On the feasibility for the system of quadratic equations, explanations

Theorem 3.2 (Sufficient condition)

Consider $f\colon \mathbb{R}^n \to \mathbb{R}^m$, s.t. $f_i(x) = x^T A_i x + 2b_i^T x$, $A_i = A_i^T$. Define $F = f(\mathbb{R}^n)$.
Then why $A = \inf\limits_{y\in F}(c,y) = \inf\limits_{y\in \operatorname{conv} F}(c,y) = B$?

1. First, $F \subseteq \operatorname{conv} F$, therefore, $B \leqslant A$.

2. Secondly, let $y_k \in \operatorname{conv} F$ be a sequence s.t. $g_k = (c, y_k) \underset{k\to\infty}{\longrightarrow} B$. $y_k = \sum\limits_{i=1}^{n_k} \alpha_i^k y_i^k$.

   $g_k(c, y_k) = \sum\limits_{i=1}^{n_k} \alpha_i^k (c, y_i^k) = \sum\limits_{i=1}^{n_k} \alpha_i^k g_i^k$. Define $g_0^k = \min\limits_{i\in\overline{1,n_k}} g_i^k$. Then $B \leqslant g_0^k \leqslant g^k$. Therefore, $g_0^k \to B$ also. This way, we have constructed a sequence $y_0^k \in F$ s.t. $(c, y_0^k) \to B$, therefore, $A \leqslant B$.

Minimum of $f(x)$

Consider $f\colon \mathbb{R}^n \to \mathbb{R}^m$. $f_i(x) = x^T A_i x + 2b_i^T x$. $A_i^T = A_i$. Let $c \in \mathbb{R}^m$
We want to find $g(c) = \inf\limits_{x\in\mathbb{R}^n}(c, f(x))$.
Define $A_c \equiv c\cdot A = \sum\limits_{i=1}^{m} c_i A_i$, $b_c = c\cdot b = \sum\limits_{i=1}^{m} c_i b_i$.
$(c, f(x)) = \sum\limits_{i=1}^{m} c_i f_i(x) = \sum c_i(x^T A_i x + 2b_i^T x) = x^T A_c x + 2b_c^T x$.
If $\exists v\colon -\alpha = v^T A_c v < 0$ then $g(c) = -\infty$: $g(\beta v) = -\beta^2\alpha + \beta 2 b_c^T v \to -\infty$, $\beta \to +\infty$.
From this point on, we assume $A_c \geqslant 0$. Let R_0 be a zero eigenspace of A_c: $R_0 = \{v\colon A_c v = 0\}$
If $\exists v \in R_0\colon v^T b_c \neq 0$ then $g(c) = -\infty$: Consider $f(\beta v) = \beta^2 v^T \cancelto{0}{(A_c v)} + 2\beta \underbrace{b_c^T v}_{\neq 0} \to -\infty$, $\beta \to \infty$

Then $R_0 \subseteq \{b_c\}^\perp$
Consider $A = \sum\limits_{i=1}^{n} \lambda_i s_i s_i^T = S\Lambda S^T$, $S = ||s_1 ... s_n||$, $S^T S = E$, $s_i^T s_j = \delta_{ij}$.
f is differentiable, then for finding $g(c)$ the gradiend $\nabla(c, f(x)) = 2A_c x + 2b_c = 0$.

$$S\Lambda S^T x = -b_c \Leftrightarrow \Lambda S^T x = -S^T b_c$$

.

Let x be $x = x^\parallel + x^\perp$, $x^\parallel \in R_0$, $x^\perp \perp R_0$.
Then neither $f(x)$ nor $\Lambda S^T x$ depend on $x^\parallel$. This means that the x minimizing $g(c)$ is defined in terms of $x^\perp$ and $x^\parallel$ is arbitrary.
Define $\lambda_i^g = \begin{cases} 0, & \lambda_i = 0 \\ 1/\lambda_i, & \lambda_i \neq 0 \end{cases}$. Define $\Lambda^g = \operatorname{diag}(\lambda_1^g, ..., \lambda_n^g)$. Then $\Lambda\Lambda^g = \delta_{ij}[\lambda_i \neq 0]$. Then $S\Lambda^g\Lambda S^T$ is a projector on $R_0^\perp$.
Consider $\Lambda^g S^T(x^\parallel + x^\perp) = -\Lambda^g S^T b_c$. But $\Lambda S^T x^\parallel = 0$, therefore, $S\Lambda^g S^T x^\perp = -S\Lambda^g S^T b_c$. But $x^\perp$ is already in $R_0^\perp$, therefore, $x^\perp = -\underbrace{S\Lambda^g S^T}_{A^g} b_c$. Here A_c^g is a pseudoinverse of A_c.

Therefore, $\boxed{x = -A_c^g b_c + x^\parallel}$, where $x^\parallel \in R_0$.
Let us notice that since $A_c^{gT} = A_c^g$

Consider $f(x) = f(x^\perp) = b_c^T A_c^g A_c A_c^g b_c - 2b_c^T A_c^g b_c$. Consider $A_c A_c^g b_c = S\Lambda \cancelto{E}{S^T S} \Lambda^g S^T b_c$. Because $R_0 \in \{b_c\}^\perp$, $\Lambda\Lambda^g S^T b_c = S^T b_c$. Therefore, $A_c A_c^g b_c = b_c$. Then $f(x) = b_c^T A_c^g b_c - 2b_c^T A_c^g b_c = \boxed{-b_c^T A_c^g b_c}$

Finding c provided d

Let $H\colon \mathbb{R}^{n+1,n+1} \to \mathbb{R}^n$ be a map s.t. $H_i(X) = \mathrm{Tr}(H_i X)$,

$$H_i = \left\| \begin{matrix} A_i & b_i \\ b_i^T & 0 \end{matrix} \right\|^{\square}$$

.

Consider a boundary point X, which is a solution of:

$$\sup \quad t \qquad \begin{cases} H(X) = y^0 + td \\ X \geqslant 0 \\ X_{n+1,n+1} = 1 \end{cases}$$

.

Define $f(t,X) = t$, $D_0 = \{(t,X) \big| X \geqslant 0,\, X_{n+1,n+1} = 1\}$, $D_1 = \{(t,X) \big| H(X) = y^0 + td\}$.
Then supremum is equivalent to

$$\sup_{(t,X)\in D_0\cap D_1} f(t,X)$$

Define a Lagrange function $L(c,t,X) = \underbrace{t}_{f(t,X)} + \sum\limits_{i=1}^{m} c_i(y_i^0 + td_i - H_i(X))$

Then the dual function is $g(c) = \sup\limits_{(t,X)\in D_0} L(c,t,X)$.

Because $L = t(1 + \sum\limits_{i=1}^{m} c_i d_i) + \sum\limits_{i=1}^{n} c_i(y_i^0 - H_i(X))$, $g = +\infty$ when $(c,d) \neq -1$. From this point we assume that $\boxed{(c,d) = -1}$.

Now, $g(c) = \sup\limits_{X_{n+1,n+1}=1, X\geqslant 0} (c, y^0 - H(X)) = (c,y^0) + \sup\limits_{y\in \mathrm{conv}\, F} -(c,y) = (c,y^0) - \inf\limits_{y\in\mathrm{conv}\, F}(c,y)$.

Then the dual problem is

$$g(c) \to \inf_{(c,d)=-1}$$