The Discrete-Time Generalized Algebraic Riccati Equation: Order Reduction and Solutions’ Structure

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Abstract

In this paper we discuss how to decompose the constrained generalized discrete-time algebraic Riccati equation arising in optimal control and optimal filtering problems into two parts corresponding to an additive decomposition $X = X_0 + \Delta$ of each solution $X$: The first part is an explicit expression of the addend $X_0$ which is common to all solutions, and does not depend on the particular $X$. The second part can be either a reduced-order discrete-time regular algebraic Riccati equation whose associated closed-loop matrix is non-singular, or a symmetric Stein equation.

Keywords: Generalized Riccati equations.

*Partially supported by the Australian Research Council under the grant FT120100604 and by the Italian Ministry for Education and Research (MIUR) under PRIN grant n. 20085FFJ2Z.
1 Introduction

This paper is concerned with the following relations

\[ X = A^\top X A - (A^\top X B + S)(R + B^\top X B)\dagger (S^\top + B^\top X A) + Q, \quad (1) \]

where the symbol \( \dagger \) denotes the Moore-Penrose pseudo-inverse operation.\(^1\)

Equation (1) subject to the constraint (2) arises for example in discrete-time LQ problems – see [18] and [5] for the finite and infinite-horizon cases, respectively. Here, \( A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, Q \in \mathbb{R}^{n \times n}, S \in \mathbb{R}^{n \times m} \) and \( R \in \mathbb{R}^{m \times m} \) are such that the Popov matrix \( \Pi \) satisfies

\[ \Pi \overset{\text{def}}{=} \begin{bmatrix} Q & S \\ S^\top & R \end{bmatrix} = \Pi^\top \geq 0. \quad (3) \]

The set of matrices \( \Sigma = (A, B; \Pi) \) is often referred to as Popov triple, and (1) is known as the generalized discrete-time algebraic Riccati equation GDARE(\( \Sigma \)). This equation, together with the additional constraint (2), is usually referred to as constrained generalized discrete-time algebraic Riccati equation, and it is herein denoted by CGDARE(\( \Sigma \)). This equation generalizes the standard discrete-time algebraic Riccati equation DARE(\( \Sigma \))

\[ X = A^\top X A - (A^\top X B + S)(R + B^\top X B)^{-1} (S^\top + B^\top X A) + Q, \quad (4) \]

as the natural equation arising in LQ optimal control and filtering problems. In fact, it is only when the underlying linear system — obtained by a full-rank factorization \( \Pi = \begin{bmatrix} C^\top \\ D^\top \end{bmatrix} \begin{bmatrix} C & D \end{bmatrix} \) and considering a system described by the quadruple \( (A, B, C, D) \) — is left invertible that the standard DARE(\( \Sigma \)) admits solutions. The dynamic optimization problem, however, may still admit solutions in the more general setting where the underlying linear system is not left-invertible. In these cases, however, the standard DARE(\( \Sigma \)) does not admit solutions and the correct equation that must be used to address the original optimization problem is the CGDARE(\( \Sigma \)), see e.g. [5]. As discussed in [11] Chapt. 6], these general situations are particularly relevant in the context of stochastic control problems, see also [2] [9] and the references cited therein. On the other hand, whenever the standard DARE(\( \Sigma \)) admits solutions, the set of its solutions coincides with the set of solutions of CGDARE(\( \Sigma \)), so that the latter is a genuine generalization of the former (here and in the rest of the paper, we are only considering symmetric solutions \( X \) both for the DARE(\( \Sigma \)) and the CGDARE(\( \Sigma \))).

\(^1\)We recall that given an arbitrary matrix \( M \in \mathbb{R}^{h \times k} \), there exists a unique matrix \( M^\dagger \in \mathbb{R}^{k \times h} \) that satisfies the following four properties: (1) \( M M^\dagger M = M \); (2) \( M^\dagger M M^\dagger = M^\dagger \); (3) \( M^\dagger M \) is symmetric; (4) \( M M^\dagger \) is symmetric. By definition, the matrix \( M^\dagger \) is the Moore-Penrose pseudo-inverse of the matrix \( M \).
In the literature, several efforts have been devoted by many authors to the task of reducing the order and difficulty of the standard DARE($\Sigma$) by means of different techniques, [16] [10, 11, 12, 8]. This interest is motivated by the fact that the standard DARE($\Sigma$) is richer than the structure of its continuous-time counterpart, the continuous-time algebraic Riccati equation. In particular, in [3] a method was presented which, differently from earlier contributions presented on this topic, aimed at iteratively decomposing DARE($\Sigma$) into a trivial part and a reduced DARE whose associated closed-loop matrix is non-singular. The subsequent contribution [8] achieves a similar goal by avoiding the need for an iterative procedure.

The development of reduction procedures for generalized Riccati equations has received much less attention in the literature. This is in part likely to be due to the technical difficulties associated with generalized Riccati equations in the discrete time. In [3], a hint is given on how the iterative reduction detailed therein could be extended to the case of an equation in the form (1), provided that the attention is restricted to the set of positive semidefinite solutions, for which condition (2) is automatically satisfied. On the other hand, CGDARE($\Sigma$) may well admit solutions that are not positive semidefinite, see e.g. [5, 6]. In [12], a Riccati equation in the form of a CGDARE($\Sigma$) is considered, and a reduction technique is proposed to the end of computing the stabilizing solution of CGDARE($\Sigma$). The main goal of this paper is to combine the generality of the framework considered in [12] with the ambition of achieving a reduction for the entire set of solutions of CGDARE($\Sigma$). This task is accomplished by developing an iterative procedure that is similar in spirit to that of [3], but which presents a richer and more articulated structure. Indeed, not only do several technical difficulties and structural differences arise in extending the results of [3] to the case of CGDARE($\Sigma$) when the set of solutions is not restricted to semidefinite ones, but also, differently from the iterations needed in [3], which are essentially performed via changes of coordinates in the state space, in the general case of a CGDARE($\Sigma$), it is necessary to also resort to changes of coordinates in the input space. The problem of obtaining a systematic procedure to decompose generalized Riccati equations into a trivial part and a reduced, “well-behaved”, part described by a regular DARE (or at times, differently from the standard case, by a symmetric Stein equation), becomes much more interesting and challenging in the case of generalized Riccati equations. Our reduction method is based on the computation of null spaces of given matrices so that it can be easily implemented in a software procedure that uses only standard linear algebra procedures which are robust and available in any numerical software package. Therefore a relevant outcome of the presented procedure is what we believe to be the first systematic numerical procedure to compute the solutions of CGDARE.
2 Problem formulation and preliminaries

First, in order to simplify the notation, for any $X = X^\top \in \mathbb{R}^{n \times n}$ we define the matrices

$$
\begin{align*}
R_X &\overset{\text{def}}{=} R + B^\top XB \\
G_X &\overset{\text{def}}{=} I_m - R_X^\top R_X \\
S_X &\overset{\text{def}}{=} A^\top XB + S \\
K_X &\overset{\text{def}}{=} R_X^\top S_X^\top \\
A_X &\overset{\text{def}}{=} A - BK_X
\end{align*}
$$

so that (2) in CGDARE($\Sigma$) can be written concisely as $\ker R_X \subseteq \ker S_X$. The term $R_X^\top R_X$ is the orthogonal projector that projects onto $\text{im} R_X = \text{im} R_X^\top$, so $G_X$ is the orthogonal projector that projects onto $\ker R_X$. Hence, $\ker R_X = \text{im} G_X$.

As already mentioned, in this paper we present a procedure that reduces CGDARE($\Sigma$) to another discrete-time algebraic Riccati equation with the same structure but smaller order and in which both $A_0 = A - BR_X^\top S_X^\top$ and $R$ are non-singular. On the other hand, this means that the Riccati equation thus obtained is indeed a standard DARE, i.e., it has the structure shown in (4), as the following result shows.

**Proposition 1** Suppose that the matrix $R$ is non-singular, and let $X = X^\top$ be any symmetric solution of CGDARE($\Sigma$). Then $R_X = R + B^\top XB$ is non-singular.

**Proof:** As shown in [5, Lemma 4.1], for any symmetric solution $X = X^\top$ of CGDARE($\Sigma$) the inclusion $\ker R_X \subseteq \ker R$ holds. As a consequence, if $R$ is non-singular, its null-space $\ker R$ is zero, and therefore so is the null-space of $R_X$. This is equivalent to the fact that $R_X$ is non-singular. 

The reduction technique presented in this paper can also be viewed from the perspective of the so-called extended symplectic pencil $N_\Sigma - zM_\Sigma$, where

$$
M_\Sigma \overset{\text{def}}{=} \begin{bmatrix}
I_n & 0 & 0 \\
0 & -A^\top & 0 \\
0 & -B^\top & 0
\end{bmatrix} \quad \text{and} \quad N_\Sigma \overset{\text{def}}{=} \begin{bmatrix}
A & 0 & B \\
Q & -I_n & S \\
S^\top & 0 & R
\end{bmatrix}.
$$

The case in which the matrix pencil $N_\Sigma - zM_\Sigma$ is regular (i.e., if there exists $z \in \mathbb{C}$ such that $\det(N_\Sigma - zM_\Sigma) \neq 0$) corresponds to the case in which CGDARE($\Sigma$) is indeed a DARE($\Sigma$), whereas the one in which $N_\Sigma - zM_\Sigma$ is singular (i.e., the determinant of $N_\Sigma - zM_\Sigma$ is the zero polynomial) corresponds to a case in which DARE($\Sigma$) does not admit solutions. It is shown in [3] for DARE($\Sigma$) and in [7] for CGDARE($\Sigma$) that if $A_X$ is singular, the Jordan structure of $A_X$ associated with the eigenvalue $\lambda = 0$ is completely determined by $N_\Sigma - zM_\Sigma$, and is independent of the particular solution $X$ of DARE($\Sigma$) or CGDARE($\Sigma$). It is shown in [3] that in the case where the matrix pencil $N_\Sigma - zM_\Sigma$ is regular — or, equivalently, the CGDARE($\Sigma$) and the standard DARE($\Sigma$) have the same solutions — the following statements are equivalent:
(1) $N_\Sigma$ is singular;

(2) $N_\Sigma - zM_\Sigma$ has a generalized eigenvalue at zero;

(3) there exists a solution $X$ of CGDARE($\Sigma$) such that the corresponding closed-loop matrix $A_X$ is singular;

(3') for any solution $X$ of CGDARE($\Sigma$), the corresponding closed-loop matrix $A_X$ is singular;

(4) at least one of the two matrices $R$ and $A_0 = A - BR^\dagger S^\top$ is singular.

The case where the matrix pencil $N_\Sigma - zM_\Sigma$ is possibly singular was investigated in [7], where it was proved that in this more general case these four facts are not equivalent. In particular, (1) is not equivalent to (2). Moreover, in the case where $N_\Sigma - zM_\Sigma$ is singular, (1) and (3) are not equivalent, nor are (3) and (4). However, it was shown in [7] Lemma 3.1] that it is still true that (1) is equivalent to (4). Furthermore, it is shown in [7, Proposition 3.4] that $r \overset{\text{def}}{=} \text{rank} R_X$ is constant for any solution $X$ of CGDARE($\Sigma$), and that $A_X$ is singular if and only if at least one of the following two conditions holds: (i) $\text{rank} R < r = \text{rank} R_X$ and (ii) $A_0 = A - BR^\dagger S^\top$ is singular. It is clear that this condition reduces to (4) in the case where $R_X$ is invertible, i.e., in the case where $N_\Sigma - zM_\Sigma$ is regular. Notice also that since both conditions are independent of the particular solution $X$ of the CGDARE($\Sigma$), the singularity of the closed-loop matrix $A_X$ is invariant with respect to the particular solution $X$.

To summarize, in the case where the matrix pencil $N_\Sigma - zM_\Sigma$ is singular, the following statements are equivalent:

(1') $N_\Sigma$ is singular;

(2') at least one of the two matrices $R$ and $A_0 = A - BR^\dagger S^\top$ is singular;

and the following statements are equivalent:

(1'') there exists a solution $X$ of CGDARE($\Sigma$) such that the corresponding closed-loop matrix $A_X$ is singular;

(2'') for any solution $X$ of CGDARE($\Sigma$), the corresponding closed-loop matrix $A_X$ is singular;

(3'') at least one of the two conditions

(a) $\text{rank} R < r = \text{rank} R_X$; or

(b) $A_0 = A - BR^\dagger S^\top$ is singular;

is satisfied.
We recall again that in [5, Lemma 4.1] it was shown that for any solution $X$ of CGDARE($\Sigma$), we have $\ker R_X \subseteq \ker R$. This means that if $R$ is non-singular, such is also $R_X$, and therefore the condition $\text{rank} R < \text{rank} R_X$ is not satisfied. Thus, in this case, the closed-loop matrix $A_X$ is non-singular for some solution $X$ of the CGDARE($\Sigma$) if and only if it is non-singular for each solution $X$ of the CGDARE($\Sigma$) and this is in turn equivalent to $A_0$ being non-singular.

3 Mathematical preliminaries

We begin this section by recalling a standard linear algebra result that is used in the derivations throughout the paper.

**Lemma 1** Consider $P = \begin{bmatrix} P_{11} & P_{12} \\ P_{12}^\top & P_{22} \end{bmatrix} = P^\top \geq 0$. Then,

(i) $\ker P_{12} \supseteq \ker P_{22}$;

(ii) $P_{12} P_{22}^\dagger P_{22} = P_{12}$;

(iii) $P_{12} (I - P_{22}^\dagger P_{22}) = 0$;

(iv) $P_{11} - P_{12} P_{22}^\dagger P_{12}^\top \geq 0$.

We now generalize a well-known result of the classic Riccati theory — which essentially shows how to eliminate the cross-penalty matrix $S$ — to the case of a constrained generalized Riccati equation.

**Lemma 2** Let $A_0 \overset{\text{def}}{=} A - BR^\dagger S^\top$ and $Q_0 \overset{\text{def}}{=} Q - SR^\dagger S^\top$. Moreover, let $\Pi_0 \overset{\text{def}}{=} \begin{bmatrix} Q_0 & 0 \\ 0 & R \end{bmatrix}$ and $\Sigma_0 \overset{\text{def}}{=} (A_0, B, \Pi_0)$. Then, the following statements hold true:

(i) CGDARE($\Sigma$) has the same set of solutions as CGDARE($\Sigma_0$)

\[
X = A_0^\top X A_0 - A_0^\top X B (R + B^\top X B)^\dagger B^\top X A_0 + Q_0, \\
\text{ker}(R + B^\top X B) \subseteq \text{ker}(A_0^\top X B);
\]

(ii) for any symmetric solution $X$ of CGDARE($\Sigma$), we have

\[
A_X = A_{0X} \overset{\text{def}}{=} A_0 - B (R + B^\top X B)^\dagger B^\top X A_0;
\]

(iii) $Q_0 \geq 0$. 

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Proof: We start proving (i). Inserting the expressions for $A_0$ and $Q_0$ into (5) yields

\[ X = A^\top X A - A^\top X B R^\dagger X^\top S^T - S R^\dagger B^\top X A + S R^\dagger B^\top X B R^\dagger S^T \]
\[-A^\top X B R^\dagger X A + A^\top X B R^\dagger X B R^\dagger S^T + S R^\dagger B^\top X B R^\dagger B^\top X A \]
\[-SR^\dagger B^\top X B R^\dagger B^\top X B R^\dagger S^T + Q - SR^\dagger S^T \]
\[= A^\top X A - A^\top X B R^\dagger S^T - SR^\dagger B^\top X A + SR^\dagger B^\top X B R^\dagger S^T \]
\[-A^\top X B R^\dagger X A + A^\top X B R^\dagger (B^\top X B + R - R) R^\dagger S^T \]
\[+SR^\dagger (B^\top X B + R - R) R^\dagger X A \]
\[-SR^\dagger (B^\top X B + R - R) R^\dagger (B^\top X B + R - R) R^\dagger S^T + Q - SR^\dagger S^T \]
\[= A^\top X A - A^\top X B R^\dagger S^T - SR^\dagger B^\top X A + SR^\dagger B^\top X B R^\dagger S^T \]
\[-A^\top X B R^\dagger X A + A^\top X B R^\dagger R^\dagger S^T - A^\top X B R^\dagger R^\dagger S^T \]
\[+SR^\dagger R^\dagger X A - S R^\dagger B^\top X A - SR^\dagger R^\dagger R^\dagger S^T \]
\[+SR^\dagger R^\dagger R^\dagger S^T + SR^\dagger R^\dagger S^T - SR^\dagger R^\dagger S^T + Q - SR^\dagger S^T. \quad (7) \]

From \( \text{ker}R_x \subseteq \text{ker}S_x \), it follows that there exists \( K \) such that \( S_x = KR_x \), which gives

\[ S_x R^\dagger_x R_x = KR_x R^\dagger_x R_x = KR_x = S_x. \quad (8) \]

Using this identity and its transpose, we can develop the terms in the right hand-side of the last equality sign of (7) as

\[ A^\top X B R^\dagger R^\dagger S^T + SR^\dagger R^\dagger S^T = S_x R^\dagger_x R^\dagger_x R^\dagger S^T = S_x R^\dagger S^T, \]

\[ SR^\dagger R^\dagger B^\top X A + SR^\dagger R^\dagger R^\dagger S^T = SR^\dagger R^\dagger R^\dagger S^T = SR^\dagger S^T_x. \]

and

\[ SR^\dagger B^\top X B R^\dagger S^T - SR^\dagger R^\dagger R^\dagger S^T = -SR^\dagger R^\dagger R^\dagger S^T = -SR^\dagger S^T. \]

Using these new simplified expressions back into (7) gives

\[ X = -A^\top X B R^\dagger - SR^\dagger S^T - SR^\dagger B^\top X A - SR^\dagger S^T + S_x R^\dagger S^T_x - SR^\dagger S^T_x \]
\[= A^\top X A - A^\top X B R^\dagger B^\top X A - SR^\dagger B^\top X A - A^\top X B R^\dagger S^T - SR^\dagger S^T_x + Q \]
\[-(A^\top X B + S) R^\dagger S^T - SR^\dagger (B^\top X A + S^T) + S_x R^\dagger S^T - SR^\dagger S^T_x \]
\[= A^\top X A - (A^\top X B + S)(R + B^\top X B)^\dagger (B^\top X A + S^T) + Q, \]
which is indeed (1). We conclude the proof of (i) showing that (2) is equivalent to (6). We write (6) as

\[ \ker R_x \subseteq \ker(A_0^\top XB) \]
\[ = \ker(A^\top XB - SR^\top XB) \]
\[ = \ker[A^\top XB - SR^\top (R + B^\top XB - R)] \]
\[ = \ker(A^\top XB + S - SR^\top R_x), \]

since SR^\top R = S in view of the second point in Lemma 1. Suppose (2) holds. Let \( \omega \in \ker R_x \). Then \( S_x \omega = (S + A^\top XB) \omega = 0 \). Thus, we have also \((A^\top XB + S - SR^\top R_x) \omega = 0 \) since \( \omega \in \ker R_x \). Conversely, suppose that (6) holds true, and take \( \omega \in \ker R_x \). Then, \((A^\top XB + S - SR^\top R_x) \omega = 0 \) implies \((S + A^\top XB) \omega = 0 \).

Let us now consider (ii). We first show that \((R^\top_x R_x - I_m)^\top 0 = 0 \). To prove this fact — which is trivial in the case of the standard DARE(\( \Sigma \)) — we use the inclusion \( \ker R_x \subseteq \ker R \), which holds true for any symmetric solution \( X \) of CGDARE(\( \Sigma \)), see [5] Lemma 4.1. In a suitable basis of the input space, \( R_x \) can be written as \( R_x = \begin{bmatrix} R_{x,1} & 0 \\ 0 & 0 \end{bmatrix} \), where \( R_{x,1} \) is invertible; let \( \mu \) be the order of \( R_{x,1} \). In this basis, \( R \) is written as \( R = \begin{bmatrix} R_1^\top & 0 \\ 0 & 0 \end{bmatrix} \), where \( R_1 \) may or may not be singular, and we obtain

\[ (R^\top_x R_x - I_m) R^\top = \left( \begin{bmatrix} R_{x,1}^{-1} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} R_{x,1} & 0 \\ 0 & 0 \end{bmatrix} - \begin{bmatrix} I_\mu & 0 \\ 0 & I_{m-\mu} \end{bmatrix} \right) \begin{bmatrix} R_1^\top & 0 \\ 0 & 0 \end{bmatrix} = 0. \]

Thus,

\[ A_{0x} = A_0 - B (R_1^\top R_x - I_m) R^\top S^\top = A_x + B (R_1^\top R_x - I_m) R^\top S^\top = A_x. \]

To prove (iii) it suffices to observe that \( Q_0 \) is the generalized Schur complement of \( R \) in \( \Pi \). Since \( \Pi \) is assumed to be positive semidefinite, then such is also \( Q_0 \).

Another useful result is the following generalization of a classic property of DARE(\( \Sigma \)).

**Lemma 3** Let \( T \in \mathbb{R}^{n \times n} \) be invertible. Let

\[ A_T \overset{\text{def}}{=} T^{-1} A_0 T, \quad B_T \overset{\text{def}}{=} T^{-1} B, \quad Q_T \overset{\text{def}}{=} T^{-1} Q_0 T. \]

Let also \( \Pi_T \overset{\text{def}}{=} \begin{bmatrix} Q_T & 0 \\ 0 & R \end{bmatrix} \) and \( \Sigma_T \overset{\text{def}}{=} (A_T, B_T, \Pi_T) \). Then, \( X \) is a solution of CGDARE(\( \Sigma \)) — and therefore also of CGDARE(\( \Sigma_0 \)) — if and only if \( X_T = T^{-1} X T \) is a solution of CGDARE(\( \Sigma_T \))

\[ X_T = A_T^\top X_T A_T - A_T^\top X_T B_T (R + B_T^\top X_T B_T) B_T^\top X_T A_T + Q_T \]
\[ \ker(R + B_T^\top X_T B_T) \subseteq \ker(A_T^\top X_T B_T) \]
**Proof**: The equations obtained by multiplying (5) to the left by $T^{-1}$ and to the right by $T$ coincides with (11) with $X_T \overset{\text{def}}{=} T^{-1}X_T$. Moreover, since $T$ is invertible, $\ker(R + B^T X B) \subseteq \ker(A_0^T X B)$ is equivalent to $\ker(R + B^T X B) \subseteq \ker(T^{-1} A_0^T X B)$, which is equivalent to (12).

4 Main results

4.1 Reduction corresponding to a singular $A_0$

In this section, we present the first fundamental result of this paper, that can be exploited as a basis for an iterative procedure – to be used whenever $A_0$ is singular – to the end of decomposing the set of solutions of CGDARE($\Sigma$) into a trivial part and a part given by the set of solutions of a reduced order CGDARE.

**Theorem 1** Let $\nu \overset{\text{def}}{=} \dim(\ker A_0)$. Let $U = \begin{bmatrix} U_1 & U_2 \end{bmatrix}$ be an orthonormal change of coordinates in $\mathbb{R}^n$, where $\im U_2 = \ker A_0$. Let $A_U \overset{\text{def}}{=} U^T A_0 U = \begin{bmatrix} \tilde{A} & 0_{n \times \nu} \end{bmatrix}$ where $\tilde{A} = \begin{bmatrix} A_1 \\ A_{21} \end{bmatrix}$ with $A_1 \in \mathbb{R}^{(n-\nu) \times (n-\nu)}$ and $A_{21} \in \mathbb{R}^{\nu \times (n-\nu)}$. Let also $B_U = U^T B$ and $Q_U = U^T Q_0 U$ be partitioned conformably, i.e., $B_U = \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}$ and $Q_U = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix}$, with $B_1 \in \mathbb{R}^{(n-\nu) \times m}$, $B_2 \in \mathbb{R}^{\nu \times m}$, $Q_{11} \in \mathbb{R}^{(n-\nu) \times (n-\nu)}$ and $Q_{22} \in \mathbb{R}^{\nu \times \nu}$. Finally, let $Q_1 \overset{\text{def}}{=} \tilde{A}^T Q_0 \tilde{A}$, $S_1 \overset{\text{def}}{=} \tilde{A}^T Q_0 B_1$ and $R_1 \overset{\text{def}}{=} R + B_1^T Q_0 B_1$.

1. Let $X$ be a solution of CGDARE($\Sigma$), and partition $X_U \overset{\text{def}}{=} U^T X U$ as $X_U = \begin{bmatrix} X_{11} & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix}$, with $X_{11} \in \mathbb{R}^{(n-\nu) \times (n-\nu)}$ and $X_{22} \in \mathbb{R}^{\nu \times \nu}$. Then,

   (i) there hold

   $$X_{12} = Q_{12} \quad \text{and} \quad X_{22} = Q_{22}$$

   (ii) The new Popov matrix $\Pi_1 \overset{\text{def}}{=} \begin{bmatrix} Q_1 \\ S_1 \end{bmatrix}$ is positive semidefinite.

   (iii) Let $\Sigma_1 \overset{\text{def}}{=} (A_1, B_1, \Pi_1)$. Then, $\Delta_1 \overset{\text{def}}{=} X_{11} - Q_{11}$ satisfies CGDARE($\Sigma_1$)

   $$\Delta_1 = A_1^T \Delta_1 A_1 - (A_1^T \Delta_1 B_1 + S_1)(R_1 + B_1^T \Delta_1 B_1)^+ (B_1^T \Delta_1 A_1 + S_1^T) + Q_1$$

   (13)

   $$\ker(R_1 + B_1^T \Delta_1 B_1) \subseteq \ker(S_1 + A_1^T \Delta_1 B_1).$$

   (14)

2. Conversely, if $\Delta_1$ is a solution of (13), then

   $$X = U \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12}^T & Q_{22} \end{bmatrix} U^T$$

   (15)

   is a solution of CGDARE($\Sigma$).
Proof: We begin proving the first point. In view of Lemma 3, $X$ is a solution of CGDARE($\Sigma$) if and only if $X_U = U^TXU$ is a solution of CGDARE($\Sigma_U$)

\[
X_U = A_U^TX_UA_U - A_U^TX_U(B_U + R + B_U^TX_UB_U)^\dagger B_U^TX_UA_U + Q_U
\]

(16)

\[
\ker(R + B_U^TX_UB_U) \subseteq \ker(A_U^TX_UB_U),
\]

(17)

where $\Pi_U =\begin{bmatrix} Q_U & 0 \\ 0 & R \end{bmatrix}$ and $\Sigma_U = (A_U, B_U, \Pi_U)$. Multiplying (16) to the left by $\begin{bmatrix} 0 & I_v \end{bmatrix}$ yields

\[
\begin{bmatrix} 0 & I_v \\ X_{11} & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix} = \begin{bmatrix} A_1^T & A_2^T \\ 0 & 0 \end{bmatrix} X_U A_U
\]

\[-\begin{bmatrix} 0 & I_v \\ A_1^T & A_2^T \\ 0 & 0 \end{bmatrix} X_U B_U (R + B_U^TX_UB_U)^\dagger B_U^TX_UA_U + \begin{bmatrix} 0 & I_v \end{bmatrix} Q_{11} Q_{12} + Q_{12} Q_{22},
\]

which gives $\begin{bmatrix} X_{12}^T & X_{22} \end{bmatrix} = \begin{bmatrix} Q_{12}^T & Q_{22} \end{bmatrix}$. This proves the first statement. To prove (ii) we observe that

\[
\Pi_1 = \begin{bmatrix} Q_1 & S_1 \\ S_1^T & R_1 \end{bmatrix} = \begin{bmatrix} \tilde{A}^T \\ B^T \end{bmatrix} Q_0 \begin{bmatrix} \tilde{A} & B \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & R \end{bmatrix} \geq 0,
\]

(18)

since, as shown in Lemma 2, $Q_0 \geq 0$. We now prove (iii). Substitution of $X_U = Q_U + \begin{bmatrix} 0 & A_1^T \\ A_1 & 0 \end{bmatrix}$ obtained in the proof of (i) into (16) gives

\[
\begin{bmatrix} \Delta_1 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} Q_1 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} A_1^T \Delta_1 A_1 & 0 \\ 0 & 0 \end{bmatrix} - \begin{bmatrix} S_1 + A_1^T \Delta_1 B_1 \\ 0 \end{bmatrix} (R_1 + B_1^T \Delta_1 B_1)^\dagger \begin{bmatrix} S_1^T + B_1^T \Delta_1 A_1 & 0 \end{bmatrix},
\]

which is equivalent to (13). We now prove that $\Delta_1$ satisfies $\ker(R_1 + B_1^T \Delta_1 B_1) \subseteq \ker(S_1 + A_1^T \Delta_1 B_1)$. Substitution of $X_U = Q_U + \begin{bmatrix} 0 & A_1^T \\ A_1 & 0 \end{bmatrix}$ into (17) gives

\[
\ker(R_1 + B_1^T \Delta_1 B_1) \subseteq \ker\left(\begin{bmatrix} \tilde{A}^T \\ 0 \end{bmatrix} Q_U B_U + \begin{bmatrix} A_1^T \Delta_1 B_1 \\ 0 \end{bmatrix}\right) = \ker\left(\begin{bmatrix} S_1 + A_1^T \Delta_1 B_1 \\ 0 \end{bmatrix}\right),
\]

which is equivalent to (14). We now prove the converse. Let $X$ be as in (15). Substituting $X_U = U^TXU = \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12}^T & Q_{22} \end{bmatrix}$ into CGDARE($\Sigma_U$) gives

\[
\begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12}^T & Q_{22} \end{bmatrix} = \begin{bmatrix} A_1^T & A_2^T \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix} \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}
\]

\[+ \begin{bmatrix} A_1^T & A_2^T \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix} B_1 (R + B_1^T B_2^T) \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix} B_2^T \]

\[\times \begin{bmatrix} B_1 & 0 \\ B_2 & 0 \end{bmatrix} \begin{bmatrix} \Delta_1 + Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix} + \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix}.
\]
Developing the products and recalling that we have defined \(Q_1 = \tilde{A}^\top Q_U \tilde{A}, S_1 = \tilde{A}^\top Q_U B_U\) and \(R_1 = R + B_U^\top Q_U B_U\) gives

\[
\begin{bmatrix}
\Delta_1 + Q_{11} & Q_{12} \\
\Delta_1 + Q_{11} & Q_{12} \\
Q_{11}^\top & Q_{12} \\
Q_{11}^\top & Q_{12}
\end{bmatrix}
= 
\begin{bmatrix}
A_1^\top \Delta_1 A_1 + Q_1 & 0 \\
A_1^\top \Delta_1 A_1 + Q_1 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
- 
\begin{bmatrix}
A_1^\top \Delta_1 B_1 + S_1 \\
A_1^\top \Delta_1 B_1 + S_1 \\
0 & 0 \\
0 & 0
\end{bmatrix}
(R_1 + B_U^\top \Delta_1 B_1)\left( R_1 + B_U^\top \Delta_1 B_1 \right)^\top
\begin{bmatrix}
\Delta_1 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\]

which is satisfied since \(\Delta_1\) is a solution of (13-14). \(\blacksquare\)

The following property, which considers the structure of the closed-loop matrix in the basis described by \(U\), is stated separately from properties (i-iii) in Theorem 1 to emphasize the differences between this first reduction and the second reduction that will be presented in the next section. In fact, while in the standard case of DARE\((\Sigma)\) this property of the closed-loop matrix applies to both the first and the second reduction procedure, in the general case of CGDARE\((\Sigma)\) the structure of the closed-loop matrix described in the following property is maintained only for the first reduction procedure.

**Proposition 2** Given a solution \(X\) of CGDARE\((\Sigma)\) and the associated solution \(\Delta_1\) of (13-14), let \(A_X\) and \(A_{\Delta_1}\) be the associated closed-loop matrices. Then,

\[
U^\top A_X U = \begin{bmatrix}
A_{\Delta_1} & 0 \\
0 & 0
\end{bmatrix}
\]

**Proof:** We first observe that the last \(v\) columns of \(U^\top A_X U\) are also zero, i.e.,

\[
U^\top A_X U = U^\top (A_0 - B R^\dagger X A_0) U
= A_U - B_U (R + B_{U}^\top X_{U} B_U)^\dagger B_{U}^\top X_{U} A_{U} = \begin{bmatrix} * & 0 \end{bmatrix}
\]

in view of the fact that the last \(v\) columns of \(A_U\) are zero. Moreover,

\[
U^\top A_X U = \begin{bmatrix}
A_1 & 0 \\
A_21 & 0
\end{bmatrix}
- \begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\left( R + \begin{bmatrix}
B_1^\top & B_2^\top
\end{bmatrix}
\begin{bmatrix}
\Delta_1 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\right)^\dagger
B_{U}^\top X_{U} A_{U}
= \begin{bmatrix}
A_1 & 0 \\
A_21 & 0
\end{bmatrix}
- \begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
(R_1 + B_U^\top \Delta_1 B_1)^\dagger B_{U}^\top X_{U} A_{U}
\]

and

\[
A_{\Delta_1} = A_1 - B_1 (R_1 + B_U^\top \Delta_1 B_1)^\dagger (B_U^\top \Delta_1 A_1 + S_1^\top) - B_1 R_U^\dagger S_1^\top + B_1 R_U^\dagger S_1^\top
= A_1 - B_1 (R_1 + B_U^\top \Delta_1 B_1)^\dagger B_U^\top \Delta_1 A_1 - B_1 (R_1 + B_U^\top \Delta_1 B_1)^\dagger R_U^\dagger S_1^\top
- B_1 R_U^\dagger S_1^\top + B_1 (R_1 + B_U^\top \Delta_1 B_1)^\dagger (R_1 + B_U^\top \Delta_1 B_1) R_U^\dagger S_1^\top
\]
where the last equality follows from the identity \((R_i + B_i^\top \Delta_i B_i)^\dagger (R_i + B_i^\top \Delta_i B_i) R_i^\dagger = R_i^\dagger\), which can be proved exactly in the same way as (9). Thus,

\[
A_{\Delta_i} = A_i - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i A_i - B R_i^\top S_i^\top - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger (R_i - R - B_i^\top \Delta_i B_i) R_i^\dagger S_i^\top \\
= A_i - B R_i^\top S_i^\top - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i A_i + B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i B_i R_i^\dagger S_i^\top \\
= A_i - B R_i^\top S_i^\top - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i (A_i - B_i R_i^\top S_i^\top).
\]

Then, denoting by \( \Gamma \) the upper-left block submatrix of order \( n - \nu \) within \( U^\top A \chi U \), we find

\[
\Gamma - A_{\Delta_i} = B_i (R_i + B_i^\top \Delta_i B_i)^\dagger (B_i^\top \Delta_i A_i - B_i^\top X \chi \overline{A}) + B_i R_i^\top S_i^\top - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i B_i R_i^\dagger S_i^\top.
\] (19)

A simple calculation shows also that

\[
B_i^\top \Delta_i A_i - B_i^\top X \chi \overline{A} = B_i^\top \Delta_i A_i - [ B_i^\top B_2^\top ] \begin{bmatrix} Q_{11} + \Delta_i & Q_{12} \\ Q_{12}^\top & Q_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}
= -[ B_i^\top B_2^\top ] \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} - B_i^\top \overline{Q}_i \overline{A} = -S_i^\top.
\]

We can use this identity in (19) and we obtain

\[
\Gamma - A_{\Delta_i} = -B_i (R_i + B_i^\top \Delta_i B_i)^\dagger S_i^\top + B_i R_i^\dagger S_i^\top - B_i (R_i + B_i^\top \Delta_i B_i)^\dagger B_i^\top \Delta_i B_i R_i^\dagger S_i^\top \\
= -B_i (R_i + B_i^\top \Delta_i B_i)^\dagger S_i^\top + B_i (R_i + B_i^\top \Delta_i B_i)^\dagger (R_i + B_i^\top \Delta_i B_i) R_i^\top S_i^\top \\
= B_i (R_i + B_i^\top \Delta_i B_i)^\dagger [(R_i + B_i^\top \Delta_i B_i) R_i^\top S_i^\top - S_i^\top - B_i^\top \Delta_i B_i R_i^\dagger S_i^\top] \\
= B_i (R_i + B_i^\top \Delta_i B_i)^\dagger (R_i R_i^\dagger S_i^\top - S_i^\top) = 0.
\]

In view of (i) of Theorem 1, all solutions of CGDARE(\( \Sigma \)) coincide along the subspace \( \mathcal{W} \triangleq \ker \left( \begin{bmatrix} l_{n-v} & 0 \\ 0 & 0 \end{bmatrix} U^\top \right) \). This means that given any two solutions \( X \) and \( Y \) of CGDARE(\( \Sigma \)), we have \( X|_{\mathcal{W}} = Y|_{\mathcal{W}} = \overline{Q}_0|_{\mathcal{W}} \).

The following result gives a property of the set of solutions of CGDARE(\( \Sigma \)), and a procedure to solve CGDARE(\( \Sigma \)) in terms of the reduced order DARE(\( \Sigma \)).

**Corollary 1** The set \( \mathcal{X} \) of solutions of CGDARE(\( \Sigma \)) is parameterized as the set of matrices that can be expressed as

\[
X = U \begin{bmatrix} \Delta_i & 0 \\ 0 & 0 \end{bmatrix} U^\top + \overline{Q}_0
\]

where \( U = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \) is defined as in Theorem 7 and \( \Delta_i \) is solution of (13),(14).

\(^2\text{Indeed, in CGDARE(\( \Sigma_i \)) the matrices } R_i \text{ and } R_i + B_i^\top \Delta_i B_i \text{ play the same role of } R \text{ and } R + B^\top X B \text{ in CGDARE(\( \Sigma \)), so that } \ker(R_i + B_i^\top \Delta_i B_i) \subseteq \ker R_i.\)
After the reduction described in Theorem [1], it may still happen that \( A_1 - B_1 R_1^\dagger S_1 \) is singular. However, since we have proved that CGDARE(\( \Sigma \)) has exactly the same structure of CGDARE(\( \Sigma \)), because \( \Pi_1 = \Pi_1^\top \geq 0 \), if \( A_1 - B_1 R_1^\dagger S_1 \) is singular we can iterate the procedure by rewriting (13-14) as

\[
\Delta_1 = A_{0,1}^\top \Delta_1 A_{0,1} - A_{0,1}^\top \Delta_1 B_1 (R_1 + B_1^\top \Delta_1 B_1)^\dagger B_1^\top \Delta_1 A_{0,1} + Q_{0,1}
\]

(20)

ker\((R_1 + B_1^\top \Delta_1 B_1) \subseteq \ker\((A_{0,1} \Delta B_1)\),

(21)

where \( A_{0,1} \) is non-singular. Notice also that this reduction procedure can be carried out only using the problem data \( A, B, Q, R, S \), so that it holds for any solution \( X \) of CGDARE(\( \Sigma \)). In other words, this procedure (and the one that will follow in the next section) can be performed without the need to compute a particular solution of the Riccati equation.

Once we have obtained the reduced-order CGDARE, if the corresponding matrix \( R \) is singular, we can proceed with the second reduction procedure outlined in the next section.

4.2 Reduction corresponding to a singular \( R \)

Consider CGDARE(\( \Sigma \), either in the form given by (12) or (5-6). Suppose \( R \) is singular. We assume that we have already performed the reduction described in the previous section. Hence, we may assume that \( A_0 \) is now non-singular. To deal with this situation, we address separately two different cases: the first leads either to a reduced-order DARE or to a symmetric Stein equation depending on the rank of \( R \), and the second leads to a reduced-order CGDARE. We first consider the case in which \( A_0^{-1} B \ker R = \{0\} \), i.e., \( B \ker R = \{0\} \). This case can in turn be divided into two sub-cases. The first is the one in which \( R \) is not the zero matrix. In this case, denoting by \( r \) the rank of \( R \), we can consider a change of coordinates in the input space that brings \( R \) in the form

\[
R = \begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix},
\]

where \( R_1 \) is non-singular, and \( r \) is its order. With respect to this basis, since \( \ker R = \text{im} \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix} \), matrix \( B \) can be written as \( B = \begin{bmatrix} B_1 & 0_{n \times (m-r)} \end{bmatrix} \), and (5-6) written in this basis
Theorem 2

Let this case, CGDARE($\Sigma$) reduces to a symmetric Stein equation

$$X = A_0^\top X A_0 - A_0^\top X B_1 (R_1 + B_1^\top X B_1)^\dagger B_1^\top X A_0 + Q_0,$$

where now $R_1$ is invertible as required, so that $R_1 + B_1^\top X B_1$ is positive definite. Hence, the latter is in fact a DARE

$$X = A_0^\top X A_0 - A_0^\top X B_1 (R_1 + B_1^\top X B_1)^{-1} B_1^\top X A_0 + Q_0.$$

If $r = 0$, i.e., if $R$ is the zero matrix, then $B \ker R = \{0\}$ implies that $B$ is also the zero matrix. In this case, CGDARE($\Sigma$) reduces to a symmetric Stein equation$^3$

$$X = A_0^\top X A_0 + Q_0.$$

We now consider the case in which $A_0^{-1} B \ker R \neq \{0\}$.

**Theorem 2** Let $\eta \overset{\text{def}}{=} \dim(A_0^{-1} B \ker R)$. Let $V = [V_1 \ V_2]$ be an orthonormal change of coordinates in $\mathbb{R}^n$ where $\im V_2 = A_0^{-1} B \ker R$. Let $Q_v \overset{\text{def}}{=} V^\top A_0 V$ and $A_v \overset{\text{def}}{=} V^\top A_0 V = \begin{bmatrix} A_1 \ & \ast \\ \ast \ & \ast \end{bmatrix}$,

$$B_v \overset{\text{def}}{=} V^\top B = \begin{bmatrix} B_1 \ \ast \\ \ast \ & \ast \end{bmatrix}, \quad R_v \overset{\text{def}}{=} R + B_v^\top Q_v B_v, \quad \text{with } A_1 = V_1^\top A_0 V_1 \in \mathbb{R}^{(n-\eta) \times (n-\eta)} \text{ and } B_1 = V_1^\top B_v \in \mathbb{R}^{(n-\eta) \times m}.$$

Let $Q_v \overset{\text{def}}{=} V^\top Q_v V = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix}$, $A_v^\top Q_v A_v = \begin{bmatrix} Q_1 \ & \ast \\ \ast \ & \ast \end{bmatrix}$, $A_v^\top Q_v B_v = \begin{bmatrix} S_1 \ \ast \\ \ast \ & \ast \end{bmatrix}$, where $Q_{11}, Q_1 \in \mathbb{R}^{(n-\eta) \times (n-\eta)}$ and $S_1 \in \mathbb{R}^{(n-\eta) \times m}$. Then,

1. Let $X$ be a solution of CGDARE($\Sigma$), and partition $X_v \overset{\text{def}}{=} V^\top X V$ as $X_v = \begin{bmatrix} X_{11} & X_{12} \\ X_{12}^\top & X_{22} \end{bmatrix}$. Then,

   (i) there hold

   $$X_{12} = Q_{12} \quad \text{and} \quad X_{22} = Q_{22}.$$

   (ii) The Popov matrix $\Pi_1 \overset{\text{def}}{=} \begin{bmatrix} Q_1 & S_1 \\ S_1^\top & R_1 \end{bmatrix}$ is positive semidefinite.

$^3$For a discussion on the properties of symmetric Stein equations we refer to [17] Section 5.3] and [13] Section 1.5].

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(iii) Let $\Sigma_i \overset{\text{def}}{=} (A_i, B_i, \Pi_i)$. Then, $\Delta_i \overset{\text{def}}{=} X_{i1} - Q_{i1}$ satisfies $\text{CGDARE}(\Sigma_i)$

\[
\Delta_i = A_i^\top \Delta_i A_i - (A_i^\top \Delta_i B_i + S_i) (R_i + B_i^\top \Delta_i B_i)^\top (B_i^\top \Delta_i A_i + S_i^\top) + Q_i
\]

(24)

\[
\ker(R_i + B_i^\top \Delta_i B_i) \subseteq \ker(S_i + A_i^\top \Delta B_i).
\]

(25)

2. Conversely, if $\Delta_i$ is a solution of (24,25), then

\[
X = V \begin{bmatrix} \Delta_i + Q_{i1} & Q_{i2} \\ Q_{i2} & Q_{22} \end{bmatrix} V^\top
\]

is a solution of $\text{CGDARE}(\Sigma)$.

**Proof:** We prove the first point. As already observed in the beginning of Section 4.1 $X$ is a solution of (11,2) – and therefore also of (5,6) – if and only if $X_V = V^\top X V$ is a solution of $\text{CGDARE}(\Sigma_V)$

\[
X_V = A_v^\top X_v A_v - A_v^\top X_v B_v (R + B_v^\top X_v B_v)^\top B_v^\top X_v A_v + Q_v
\]

(26)

\[
\ker(R + B_v^\top X_v B_v) \subseteq \ker(A_v^\top X_v B_v),
\]

(27)

where $\Pi_v = \begin{bmatrix} Q_v & 0 \\ 0 & R \end{bmatrix}$ and $\Sigma_v = (A_v, B_v, \Pi_v)$. We can re-write (26) as

\[
X_V = A_v^\top X_v V^\top [I_n - B (R + B^\top X B)^\top B^\top X] A V + Q_v.
\]

Post-multiplying the latter by $\begin{bmatrix} 0 \\ I_n \end{bmatrix}$ and considering a basis matrix $K_R$ for $\ker R$, so that we can write $V_2 = A^{-1} B K_R$, gives

\[
\begin{bmatrix} X_{12} \\ X_{22} \end{bmatrix} = A_v^\top X_v V^\top [I_n - B (R + B^\top X B)^\top B^\top X] A V_2 + \begin{bmatrix} Q_{12} \\ Q_{22} \end{bmatrix}
\]

\[
= V^\top A_v^\top X B [I_n - R_v^\top (B^\top X B + R - R)] K_R + \begin{bmatrix} Q_{12} \\ Q_{22} \end{bmatrix}
\]

\[
= V^\top A_v^\top X B (I_n - R_v^\top R_x - R_v^\top R) K_R + \begin{bmatrix} Q_{12} \\ Q_{22} \end{bmatrix}
\]

Recalling that $\text{im} G_X = \ker R_x$, and that by virtue of (6) there holds $\ker R_x \subseteq \ker( A_v^\top X B) , we get $V^\top A_v^\top X B G_X K_R = 0$, from which (i) immediately follows. To prove (ii) we observe that

\[
\Pi_i = \begin{bmatrix} I_{n-\eta} & 0 & 0 \\ 0 & 0 & I_m \end{bmatrix} \begin{bmatrix} A_v^\top & B_v^\top \end{bmatrix} Q_V \begin{bmatrix} I_{n-\eta} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & I_m \\ 0 & R \end{bmatrix} \geq 0.
\]

(28)
In order to prove (iii), we first observe that in view of the previous considerations we have 
\( X_v = Q_v + \begin{bmatrix} A_1 & 0 \\ 0 & 0 \end{bmatrix} \). Substitution of this expression into (26)-(27) yields
\[
\begin{bmatrix}
\Delta_1 & 0 \\
0 & 0
\end{bmatrix} = \begin{bmatrix}
Q_1 & 0 \\
0 & 0
\end{bmatrix} + \begin{bmatrix}
A_1^\top \Delta_1 A_1 & 0 \\
0 & 0
\end{bmatrix} - \begin{bmatrix}
S_1 + A_1^\top \Delta_1 B_1 \\
0
\end{bmatrix}(R_1 + B_1^\top \Delta_1 B_1)^\top \begin{bmatrix}
S_1^\top + B_1^\top \Delta_1 A_1 & 0
\end{bmatrix},
\]
whose block in position (1,1) is exactly (24). We now prove that \( \Delta_1 \) satisfies (25). Substitution of \( X_v = Q_v + \begin{bmatrix} \Delta_1 & 0 \\ 0 & 0 \end{bmatrix} \) into (27) gives
\[
\ker(R_1 + B_1^\top \Delta_1 B_1) \subseteq \ker \left( \begin{bmatrix}
S_1 + A_1^\top \Delta_1 B_1 \\
* \\
\end{bmatrix} \right),
\]
from which (25) immediately follows.

The second point can be proved by reversing these arguments along the same lines of the second part of the proof of Theorem 1.

In view of (i) of Theorem 2 all solutions of CGDARE(\( \Sigma \)) coincide along \( \mathcal{V} \equiv \ker \left( \begin{bmatrix}
I_n - \eta \\
0
\end{bmatrix} V^\top \right) \).

This means that given any two solutions \( X \) and \( Y \) of CGDARE(\( \Sigma \)), we have \( X|_{\mathcal{V}} = Y|_{\mathcal{V}} = Q_0|_{\mathcal{V}} \).

**Corollary 2** The set \( \mathcal{X} \) of solutions of CGDARE(\( \Sigma \)) is parameterized as the set of matrices
\[
X = V \begin{bmatrix}
\Delta_1 & 0 \\
0 & 0
\end{bmatrix} V^\top + Q_0
\]
where \( V = \begin{bmatrix} V_1 & V_2 \end{bmatrix} \) is defined as in Theorem 2 and \( \Delta_1 \) is solution of (24)-(25).

**Remark 1** In [3] it is shown that if \( X \) is a solution of DARE(\( \Sigma \)) and we consider the associated solution \( \Delta_1 \) of the reduced DARE(\( \Sigma_1 \)), and if we denote by \( A_X \) and \( A_{\Delta_1} \) the associated closed-loop matrices, there holds
\[
V^\top A_X V = \begin{bmatrix}
A_{\Delta_1} & 0 \\
0 & 0_{\eta \times \eta}
\end{bmatrix}.
\]
This is a simple consequence of the fact that in the case of a solution \( X \) of DARE(\( \Sigma \)), the matrix \( R_X \) is invertible. We now show via a simple example that this fact does not hold in general in the case of CGDARE(\( \Sigma \)). Consider a Popov triple \( \Sigma \) described by the matrices
\[
A = \begin{bmatrix}
0 & 2 & 0 \\
2 & 2 & 0 \\
0 & 0 & -5
\end{bmatrix}, \quad B = \begin{bmatrix}
-1 \\
0 \\
0
\end{bmatrix}, \quad Q = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 24
\end{bmatrix}, \quad R = 0, \quad S = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}.
\]
In this case $A_0 = A$ is invertible, and $A_0^{-1}B \text{ker}R = \text{span}\left\{ \begin{bmatrix} 1 & 0 \end{bmatrix} \right\}$. Let $V_2 = \begin{bmatrix} -1/\sqrt{2} \\ 1/\sqrt{2} \\ 0 \end{bmatrix}$ and $V = \begin{bmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & 1 & 0 \end{bmatrix}$. Then, we compute

$$A_V = V^\top A_0 V = \begin{bmatrix} 3 & 0 & -1 \\ 0 & -5 & 0 \\ -1 & 0 & -1 \end{bmatrix}, \quad B_V = V^\top B = \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \end{bmatrix}, \quad Q_V = V^\top Q_0 V = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 24 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$A_V^\top Q_V A_V = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 600 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad A_V^\top Q_V B_V = 0,$$

so that the matrices of the reduced CGDARE($\Sigma_1$) are

$$A_1 = \begin{bmatrix} 3 & 0 & -5 \\ 0 & 0 & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 1/\sqrt{2} \\ 0 \end{bmatrix}, \quad Q_1 = \begin{bmatrix} 0 \\ 0 & 600 \\ 0 & 0 \end{bmatrix}, \quad S_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad R_1 = 0.$$

A simple direct calculation shows that the only solution of this reduced CGDARE is $X_1 = \begin{bmatrix} 0 \\ 0 \\ -25 \end{bmatrix}$. Thus, the only solution of the original CGDARE($\Sigma$) is $X = V \left( Q_V + \begin{bmatrix} X_1 \\ 0 \end{bmatrix} \right) V^\top = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$. The corresponding closed-loop matrix coincides with $A$, i.e., $A_X = A$. Now,

$$V^\top A_X V = \begin{bmatrix} 3 & 0 & -1 \\ 0 & -5 & 0 \\ -1 & 0 & -1 \end{bmatrix}$$

This shows that neither of the two zero submatrices in the second block-column of (29) is zero in the general case of CGDARE($\Sigma$). While the submatrix in the upper left block of $A_X$ still coincides with $A_{\lambda_1}$, in the case of CGDARE($\Sigma$) it is also no longer true that the spectrum of $A_{\lambda_1}$ is contained in that of $A_X$. Indeed, in this case $\sigma(A_{\lambda_1}) = \{-5, 3\}$ whereas $\sigma(A_X) = \{-5, 1 \pm \sqrt{5}\}$. This difference between DARE and CGDARE is related to the fact that in this generalized case the reduction can correspond simply to the singularity of $R$ which does not imply the singularity of $A_X$ as discussed in Section 2.

**Remark 2** As for the reduction described in Theorem 1, it may occur that, as a result of the reduction illustrated in Theorem 2 $A_1 - B_1 R_1^\dagger S_1^\top$ and/or $R_1$ be still singular. However, we have showed that $\Pi_1$ is symmetric and positive semidefinite. This means that if $A_1 - B_1 R_1^\dagger S_1^\top$ is singular, we can repeat the reduction procedure described in Theorem 1 while if $A_1 - B_1 R_1^\dagger S_1^\top$ is non-singular but $R_1$ is singular, we can repeat the reduction procedure described in Theorem 2. Since the order of the Riccati equation lowers at each reduction step, after at most $n$ steps, either we have computed the unique solution of the original CGDARE($\Sigma$), or we have obtained a symmetric Stein equation (which is linear), or we obtained a “well-behaved” DARE of maximally reduced order where the corresponding $R$ and $A - BR_1^\dagger S_1^\top$ matrices are non-singular.
5 Numerical examples

Example 5.1 Using the reduction techniques developed in the previous sections, we want to study the set of solutions of the CGDARE($\Sigma$) where $\Sigma$ is given by the matrices

$$A = \begin{bmatrix} 0 & -4 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & -1 \\ 3 & 0 \end{bmatrix}, \quad Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad R = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}. $$

First notice that since $S$ is the zero matrix, $A_0$ and $Q_0$ coincide with $A$ and $Q$, respectively. Thus, in this case both $A_0$ and $R$ are singular. We begin with a reduction that corresponds to the singularity of $A_0$. Since $\ker A_0 = \text{span}\{\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}\}$, we can consider a basis matrix $U = [U_1 \mid U_2]$ given by $U = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$, so that

$$A_U = \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 4 & 0 & 0 \end{bmatrix}, \quad \tilde{A} = \begin{bmatrix} 3 & 0 \\ 0 & -1 \\ 4 & 0 \end{bmatrix}, \quad B_U = \begin{bmatrix} -3 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix}, \quad Q_U = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}. $$

Thus,

$$A_1 = \begin{bmatrix} 3 & 0 \\ 0 & -1 \end{bmatrix}, \quad B_1 = \begin{bmatrix} -3 & 0 \\ 0 & 0 \end{bmatrix}, \quad S_1 = \begin{bmatrix} 0 & -4 \\ 0 & 0 \end{bmatrix}, \quad Q_1 = \begin{bmatrix} 16 & 0 \\ 0 & 0 \end{bmatrix}, \quad R_1 = \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix}. $$

In view of Corollary 1, $X$ is a solution of CGDARE($\Sigma$) if and only if it can be written as

$$X = Q_0 + U \begin{bmatrix} \Delta_1 & 0 \\ 0 & 0 \end{bmatrix} U^T, $$

where $\Delta_1$ is an arbitrary solution of (13-14). To maintain the notations as consistent as possible to those employed in Section 4.2, we define $\bar{A} \defeq A_1, \bar{B} \defeq B_1, \bar{Q} \defeq Q_1, \bar{\Sigma} \defeq S_1, \bar{R} \defeq R_1$ and $\bar{\Sigma} \defeq \Delta_1$. With this notation, (13-14) can be re-written as

$$\bar{X} = \bar{A}_0^\top \bar{X} \bar{A}_0 - \bar{A}_0^\top \bar{X} \bar{B} (\bar{R} + \bar{B}^\top \bar{X} \bar{B})^{\top} \bar{B}^\top \bar{X} \bar{A}_0 + \bar{Q}_0 \tag{30} $$

$$\ker(\bar{R} + \bar{B}^\top \bar{X} \bar{B}) \subseteq \ker(\bar{A}_0^\top \bar{X} \bar{A}_0), \tag{31} $$

where $\bar{A}_0 = \bar{A} - \bar{B} \bar{R}^\top \bar{S}^\top = \bar{A}$ and $\bar{Q}_0 = \bar{Q} - \bar{S} \bar{R}^\top \bar{S}^\top = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$. Matrix $\bar{A}_0$ is invertible, whereas $\bar{R}$ is singular. Thus, we can apply the reduction procedure in Section 4.2 (we will employ the same notation used in Section 4.2, with the only exception that all the letters will have a bar, to distinguish this second reduction from the first one). A simple calculation shows that $\text{im}(\bar{A}_0^{-1} \bar{B} \ker \bar{R}) = \text{span}\{\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\}$. Thus, we can consider a basis matrix $V = [ V_1 \mid V_2 ]$ given by $V = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$. Hence, we define $\bar{X}_v \defeq V^\top \bar{X} V$ along with

$$\bar{A}_v = V^\top \bar{A}_0 V = \begin{bmatrix} -1 & 0 \\ 0 & 3 \end{bmatrix}, \quad \bar{B}_v = V^\top \bar{B} = \begin{bmatrix} 0 & 0 \\ -3 & 0 \end{bmatrix}, \quad \bar{Q}_v = V^\top \bar{Q}_0 V = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, $$

so that $\bar{A}_v = -1, \bar{B}_v = [0, 0], \bar{\Sigma}_v = [0, 0], \bar{Q}_v = 0, \bar{R}_v = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$. In view of Corollary 2, $\bar{X}$ is a solution of (30-31) if and only if

$$\bar{X} = \bar{Q}_0 + V \begin{bmatrix} \bar{A}_v & 0 \\ 0 & 0 \end{bmatrix} V^\top.$$
with $\overline{\Delta}_i$ being an arbitrary solution of

$$
\overline{\Delta}_i = \overline{\Delta}_i \overline{\Delta}_1 - \overline{\Delta}_i \overline{\Delta}_1 (\overline{\mathcal{R}}_1 + \overline{\mathcal{B}}_1 \overline{\mathcal{B}}_1) (\overline{\mathcal{R}}_1 + \overline{\mathcal{B}}_1 \overline{\mathcal{B}}_1) \overline{\Delta}_1 + \overline{\mathcal{Q}}_i,
$$

(32)

$$
\ker(\overline{\mathcal{R}}_1 + \overline{\mathcal{B}}_1 \overline{\mathcal{B}}_1) \subseteq \ker(\overline{\mathcal{R}}_1 \overline{\Delta}_1 \overline{\mathcal{B}}_1).
$$

(33)

We still have $\overline{\mathcal{R}}_1$ singular, and $\overline{\mathcal{A}}_1 - \overline{\mathcal{B}}_1 \overline{\mathcal{R}}_1 \overline{\mathcal{B}}_1$ is invertible. On the other hand, $\overline{\mathcal{B}}_1 \ker\overline{\mathcal{R}}_1 = \{0\}$, so that the reduction associated to the singularity of $\overline{\mathcal{R}}_1$ cannot be carried out. Using a change of coordinates in the input space given by $\Omega = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$, we obtain

$$
\hat{\mathcal{R}}_1 = \Omega^{-1} \overline{\mathcal{R}}_1 \Omega = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \hat{\mathcal{B}}_1 = \overline{\mathcal{B}}_1 \Omega = \begin{bmatrix} 0 & 0 \end{bmatrix}^	op,
$$

so that $\hat{\mathcal{R}}_{1,0} = 1$ and $\hat{\mathcal{B}}_{1,0} = 0$. Thus, (32)(33) can be written in this basis as

$$
\overline{\Delta}_1 = \overline{\Delta}_1 \overline{\Delta}_1 \overline{\mathcal{A}}_1 - \overline{\Delta}_1 \overline{\Delta}_1 \overline{\mathcal{B}}_{1,0} (\hat{\mathcal{R}}_{1,0} + \hat{\mathcal{B}}_{1,0,0} \hat{\mathcal{A}}_1 + \overline{\mathcal{Q}}_i)
$$

(34)

$$
\ker(\hat{\mathcal{R}}_{1,0} + \hat{\mathcal{B}}_{1,0,0} \overline{\mathcal{A}}_1 + \overline{\mathcal{Q}}_i) \subseteq \ker(\overline{\Delta}_1 \overline{\mathcal{A}}_1 + \overline{\mathcal{Q}}_i)
$$

(35)

which reduce to the trivial equation $\overline{\Delta}_1 = \overline{\Delta}_1$ subject to the trivial constraint $\ker\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \subseteq \ker\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$. Any $\xi \equiv \overline{\Delta}_i \in \mathbb{R}$ satisfies this reduced Riccati equation. Thus, the solutions of (33)(34) are given by $\hat{\mathcal{X}} = V \begin{bmatrix} 0 & 0 \\ 0 & \xi \end{bmatrix} V^	op = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, $\xi \in \mathbb{R}$, so that – recalling that $Q_0 = Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ and $U = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & 0 \end{bmatrix}$ – the set of solutions of the original CGDARE($\Sigma$) is parametrized by

$$
X = Q_0 + U \begin{bmatrix} 0 & 0 \\ 0 & \xi \\ 0 & 0 \end{bmatrix} U^	op = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \xi \end{bmatrix}, \, \xi \in \mathbb{R}.
$$

**Example 5.2** Using the reduction techniques developed here, we want to study the set of solutions of the CGDARE($\Sigma$) where $\Sigma$ is given by the matrices

$$
A = \begin{bmatrix} 4 & 0 & 0 \\ -3 & 0 & 0 \\ 0 & 0 & -3 \end{bmatrix}, \quad B = \begin{bmatrix} 3 & -5 \\ 1 & 1 \\ 0 & 0 \end{bmatrix}, \quad Q = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 16 \end{bmatrix}, \quad R = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.
$$

Since $S$ is the zero matrix, $A_0 = A$ and $Q_0 = Q$. Both $A_0$ and $R$ are singular. We begin with a reduction that corresponds to the singularity of $A_0$. Since $\ker A_0 = \text{span}\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$, we can consider a basis matrix $U = \begin{bmatrix} U_1 & U_2 \end{bmatrix}$ given by $U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$, so that

$$
A_U = \begin{bmatrix} 4 & 0 & 0 \\ 0 & -3 & 0 \\ -3 & 0 & 0 \end{bmatrix}, \quad \tilde{A} = \begin{bmatrix} 4 & 0 \\ 0 & -3 \\ -3 & 0 \end{bmatrix}, \quad B_U = \begin{bmatrix} 3 & -5 \\ 0 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad Q_U = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 16 & 0 \\ 0 & 0 & 0 \end{bmatrix}.
$$

Hence

$$
A_1 = \begin{bmatrix} 4 & 0 \\ 0 & -3 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 3 & -5 \\ 0 & 0 \end{bmatrix}, \quad S_1 = \begin{bmatrix} 36 & -60 \\ 0 & 0 \end{bmatrix}, \quad Q_1 = \begin{bmatrix} 48 & 0 \\ 0 & 144 \end{bmatrix}, \quad R_1 = \begin{bmatrix} 27 & -45 \\ -45 & 75 \end{bmatrix}.
$$
In view of Corollary 1, $X$ is a solution of CGDARE($\Sigma$) if and only if it can be written as

$$X = Q_0 + U \begin{bmatrix} \Delta_1 & 0 \\ 0 & 0 \end{bmatrix} U^T,$$

where $\Delta_1$ is an arbitrary solution of (13-14). As in Example 5.1, to maintain the notations as consistent as possible to those employed in Section 4.2, we define $A \overset{\text{def}}{=} A_1$, $B \overset{\text{def}}{=} B_1$, $Q \overset{\text{def}}{=} Q_1$, $S \overset{\text{def}}{=} S_1$, $R \overset{\text{def}}{=} R_1$ and $\bar{X} \overset{\text{def}}{=} \Delta_1$. With this notation, (13-14) can be re-written as in (30-31) where

$$A_0 = A - BR_1^*S_1^T = \begin{bmatrix} 0 & 0 \\ 0 & -3 \end{bmatrix}$$

and

$$Q_0 = Q - SR_1^*S_1^T = \begin{bmatrix} 0 & 0 \\ 0 & 144 \end{bmatrix}.$$

Both $A_0$ and $R$ are singular. We can reapply the reduction procedure in Section 4.1 (we will employ the same notation used in Section 4.1, with the only exception that all the letters will have a tilde, to distinguish this reduction from the first one). Now $\ker(A_0) = \text{span}\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \}$. Thus, we can consider a basis matrix $U = \begin{bmatrix} U_1 & U_2 \end{bmatrix}$ given by $U = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$. Hence, we define $\bar{X} = U^T X U$ along with $\bar{A} = U^T A U = \begin{bmatrix} -3 & 0 \\ 0 & 0 \end{bmatrix}$, $\bar{B} = U^T B = \begin{bmatrix} 0 & 0 \\ 3 & -5 \end{bmatrix}$, $\bar{Q} = U^T Q U = \begin{bmatrix} 144 & 0 \\ 0 & 0 \end{bmatrix}$.

We have thus obtained the matrices of the reduced-order Riccati equation

$$\bar{A}_1 = -3, \quad \bar{B}_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \bar{S}_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \bar{Q}_1 = 1296, \quad \bar{R}_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

In view of Corollary 2, $X$ is a solution of (30-31) if and only if

$$\bar{X} = \bar{Q}_0 + \bar{U} \begin{bmatrix} \bar{\Delta}_1 & 0 \\ 0 & 0 \end{bmatrix} \bar{U}^T$$

with $\bar{\Delta}_1$ being an arbitrary solution of (32-33). We still have $\bar{R}_1$ singular, and $\bar{A}_1 - \bar{B}_1\bar{R}_1^\top\bar{S}_1^\top = \bar{A}_1$ is invertible. On the other hand, $\bar{B}_1 \ker(\bar{R}_1) = \{0\}$, so that the reduction associated to the singularity of $\bar{R}_1$ cannot be carried out. Since $\bar{R}_1$ is the zero matrix, and so is $\bar{B}_1$, (34-35) can be written as the symmetric Stein equation

$$\bar{\Delta}_1 = \bar{A}_1^\top \bar{\Delta}_1 \bar{A}_1 + \bar{Q}_1$$

subject to the trivial constraint $\ker(0) \subseteq \ker(0)$. This equation therefore reduces to

$$\bar{\Delta}_1 = 9\bar{\Delta}_1 + 1296$$

which admits the solution $\bar{\Delta}_1 = -162$. Thus, the matrix $\bar{X} = \bar{U} \begin{bmatrix} -162 & 0 \\ 0 & 0 \end{bmatrix} \bar{U}^T + \bar{Q}_0 = \begin{bmatrix} 0 & 0 \\ 0 & 18 \end{bmatrix}$

satisfies (30-31), and, recalling that $Q_0 = Q = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 16 \end{bmatrix}$ and $U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$, we find

$$X = Q_0 + U \begin{bmatrix} 0 & 0 & 0 \\ 0 & -18 & 0 \\ 0 & 0 & 0 \end{bmatrix} \bar{U}^T = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -2 \end{bmatrix},$$

which is the only solution of the original CGDARE($\Sigma$).
Concluding remarks

We have shown how a general CGDARE($\Sigma$) may be reduced to a well-behaved DARE($\Sigma$) of smaller order featuring a non-singular closed-loop matrix. This reduction may be performed through repeated steps each of which may be easily implemented via robust linear algebraic routines thus providing an effective tool to deal with generalized Riccati equations in practical situations.

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