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CONVEX SETS WITH SEMIDEFINITE REPRESENTATION

JEAN B. LASSERRE

ABSTRACT. We provide a sufficient condition on a class of compact basic semialgebraic sets $\mathbf{K} \subset \mathbb{R}^n$ for their convex hull $\text{co}(\mathbf{K})$ to have a semidefinite representation (SDr). This SDr is explicitly expressed in terms of the polynomials g_j that define \mathbf{K} . Examples are provided. We also provide an approximate SDr; that is, for every fixed $\epsilon > 0$, there is a convex set \mathbf{K}_ϵ such that $\text{co}(\mathbf{K}) \subseteq \mathbf{K}_\epsilon \subseteq \text{co}(\mathbf{K}) + \epsilon \mathbf{B}$ (where \mathbf{B} is the unit ball of \mathbb{R}^n), and \mathbf{K}_ϵ has an explicit SDr in terms of the g_j 's. For convex and compact basic semi-algebraic sets \mathbf{K} defined by concave polynomials, we provide a simpler explicit SDr when the nonnegative Lagrangian L_f associated with \mathbf{K} and any linear $f \in \mathbb{R}[X]$ is a sum of squares. We also provide an approximate SDr specific to the convex case.

1. INTRODUCTION

An important issue raised in e.g. Ben-Tal and Nemirovski [2], Helton and Vinnikov [4], Parrilo and Sturmfels [14], is to characterize convex sets of \mathbb{R}^n that have a *lifted LMI* (*Linear Matrix Inequalities*) (or a *semidefinite representation* (SDr)), and called SDr sets in [2] (that is, sets which are semidefinite representable).

Recall that a convex set $\Omega \subset \mathbb{R}^n$ is SDr if there exist integers m, p and real $p \times p$ symmetric matrices $\{A_i\}_{i=0}^n, \{B_j\}_{j=1}^m$ such that:

$$(1.1) \quad \Omega = \{x \in \mathbb{R}^n : \exists y \in \mathbb{R}^m \text{ s.t. } A_0 + \sum_{i=1}^n A_i x_i + \sum_{j=1}^m B_j y_j \succeq 0\}$$

(where the notation $A \succeq 0$ stands for the matrix A is positive semidefinite). In other words, Ω is the linear projection on \mathbb{R}^n of the convex set

$$\Omega' := \{(x, y) \in \mathbb{R}^n \times \mathbb{R}^m : A_0 + \sum_{i=1}^n A_i x_i + \sum_{j=1}^m B_j y_j \succeq 0\} (\subset \mathbb{R}^{n+m})$$

of the *lifted* space \mathbb{R}^{n+m} . The set Ω' is called a *semidefinite representation* (SDr) of Ω and is a lifted LMI because one sometimes needs additional variables $y \in \mathbb{R}^m$ to obtain a description of Ω via appropriate LMIs. For instance:

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- The intersection of half-spaces, i.e., a polyhedron $\{x \in \mathbb{R}^n : Ax \leq b\}$, is a trivial example of convex sets whose SDr is readily available without lifting. Indeed $Ax \leq b$ is an LMI with diagonal matrices A_i in (1.1).
- The intersection of ellipsoids

$$\Omega := \{x \in \mathbb{R}^n : x^T Q_j x + b^T x + c_j \geq 0, j = 1, \dots, m\}$$

(where $-Q_j \succeq 0$ for all $j = 1, \dots, m$) is a SDr set with lifted LMI representation in $\mathbb{R}^{(n+1)(n+2)/2-1}$:

$$(1.2) \quad \Omega' = \left\{ (x, Y) : \begin{array}{l} \begin{bmatrix} 1 & x^T \\ x & Y \end{bmatrix} \succeq 0 \\ \text{trace}(Q_j Y) + b^T x + c_j \geq 0, \quad j = 1, \dots, m. \end{array} \right\}.$$

- The epigraph of a univariate convex polynomial is a SDr set.
- Convex sets of \mathbb{R}^2 described from genus-zero plane curves are SDr sets; see Parrilo [14].
- *Hyperbolic* cones obtained from 3-variables hyperbolic homogeneous polynomials are SDr sets; see the proof of the Lax conjecture in Lewis et al. [13].

So far, and except for the special cases cited above, little is known. In addition, even if a convex set \mathbf{K} is known to be SDr, there is no systematic procedure to obtain its SDr, i.e., the set of lifted LMIs whose projection describe \mathbf{K} . However, Helton and Vinnikov [4] have proved recently that *rigid convexity* is a necessary condition for a set to be SDr (and sufficient for dimension $n = 2$). Chua and Tuncel [3] consider even more general lifted conic representations of convex sets, called lifted G-representations (SDr being a special case) and discuss various geometric properties of convex sets admitting such lifted G-representations, as well as measures of "goodness" for such representations.

In this paper, we consider the convex hull $\text{co}(\mathbf{K})$ of compact basic semi-algebraic sets $\mathbf{K} \subset \mathbb{R}^n$ of the form

$$(1.3) \quad \mathbf{K} = \{x \in \mathbb{R}^n : g_j(x) \geq 0, \quad j = 1, \dots, m\},$$

for some given polynomials $g_j \in \mathbb{R}[X]$, $j = 1, \dots, m$. Notice that the class of sets (1.3) is fairly general as \mathbf{K} can be nonconvex (even disconnected), as well as discrete.

Contribution: Our contribution is twofold:

I. We first provide a sufficient condition (and a variant of it) on the defining polynomials $(g_j) \subset \mathbb{R}[X]$ of \mathbf{K} that we call *Schmüdgen's Bounded Degree Representation* (S-BDR) of *affine* polynomials and its *Putinar-Prestel* variant (PP-BDR). A basic compact semi-algebraic set has the S-BDR (resp.

PP-BDR) property if almost all affine polynomials $f \in \mathbb{R}[X]$ positive on \mathbf{K} (hence on $\text{co}(\mathbf{K})$) belong to $P_r(g)$ (resp. $Q_r(g)$), a subset of the preordering $P(g)$ (resp. quadratic module $Q(g)$) generated by the g_j . When $f \in P_r(g)$ or $Q_r(g)$, all elements in the representation of f in the preordering $P(g)$ or in the quadratic module $Q(g)$, have degree at most r .

Recall that when \mathbf{K} is compact then $f > 0$ on \mathbf{K} implies $f \in P(g)$ (or $f \in Q(g)$ if $N - \|X\|^2 \in Q(g)$ for some N), and so the S-BDR (or PP-BDR) property is stronger in that it requires $f \in P_r(g)$ (or $Q_r(g)$). On the other hand, this requirement is only concerned with the class of positive *affine* polynomials.

For instance, this property holds for intersections of halfspaces and ellipsoids, i.e., when the g_j 's are affine or quadratic and concave. But we also exhibit some nontrivial non convex compact semi-algebraic sets \mathbf{K} with the PP-BDR property. For instance, we show that when $m = 2$ and the g_j 's are quadratic, or when $n = 2$ and the g_j 's are quartic, then the PP-BDR property holds generically, and with order $r = 1$ and $r = 2$, respectively.

When the S-BDR or PP-BDR property holds then one can immediately obtain an *explicit* SDr of $\text{co}(\mathbf{K})$, expressed directly in terms of the defining polynomials g_j .

We also obtain an approximate result of the following flavor. For every fixed $\epsilon > 0$, we exhibit a convex set \mathbf{K}_ϵ such that (a) $\text{co}(\mathbf{K}) \subseteq \mathbf{K}_\epsilon \subseteq \text{co}(\mathbf{K}) + \epsilon \mathbf{B}$ (where \mathbf{B} is the unit ball of \mathbb{R}^n), and (b) \mathbf{K}_ϵ has an *explicit* SDr expressed directly in terms of the polynomials g_j that define \mathbf{K} . This result improves significantly upon [8] where we have provided *outer* convex approximations of $\text{co}(\mathbf{K})$, i.e., a monotone nonincreasing sequence of convex sets \mathbf{K}_r , with $\mathbf{K}_r \downarrow \text{co}(\mathbf{K})$, and where each \mathbf{K}_r has a SDr. And so, if $x \notin \text{co}(\mathbf{K})$ then $x \notin \mathbf{K}_r$ for all $r \geq r(x)$ for some $r(x)$ that *depends* on x , an undesirable feature.

II. However, for general basic semialgebraic sets \mathbf{K} , one cannot expect that the S-BDR (or PP-BDR) property holds (if it ever holds) for *nice* values of the order r . Indeed otherwise one could minimize *any* affine polynomial on \mathbf{K} *efficiently*. Therefore, from a practical point of view, the most interesting case is essentially when \mathbf{K} is convex ... and even more ... when the defining polynomials g_j in (1.3) are concave, because then one may hope for the S-BDR or PP-BDR property to hold for interesting values of r .

So, our second contribution is concerned with the case of compact convex basic semialgebraic sets \mathbf{K} defined by *concave* polynomials. We first show that the PP-BDR property holds for \mathbf{K} whenever the Lagrangian L_f associated with \mathbf{K} and an arbitrary *linear* $f \in \mathbb{R}[X]$ is a sum of squares (s.o.s.) (by construction it is already nonnegative). In this case, \mathbf{K} has a natural SDr based on the Karush-Kuhn-Tucker optimality conditions. This makes an interesting connection between convexity and s.o.s. Finally, we also provide an *approximate* SDr of \mathbf{K} , specific to the convex case.

2. I. SEMIDEFINITE REPRESENTATION OF $\text{co}(\mathbf{K})$

2.1. Notation and definitions. For a real symmetric matrix A the notation $A \succeq 0$ (resp. $A \succ 0$) stands for A is positive semidefinite (resp. positive definite). Let $\mathbb{R}[X]$ be the ring of real polynomials in the variables $X = (X_1, \dots, X_n)$ and let $\Sigma^2 \subset \mathbb{R}[X]$ be its subset of sums of squares (s.o.s.) (whereas Σ_d^2 is that of degree at most $2d$). For $x \in \mathbb{R}^n$, let $\|x\|$ denote its euclidean norm.

With $d \in \mathbb{N}$, let $s(d) := \binom{n+d}{n}$, and let $u(X) \in \mathbb{R}^{s(d)}$ be the column vector

$$u_d(X) = (1, X_1, \dots, X_n, X_1^2, X_1X_2, \dots, X_n^d)^T,$$

whose components form the usual canonical basis of the vector space $\mathbb{R}[X]_d$ (of dimension $s(d)$) of real polynomials of degree at most d .

Given an infinite sequence $y := \{y_\alpha\}_{\alpha \in \mathbb{N}^n}$ indexed in the canonical basis $u_\infty(X)$, let $L_y : \mathbb{R}[X] \rightarrow \mathbb{R}$ be the linear mapping

$$(2.1) \quad f \in \mathbb{R}[X] (= \sum_{\alpha \in \mathbb{N}^n} f_\alpha X^\alpha) \longmapsto L_y(f) := \sum_{\alpha \in \mathbb{N}^n} f_\alpha y_\alpha,$$

and let $\mathbf{f} = \{f_\alpha\} \in \mathbb{R}^{s(d)}$ be the vector of coefficients of $f \in \mathbb{R}[X]_d$ in the basis $u_d(X)$.

Moment matrix. Let $M_d(y)$ be the $s(d) \times s(d)$ real matrix with rows and columns indexed in the basis $u_d(X)$, and defined by:

$$(2.2) \quad M_d(y)(\alpha, \beta) = y_{\alpha+\beta}, \quad \alpha, \beta \in \mathbb{N}^n, \quad |\alpha|, |\beta| \leq d,$$

where for every $\alpha \in \mathbb{N}^n$, the notation $|\alpha|$ stands for $\sum_{i=1}^n \alpha_i$.

Equivalently, $M_d(y) = L_y(u_d(X)u_d(X)^T)$, meaning that L_y is applied *entrywise* to the polynomial matrix $u_d(X)u_d(X)^T$. The matrix $M_d(y)$ is called the *moment* matrix associated with the sequence y ; see e.g. [9]. If y has a *representing measure* μ_y (i.e., if $y_\alpha = \int X^\alpha d\mu_y$ for every $\alpha \in \mathbb{N}^n$) then, one has

$$(2.3) \quad \langle \mathbf{f}, M_d(y)\mathbf{f} \rangle = \int f^2 d\mu_y \geq 0, \quad \forall f \in \mathbb{R}[X]_d,$$

so that $M_d(y) \succeq 0$.

Localizing matrix. Similarly, given $y = \{y_\alpha\}$ and $\theta \in \mathbb{R}[X]$, let $M_d(\theta y)$ be the $s(d) \times s(d)$ matrix defined by:

$$(2.4) \quad M_d(\theta y) := L_y(\theta(X)u_d(X)u_d(X)^T),$$

i.e., L_y is applied entrywise to the polynomial matrix $\theta(X)u_d(X)u_d(X)^T$. The matrix $M_d(\theta y)$ is called the *localizing* matrix associated with the sequence y and the polynomial θ (see again [9]). Notice that the localizing matrix with respect to the constant polynomial $\theta \equiv 1$ is the moment matrix $M_d(y)$ in (2.2).

If y has a representing measure μ_y with support contained in the level set $\{x \in \mathbb{R}^n : \theta(x) \geq 0\}$ (where $\theta \in \mathbb{R}[X]$), then

$$(2.5) \quad \langle \mathbf{f}, M_d(\theta y) \mathbf{f} \rangle = \int f^2 \theta d\mu_y \geq 0 \quad \forall f \in \mathbb{R}[X]_d,$$

so that $M_d(\theta y) \succeq 0$.

2.2. Semidefinite representation of $\text{co}(\mathbf{K})$. Let $\mathbf{K} \subset \mathbb{R}^n$ be the basic closed semi-algebraic set defined in (1.3) for some polynomials $g_j \in \mathbb{R}[X]$, $j = 1, \dots, m$.

For every $J \subseteq \{1, \dots, m\}$, let $g_J := \prod_{j \in J} g_j$, with the convention $g_\emptyset \equiv 1$, and let $P(g) \subset \mathbb{R}[X]$ be the *preordering* generated by the g_j 's, i.e.,

$$P(g) := \left\{ \sum_{J \subseteq \{1, \dots, m\}} \sigma_J g_J : \sigma_J \in \Sigma^2 \right\},$$

and given $r \in \mathbb{N}$, define $P_r(g) \subset P(g)$ to be the set

$$(2.6) \quad P_r(g) := \left\{ \sum_{J \subseteq \{1, \dots, m\}} \sigma_J g_J : \sigma_J \in \Sigma^2, \deg \sigma_J + \deg g_J \leq 2r \right\}.$$

Similarly, let $Q(g) \subset \mathbb{R}[X]$ be the *quadratic module* generated by the g_j 's, i.e.,

$$Q(g) := \left\{ \sum_{j=0}^m \sigma_j g_j : \sigma_j \in \Sigma^2 \right\}$$

(with the convention $g_0 \equiv 1$), and given $r \in \mathbb{N}$, define $Q_r(g) \subset Q(g)$ to be the set

$$(2.7) \quad Q_r(g) := \left\{ \sum_{j=0}^m \sigma_j g_j : \sigma_j \in \Sigma^2, \deg \sigma_j + \deg g_j \leq 2r \right\}.$$

Definition 1 (Semi Definite representation (SDr)). A convex set $\Omega \subset \mathbb{R}^n$ has a SDr (or is a SDr set) if it has the form

$$(2.8) \quad \Omega = \left\{ x \in \mathbb{R}^n : \exists y \in \mathbb{R}^m \text{ s.t. } A_0 + \sum_{i=1}^n A_i x_i + \sum_{k=1}^p B_k y_k \succeq 0 \right\}$$

for some integer p and real symmetric matrices $\{A_i\}$ and $\{B_k\}$.

For an affine polynomial $X \mapsto f_0 + \sum_{i=1}^n f_i X_i$, let $(f_0, \mathbf{f}) \in \mathbb{R} \times \mathbb{R}^n$ be its vector of coefficients.

Definition 2 (Schmüdgen's Bounded Degree Representation of affine polynomials). Given a compact set $\mathbf{K} \subset \mathbb{R}^n$ defined as in (1.3), one says that *Schmüdgen's Bounded Degree Representation* (S-BDR) of affine polynomials holds for \mathbf{K} if there exists $r \in \mathbb{N}$ such that

$$(2.9) \quad [f \text{ affine and positive on } \mathbf{K}] \Rightarrow f \in P_r(g),$$

except perhaps on a set of vectors \mathbf{f} in \mathbb{R}^n with Lebesgue measure zero. Call r its order.

Definition 3 (Putinar-Prestel's Bounded Degree Representation of affine polynomials). Given a compact set $\mathbf{K} \subset \mathbb{R}^n$ defined as in (1.3), one says that *Putinar-Prestel's Bounded Degree Representation* (PP-BDR) of affine polynomials holds for \mathbf{K} if there exists $r \in \mathbb{N}$ such that

$$(2.10) \quad [f \text{ affine and positive on } \mathbf{K}] \Rightarrow f \in Q_r(g),$$

except perhaps on a set of vectors \mathbf{f} in \mathbb{R}^n with Lebesgue measure zero. Call r its order.

Remark 1. (a) Observe that if \mathbf{K} is compact, by Schmüdgen's Positivstellensatz [17]

$$[f \in \mathbb{R}[X] \text{ and } f \text{ positive on } \mathbf{K}] \Rightarrow f \in P_r(g),$$

for some $r(f)$. The S-BDR property states that $r(f) < r$ for almost all affine $f \in \mathbb{R}[X]$, positive on \mathbf{K} .

(b) If for some N , the polynomial $N - \|X\|^2$ is in $Q(g)$, then by Putinar's Positivstellensatz [16]

$$[f \in \mathbb{R}[X] \text{ and } f \text{ positive on } \mathbf{K}] \Rightarrow f \in Q_r(g),$$

for some $r(f)$; see also Jacobi and Prestel [7]. The PP-BDR property states that $r(f) < r$ for almost all affine $f \in \mathbb{R}[X]$, positive on \mathbf{K} .

(c) Finally, the PP-BDR property implies the S-BDR property.

For every $J \subseteq \{1, \dots, m\}$ let $r_J := \lceil \deg g_J / 2 \rceil$.

Theorem 2. Let $\mathbf{K} \subset \mathbb{R}^n$ be compact and defined as in (1.3).

(a) If the S-BDR property holds for \mathbf{K} with order r , then $\text{co}(\mathbf{K})$ is a SDR set with SDR

$$(2.11) \quad \left\{ (x, y) \in \mathbb{R}^n \times \mathbb{R}^{s(2r)} : \begin{cases} M_{r-r_J}(g_J y) \succeq 0, & J \subseteq \{1, \dots, m\} \\ L_y(X_i) = x_i, & i = 1, \dots, n \\ y_0 = 1 \end{cases} \right\}.$$

(b) If the PP-BDR property holds for \mathbf{K} with order r , then $\text{co}(\mathbf{K})$ is a SDR set with SDR

$$(2.12) \quad \left\{ (x, y) \in \mathbb{R}^n \times \mathbb{R}^{s(2r)} : \begin{cases} M_{r-r_j}(g_j y) \succeq 0, & j = 0, 1, \dots, m \\ L_y(X_i) = x_i, & i = 1, \dots, n \\ y_0 = 1 \end{cases} \right\}.$$

Proof. We only prove (a) as (b) is proved in exactly the same manner. Let $\Omega \subset \mathbb{R}^n \times \mathbb{R}^{s(r)}$ be the set defined in (2.11). We have to show that $(\exists y : (x, y) \in \Omega) \Leftrightarrow x \in \text{co}(\mathbf{K})$.

1. $x \in \text{co}(\mathbf{K}) \Rightarrow (x, y) \in \Omega$ for some $y \in \mathbb{R}^{s(r)}$. Observe that by the definition of $\text{co}(\mathbf{K})$,

$$x \in \text{co}(\mathbf{K}) \Leftrightarrow x = \int X d\mu$$

for some probability measure μ supported on \mathbf{K} . Let $y = (y_\alpha) \in \mathbb{R}^{s(r)}$ be the sequence of moments of μ up to order $2r$, i.e.

$$y_\alpha = L_y(X^\alpha) = \int X^\alpha d\mu, \quad \alpha \in \mathbb{N}^n; |\alpha| \leq 2r.$$

The sequence y is well defined because μ has compact support; in particular $y_0 = 1$. From the definition of μ one has $L_y(X_i) = \int X_i d\mu = x_i$. In addition, as μ is supported on \mathbf{K} , one has $M_{r-r_J}(g_J y) \succeq 0$ for all subsets $J \subseteq \{1, \dots, m\}$ (just take $\theta := g_J$ in (2.5)). And so $(x, y) \in \Omega$.

2. $\exists y : (x, y) \in \Omega \Rightarrow x \in \text{co}(\mathbf{K})$. We prove it by contradiction.

Let $x \notin \text{co}(\mathbf{K})$ and assume that there exists $y \in \mathbb{R}^{s(r)}$ such that $(x, y) \in \Omega$. As $\text{co}(\mathbf{K})$ is convex and compact, by the Hahn-Banach separation theorem, there exists $(f_0, \mathbf{f}) \in \mathbb{R} \times \mathbb{R}^n$ such that

$$(2.13) \quad \langle \mathbf{f}, x \rangle < f_0 \quad \text{and} \quad \langle \mathbf{f}, z \rangle > f_0 \quad \forall z \in \text{co}(\mathbf{K}),$$

and so the affine polynomial $f \in \mathbb{R}[X]$, $X \mapsto f(X) := -f_0 + \sum_i f_i X_i$ is positive on \mathbf{K} .

By the PP-BDR property of \mathbf{K} with order r , one has $f \in P_r(g)$ or $\tilde{f} \in P_r(g)$ for some affine $\tilde{f} \in \mathbb{R}[X]$ with coefficient vector $(\tilde{\mathbf{f}}, \tilde{f}_0)$ such that $\|\tilde{\mathbf{f}}\| = 1$ and some $\epsilon > 0$ such that $\|(\tilde{\mathbf{f}}, \tilde{f}_0) - (\mathbf{f}, f_0)\| < \epsilon$, with $\epsilon > 0$ as small as desired. Therefore, one may choose ϵ sufficiently small to ensure that $(\tilde{\mathbf{f}}, \tilde{f}_0)$ also satisfies (2.13) and so, one may rename \tilde{f} as f and safely assume that $f \in P_r(g)$. Hence,

$$(2.14) \quad f(X) = \sum_{J \subseteq \{1, \dots, m\}} \sigma_J g_J, \quad \sigma_J \in \Sigma^2; \deg \sigma_J + \deg g_J \leq 2r.$$

Observe that as σ_J is s.o.s. and $\deg \sigma_J + \deg g_J \leq 2r$, one has

$$(2.15) \quad L_y(\sigma_J g_J) \geq 0 \quad \forall J \subseteq \{1, \dots, m\}.$$

Applying the linear functional L_y to the polynomial f in (2.14) yields the contradiction

$$\begin{aligned} 0 > \mathbf{f}^T x - f_0 &= -f_0 y_0 + \sum_{i=1}^n L_y(f_i X_i) \quad [\text{as } y_0 = 1, L_y(X_i) = x_i \forall i] \\ &= L_y(f(X)) = \sum_{J \subseteq \{1, \dots, m\}} L_y(g_J \sigma_J) \quad [\text{by (2.14)}] \\ &\geq 0 \quad [\text{by (2.15)}]. \end{aligned}$$

This proves that there is no y such that $(x, y) \in \Omega$, the desired result. \square

Notice that in Theorem 2, the SDr (2.11) and (2.12) of $\text{co}(\mathbf{K})$ are given *explicitly* in terms of the data g_j 's that define \mathbf{K} .

2.3. Examples of convex \mathbf{K} . We have already seen that the intersection \mathbf{K} of half-spaces and/or ellipsoids is a SDr set. But we here show that the PP-BDR property holds for such sets \mathbf{K} , and also for the intersection of level sets of quartic polynomials in two variables. Of course, one already knows how to build up a SDr for \mathbf{K} at least in the first two cases. But this is to illustrate that the domain of application of Theorem 2 is not empty and not trivial.

Example 1. Let us start with \mathbf{K} being a convex polytope defined by linear inequalities, i.e., $g_j \in \mathbb{R}[X]$ is affine in X for all $j = 1, \dots, m$. Hence $\text{co}(\mathbf{K}) \equiv \mathbf{K}$ and this description of \mathbf{K} by the g_j 's is already a SDr; it is even a linear system. We briefly prove that the PP-BDR property holds for \mathbf{K} with order 0. Let $f \in \mathbb{R}[X]$ be affine with coefficient vector $(f_0, \mathbf{f}) \in \mathbb{R} \times \mathbb{R}^n$, and write

$$\begin{aligned} g_j(X) &= g_{j0} + \sum_{i=1}^n g_{ji} X_i, & j = 1, \dots, m \\ f(X) &= f_0 + \sum_{i=1}^n f_i X_i. \end{aligned}$$

Next, let $G \in \mathbb{R}^{m \times n}$ be the matrix $G(j, i) = g_{ji}$, $j = 1, \dots, m$, $i = 1, \dots, n$, and $\mathbf{g} = (g_{j0}) \in \mathbb{R}^m$. If f is nonnegative on \mathbf{K} then by Farkas lemma $\mathbf{f} = \lambda^T G$ and $f_0 \geq \lambda^T \mathbf{g}$, for some nonnegative vector $\lambda \in \mathbb{R}^m$. Therefore $f(X) = u + \sum_{j=1}^m \lambda_j g_j(X)$, for some nonnegative scalar u , which proves that $f \in Q_1(g)$. That is, the PP-BDR property holds for \mathbf{K} with order $r = 1$.

Example 2. Let $g_j \in \mathbb{R}[X]$ be concave and quadratic, for all $j = 1, \dots, m$. Then \mathbf{K} is convex and it is well-known that \mathbf{K} is a SDr set. Let $f \in \mathbb{R}[X]$ be affine with coefficient vector $(f_0, \mathbf{f}) \in \mathbb{R} \times \mathbb{R}^n$, and nonnegative on \mathbf{K} , so that $f^* := \min_{x \in \mathbf{K}} f(x) \geq 0$. Assume that \mathbf{K} is compact with nonempty interior. Convexity along with Slater's condition¹ imply that the KKT optimality conditions hold at any global minimizer $x^* \in \mathbf{K}$, i.e.,

$$\mathbf{f} - \sum_{j=1}^m \lambda_j \nabla g_j(x^*) = 0; \quad \lambda_j g_j(x^*) = 0, \quad j = 1, \dots, m,$$

for some nonnegative Lagrange multipliers $\lambda \in \mathbb{R}_+^m$. Then x^* is also a global minimizer of the (convex) quadratic Lagrangian $L_f := f - \sum_{j=1}^m \lambda_j g_j$ on the whole \mathbb{R}^n . Therefore, $L_f - f^* \geq 0$ on \mathbb{R}^n and being quadratic, $L_f - f^* \in \Sigma^2$. Hence

$$f = f^* + (L_f - f^*) + \sum_{j=1}^m \lambda_j g_j,$$

¹Slater's condition states that there exists $x_0 \in \mathbf{K}$ such that $g_j(x_0) > 0$ for every $j = 1, \dots, m$. If Slater's condition holds and f is convex and differentiable, then the Karush-Kuhn-Tucker (KKT) optimality conditions hold at any minimizer $x^* \in \mathbf{K}$ of the convex optimization problem: $\min_x \{f(x) : x \in \mathbf{K}\}$

that is, $f \in Q_1(g)$ (as $f^* \geq 0$). And so the PP-BDR property holds for \mathbf{K} with order $r = 1$, and \mathbf{K} has the SDr (2.12). Writing $g_j(x) = x^T Q_j x + b^T x + c_j$ for some positive semidefinite matrix $-Q_j \succeq 0$, $j = 1, \dots, m$, the SDr (2.12) is nothing less than (1.2) already encountered in the introduction.

Example 3. Let $n = 2$ with g_j concave and $\deg g_j = 2$ or 4 , for all $j = 1, \dots, m$, so that \mathbf{K} is convex. Assume \mathbf{K} is compact with nonempty interior. It is known that in general \mathbf{K} is not representable by a LMI in the variables x_1 and x_2 only;. For instance take $m = 1$ and $g_1(X) = 1 - X_1^4 - X_2^4$. The rigid convexity condition of Helton and Vinnikov [4] is violated, but on the other hand, \mathbf{K} is known to be SDr.

Let $f \in \mathbb{R}[X]$ be affine and nonnegative on \mathbf{K} with global minimum $f^* \geq 0$ on \mathbf{K} . Again, convexity along with Slater's condition implies that the KKT optimality conditions hold at any global minimizer $x^* \in \mathbf{K}$. And so there exist nonnegative Lagrange multipliers $\lambda \in \mathbb{R}_+^m$ such that the (convex) Lagrangian $L_f := f - \sum_{j=1}^m \lambda_j g_j$ also has optimal value f^* and, in addition, $x^* \in \mathbf{K}$ is a global minimizer of L_f on \mathbb{R}^2 . Therefore, the polynomial $L_f - f^*$ being nonnegative on \mathbb{R}^2 and being quadratic or quartic in 2 variables, is s.o.s. That is $L_f - f^* = \sigma$ for some $\sigma \in \Sigma^2$ and $\deg \sigma \leq 4$. But then

$$f = f^* + (L_f - f^*) + \sum_{j=1}^m \lambda_j g_j \in Q_2(g)$$

because as $f^* \geq 0$, $f^* + (L_f - f^*) \in \Sigma^2$. That is, the PP-BDR property holds for \mathbf{K} with order $r = 2$. Hence, \mathbf{K} has the SDr (2.12).

2.4. Examples with nonconvex \mathbf{K} .

Example 4. Let $m = 2$ with

$$(2.16) \quad g_i(X) = X^T A_i X + c_i, \quad i = 1, 2,$$

for some real symmetric matrices A_i , and vector $\mathbf{c} = (c_1, c_2) \in \mathbb{R}^2$.

Given a linear polynomial $f \in \mathbb{R}[X]$ with coefficient vector $\mathbf{f} = (f_i)_{i=1}^n \in \mathbb{R}^n$, consider the SDP

$$(2.17) \quad \mathbf{Q} : \min_y \{ L_y(f) : M_1(y) \succeq 0; L_y(g_i) \geq 0; i = 1, 2; y_0 = 1 \}$$

with optimal value denoted $\inf \mathbf{Q}$ ($\min \mathbf{Q}$ if the infimum is achieved at some y^*), and with dual

$$\mathbf{Q}^* : \max_{\lambda, \gamma, \sigma} \{ \gamma : f - \gamma = \sigma + \lambda_1 g_1 + \lambda_2 g_2; \lambda_1, \lambda_2 \geq 0; \sigma \in \Sigma_2^2 \}$$

where Σ_2^2 is the set of s.o.s. of degree 2. Let $A_\lambda := \lambda_1 A_1 + \lambda_2 A_2$ and introduce the matrix

$$(2.18) \quad H(\lambda, \gamma) := \left[\begin{array}{c|c} -\gamma - \langle \lambda, \mathbf{c} \rangle & \mathbf{f}^T / 2 \\ \hline \mathbf{f} / 2 & -A_\lambda \end{array} \right].$$

Then \mathbf{Q}^* has the equivalent form

$$(2.19) \quad \mathbf{Q}^* : \max_{\lambda \geq 0, \gamma} \{ \gamma : H(\lambda, \gamma) \succeq 0 \},$$

with optimal value denoted $\sup \mathbf{Q}^*$ ($\max \mathbf{Q}^*$ if the sup is achieved). Obviously

$$\inf \mathbf{Q} \leq f^* := \min_x \{ f(x) : x \in \mathbf{K} \},$$

and $\min \mathbf{Q} = f^*$ holds if for instance $M_1(y^*)$ is rank one at some optimal solution y^* . Indeed, in this case, $y^* = (1, x^*, (x_1^*)^2, x_1^*x_2^*, \dots, (x_n^*)^2)$, which implies $L_{y^*}(f) = f(x^*)$ and $L_{y^*}(g_i) = g_i(x^*) \geq 0$, $i = 1, 2$.

Theorem 3. *Let $\mathbf{K} \subset \mathbb{R}^n$ be defined as in (1.3) with $m = 2$ and g_j as in (2.16), and let \mathbf{Q} be as in (2.17). Assume that \mathbf{K} is compact with nonempty interior and*

$$(2.20) \quad \lambda_1 A_1 + \lambda_2 A_2 \prec 0$$

for some $\lambda = (\lambda_1, \lambda_2) \geq 0$. Then for generic $\mathbf{f} \in \mathbb{R}^n$:

(a) $\min \mathbf{Q} = f^*$

(b) *The PP-BDR property holds for $\text{co}(\mathbf{K})$ with order $r = 1$, and so $\text{co}(\mathbf{K})$ has the SDr (2.12), i.e.,*

$$\{ M_1(y) \succeq 0; L_y(g_j) \geq 0, j = 1, 2; L_y(X_i) = x_i, i = 1, \dots, n; y_0 = 1 \}.$$

Proof. (a) Slater's condition holds for \mathbf{Q} and \mathbf{Q}^* . Indeed as \mathbf{K} has nonempty interior, let μ be the uniform probability measure on \mathbf{K} , with (well-defined) sequence of moment $y = (y_\alpha)$ (hence with $y_0 = 1$). It satisfies $M_1(y) \succ 0$ and $L_y(g_1) > 0$ as well as $L_y(g_2) > 0$.

Next, in view of (2.20), one may find $\lambda_1, \lambda_2 > 0$ and $\gamma \in \mathbb{R}$ such that $A_\lambda \prec 0$ and $H(\lambda, \gamma) \succ 0$. With $X \mapsto \sigma(X) := (1, X)^T H(\lambda, \gamma) \begin{bmatrix} 1 \\ X \end{bmatrix} \in \Sigma_2^2$, one obtains a strictly feasible solution $(\gamma, \lambda, \sigma)$ of \mathbf{Q}^* . As the value of both primal and dual strictly feasible solutions are finite, it follows that there is no duality gap, i.e., $\min \mathbf{Q} = \max \mathbf{Q}^*$, and both \mathbf{Q} and \mathbf{Q}^* are solvable.

Next, zero-duality gap yields complementarity² at optimal solutions y^* and $(\gamma^*, \lambda^*, \sigma^*)$ of \mathbf{Q} and \mathbf{Q}^* , i.e., $\text{trace}(M_1(y^*)H(\lambda^*, \gamma^*)) = 0$. Therefore $H(\lambda^*, \gamma^*)$ must be singular. Notice that $H(\lambda, \gamma) \succeq 0$ implies that

$$(2.21) \quad -2A_\lambda u = \mathbf{f}$$

for some $u \in \mathbb{R}^n$ and $\gamma + \lambda_1 c_1 + \lambda_2 c_2 \leq u^T A_\lambda u$.

We next prove that generically (i.e., except perhaps for a set of vectors $\{\mathbf{f}\} \subset \mathbb{R}^n$ with zero Lebesgue measure) $A_{\lambda^*} \prec 0$, and so $\text{rank} H(\lambda^*, \gamma^*) = n - 1$. Indeed, consider the set of $\lambda \in \mathbb{R}_+^2$ with $\lambda_1 \lambda_2 \neq 0$, such that A_λ is singular. Equivalently, after scaling by $\rho := \lambda_1 + \lambda_2 > 0$, and letting $\alpha := \lambda_1 / (\lambda_1 + \lambda_2)$, the set of $\alpha \in [0, 1]$ such that the determinant of the real symmetric matrix $B := A_2 + \alpha(A_1 - A_2)$ vanishes. Such an α must be a root in $[0, 1]$ of the characteristic polynomial of B , which has at most n

²See for instance Alizadeh et al. [1] or Pataki and Tuncel [15]

solutions (α_k) . So A_λ is singular only on the (at most n) rays $(\lambda_1^k, \lambda_2^k) = \rho(\alpha_k, 1 - \alpha_k)$, with $\rho \geq 0$ and $\alpha_k \in [0, 1]$. For each α_k , the image space of $A_{\lambda^k} = \rho(\alpha_k A_1 + (1 - \alpha_k) A_2)$ is at most $(n - 1)$ -dimensional, and (2.21) holds if and only if

$$\mathbf{f} = -2\rho(\alpha_k A_1 + (1 - \alpha_k) A_2) u,$$

for some $u \in \mathbb{R}^n$, i.e., if and only if

$$(2.22) \quad v_j^T \mathbf{f} = 0, \quad j = 1, \dots, p$$

where $(v_j)_{j=1}^p$ is a basis of $\text{Ker}(\alpha_k A_1 + (1 - \alpha_k) A_2)$.

If $p \geq 1$ then there is no solution in general, except perhaps on a set $\{\mathbf{f}\}_k \subset \mathbb{R}^n$ of zero Lebesgue measure. Therefore, as the set $\cup_k \{\mathbf{f}\}_k$ has zero Lebesgue measure, $A_{\lambda^*} \prec 0$ at an optimal solution $\lambda^* > 0$, for generic $\mathbf{f} \in \mathbb{R}^n$. Similar arguments are also valid if $\lambda_1 = 0$ or $\lambda_2 = 0$, as \mathbf{f} must belong to the image space of A_1 or A_2 .

And so, $H(\lambda^*, \gamma^*)$ has only one zero eigenvalue, which by complementarity, implies that $M_1(y^*)$ is rank-one. This in turn implies the desired result $\min \mathbf{Q} = f^*$.

(b) From $\min \mathbf{Q} = \max \mathbf{Q}^* = f^*$, for generic $\mathbf{f} \in \mathbb{R}^n$ and $\mathbf{c} \in \mathbb{R}^2$

$$f - f^* = \sigma^* + \lambda_1^* g_1 + \lambda_2^* g_2,$$

for some $\lambda^* \in \mathbb{R}_+^2$ and some $\sigma^* \in \Sigma^2$ of degree 2, that is, $f - f^* \in Q_1(g)$. In other words, the PP-BDR property holds for \mathbf{K} with order $r = 1$, and so, $\text{co}(\mathbf{K})$ has the SDr (2.12) which is the same as that of Theorem 3(b). \square

Figures 1, 2 and 3 respectively, display three examples of sets $\mathbf{K}_1, \mathbf{K}_2, \mathbf{K}_3 \subset \mathbb{R}^2$ that have the PP-BDR property with order $r = 1$. In all cases $g_1(X) = 1 - X_1^2 - X_2^2$, and

$$\begin{aligned} g_2(X) &= (X_1 - 1)^2 + X_2^2 - 1 && \text{[for } \mathbf{K}_1 \text{]} \\ &= 1/8 - X_1 X_2 && \text{[for } \mathbf{K}_2 \text{]} \\ &= X_1 X_2 - 1/8 && \text{[for } \mathbf{K}_3 \text{].} \end{aligned}$$

Notice that \mathbf{K}_3 is not even connected, and that for \mathbf{K}_1 , one even has a linear term X_1 in the polynomial g_2 .

Remark 4. Theorem 3 illustrates the fact that the PP-BDR property is specific to the representation of affine polynomials. Indeed if $f \in \mathbb{R}[X]$ is now an arbitrary quadratic polynomial $X \mapsto f(X) = X^T A_0 X + \mathbf{f}^T x + f_0$, then in general (and except in some special cases as those treated in [21]) $f - f^* \notin Q_1(g)$ even for generic data A_0, \mathbf{f} . See for instance some complexity results in quadratic optimization in Ye and Zhang [21].

Example 5. With \mathbf{K} as in (1.3), let $\widehat{\mathbf{K}} := \mathbf{K} \cap \{-1, 1\}^n$. The results in Lasserre [9, 10] show that $\widehat{\mathbf{K}}$ has the PP-BDR property with order $r = n + \max_j \lceil \deg g_j / 2 \rceil$. Hence $\text{co}(\widehat{\mathbf{K}})$ has the SDr (2.12) with the additional constraints $y_\alpha = y_{\alpha \bmod 2}$ for all α . In this case, the PP-BDR property is not useful for practical purposes because r depends on n , and the corresponding SDP has 2^n variables y_α .

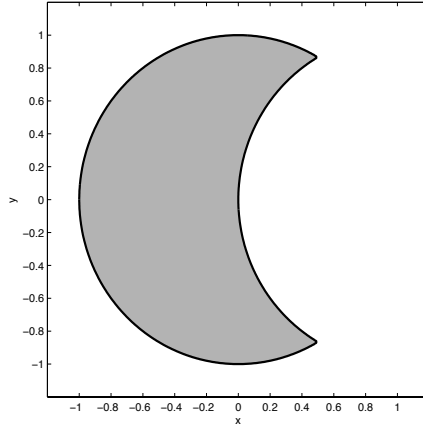


FIGURE 1. $\mathbf{K}_1 : g_2(X) = (X_1 - 1)^2 + X_2 - 1$

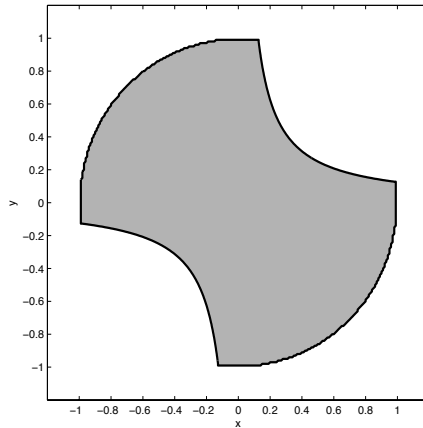


FIGURE 2. $\mathbf{K}_2 : g_2(X) = 1/8 - X_1X_2$

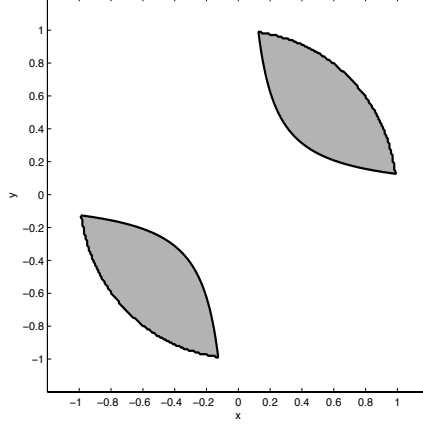
2.5. An approximate SDr set. With $\mathbf{B} := \{x \in \mathbb{R}^n : \|x\| \leq 1\}$ and given a compact set $\Omega \subset \mathbb{R}^n$ and $\rho > 0$, let

$$\Omega + \rho \mathbf{B} = \{x \in \mathbb{R}^n \mid \inf_{y \in \Omega} \|x - y\| \leq \rho\}.$$

In this section we prove that given any $\epsilon > 0$, there is a convex SDr set in sandwich between $\text{co}(\mathbf{K})$ and $\text{co}(\mathbf{K}) + \epsilon \mathbf{B}$ and with an explicit SDr in terms of the g_j 's that define \mathbf{K} . For this purpose we use a result of Prestel (later refined by Schweighofer [18]) on a degree bound in Schmüdgen's Positivstellensatz (and similarly a result of Nie and Schweighofer [19] on a degree bound in Putinar's Positivstellensatz).

We first need the following intermediate result.

Lemma 5. (a) *Let $\Omega \subset \mathbb{R}^n$ be a compact convex set and let $\epsilon > 0$ be fixed. If $x \notin \Omega + \epsilon \mathbf{B}$ then there exists a linear $f \in \mathbb{R}[X]$ whose coefficient vector*

FIGURE 3. $\mathbf{K}_2 : g_2(X) = X_1X_2 - 1/8$

$\mathbf{f} \in \mathbb{R}^n$ satisfies $\|\mathbf{f}\| = 1$, and a scalar f^* such that

$$(2.23) \quad f(z) \geq f^* \quad \forall z \in \Omega \quad \text{and} \quad f(x) < f^* - \epsilon.$$

In addition, $|f^*| \leq \tau_\Omega := \max\{\|x\| : x \in \Omega\}$.

(b) For any compact set $\mathbf{K} \subset \mathbb{R}^n$, and any $\mathbf{f} \in \mathbb{R}^n$ with $\|\mathbf{f}\| = 1$, let $f^* := \min_{x \in \mathbf{K}} \mathbf{f}^T x$, and let $\tau_{\mathbf{K}} := \max\{\|x\| : x \in \mathbf{K}\}$. Then

$$(2.24) \quad \min_{x \in \text{co}(\mathbf{K})} \mathbf{f}^T x = f^* \quad \text{and} \quad |f^*| \leq \tau_{\mathbf{K}}.$$

Proof. (a) With $x \notin \Omega + \epsilon\mathbf{B}$, let $x^* \in \Omega$ be its projection on Ω (well defined because Ω is compact and convex). Let $\mathbf{f} := (x^* - x)/\|x - x^*\|$ so that $\|\mathbf{f}\| = 1$, and let $f^* := \mathbf{f}^T x^*$, so that $|f^*| \leq \|\mathbf{f}\| \max\{\|x\| : x \in \Omega\} = \tau_\Omega$.

Then with $f \in \mathbb{R}[X]$ being the linear polynomial with coefficient vector \mathbf{f} , one has $f(z) \geq f^*$ for all $z \in \Omega$ because

$$f(z) = \mathbf{f}^T z = \mathbf{f}^T x^* + \mathbf{f}^T (z - x^*) = f^* + \langle x\vec{x}^*, x\vec{x}^* z \rangle \geq f^*$$

(since $\langle x\vec{x}^*, x\vec{x}^* z \rangle \geq 0$), and

$$f(x) - f^* = \mathbf{f}^T (x - x^*) = -\|x - x^*\| < -\epsilon.$$

(b) Indeed, $f^* = \min_{x \in \mathbf{K}} \mathbf{f}^T x = \min_{x \in \text{co}(\mathbf{K})} \mathbf{f}^T x$. Moreover, $|\mathbf{f}^T x| \leq \|\mathbf{f}\| \cdot \|x\| \leq \tau_{\mathbf{K}}$ for all $x \in \mathbf{K}$. \square

Then we have the following result.

Theorem 6. Let $\mathbf{K} \subset \mathbb{R}^n$ be a compact set as defined in (1.3).

(a) For every fixed $\epsilon > 0$ there is a integer $r_\epsilon \in \mathbb{N}$ such that the SDr set \mathbf{K}_ϵ defined by

$$(2.25) \quad \mathbf{K}_\epsilon := \left\{ x \in \mathbb{R}^n : \begin{cases} \exists y \in \mathbb{R}^{s(2r_\epsilon)} : \\ M_{r_\epsilon - r_j}(g_J y) \succeq 0, & J \subseteq \{1, \dots, m\} \\ L_y(X_i) = x_i, & i = 1, \dots, n \\ y_0 = 1 \end{cases} \right\}$$

satisfies $\text{co}(\mathbf{K}) \subseteq \mathbf{K}_\epsilon \subset \mathbf{K} + \epsilon \mathbf{B}$.

(b) Assume that the polynomial $N - \|X\|^2$ is in the quadratic module $Q(g)$. Then for every fixed $\epsilon > 0$ there is an integer $r_\epsilon \in \mathbb{N}$ such that the SDr set \mathbf{K}_ϵ defined by

$$(2.26) \quad \mathbf{K}_\epsilon := \left\{ x \in \mathbb{R}^n : \begin{cases} \exists y \in \mathbb{R}^{s(2r_\epsilon)} : \\ M_{r_\epsilon - r_j}(g_j y) \succeq 0, & j = 0, \dots, m \\ L_y(X_i) = x_i, & i = 1, \dots, n \\ y_0 = 1 \end{cases} \right\}$$

satisfies $\text{co}(\mathbf{K}) \subseteq \mathbf{K}_\epsilon \subset \mathbf{K} + \epsilon \mathbf{B}$.

In both cases (a) and (b), bounds on r_ϵ are available.

Proof. (a) That $\text{co}(\mathbf{K}) \subseteq \mathbf{K}_\epsilon$ is straightforward and as in the proof of Theorem 2. Next, let $x \notin \text{co}(\mathbf{K}) + \epsilon \mathbf{B}$ be fixed. Then by Lemma 5 (with $\Omega := \text{co}(\mathbf{K})$) there exists $\mathbf{f} \in \mathbb{R}^n$ and $f^* := \min_{x \in \text{co}(\mathbf{K})} \mathbf{f}^T x$ such that (2.23) holds. In addition, $\|\mathbf{f}\| = 1$ and $|f^*| \leq \tau_{\mathbf{K}}$.

Let $f \in \mathbb{R}[X]$ be the affine polynomial with coefficient vector $(\mathbf{f}, -f^*) \in \mathbb{R}^n \times \mathbb{R}$ so that $f + \epsilon \geq \epsilon > 0$ on \mathbf{K} . By Schmüdgen Positivstellensatz [17], $f + \epsilon \in P(g)$. Even more, $f + \epsilon \in P_{r_\epsilon}(g)$ for some integer $r_\epsilon \in \mathbb{N}$ that does *not* depend on the precise value of f but *only* on its degree (here 1) and norm (here $\|\mathbf{f}\| = 1$ and $|f^*| \leq \tau_{\mathbf{K}}$); see Schweighofer [18]. So let \mathbf{K}_ϵ be the SDr set defined in (2.25) with this r_ϵ . If $x \in \mathbf{K}_\epsilon$, we obtain the contradiction

$$\begin{aligned} 0 &> \mathbf{f}^T x - f^* + \epsilon \\ &= (\epsilon - f^*)y_0 + \sum_{i=1}^n L_y(f_i X_i) \quad [\text{as } y_0 = 1 \text{ and } L_y(X_i) = x_i \quad \forall i] \\ &= L_y(f(X) + \epsilon) = \sum_{J \subseteq \{1, \dots, m\}} L_y(g_J \sigma_J) \quad [\text{as } f + \epsilon \in P_{r_\epsilon}(g)] \\ &\geq 0 \quad [\text{by (2.15)}]. \end{aligned}$$

Hence $\mathbf{K}_\epsilon \subset \text{co}(\mathbf{K}) + \epsilon \mathbf{B}$, the desired result.

(b) The proof is very similar except that now we invoke Putinar Positivstellensatz [16] and Nie and Schweighofer [19] to replace $P_{r_\epsilon}(g)$ with $Q_{r_\epsilon}(g)$. Finally, bounds on r_ϵ can be found for both cases (a) and (b) in [18] and [19] respectively. \square

Hence, no matter if $\text{co}(\mathbf{K})$ is SDr, for every $\epsilon > 0$, there is always a SDr set \mathbf{K}_ϵ in sandwich between $\text{co}(\mathbf{K})$ and $\text{co}(\mathbf{K}) + \epsilon \mathbf{B}$. In addition, the SDr of \mathbf{K}_ϵ is explicit in terms of the polynomials (g_j) that define \mathbf{K} . This is a

significant improvement upon the *outer* convex approximations $\Delta_r \downarrow \text{co}(\mathbf{K})$ of [8], where each Δ_r has a SDr. Indeed in [8], if $x \notin \text{co}(\mathbf{K})$ then $x \notin \Delta_r$ for all $r \geq r(x)$ for some $r(x)$ that *depends* on x , an undesirable feature.

3. II. SDR FOR COMPACT CONVEX BASIC SEMIALGEBRAIC SETS

In this section, $\mathbf{K} \subset \mathbb{R}^n$ defined in (1.3) is compact and convex, and we assume that one knows a scalar $\tau_{\mathbf{K}}$ such that:

$$(3.1) \quad x \in \mathbf{K} \quad \Rightarrow \quad \|x\| \leq \tau_{\mathbf{K}}.$$

Lemma 7. *Let $\mathbf{K} \subset \mathbb{R}^n$ be as in (1.3), and assume that the g_j 's that define \mathbf{K} are all concave and Slater's condition holds. Given $f \in \mathbb{R}[X]$, let $f^* := \min_{\mathbf{K}} f(x)$.*

For every linear $f \in \mathbb{R}[X]$ with $\|f\| = 1$, there exists $\lambda(f) \in \mathbb{R}_+^m$ such that

$$(3.2) \quad X \mapsto L_f(X) := f(X) - f^* - \sum_{j=1}^m \lambda_j(f) g_j(X) \geq 0 \quad \text{on } \mathbb{R}^n$$

$$(3.3) \quad |f^*| \leq \tau_{\mathbf{K}}; \quad \lambda_j(f) \leq M_{\mathbf{K}}, \quad j = 1, \dots, m,$$

where $M_{\mathbf{K}}$ is independent of f .

Proof. As the g_j 's are concave, \mathbf{K} is compact and convex. In addition, as Slater's condition holds and f is convex, there exist nonnegative Lagrange multipliers $\lambda(f) \in \mathbb{R}_+^m$ such that

$$\nabla f(x^*) = \sum_{j=1}^m \lambda_j(f) \nabla g_j(x^*); \quad \lambda_j(f) g_j(x^*) = 0, \quad \forall j = 1, \dots, m,$$

where $x^* \in \mathbf{K}$ is a (global) minimizer of f on \mathbf{K} . Therefore the Lagrangian L_f defined in (3.2) is convex, with f^* as its global minimum on \mathbb{R}^n and x^* as global minimizer. Recall that Slater's condition states that $g_j(x_0) > 0$, $j = 1, \dots, m$, for some x_0 . And so, from

$$L_f(x_0) = f(x_0) - f^* - \sum_{j=1}^m \lambda_j(f) g_j(x_0) \geq 0,$$

we deduce that for every $j = 1, \dots, m$,

$$0 \leq \lambda_j(f) \leq \frac{f(x_0) - f^*}{g_j(x_0)} \leq \frac{2\tau_{\mathbf{K}}}{g_j(x_0)} \leq \frac{2\tau_{\mathbf{K}}}{\min_{j=1, \dots, m} g_j(x_0)} =: M_{\mathbf{K}},$$

where we have used $\|f\| = 1$. Therefore (3.3) holds and $M_{\mathbf{K}}$ above is independent of f . \square

Theorem 8. *Let $\mathbf{K} \subset \mathbb{R}^n$ be compact and defined as in (1.3). Assume that the g_j 's that define \mathbf{K} are all concave and Slater's condition holds. Given a linear polynomial $f \in \mathbb{R}[X]$, let L_f be the Lagrangian defined in (3.2).*

If L_f is s.o.s. for every linear $f \in \mathbb{R}[X]$, then the PP-BDR property holds for \mathbf{K} with order $r = \max_{j=1, \dots, m} \lceil \deg g_j / 2 \rceil$, and \mathbf{K} is a SDr set. In addition, the convex set

$$(3.4) \quad \Omega := \left\{ (x, y) \in \mathbb{R}^n \times \mathbb{R}^{s(2r)} : \begin{cases} M_r(y) & \succeq 0 \\ L_y(g_j) & \geq 0, \quad j = 1, \dots, m \\ L_y(X_i) & = x_i, \quad i = 1, \dots, n \\ y_0 & = 1 \end{cases} \right\}$$

is a SDr of \mathbf{K} .

Proof. Let $x \in \mathbf{K}$ and let $y = (x^\alpha) \in \mathbb{R}^{s(r)}$. Then $M_r(y) \succeq 0$ and $L_y(g_j) = g_j(x) \geq 0$ for all $j = 1, \dots, m$. Therefore, $(x, y) \in \Omega$.

Conversely, let $x \notin \mathbf{K}$, and suppose that $(x, y) \in \Omega$ for some $y \in \mathbb{R}^{s(r)}$. As $x \notin \mathbf{K}$ there exists $(f^*, \mathbf{f}) \in \mathbb{R} \times \mathbb{R}^n$ with $\|\mathbf{f}\| = 1$ such that $\mathbf{f}^T z \geq f^*$ for all $z \in \mathbf{K}$ and $\mathbf{f}^T x < f^*$. Actually, $f^* = \min_{x \in \mathbf{K}} f(x)$ where $f \in \mathbb{R}[X]$ is linear with vector of coefficients \mathbf{f} . Let L_f be as in (3.2). If L_f is s.o.s. then $f - f^* = \sigma + \sum_{j=1}^m \lambda_j(f) g_j$ for some s.o.s. polynomial $\sigma \in \mathbb{R}[X]$ of degree at most $2r$. Therefore, one obtains the contradiction

$$\begin{aligned} 0 &> \mathbf{f}^T x - f^* = f(x) - f^* \\ &\geq L_y(f - f^*) = L_y(\sigma + \sum_{j=1}^m \lambda_j g_j) \\ &\geq 0 \quad [\text{as } (x, y) \in \Omega]. \end{aligned}$$

□

Remark 9. Interestingly, Theorem 8 has a rephrasing in terms of the support function $\mathbf{f} \mapsto \sigma_{\mathbf{K}}(\mathbf{f})$ of \mathbf{K} , defined by:

$$\mathbf{f} \mapsto \sigma_{\mathbf{K}}(\mathbf{f}) := \sup \{ \langle \mathbf{f}, x \rangle : x \in \mathbf{K} \}.$$

For more details on the support function and its properties, the interested reader is referred to e.g. Hiriart-Urruty and Lemarechal [6, Chapter V].

For every linear polynomial $f \in \mathbb{R}[X]$, let $\mathbf{f} \in \mathbb{R}^n$ be its vector of coefficients. Then observe that in Theorem 8, and with $r = \max_{j=1, \dots, m} \lceil \deg g_j / 2 \rceil$, the statement " L_f is s.o.s. for every linear $f \in \mathbb{R}[X]$ " can be replaced with the new statement " $f + \sigma_{\mathbf{K}}(-\mathbf{f}) \in Q_r(g)$ for every linear $f \in \mathbb{R}[X]$ ".

The SDr (3.4) of \mathbf{K} is very natural as it is based on the Karush-Kuhn-Tucker optimality conditions. Existence of such a SDr reduces to the real algebraic problem of checking whether the Lagrangian L_f is s.o.s. for every (in fact, almost all) linear $f \in \mathbb{R}[X]$. Examples 2 and 3 in §2.3 provide such instances of sets \mathbf{K} with the PP-BDR property and with SDr (3.4).

Hence, an important issue to find sufficient conditions to ensure that the Lagrangian L_f is s.o.s., and if possible, conditions that can be checked

directly from the data g_j . For instance, in Lasserre [12] one finds sets of sufficient conditions on the coefficients of a polynomial f to ensure it is s.o.s. Also, after the present paper was written, Helton and Nie [5] have provided several sufficient conditions for the Lagrangian L_f to be s.o.s. In particular, if the Hessian $-\nabla^2 g_j(X)$ can be written $P_j(X)P_j(X)^T$ for some (not necessarily square) matrix $P_j(X)$ (i.e. $-\nabla^2 g_j(X)$ is a sum of squares), $j = 1, \dots, m$, then L_f is s.o.s.

Example 6. Consider the class of convex sets $\mathbf{K} \subset \mathbb{R}^n$ with $g_j \in \mathbb{R}[X]$ concave and of the form

$$(3.5) \quad g_j(X) = - \sum_{i=1}^n g_{ji} X_i^{2d} + h_j(X) + g_{j0}, \quad j = 1, \dots, m,$$

with $(g_{ji}) \subset \mathbb{R}_+$, and $h_j \in \mathbb{R}[X]$ linear for every $j = 1, \dots, m$. Then $-\nabla^2 g_j(X)$ is the diagonal matrix with diagonal elements $(g_{ii} X_i^{2d-2})$ and so can be written as $P_j(X)P_j(X)^T$ with $P_j(X) = (\nabla^2 g_j(X))^{1/2}$. Therefore, by Theorem 8, \mathbf{K} has the SDr (3.4).

Taking $\mathbf{K} := \{x \in \mathbb{R}^n : \|x\|_d := (\sum_{i=1}^n x_i^{2d})^{1/2d} \leq 1\}$ as a particular case of Example 6, one may thus conclude that the p -Euclidean ball is SDr, for all $d \geq 1$.

Approximate SDr. When one does not know whether the Lagrangian L_f is s.o.s. for all (in fact, almost all) linear $f \in \mathbb{R}[X]$, we next provide an approximation result. Namely we provide a semidefinite representation $\Omega_{\mathbf{r}}$ for an arbitrarily close convex approximation \mathbf{K}_r of \mathbf{K} . This approximation is in the spirit of that of §2.5, but specific to the convex case. We first need the following crucial auxiliary results.

Lemma 10. *Let $\mathbf{K} \subset \mathbb{R}^n$ be as in (1.3), $\tau_{\mathbf{K}}$ as in (3.1), and assume that the g_j 's that define \mathbf{K} are all concave and Slater's condition holds. Let $X \mapsto \Theta_r(X) := \sum_{i=1}^n \left(\frac{X_i}{\tau_{\mathbf{K}}}\right)^{2r}$.*

Then for every $\epsilon > 0$ there exists $r(\epsilon)$ such that for every linear $f \in \mathbb{R}[X]$ with $\|\mathbf{f}\| = 1$ and L_f as in (3.2),

$$(3.6) \quad L_f + \epsilon(1 + \Theta_r) \quad \text{is s.o.s.} \quad \forall r \geq r(\epsilon).$$

Equivalently, $f - f^ + \epsilon(1 + \Theta_r) \in Q_r(g)$.*

Proof. By Lemma 7, $L_f \geq 0$ and observe that the coefficients of the polynomial L_f are all uniformly bounded in \mathbf{f} whenever $\|\mathbf{f}\| = 1$. Indeed,

$$0 \leq \lambda_j(f) \leq M_{\mathbf{K}} \quad \forall j = 1, \dots, m; \quad |f^*| \leq \tau_{\mathbf{K}},$$

with $\tau_{\mathbf{K}}$ as in (3.1) and $M_{\mathbf{K}}$ as in Lemma 7. Hence, in view of the definition (3.2) of the polynomial L_f , its coefficients $(L_f)_{\alpha}$ are all bounded, uniformly in \mathbf{f} .

Next, $L_f \geq 0$ implies that L_f is nonnegative on the box $[-\tau_{\mathbf{K}}, \tau_{\mathbf{K}}]^n$. Therefore (3.6) follows from Lasserre and Netzer [11, §3.3], where it was

proved that the degree $r(\epsilon)$ does *not* depend on the precise value of the coefficients of L_f but only on ϵ , the dimension n , the degree of L_f and the *size* of its coefficients. Here, whenever \mathbf{f} varies, the degree of L_f takes *finitely* many values (depending on which Lagrange multipliers λ_j are zero), and its coefficients are uniformly bounded. \square

Next, in view of (3.1) and with $\Theta_r \in \mathbb{R}[X]$ as in Lemma 10,

$$(3.7) \quad \Theta_r(x) \leq 1 \quad \forall x \in \mathbf{K}, \quad \forall r \in \mathbb{N}.$$

Theorem 11. *Let $\mathbf{K} \subset \mathbb{R}^n$ as in (1.3) be compact, with $\tau_{\mathbf{K}}$ as in (3.1). Assume that the g_j 's that define \mathbf{K} are all concave and Slater's condition holds. With $r \in \mathbb{N}$, $r \geq \lceil \deg g_j / 2 \rceil$, $j = 1, \dots, m$, let $\Theta_r(X) = \sum_{i=1}^n \left(\frac{X_i}{\tau_{\mathbf{K}}} \right)^{2r}$, and let $\mathbf{K}_r \subset \mathbb{R}^n$ be the convex set:*

$$(3.8) \quad \mathbf{K}_r := \left\{ x \in \mathbb{R}^n : \begin{array}{l} \exists y \in \mathbb{R}^{s(2r)} \quad \text{s.t.} \\ M_r(y) \geq 0 \\ L_y(g_j) \geq 0, \quad j = 1, \dots, m \\ L_y(\Theta_r) \leq 1 \\ L_y(X_i) = x_i, \quad i = 1, \dots, n \\ y_0 = 1 \end{array} \right\}.$$

Then for every $\epsilon > 0$, there exists $r \in \mathbb{N}$ such that

$$(3.9) \quad \mathbf{K} \subseteq \mathbf{K}_r \subseteq \mathbf{K} + \epsilon \mathbf{B},$$

and the convex set

$$(3.10) \quad \mathbf{\Omega}_r := \left\{ (x, y) \in \mathbb{R}^n \times \mathbb{R}^{s(2r)} : \begin{array}{l} M_r(y) \geq 0 \\ L_y(g_j) \geq 0, \quad j = 1, \dots, m \\ L_y(\Theta_r) \leq 1 \\ L_y(X_i) = x_i, \quad i = 1, \dots, n \\ y_0 = 1 \end{array} \right\}$$

is a SDr of \mathbf{K}_r .

Proof. Let $x \in \mathbf{K}$. Then the vector $y = (x^\alpha) \in \mathbb{R}^{s(r)}$ satisfies the constraints described in (3.8), so that $\mathbf{K} \subseteq \mathbf{K}_r$ for all $r \geq \lceil \deg g_j / 2 \rceil$, $j = 1, \dots, m$.

To prove $\mathbf{K}_r \subseteq \mathbf{K} + \epsilon \mathbf{B}$, we proceed by contradiction. With $\epsilon > 0$ fixed, let $x \notin \mathbf{K} + \epsilon \mathbf{B}$ be fixed but arbitrary, and with $r(\epsilon/2)$ as in Lemma 10, let $r \geq r(\epsilon/2)$ be fixed arbitrary. Let $f \in \mathbb{R}[X]$ be as in Lemma 5 so that $f(x) - f^* < -\epsilon$. Next, with L_f being the Lagrangian associated with f , by Lemma 10,

$$(3.11) \quad L_f + \frac{\epsilon}{2}(1 + \Theta_r) = \sigma,$$

for some s.o.s. polynomial $\sigma \in \mathbb{R}[X]$ of degree $2r$. Equivalently,

$$f - f^* + \frac{\epsilon}{2}(1 + \Theta_r) = \sigma + \sum_{j=1}^m \lambda_j(f) g_j.$$

Now, suppose that $x \in \mathbf{K}_r$. There exists $y \in \mathbb{R}^{s(r)}$ such that $(x, y) \in \mathbf{\Omega}_r$. In particular, $L_y(\Theta_r) \leq 1$, $L_y(g_j) \geq 0$, $j = 1, \dots, m$, and $L_y(\sigma) \geq 0$ for every $\sigma \in \Sigma_r^2$ (because $M_r(y) \succeq 0$). And so, we obtain the contradiction

$$\begin{aligned} 0 > \mathbf{f}^T x - f^* + \epsilon &= f(x) - f^* + \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &\geq L_y(f - f^*) + \frac{\epsilon}{2} L_y(1 + \Theta_r) \\ &= L_y(\sigma) + \sum_{j=1}^m \lambda_j(f) L_y(g_j) \quad [\text{by (3.11)}] \\ &\geq 0 \quad [\text{as } (x, y) \in \mathbf{\Omega}_r]. \end{aligned}$$

Therefore $x \notin \mathbf{K}_r$. As $x \notin \mathbf{K} + \epsilon \mathbf{B}$ was arbitrary, this implies $\mathbf{K}_r \subseteq \mathbf{K} + \epsilon \mathbf{B}$. Finally, that $\mathbf{\Omega}_r$ in (3.10) is a SDr of \mathbf{K}_r , follows from the definition (3.8) of \mathbf{K}_r . \square

The SDr $\mathbf{\Omega}_r$ of the convex set \mathbf{K}_r in Theorem 11 resembles the SDr $\mathbf{\Omega}$ of \mathbf{K} in Theorem 8. The only difference is the index r which is larger than $\max_j \lceil \deg g_j / 2 \rceil$, and the additional constraint $L_y(\Theta_r) \leq 1$.

Hence, it is worth noticing that if \mathbf{K} does not admit the SDr $\mathbf{\Omega}$ of Theorem 8, one still obtains a SDr $\mathbf{\Omega}_r$ of an *arbitrarily close* convex approximation \mathbf{K}_r of \mathbf{K} , explicit in terms of the concave polynomials (g_j) that define \mathbf{K} .

4. CONCLUSION

We have considered the class of compact basic semialgebraic sets $\mathbf{K} \subset \mathbb{R}^n$, and have provided sufficient conditions for its convex hull $\text{co}(\mathbf{K})$ to have a SDr expressed directly in terms of the polynomials that define \mathbf{K} . When \mathbf{K} is convex and defined by concave polynomials, we have shown that if for every linear polynomial $f \in \mathbb{R}[X]$, the associated (nonnegative) Lagrangian L_f is s.o.s., then \mathbf{K} has a simpler specific SDr. Finally, we have also provided a SDr of an arbitrarily close approximation \mathbf{K}_ϵ of $\text{co}(\mathbf{K})$ (and of \mathbf{K} in the convex case). An interesting issue of further investigation is to provide concrete conditions on the concave polynomials g_j 's, to ensure that the Lagrangian L_f is s.o.s. The work in [5] provides some interesting results in this direction.

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