \|\bar{s}\| \geq -x_0 s_0. \quad (13)$$

Consequently, $x_0 s_0 + \cot^2 \theta \bar{x}^\top \bar{s} \geq 0$. Now, $x_0 s_0 + \cot^2 \theta \bar{x}^\top \bar{s} = 0$ if and only if $\cot^2 \theta \bar{x}^\top \bar{s} = -x_0 s_0$, therefore if and only if the inequalities in (13) are satisfied as equalities. But if this is true then either $x = 0$ or $s = 0$, in which case $x_0 \bar{s} + s_0 \bar{x} = 0$, or $x \neq 0$ and $s \neq 0$, $\bar{x} = -\alpha \bar{s}$, where $\alpha > 0$, and $x_0 = \|\bar{x}\| = \alpha \|\bar{s}\| = \alpha s_0$, i.e., $\bar{x} + \frac{x_0}{s_0} \bar{s} = 0$. The proof is complete. \square

As a result, the complementary slackness condition for the CP problems (12) is given by the equation $(x \circ s)_\theta = 0$. Thus, the corresponding linear system is:

$$\begin{aligned} A_{\theta^2} x &= b, \\ A^\top y + s &= c, \\ (x \circ s)_\theta &= 0, \\ x, s &\succeq_\theta 0. \end{aligned}$$

The logarithmic barrier problem associated with the primal problem in (12) is the problem:

$$\begin{aligned} \min \quad & c_\theta^\top x - \mu_\theta \ln \det_\theta(x) \\ \text{s.t.} \quad & A_{\theta^2} x = b, \\ & x \succ_\theta 0, \end{aligned} \quad (14)$$

where the barrier parameter $\mu_\theta := \frac{1}{2} x_\theta^\top s_\theta > 0$ is the normalized duality gap. The Lagrangian dual of (14) is the problem:

$$\begin{aligned} \max \quad & b^\top y + \mu_\theta \ln \det_\theta(s) \\ \text{s.t.} \quad & A^\top y + s = c, \\ & s \succ_\theta 0, \end{aligned} \quad (15)$$

which is the logarithmic barrier problem associated with the dual problem in (12).

As the CP problems (14) and (15) are, respectively, concave and convex, x and (y, s) are optimal solutions to (14) and (15), respectively, if and only if they satisfy the following optimality conditions:

$$\begin{aligned} A_{\theta^2}x &= b, \\ A^\top y + s &= c, \\ (x \circ s)_\theta &= \sigma \mu_\theta e, \\ x, s &\succ_\theta 0. \end{aligned} \tag{16}$$

Now, we apply Newton's method to this system to get the following linear system:

$$\begin{aligned} A_{\theta^2}\Delta x &= b - A_{\theta^2}x, \\ A^\top\Delta y + \Delta s &= c - s - A^\top y, \\ (\Delta x \circ s)_\theta + (x \circ \Delta s)_\theta &= \sigma \mu_\theta e - (x \circ s)_\theta, \end{aligned} \tag{17}$$

where $(\Delta x, \Delta s, \Delta y) \in \mathcal{E}^n \times \mathcal{E}^n \times \mathbb{R}^m$ and $\sigma \in [0, 1]$ is a centering parameter. We study short-, semi-long-, and long-step algorithms associated with the following centrality measures defined for $(x, s) \in \text{Int}(\mathcal{Q}_\theta^n) \times \text{Int}(\mathcal{Q}_\theta^n)$ with respect to θ :

$$\begin{aligned} d_{\theta,F}(x, s) &:= \frac{\|Q_{\theta,x^{1/2}}s - \mu_\theta e\|_F}{\sqrt{(\lambda_{\theta,1}(Q_{\theta,x^{1/2}}s) - \mu_\theta)^2 + (\lambda_{\theta,2}(Q_{\theta,x^{1/2}}s) - \mu_\theta)^2}}, \\ d_{\theta,2}(x, s) &:= \|Q_{\theta,x^{1/2}}s - \mu_\theta e\|_2 \\ &= \max \{ |\lambda_{\theta,1}(Q_{\theta,x^{1/2}}s) - \mu_\theta|, |\lambda_{\theta,2}(Q_{\theta,x^{1/2}}s) - \mu_\theta| \}, \\ d_{\theta,-\infty}(x, s) &:= \mu_\theta - \min \{ \lambda_{\theta,1}(Q_{\theta,x^{1/2}}s), \lambda_{\theta,2}(Q_{\theta,x^{1/2}}s) \}. \end{aligned}$$

Let $\gamma \in (0, 1)$ be a given constant. With respect to θ , we define the following neighborhoods of the central path for CP:

$$\begin{aligned} \mathcal{N}_{\theta,F}(\gamma) &:= \{(x, s, y) \in \mathcal{F}_\theta^0(P) \times \mathcal{F}_\theta^0(D) : d_{\theta,F}(x, s) \leq \gamma \mu_\theta\}, \\ \mathcal{N}_{\theta,2}(\gamma) &:= \{(x, s, y) \in \mathcal{F}_\theta^0(P) \times \mathcal{F}_\theta^0(D) : d_{\theta,2}(x, s) \leq \gamma \mu_\theta\}, \\ \mathcal{N}_{\theta,-\infty}(\gamma) &:= \{(x, s, y) \in \mathcal{F}_\theta^0(P) \times \mathcal{F}_\theta^0(D) : d_{\theta,-\infty}(x, s) \leq \gamma \mu_\theta\}. \end{aligned} \tag{18}$$

Note that, by item i of [23, Proposition 21], $Q_{\theta,s^{1/2}}x$ and $Q_{\theta,s^{1/2}}x$ operator commute, and thus the centrality measures $d_{\theta,\cdot}(x, s)$ and their corresponding neighborhoods $\mathcal{N}_{\theta,\cdot}(\gamma)$ are symmetric with respect to x and s . Note also that, by item ii of [23, Proposition 21], $Q_{\theta,x^{1/2}}s$ and $Q_{\theta,\tilde{x}^{1/2}}\tilde{s}$ have the same eigenvalues, and that all neighborhoods can be defined in terms of the eigenvalues of $Q_{\theta,x^{1/2}}s$, therefore the three neighborhoods defined in (18) are scaling invariant, i.e. (x, s) is in the neighborhood if and only if (\tilde{x}, \tilde{s}) is. Furthermore, it is easy to see that

$$d_{\theta,F}(x, s) \geq d_{\theta,2}(x, s) \geq d_{\theta,-\infty}(x, s),$$

which implies that

$$\mathcal{N}_{\theta,F}(\gamma) \subseteq \mathcal{N}_{\theta,2}(\gamma) \subseteq \mathcal{N}_{\theta,-\infty}(\gamma) \subseteq \mathcal{Q}_\theta^n \times \mathcal{Q}_\theta^n.$$

One can see that the vectors x and s may not operator commute, hence the statement that “ $(x \circ s)_\theta = \sigma \mu_\theta e$ implies $x = \sigma \mu_\theta s^{-1}$ ” may not be true. Such a statement holds if x and s operator commute (see [10, Chapter II]). So, we need to scale the optimality conditions (17) so that the scaled vectors operator commute (or equivalently, the scaled vectors are simultaneously decomposed). We use an effective way of scaling proposed originally by Monteiro [19] and Zhang [25] for semidefinite programming, and then generalized by Schmieta and Alizadeh [23] for general symmetric programming. From now on, with respect to θ and $p \succ_\theta 0$, we define

$$\tilde{x} := Q_{\theta,p} x, \quad \tilde{s} := Q_{\theta,p^{-1}} s, \quad \tilde{c} := Q_{\theta,p^{-1}} c, \quad \tilde{c}_{\theta^2} := Q_{\theta,p^{-1}} c_{\theta^2}, \quad \tilde{A} := A Q_{\theta,p^{-1}},$$

and

$$\tilde{A}_{\theta^2} := A_{\theta^2} Q_{\theta,p^{-1}}.$$

Note that, using item 2 of [23, Lemma 8], we have $Q_{\theta,p} Q_{\theta,p^{-1}} = Q_{\theta,p} (Q_{\theta,p})^{-1} = I_n$ for $p \succ_\theta 0$. With this change of variables, Problem (14) becomes

$$\begin{aligned} \min \quad & \tilde{c}_{\theta^2}^\top \tilde{x} - \mu_\theta \ln \det_\theta(\tilde{x}) \\ \text{s.t.} \quad & \tilde{A}_{\theta^2} \tilde{x} = b, \\ & \tilde{x} \succ_\theta 0, \end{aligned} \tag{19}$$

and Problem (15) becomes

$$\begin{aligned} \max \quad & b^\top y + \mu_\theta \ln \det_\theta(\tilde{s}) \\ \text{s.t.} \quad & \tilde{A}^\top y + \tilde{s} = \tilde{c}, \\ & \tilde{s} \succ_\theta 0, \end{aligned} \tag{20}$$

Note that Problems (14) and (19) have the same maximizer, but their optimal objective values are equal up to a constant. Similarly, Problems (15) and (20) have the same minimizer but their optimal objective values differ by a constant. We have the following lemma and proposition.

Lemma 4 (Lemma 28, [23]). *Let $p \in \mathcal{E}^n$ be invertible. Then $(x \circ s)_\theta = \sigma \mu_\theta e$ if and only if $(\tilde{x} \circ \tilde{s})_\theta = \sigma \mu_\theta e$.*

Proposition 1. *The point (x, s, y) satisfies the optimality conditions (16) if and only if the point $(\tilde{x}, \tilde{s}, y)$ satisfies the relaxed optimality conditions*

$$\begin{aligned} \tilde{A}_{\theta^2} \tilde{x} &= b, \\ \tilde{A}^\top y + \tilde{s} &= \tilde{c}, \\ (\tilde{x} \circ \tilde{s})_\theta &= \sigma \mu_\theta e, \\ \tilde{x}, \tilde{s} &\succ_\theta 0. \end{aligned}$$

Proof. The proof follows from Lemma 4, the fact that $Q_{\theta,p}(\mathcal{Q}_\theta^n) = \mathcal{Q}_\theta^n$, and likewise, as an operator, $Q_{\theta,p}(\text{Int}(\mathcal{Q}_\theta^n)) = \text{Int}(\mathcal{Q}_\theta^n)$, because \mathcal{Q}_θ^n is a symmetric cone (see also [4, Theorem 6]). \square

As a result of Proposition 1, we conclude that the set directions $(\Delta x, \Delta s, \Delta y)$ satisfies the optimality conditions (17) if and only if the set directions $(\widetilde{\Delta x}, \widetilde{\Delta s}, \Delta y)$ satisfies the following relaxed optimality conditions:

$$\begin{aligned} \widetilde{A}_{\theta^2} \widetilde{\Delta x} &= b - \widetilde{A}_{\theta^2} \widetilde{x}, \\ \widetilde{A}^\top \Delta y + \widetilde{\Delta s} &= \widetilde{c} - \widetilde{s} - \widetilde{A}^\top y, \\ (\widetilde{\Delta x} \circ \widetilde{s})_\theta + (\widetilde{x} \circ \widetilde{\Delta s})_\theta &= \sigma \mu_\theta e - (\widetilde{x} \circ \widetilde{s})_\theta. \end{aligned} \quad (21)$$

To compute the Newton directions $(\widetilde{\Delta x}, \widetilde{\Delta s}, \Delta y)$, we write the system of equations (21) in the following block matrix form:

$$\begin{bmatrix} \widetilde{A}_{\theta^2} & 0^\top & 0^\top \\ 0 & \widetilde{A}^\top & I_n \\ \text{Arw}_\theta(\widetilde{s}) & 0^\top & \text{Arw}_\theta(\widetilde{x}) \end{bmatrix} \begin{bmatrix} \widetilde{\Delta x} \\ \Delta y \\ \widetilde{\Delta s} \end{bmatrix} = \begin{bmatrix} r_{\theta,p} \\ r_d \\ r_{\theta,c} \end{bmatrix}, \quad (22)$$

where

$$r_{\theta,p} := b - \widetilde{A}_{\theta^2} \widetilde{x}, \quad r_d := \widetilde{c} - \widetilde{s} - \widetilde{A}^\top y, \quad \text{and} \quad r_{\theta,c} := \sigma \mu_\theta e - (\widetilde{x} \circ \widetilde{s})_\theta.$$

Solving (22) by applying block Gaussian elimination, we obtain

$$\begin{aligned} \Delta y &= (\widetilde{A}_{\theta^2} \text{Arw}_\theta^{-1}(\widetilde{s}) \text{Arw}_\theta(\widetilde{x}) \widetilde{A}^\top)^{-1} (r_{\theta,p} + \widetilde{A}_{\theta^2} \text{Arw}_\theta^{-1}(\widetilde{s}) (\text{Arw}_\theta(\widetilde{x}) r_d - r_{\theta,c})), \\ \widetilde{\Delta s} &= r_d - \widetilde{A}^\top \Delta y, \\ \widetilde{\Delta x} &= \text{Arw}_\theta^{-1}(\widetilde{s}) (r_{\theta,c} - \text{Arw}_\theta(\widetilde{x}) \widetilde{\Delta s}). \end{aligned} \quad (23)$$

As we can see, each choice of p leads to a different search direction. As we mentioned earlier, we are interested in the class of p for which the scaled elements are simultaneously decomposed. Hence, it is sufficient to choose p so that \widetilde{x} and \widetilde{s} operator commute. That is, we restrict our attention to the following set of scalings:

$$\mathcal{C}_\theta(x, s) := \{p \succ_\theta 0 : \widetilde{x} \text{ and } \widetilde{s} \text{ operator commute}\}.$$

We introduce the following definition [1].

Definition 2. The set of directions $(\Delta x, \Delta s, \Delta y)$ arising from those $p \in \mathcal{C}(x, s)$ is called the *commutative class of directions*, and a direction in this class is called a *commutative direction*.

The following three choices of p are the most common in practice [23] (see also [2, 3, 5]):

- **Choice I (The HRVW/KSH/M direction):** We may choose $p = s^{1/2}$ and obtain $\tilde{s} = e$. This choice is analogue of the XS direction in semidefinite programming, and is known as the HRVW/KSH/M direction (it was introduced by Helmberg, Rendl, Vanderbei, and Wolkowicz [11], and Kojima, Shindoh, and Hara [17] independently, and then rediscovered by Monteiro [19]).
- **Choice II (The dual HRVW/KSH/M direction):** We may choose $p = x^{-1/2}$ and obtain $\tilde{x} = e$. This choice of directions arises by switching the roles of X and S ; it is analogue of the SX direction in semidefinite programming, and is known as the dual HRVW/KSH/M direction.
- **Choice III (The NT direction):** We choose p in such a way that $\tilde{x} = \tilde{s}$. In this case we choose

$$p = \left(Q_{\theta, x^{1/2}} \left(Q_{\theta, x^{1/2}} s \right)^{-1/2} \right)^{-1/2} = \left(Q_{\theta, s^{-1/2}} \left(Q_{\theta, s^{1/2}} x \right)^{1/2} \right)^{-1/2}.$$

This choice of directions was introduced by Nesterov and Todd [21, 22] and is known as the NT direction.

After we compute the Newton directions $(\widetilde{\Delta x}, \widetilde{\Delta s}, \Delta y)$ using (23), we can compute the Newton directions $(\Delta x, \Delta s, \Delta y)$ by applying the inverse scaling to $(\widetilde{\Delta x}, \widetilde{\Delta s}, \Delta y)$ (see Algorithm 1). The corresponding $(\Delta x, \Delta s, \Delta y)$ is different from the one obtained by solving system (17) directly. In fact, the former depends on p , while the latter is yielded as a special case when $p = e$. It is clear that $p = e$ may not be in $\mathcal{C}(x, s)$.

5. The path-following algorithms for solving CPs

In this section we introduce short-, semi-long-, and long-step path-following algorithms for solving the CP problems (12). This class is stated formally in Algorithm 1.

Algorithm 1: THE PATH-FOLLOWING ALGORITHM FOR SOLVING CP (12)

Require: $\varepsilon \in (0, 1)$, $\sigma \in (0, 1)$, $\gamma \in (0, 1)$, $(x^{(0)}, y^{(0)}, s^{(0)}) \in \mathcal{N}_{\theta, \cdot}(\gamma)$,

set $\mu_{\theta}^{(0)} = \frac{1}{2} x_{\theta}^{(0)\top} s_{\theta}^{(0)}$ and $k = 0$.

while $\mu_{\theta}^{(k)} \geq \varepsilon \mu_{\theta}^{(0)}$ **do**

choose a scaling vector $p_k \in \mathcal{C}_{\theta}(x^{(k)}, s^{(k)})$,

let $(\widetilde{x}^{(k)}, \widetilde{s}^{(k)}, y^{(k)}) = (Q_{\theta, p_k} x^{(k)}, Q_{\theta, p_k^{-1}} s^{(k)}, y^{(k)})$,

compute $(\widetilde{\Delta x}^{(k)}, \widetilde{\Delta s}^{(k)}, \Delta y^{(k)})$ using (23),

let $(\Delta x^{(k)}, \Delta s^{(k)}, \Delta y^{(k)}) = (Q_{\theta, p_k^{-1}} \widetilde{\Delta x}^{(k)}, Q_{\theta, p_k} \widetilde{\Delta s}^{(k)}, \Delta y^{(k)})$,

choose the largest step length $\alpha^{(k)}$ such that
 $(x^{(k+1)}, y^{(k+1)}, s^{(k+1)}) = (x^{(k)}, y^{(k)}, s^{(k)}) + \alpha^{(k)} (\Delta x^{(k)}, \Delta y^{(k)}, \Delta s^{(k)}) \in \mathcal{N}_{\theta, \cdot}(\gamma)$,
 set $\mu_{\theta}^{(k+1)} = \frac{1}{2} x_{\theta}^{(k+1)\top} s_{\theta}^{(k+1)}$ and $k = k + 1$.
end while

In Algorithm 1, ϵ is the desired accuracy of the solution. The general variant of the algorithm is determined by the choice σ and the neighborhood as follows:

- The short-step algorithm is obtained by choosing $\sigma = 1 - \delta/\sqrt{r}$, with $\delta \in (0, 1)$, and $\mathcal{N}_{\theta, F}(\gamma)$ as the neighborhood.
- The semi-long-step algorithm is obtained by choosing $\sigma \in (0, 1)$ and $\mathcal{N}_{\theta, 2}(\gamma)$ as the neighborhood.
- The long-step algorithm is obtained by choosing $\sigma \in (0, 1)$ and $\mathcal{N}_{\theta, -\infty}(\gamma)$ as the neighborhood.

The following theorem gives polynomial convergence results for Algorithm 1.

Theorem 3. *Consider Algorithm 1. If the NT direction is used at every iteration, then the short-step algorithm will terminate in $\mathcal{O}(\sqrt{2} \log \epsilon^{-1})$ iterations, and the semi-long and long-step algorithm will terminate in $\mathcal{O}(2 \log \epsilon^{-1})$ iterations. If the HRVW/KSH/M direction or the dual HRVW/KSH/M direction is used at every iteration, then the short-step algorithm will terminate in $\mathcal{O}(\sqrt{2} \log \epsilon^{-1})$ iterations, the semi-long-step algorithm will terminate in $\mathcal{O}(2 \log \epsilon^{-1})$ iterations, and long-step algorithm will terminate in $\mathcal{O}(2\sqrt{2} \log \epsilon^{-1})$ iterations.*

Theorem 3 is a consequence of Theorem 2 (which will be proved in the remaining part of this paper) and [23, Theorem 37] where the underlying symmetric cone is the circular cone.

6. Proving self-concordance for the circular logarithmic barrier

In this section, we prove Theorem 2. To do so, we first obtain a representation for the gradient, the Hessian and the third directional derivative of the logarithmic barrier in the circular case.

Recall that the circular logarithmic barrier is defined as $f_{\theta}(y) = -\ln \det_{\theta}(s(y))$ for all y in $\text{Int}(\mathcal{H}_{\theta})$, where $s(y) = A^{\top}y - c$ and $\mathcal{H}_{\theta} = \{y \in \mathbb{R}^m : s(y) \succeq_{\theta} 0\}$. Throughout the following proof, we let $y \in \mathbb{R}^m$ be such that $s(y) \succ_{\theta} 0$.

Proof of Theorem 2. Note that

$$\nabla_y s(y) = \nabla_y (A^{\top}y - c) = A^{\top}.$$

Then, by using item 1 of Lemma 2 and applying chain rule, we have

$$\nabla_y f_\theta(y) = -\nabla_y \ln \det_\theta(s(y)) = -(\nabla_y s)_{\theta^2}^\top s^{-1} = -A_{\theta^2} s^{-1},$$

and consequently, using item 2 of Lemma 2 and applying chain rule, we also have

$$\nabla_{yy}^2 f_\theta(y) = -A_{\theta^2} \nabla_y s^{-1} = A_{\theta^2} Q_{\theta, s^{-1}} \nabla_y s = A_{\theta^2} Q_{\theta, s^{-1}} A^\top.$$

Let

$$H = H(y) := \nabla_{yy}^2 f_\theta(y) = A_{\theta^2} Q_{\theta, s^{-1}} A^\top. \quad (24)$$

Note that the Hessian matrix H is positive definite under Assumption 1 and the assumption that $s = s(y) \succ_\theta 0$.

Let $h \in \mathbb{R}^m$, $h \neq 0$, $\bar{a}_i := Q_{\theta, s^{-1/2}} a_i$, $\bar{A} := A Q_{\theta, s^{-1/2}}$, and let $p := \bar{A}h$ be a vector in \mathcal{E}^n with the eigenvalues $\lambda_{\theta,1}(p)$ and $\lambda_{\theta,2}(p)$. Using (24), we have

$$h^\top H h = (\bar{A}h)_{\theta^2}^\top \bar{A}h = \|\bar{A}h\|_{\theta, F}^2 = \|p\|_{\theta, F}^2 = \lambda_{\theta,1}^2(p) + \lambda_{\theta,2}^2(p). \quad (25)$$

Let u and v be two vectors in \mathcal{E}^n such that u is invertible. We have

$$\begin{aligned} \nabla_u Q_{\theta, u^{-1}}[v] &= \nabla_u (2\text{Arw}(u^{-1})^2 - \text{Arw}(u^{-2})) [v] \\ &= -2\text{Arw}(Q_{\theta, u^{-1}}v) \text{Arw}(u^{-1}) - 2\text{Arw}(u^{-1}) \text{Arw}(Q_{\theta, u^{-1}}v) + \\ &\quad 2\text{Arw}(Q_{\theta, u^{-1}}v \circ u^{-1}) \\ &= -2Q_{\theta, (Q_{\theta, u^{-1}}v), u^{-1}}. \end{aligned}$$

Note that $s^{-1/2}$ is the unique positive definite vector having $(s^{-1/2})^2 = s^{-1}$. Plugging in $s(y)$ for u in the positive equation yields

$$\nabla_s Q_{\theta, s(y)^{-1}}[u] = -2Q_{\theta, (Q_{\theta, s^{-1}}Au), s^{-1}} = -2Q_{\theta, s^{-1/2}} \text{Arw}(\bar{A}u) Q_{\theta, s^{-1/2}}. \quad (26)$$

Using (24) and (26), we have

$$\nabla_y H[u] = -2\bar{A}_{\theta^2} \text{Arw}(\bar{A}u) \bar{A}^\top.$$

Then

$$\nabla_y (h^\top H h)[u] = -2p_{\theta^2}^\top (\text{Arw}(\bar{A}u)p).$$

Therefore,

$$\nabla_{yyy}^3 f_\theta[h, h, h] = \nabla_y (h^\top H h)[h] = -2p_{\theta^2}^\top (\text{Arw}(p)p). \quad (27)$$

It is immediate from the fact that $\|\text{Arw}(p)\|_{\theta,2} = \|p\|_{\theta,2}$, the fact that $\|p\|_{\theta,2} \leq \|p\|_{\theta,F}$, and (27) that

$$\begin{aligned}
|\nabla_{yyy}^3 f_\theta[h, h, h]| &= 2 |p_{\theta^2}^\top (\text{Arw}(p)p)| \\
&\leq 2 \|\text{Arw}(p)\|_{\theta,2} p_{\theta^2}^\top p \\
&= 2 \|p\|_{\theta,2} p_{\theta^2}^\top p \\
&= 2 \|p\|_{\theta,2} \left(\lambda_{\theta,1}^2(p) + \lambda_{\theta,2}^2(p) \right) \\
&= 2 \|p\|_{\theta,2} h^\top H(x) h \\
&= 2 \|p\|_{\theta,2} |\nabla_{yy}^2 f_\theta[h, h]| \\
&\leq 2 \|p\|_{\theta,F} |\nabla_{yy}^2 f_\theta[h, h]| \\
&= 2 (|\nabla_{yy}^2 f_\theta[h, h]|)^{3/2},
\end{aligned} \tag{28}$$

where we used (25) to obtain the third and last equalities and (24) to obtain the fourth equality.

It follows from (28), and

$$\nabla_x f_\theta(x)^\top (\nabla_{xx}^2 f_\theta(x))^{-1} \nabla_x f_\theta(x) = e_{\theta^2}^\top \bar{A}^\top (\bar{A}_{\theta^2} \bar{A}^\top)^{-1} \bar{A} e \leq e^\top e = 1,$$

that f_θ is a 1-self-concordant barrier for \mathcal{H}_θ . In addition, it is clear that f tends to infinity for any sequence approaching a boundary point of \mathcal{H}_θ . Thus, the logarithmic barrier f_θ is a strongly 1-self-concordant barrier for \mathcal{H}_θ . The result is established. \square

7. Simulation experiments

In order to verify the efficiency of the proposed algorithm, we give in this section some simulation experiments. All our numerical experiments are carried out on a PC with Intel(R) Dual CPU at 2.20 GHz and 2 GB of physical memory. The PC runs MATLAB Version: 7.4.0.287 (R2007a) on Windows XP Enterprise 32-bit operating system.

Example 1. Consider the primal-dual pair of CP problem with the following data [?]:

$$A = [A_1, A_2, A_3, A_4],$$

where

$$A_1 = \begin{bmatrix} 5 & 1 & 1 \\ 1 & 1 & 1 \\ 4 & 6 & 3 \\ 1 & 4 & 3 \\ 3 & 3 & 5 \\ 3 & 3 & 3 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 3 & 6 & 6 \\ 1 & 6 & 2 \\ 6 & 2 & 1 \\ 5 & 4 & 1 \\ 6 & 5 & 1 \\ 4 & 3 & 4 \end{bmatrix}, \quad A_3 = \begin{bmatrix} 4 & 3 & 6 \\ 3 & 2 & 6 \\ 2 & 5 & 1 \\ 1 & 5 & 2 \\ 5 & 6 & 5 \\ 4 & 3 & 3 \end{bmatrix}, \quad A_4 = \begin{bmatrix} 3 & 3 & 1 \\ 6 & 1 & 2 \\ 6 & 2 & 6 \\ 5 & 2 & 5 \\ 4 & 4 & 5 \\ 6 & 1 & 6 \end{bmatrix},$$

θ	DG	CPU(s)	IN
$\frac{\pi}{11}$	0.01878	0.29687	66
$\frac{\pi}{8}$	0.00875	0.26562	62
$\frac{\pi}{6}$	0.00507	0.31250	76
$\frac{\pi}{5}$	0.00306	0.28125	67
$\frac{\pi}{4}$	0.00182	0.29687	67
$\frac{\pi}{3}$	0.00085	0.25000	67

Table 1. The results for Example 1.

and

$$b = \begin{bmatrix} 43 \\ 32 \\ 51 \\ 39 \\ 54 \\ 44 \end{bmatrix}, \quad c_i = \begin{bmatrix} 2 \\ 1 \\ 0 \end{bmatrix}, \quad x_i = s_i = \begin{bmatrix} 2 \cot \theta_i \\ 1 \\ 0 \end{bmatrix}, \quad i = 1, 2, 3, 4, \quad y = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

where x_i and s_i , for $i = 1, 2, 3, 4$, denote the initial starting point of the algorithm, θ denotes the angles $(\theta_1, \theta_2, \theta_3, \theta_4)$, and $\mathcal{Q}_\theta^n = \mathcal{Q}_{\theta_1}^3 \times \mathcal{Q}_{\theta_2}^3 \times \mathcal{Q}_{\theta_3}^3 \times \mathcal{Q}_{\theta_4}^3$ (with $n = 12$) denotes the Cartesian product of four 3rd-dimensional circular cones.

We use $\varepsilon = 10^{-4}$ as the default accuracy parameter and choose the rotation angles as $\theta = \frac{\pi}{11}, \frac{\pi}{8}, \frac{\pi}{6}, \frac{\pi}{5}, \frac{\pi}{4}, \frac{\pi}{3}$. The numerical results are summarized in Table 1 where we present the duality gap (DG), the CPU time and the required iteration numbers (IN) of the proposed Algorithm 1 for obtaining an ε -approximate optimal solution of the underlying problem.

Example 2. In this example, we test some various dimensions primal-dual pair of CP problems in which the coefficient matrix A is generated randomly. For these circular programming problems, we choose the rotation angles as $\theta = \frac{\pi}{10}, \frac{\pi}{6}, \frac{\pi}{5}, \frac{\pi}{4}, \frac{\pi}{3}$ and the accuracy parameter ε as $\varepsilon = 10^{-5}$. The numerical results obtained for these problems are shown in Table 2.

The test results in Table 2 show that the path-following method can efficiently solve different kinds of circular programming.

8. Conclusions

Circular programming problems are a new class of symmetric optimization problems with a special structure. There is a particular Euclidean Jordan algebra that underlies the analysis of interior point algorithms for the circular programming. In this paper, we have used the machinery of this particular Euclidean Jordan algebra to derive polynomial-time path-following algorithms for circular programming problems. We

θ	$\frac{\pi}{10}$		$\frac{\pi}{6}$		$\frac{\pi}{5}$		$\frac{\pi}{4}$		$\frac{\pi}{3}$	
(m, n)	IN	CPU(s)	IN	CPU(s)	IN	CPU(s)	IN	CPU(s)	IN	CPU(s)
(10,15)	11	0.03125	13	0.03125	10	0.03125	14	0.03125	53	0.09375
(15,20)	25	0.06250	47	0.09375	63	0.12500	70	0.17187	40	0.09375
(25,30)	40	0.12500	17	0.06250	46	0.15625	70	0.25000	43	0.12500
(30,40)	15	0.06250	43	0.15625	33	0.12500	73	0.31250	13	0.06250
(40,50)	25	0.15625	17	0.12500	36	0.25000	71	0.40625	29	0.18750
(55,70)	27	0.31250	46	0.45312	18	0.20312	36	0.34375	23	0.21875
(65,85)	16	0.17187	12	0.17187	40	0.45312	51	0.78125	12	0.18750
(85,100)	22	0.34375	16	0.28125	23	0.37500	68	1.07812	46	0.71875
(100,150)	25	0.78125	45	1.31250	56	0.90625	25	0.81250	17	0.51562
(150,250)	17	1.60937	22	2.06250	31	2.98437	46	1.31250	44	4.12500
(250,400)	15	5.65625	10	3.68750	11	4.04687	17	6.23437	6	2.21875
(400,700)	3	5.21875	4	4.98437	5	8.32812	19	7.03125	4	6.62500

Table 2. The numerical results of Example 2.

have also proved the polynomial convergence results of the proposed algorithms by showing that the circular logarithmic barrier is a strongly self-concordant barrier. Some preliminary numerical results were provided to demonstrate the implementation of the proposed algorithm. The numerical results show the path-following algorithms for circular programming problems are simple and efficient.

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