

CLASSICAL SYSTEM THEORY REVISITED FOR TURNPIKE IN STANDARD STATE SPACE SYSTEMS AND IMPULSE CONTROLLABLE DESCRIPTOR SYSTEMS

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Abstract. The concept of turnpike connects the solution of long but finite time horizon optimal control problems with steady state optimal controls. A key ingredient of the analysis of the turnpike is the linear quadratic regulator problem and the convergence of the solution of the associated differential Riccati equation as the terminal time approaches infinity. This convergence has been investigated in linear systems theory in the 1980s. We extend classical system theoretic results for the investigation of turnpike properties of standard state space systems and descriptor systems. We present conditions for turnpike in the nondetectable case and for impulse controllable descriptor systems. For the latter, in line with the theory for standard linear systems, we establish existence and convergence of solutions to a generalized differential Riccati equation.

Key words. linear systems, descriptor systems, optimal control, long time behavior, Riccati equations

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1. Introduction. The notion of *turnpike* has been used in economics since long and in control theory (see, e.g., the textbook [33]) since with an increasing interest in the last decade. Turnpike denotes the property of the control and the solution to a finite time optimization problem to be close to the optimal values for the associated steady state problem most of the time.

The backbone of most turnpike results for time autonomous systems is the turnpike for a relevant linear quadratic regulator (LQR) optimization problem. And the turnpike of the LQR problem is intimately linked to the decay of the solution to the associated generalized differential Riccati equation towards the stabilizing solution of an algebraic Riccati equation; see e.g. [28, Lem. 2.6].

In the first part of this manuscript, we use classical mathematical systems theoretic results as presented by Callier, Willems, and Winkin [7] to show the turnpike property of the LQR problem. For that we extend the results to the affine linear optimal control problem using an explicit formula of the state transition matrices of the closed loop system. Having connected the system theoretic toolbox to the investigation of turnpike behaviors, we can immediately provide new general results for cases where the system is not detectable which is a current research issue; see [30].

In the second part of the paper, we derive turnpike properties of linear quadratic optimal control problems that are constrained by descriptor systems. Descriptor systems are also commonly referred to as differential algebraic equations (DAEs). To our best knowledge turnpike for DAEs has not been addressed so far.

In analogy with the standard LQR case, we will link the asymptotic behavior of an associated differential Riccati equation to the turnpike property.

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Early considerations on Riccati equations for DAEs were made in [14] by examining LQ-regulators for singularly perturbed ordinary differential equations. An extensive investigation and fundamental results for the finite time LQR problem for DAEs has been provided by Bender and Laub [4] who expanded also on the work of Cobb [8] and Pandolfi [26].

Bender and Laub defined several equivalent relevant Riccati equations in standard state space form; see [4, Sec. IV]. A generalized Riccati equation which, in particular, can be stated in the original system coefficients is not addressed in [4] apart from noting that the most obvious symmetric formulation is not well suited. We also mention the extension of the work by [4] to endpoint constraints [34]. The nonsymmetric differential Riccati that is formulated in the original coordinate system and that also a main subject of this paper has been treated in [12]. There the relation the LQR problem for descriptor system has been discussed and the existence of solutions under general conditions has been shown. Before, this nonsymmetric differential generalized Riccati equation has been considered in [21], where necessary conditions for existence of solutions in general and sufficient conditions for some special cases were derived.

The related nonsymmetric generalized algebraic Riccati has been investigated in [13] and applied in the context of model reduction for infinite time-horizon control systems in [25].

Apart from this branch, the literature on the DAE LQR optimization problem on finite time horizons has been enriched with results on suitable reformulations of the optimality conditions [16], on particularly structured cases [2, 11], and on the problem with time-varying coefficients [18, 20, 22]. In the course of the investigations, several formulations of generalized differential Riccati equations have been proposed; see the discussion in [22].

This work contributes to the theory on Riccati equations for descriptor systems in the following respects. We show that under the conditions used in [4, 12] and an additional definiteness condition on the optimization problem, the solution of the nonsymmetric generalized differential Riccati equations has a distinguished structure and converges to the stabilizing solution of the associated algebraic Riccati equation. This structure also implies that the provided optimal feedback gains make the closed-loop system *impulse-free* so that they are a *best choice* according to a conjecture stated in [4, Sec. VII].

With the convergence of the gains and the closed-loop being impulse free, we then can show that the DAE constrained LQ optimization problem has the turnpike property.

The line of arguments and results in this paper are as follows. In Section 2, we introduce the linear quadratic regulator (LQR) problem for standard state space systems, the notion of turnpike, and classical results on the asymptotic behavior of the solutions and the controls that immediately imply well known turnpike results. Next, in Section 3, we derive explicit formulas for the solutions to the affine LQR problem, i.e. the LQR problem with nonzero target states. Then the arguments of the first section can be applied to conclude turnpike properties also in this case. In the second part of the paper, we consider the LQR problem with DAE constraints. Therefore, we introduce the relevant concepts in Section 4 and prove existence and asymptotic decay of solutions of the generalized differential Riccati equation in Section 5. Finally, we can prove turnpike properties of the affine LQR problem with DAE constraints in Section 6. We conclude the paper with summarising remarks and an overview of related open research questions.

2. Basic Notations, Notions and Results for the Linear Quadratic Regulator Problem. We consider the finite time horizon linear quadratic optimization problem.

Problem 2.1 (Finite horizon optimal control problem). For coefficients $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $C \in \mathbb{R}^{k \times n}$, and $F \in \mathbb{R}^{\ell \times n}$, for an initial value $x_0 \in \mathbb{R}^n$, for target outputs $y_c \in \mathbb{R}^k$ and $y_e \in \mathbb{R}^\ell$ and a terminal time $t_1 > 0$, consider the optimization of the cost functional

$$\frac{1}{2} \int_0^{t_1} \|Cx(s) - y_c\|^2 + \|u(s)\|^2 ds + \frac{1}{2} \|Fx(t_1) - y_e\|^2 \rightarrow \min_u$$

subject to

$$\dot{x}(t) = Ax(t) + Bu(t), \quad x(0) = x_0.$$

Problem 2.2 (Steady state optimal control problem). Consider

$$\|Cx - y_c\|^2 + \|u\|^2 ds \rightarrow \min_u$$

subject to

$$0 = Ax + Bu.$$

If $y_c = 0$ and $y_e = 0$, then we will refer to Problems 2.1 and 2.2 as *homogeneous* LQR problems, otherwise as *affine* LQR problems.

DEFINITION 2.3. *The finite time optimal control problem has the turnpike property, if for some constant vectors x_s and u_s it holds that*

$$\|x(t) - x_s\| \leq \text{const}(e^{-\lambda t} + e^{-\lambda(t_1-t)})$$

and

$$\|u(t) - u_s\| \leq \text{const}(e^{-\lambda t} + e^{-\lambda(t_1-t)})$$

for $t \leq t_1$ and for positive constants const and λ independent of t_1 .

Remark 2.4. Throughout this manuscript, the notation const will be used to denote a generic constant value that is independent of t and t_1 but unspecified otherwise.

The turnpike property refers to the phenomenon that the solution to the finite time horizon problem is close to some steady state (x_s, u_s) most of the time. Typically, this steady state is the solution to the associated steady state optimal control problem. However, as it will turn out in the consideration of differential algebraic equations below, the notion of an associated steady state problem might be not well-posed.

Assumption 2.5. We assume that A , B , and C in Problems 2.1 and 2.2 are such that the *algebraic Riccati equation*

$$(2.1) \quad A^*X + XA - XBB^*X + C^*C = 0$$

has a stabilizing solution $P_+ \in \mathbb{R}^{n \times n}$ which means that the eigenvalues of

$$A_+ := A - BB^*P_+$$

all have negative real part.

Remark 2.6. Assumption 2.5 requires that (A, B) are *stabilizable*. Detectability of (C, A) is not required, since P_+ may exist in the case where detectability is not given, see, e.g., [24, 15].

Note that A_+ is invertible.

LEMMA 2.7. *Under Assumption 2.5, the solution to the steady state optimal control problem is given as*

$$\begin{aligned} x_s &= (A - BB^*P_+)^{-1}BB^*(A^* - P_+BB^*)^{-1}C^*y_c \\ &= A_+^{-1}BB^*A_+^{-*}C^*y_c \end{aligned}$$

and

$$u_s = -B^*P_+x_s - B^*w_s,$$

where

$$w_s = A_+^{-*}C^*y_c.$$

Proof. One can confirm directly that x_s and u_s fulfill the first order necessary optimality conditions for Problem 2.2. \square

The turnpike property is intimately linked to the convergence of the solution P to the differential Riccati equation towards the stabilizing solution P_+ of the associated algebraic Riccati equation. In fact, this convergence appears as a necessary condition for turnpike in linear quadratic systems in the fundamental work by Porreta and Zuazua [28, Cor. 2.7]. On the other hand, basic system theoretic investigations of the convergence of P towards P_+ , as presented in [7], resulted in the formula

$$\|x_h(t) - e^{\{tA_+\}}x_0\| \leq \text{const } e^{\{\lambda t_1\}}e^{\{\lambda(t_1-t)\}},$$

with $\lambda < 0$ being the *spectral abscissa* of A_+ and where x_h is the solution to Problem 2.1 with $y_c = 0$ and $y_e = 0$; cp. [7, Thm. 4]. Since $e^{\{tA_+\}}x_0$ goes to zero exponentially with rate λ and since $x_s = 0$ for the homogeneous problem with $y_c = 0$, from (2), one can directly infer turnpike for the homogeneous case:

$$\begin{aligned} (2.2) \quad \|x_h(t) - 0\| &\leq \|x_h(t) - e^{\{tA_+\}}x_0\| + \|e^{\{tA_+\}}x_0\| \\ &\leq \text{const } e^{\{\lambda t_1\}}e^{\{\lambda(t_1-t)\}} + \text{const } e^{\{\lambda t\}} \\ &\leq \text{const}(e^{\{\lambda(t_1-t)\}} + e^{\{\lambda t\}}). \end{aligned}$$

Below, we will extend this result from [7] to the inhomogeneous case. Therefore, we recall the following well-known link between the solution to the finite time optimal control problem and the differential Riccati equation combined with a feedforward term that accounts for the inhomogeneities.

THEOREM 2.8 (Ch. 3.1 of [23]). *The solution to Problem 2.1 is given as (x, u) where*

$$u(t) = -B^*(P(t)x(t) + w(t)),$$

where P is the unique solution to the differential Riccati equation (DRE)

$$(2.3) \quad -\dot{P}(t) = A^*P(t) + P(t)A - P(t)BB^*P(t) + C^*C, \quad P(t_1) = F^*F,$$

where w is the solution to

$$(2.4) \quad -\dot{w}(t) = (A^* - P(t)BB^*)w(t) - C^*y_c, \quad w(t_1) = -F^*y_e,$$

and where x solves

$$\dot{x}(t) = (A - BB^*P(t))x(t) - BB^*w(t), \quad x(0) = x_0.$$

In what follows we will use the abbreviation $S = F^*F$.

Note that in Theorem 2.8 that characterizes the optimal controls for finite times, stability does not play a role so that the coefficients (A, B, C) and F can be arbitrary. In order to link to the steady state, however, we will require Assumption 2.5 to hold. In this case, namely if P_+ exists, the following quantities are well-defined; see (see [7, Lem. 1, Lem. 5]):

1. The closed loop reachability Gramian

$$(2.5) \quad W := \int_0^\infty e^{\{sA_+\}} BB^* e^{\{sA_+^*\}} ds,$$

2. the closed loop reachability Gramian on $[0, \tau]$

$$(2.6) \quad W(\tau) = \int_0^\tau e^{\{sA_+\}} BB^* e^{\{sA_+^*\}} ds = W - e^{\{\tau A_+\}} W e^{\{\tau A_+^*\}}$$

3. as well as the sliding terminal condition.

$$(2.7) \quad \tilde{S}(\tau) := (S - P_+)[I + W(\tau)(S - P_+)]^{-1}$$

For the latter, the following Lemma is relevant:

LEMMA 2.9 ([7, Lem. 5]). *Let Assumption 2.5 hold and consider W , $W(\tau)$, and \tilde{S} as defined in (2.5), (2.6), and (2.7). If $[I + W(S - P_+)]$ is invertible, then $\tau \rightarrow \tilde{S}(\tau)$ is a decreasing function and for any $\tau \geq 0$, meaning that*

$$S - P_+ = \tilde{S}(0) \geq \tilde{S}(\tau) \geq \tilde{S}(\infty) = [I + W(S - P_+)]^{-1}.$$

Moreover, for the spectral norm it holds that

$$K(\tilde{S}) := \sup_{\tau \geq 0} \|\tilde{S}(\tau)\| = \max\{\|S - P_+\|, \|\tilde{S}(\infty)\|\}.$$

Remark 2.10. For the spectral norm of the Gramians it holds that

$$\|W(\tau)\| \leq \|W\|.$$

The condition that $[I + W(S - P_+)]$ is invertible, was shown to be necessary and sufficient for the convergence of $P(t) \rightarrow P_+$ as $t_1 \rightarrow \infty$; see [7, Thm. 2]. For what follows we will assume that this condition holds.

Assumption 2.11. Let Assumption 2.5 hold and consider W , $W(\tau)$, and \tilde{S} as defined in (2.5). Then F , as it defines the terminal constraint in Problem 2.1, is such with $S = F^*F$ the matrix

$$[I + W(S - P_+)]$$

is invertible.

Remark 2.12. Most literature on turnpike properties of optimal control problems assume that (C, A) is detectable, which is a sufficient condition for Assumption 2.11. However, the undetectable subspace for (C, A) can be compensated for if the nullspace of the terminal constraint F only has the trivial intersection with it, which provides a necessary and sufficient condition for the convergence of $P(t)$ towards P_+ ; see [7, Thm. 2].

We illustrate the implications of Remark 2.12 in a numerical example.

Consider the optimal control problem Problem 4.1 with $t_1 = 10$, $y_c = 0$, and $y_e = 1$ and with the coefficients

$$(2.8) \quad A = \begin{bmatrix} 2 & 0 \\ 0 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad C = [0 \quad \sqrt{3}],$$

borrowed from an example in [24, pp. 31]. Here, (A, B) is controllable and, thus, stabilizable, while (C, A) is not detectable. Still, a stabilizing solution to the associated algebraic Riccati equation (2.1) exists.

Then, as implied by the conditions laid out in Remark 2.12, the solution to the differential Riccati equation that starts in F^*F converges to the stabilizing solution if, and only, the nullspace of F and the space that is not detected by (C, A) – which in this case is spanned by $[1 \ 0]^*$ – intersect only trivially.

Accordingly, with the choice $F = C$, the solution of the differential Riccati equation converges to $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ which is a symmetric positive definite solution to the ARE that, however, is not stabilizing. Then, also the associated optimal state x does not satisfy the turnpike property as it can be seen from the logarithmic plot of the components of $|x|$ in Figure 1.

Vice versa, with the choice of $F = [\sqrt{3} \ 0]$, Assumption 2.11 holds, the solution to the DRE converges to a stabilizing solution of the ARE, the optimal state x satisfies the turnpike estimate; cp. the second column of Figure 1.

3. Explicit Formulas for the Optimal States and Controls of the Affine Problem. In this section, we use an explicit formula of the state transition matrices to derive formulas for the solution to the finite time optimal control problem.

LEMMA 3.1. *Under Assumption 2.5, the fundamental solution matrix U to*

$$\dot{U} = (A - BB^*P(t))U, \quad U(t_1) = I,$$

where P solves the DRE with $P(t_1) = S$ is given as

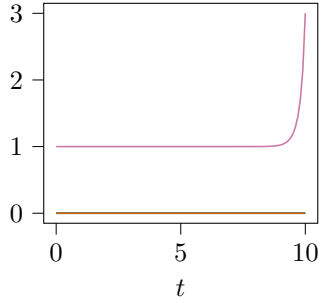
$$(3.1) \quad U(t) = e^{\{-(t_1-t)A_+\}} (I - [W - e^{\{(t_1-t)A_+\}} W e^{\{(t_1-t)A_+^*}\}]} (P_+ - S).$$

Proof. This formula has been used in the literature in a more or less explicit way. A direct derivation is provided [3, Proof of Thm. 3.4]. \square

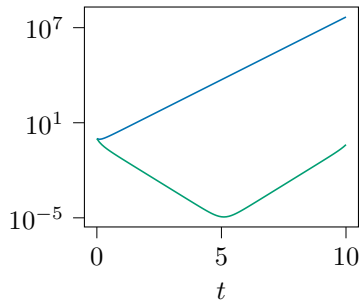
The case of $F = C$:

The case of $F \perp C$:

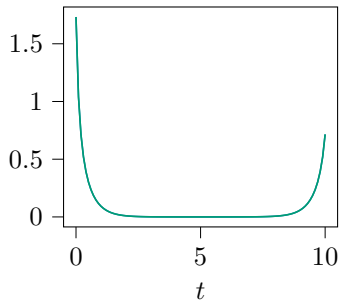
DRE solution components



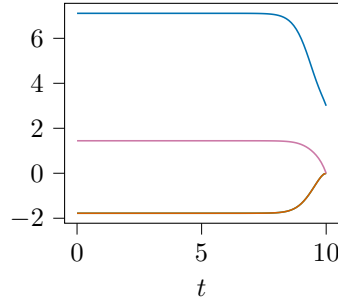
State (log of $|x|$)



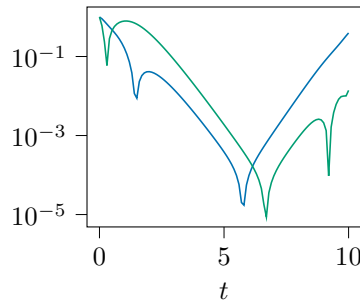
Output (Fx, Cx)



DRE solution components



State (log of $|x|$)



Output (Fx, Cx)

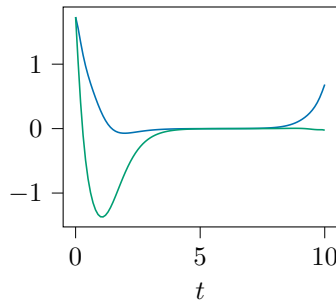


FIG. 1. Example simulation results of the optimal control problem Problem 2.1 with coefficients as in (2.8), with the initial value $x(0) = [1 \ 1]^*$ and choices of the endpoint constraint F that illustrate the sufficiency and necessity of Assumption 2.11 for the turnpike property as in Definition 2.3.

COROLLARY 3.2 (Of Lemma 3.1). Given initial conditions α, β and an inhomogeneity f . With U as in (3.1), the state transition for the forward evolution of

$$\dot{x}(t) = (A - BB^*P(t))x + f(t), \quad x(t_0) = \alpha$$

is given as

$$x(t) = U(t)U(t_0)^{-1}\alpha + \int_{t_0}^t U(t)U(s)^{-1}f(s)ds$$

and the backwards propagation of, say,

$$-\dot{y}(t) = (A^* - P(t)BB^*)y(t) + f(t), \quad y(t_0) = \beta$$

is given as

$$y(t) = U(t)^{-*}U(t_0)^*\beta - \int_{t_0}^t U(t)^{-*}U(s)^*f(s)ds.$$

Before we apply the formulas to the evolution of the optimal state, we introduce a number of relations and simplifications. We write

$$U(t) = e^{\{(t_1-t)A_+\}}(I + W(t_1 - t)(S - P_+))$$

and

$$U(t)^{-*} = e^{\{(t_1-t)A_+^*\}}(I + W(t_1 - t)(S - P_+))^{-1}$$

using that P_+ , S , and W are symmetric.

Moreover, with the help of the identity

$$\begin{aligned} (I + \gamma_t)(I + \gamma_s)^{-1} &= (I + \gamma_t)[I - \gamma_s(I + \gamma_s)^{-1}] \\ &= I + \gamma_t - (I + \gamma_t)\gamma_s(I + \gamma_s)^{-1} \\ &= I + [\gamma_t(I + \gamma_s) - (I + \gamma_t)\gamma_s](I + \gamma_s)^{-1} \\ &= I + [\gamma_t - \gamma_s](I + \gamma_s)^{-1} \\ &= I - [\gamma_s - \gamma_t](I + \gamma_s)^{-1}, \end{aligned}$$

we compute

$$\begin{aligned} U(t)U(s)^{-1} &= e^{\{(t_1-t)A_+\}}(I + W(t_1 - t)(S - P_+)) \times \\ &\quad (I + W(t_1 - s)(S - P_+))^{-1}e^{\{(t_1-s)A_+\}} \\ &= e^{\{(t_1-t)A_+\}}[I - [W(t_1 - s) - W(t_1 - t)]\tilde{S}(t_1 - s)]e^{\{(t_1-s)A_+\}} \\ &= e^{\{(t_1-t)A_+\}}[I - e^{\{(t_1-t)A_+\}}W(t - s)e^{\{(t_1-t)A_+^*\}}\tilde{S}(t_1 - s)]e^{\{(t_1-s)A_+\}} \\ &= e^{\{(t-s)A_+\}} - W(t - s)e^{\{(t_1-t)A_+^*\}}\tilde{S}(t_1 - s)e^{\{(t_1-s)A_+\}} \end{aligned}$$

and

$$\begin{aligned} (3.2) \quad U(t)^{-*}U(s)^* &= e^{\{(t_1-t)A_+^*\}}[I - \tilde{S}(t_1 - t)e^{\{(t_1-s)A_+\}}W(s - t)e^{\{(t_1-s)A_+^*\}}]e^{\{(t_1-s)A_+^*\}} \\ &= e^{\{(s-t)A_+^*\}} - e^{\{(t_1-t)A_+^*\}}\tilde{S}(t_1 - t)e^{\{(t_1-s)A_+\}}W(s - t) \end{aligned}$$

with the definition of W and \tilde{S} as in (2.5) and (2.7).

For the case that $s = t_1$, we have

$$U(t)^{-*}U(t_1)^* = e^{\{(t_1-t)A_+^*\}}[I - \tilde{S}(t_1 - t)W(t_1 - t)].$$

Now we can express the feedforward w as defined in (2.4) via

$$w(t) = w_h(t) + w_p(t) := -U(t)^{-*}U(t_1)^*F^*y_e + \int_{t_1}^t U(t)^{-*}U(s)^*C^*y_c \, ds$$

with

$$(3.3) \quad w_h(t) = -e^{\{(t_1-t)A_+^*\}}[I - \tilde{S}(t_1-t)W(t_1-t)]F^*y_e$$

which is the feedforward induced by the nonzero terminal constraint y_e and the part w_p that belongs to the inhomogeneity induced by y_c . With the help of expression (3.2) for $U(t)^{-*}U(s)^*$, we calculate

$$(3.4) \quad \begin{aligned} w_p(t) &= \int_{t_1}^t e^{\{(s-t)A_+^*\}} \, ds \, C^*y_c \\ &\quad - \int_{t_1}^t e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) e^{\{(t_1-s)A_+\}} W(s-t) \, ds \, C^*y_c \\ &= A_+^{-*} [I - e^{\{(t_1-t)A_+^*\}}] C^*y_c \\ &\quad - e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) \int_{t_1}^t e^{\{(t_1-s)A_+\}} W(s-t) \, ds \, C^*y_c \\ &= A_+^{-*} [I - e^{\{(t_1-t)A_+^*\}}] C^*y_c \\ &\quad - e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) \int_{t_1}^t e^{\{(t_1-s)A_+\}} [W - e^{\{(s-t)A_+\}} W e^{\{(s-t)A_+^*\}}] \, ds \, C^*y_c \\ &= A_+^{-*} [I - e^{\{(t_1-t)A_+^*\}}] C^*y_c \\ &\quad - e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) \int_{t_1}^t e^{\{(t_1-s)A_+\}} W - e^{\{(t_1-t)A_+\}} W e^{\{(s-t)A_+^*\}}] \, ds \, C^*y_c \\ &= A_+^{-*} C^*y_c - e^{\{(t_1-t)A_+^*\}} C^*y_c \\ &\quad - e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) [A_+^{-1}W - A_+^{-1}e^{\{(t_1-t)A_+\}} W] C^*y_c \\ &\quad - e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1-t) [-e^{\{(t_1-t)A_+\}} W A_+^{-*} + \\ &\quad \quad \quad e^{\{(t_1-t)A_+\}} W e^{\{(t_1-t)A_+^*\}} A_+^{-*}] C^*y_c \end{aligned}$$

For the optimal solution x , we can derive the formula

(3.5)

$$\begin{aligned}
x(t) &= U(t)U(0)^{-1}x_0 - \int_0^t U(t)U(s)^{-1}BB^*w(s) \, ds \\
&= x_h(t) - \int_0^t [e^{\{(t-s)A_+\}} - W(t-s)e^{\{(t_1-t)A_+^*\}}\tilde{S}(t_1-s)e^{\{(t-s)A_+\}}]BB^*w(s) \, ds \\
&= x_h(t) - \int_0^t e^{\{(t-s)A_+\}}BB^*w(s) \, ds + \\
&\quad \int_0^t W(t-s)e^{\{(t_1-t)A_+^*\}}\tilde{S}(t_1-s)e^{\{(t-s)A_+\}}BB^*w(s) \, ds \\
&=: x_h(t) - I_1[w] + I_2[w],
\end{aligned}$$

where I_1 and I_2 denote the integrals, respectively.

We anticipate that all terms that include $e^{\{(t_1-\tau)A_+\}}$ will be estimated as going to zero as $t_1 \rightarrow \infty$. Accordingly, the only substantial contribution of w to x will be given by I_1 and the constant part in (3.4):

$$\begin{aligned}
-I_1[A_+^{-*}C^*y_c] &= - \int_0^t e^{\{(t-s)A_+\}}BB^*A_+^{-*}C^*y_c \, ds \\
&= A_+^{-1}BB^*A_+^{-*}C^*y_c - A_+^{-1}e^{\{tA_+\}}C^*y_c \\
&= x_s - e^{\{tA_+\}}A_+^{-1}C^*y_c,
\end{aligned}$$

which is the solution to the steady state optimization problem (cp. Lemma 2.7) plus a term that decays to 0 as $t \rightarrow \infty$.

For the part $-e^{\{(t_1-t)A_+^*\}}C^*y_c$ of w_p we calculate

$$\begin{aligned}
-I_1[-e^{\{(t_1-t)A_+^*\}}C^*y_c] &= \int_0^t e^{\{(t-s)A_+\}}BB^*e^{\{(t_1-s)A_+^*\}}C^*y_c \, ds \\
&= \int_0^t e^{\{(t-s)A_+\}}BB^*e^{\{(t-s)A_+^*\}} \, ds e^{\{(t_1-t)A_+^*\}}C^*y_c \\
&= W(t)e^{\{(t_1-t)A_+^*\}}C^*y_c,
\end{aligned}$$

which because of the uniform boundedness of $W(t)$ decays to zero exponentially as $t_1 \rightarrow \infty$.

For the remaining part of w_p in (3.4), we note that, by the stability of A_+ ,

$$c(t_1, t) := \left\| \left[A_+^{-1} \left[I - e^{\{(t_1-t)A_+\}} \right] W + e^{\{(t_1-t)A_+\}} W \left[I - e^{\{(t_1-t)A_+^*\}} \right] A_+^{-*} \right] \right\|$$

is bounded independently of t_1 and $t \leq t_1$. With that we can estimate the remaining contribution of w_p to I_1 as

$$\int_0^t \| e^{\{(t-s)A_+\}}BB^*e^{\{(t-s)A_+^*\}} \| \, ds \| e^{\{(t_1-t)A_+^*\}} \| \| K(\tilde{S})c(t_1, t) \| C^*y_c \|,$$

which, again, is a term that decays as $t_1 \rightarrow \infty$.

The contribution by $I_1(w_h)$ (cp. (3.3) and (3.5)) reads

$$\begin{aligned}
 & \int_0^t e^{\{(t-s)A_+\}} BB^* w_h(s) \, ds \\
 &= - \int_0^t e^{\{(t-s)A_+\}} BB^* e^{\{(t_1-s)A_+^*\}} [I - \tilde{S}(t_1 - s)W(t_1 - s)] \, ds F^* y_e \\
 &= - \int_0^t e^{\{(t-s)A_+\}} BB^* e^{\{(t-s)A_+^*\}} e^{\{(t_1-t)A_+^*\}} [I - \tilde{S}(t_1 - s)W(t_1 - s)] \, ds F^* y_e \\
 &= - \int_0^t e^{\{(t-s)A_+\}} BB^* e^{\{(t-s)A_+^*\}} \, ds e^{\{(t_1-t)A_+^*\}} F^* y_e \\
 & \quad + \int_0^t e^{\{(t-s)A_+\}} BB^* e^{\{(t-s)A_+^*\}} e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1 - s)W(t_1 - s) \, ds F^* y_e.
 \end{aligned}$$

With the uniform boundedness of $\tau \rightarrow \tilde{S}(\tau), W(\tau)$ (cp. Lemma 2.9 and Remark 2.10) we get the estimate

$$\begin{aligned}
 & \left\| \int_0^t e^{\{(t-s)A_+\}} BB^* w_h(s) \, ds \right\| \\
 & \leq \|W(t)\| \|e^{\{(t_1-t)A_+^*\}}\| \left(1 + \sup_{0 \leq \tau \leq t} \{\|\tilde{S}(t_1 - \tau)W(t_1 - \tau)\|\}\right) \|F^* y_e\| \\
 & \leq \|W\| (1 + K(\tilde{S})\|W\| \|F^* y_e\|) e^{\{(t_1-t)\lambda\}} =: \text{const } e^{\{(t_1-t)\lambda\}}.
 \end{aligned}$$

Finally, we note that the integrands of I_2 equal the integrands of I_1 up to the factor $W(t-s)e^{\{(t_1-t)A_+^*\}} \tilde{S}(t_1 - s)$ which is uniformly bounded by $K(S)\|W\| \|e^{\{(t_1-t)A_+^*\}}\|$. Accordingly, the contribution of $I_2(w)$ can be estimated by the contributions of I_1 times a factor that includes $e^{\{(t_1-t)\lambda\}}$ but is independent of t and t_1 otherwise.

We collect the above calculations in the following lemma:

LEMMA 3.3. *Let Assumptions 2.5 and 2.11 hold. Then the solution x to the finite time optimal control problem Problem 2.1 is given as*

$$x(t) = x_h(t) + x_s - e^{\{tA_+\}} A_+^{-1} C^* y_c + g(t, t_1)$$

where x_h solves Problem 2.1 for $y_c = 0$ and $y_e = 0$, where x_s is the solution to the steady state optimal control problem Problem 2.2, and where $g(t, t_1)$ can be estimated like

$$\|g(t, t_1)\| \leq \text{const } e^{\{(t_1-t)\lambda\}}$$

where $\lambda < 0$ is the spectral abscissa of A_+ .

COROLLARY 3.4 (of Lemma 3.3). *With x as in Lemma 3.3, the optimal input u for Problem 2.1 is given as*

Lemma 3.3 directly implies the turnpike property for the solutions to Problem 2.1; cp. Definition 2.3.

THEOREM 3.5. *Under Assumptions 2.5 and 2.11, for the solutions (x, u) to Problem 2.1 and (x_s, u_s) to 2.2 it holds that*

$$\|x(t) - x_s\| \leq \text{const}(e^{\{t\lambda\}} + e^{\{(t_1-t)\lambda\}})$$

and

$$\|u(t) - u_s\| \leq \text{const}(e^{\{t\lambda\}} + e^{\{(t_1-t)\lambda\}}),$$

for a constant $\text{const} > 0$ independent of t_1 and $\lambda < 0$ being the spectral abscissa of A_+ .

Proof. By Lemma 3.3, we have that

$$\begin{aligned} \|x(t) - x_s\| &\leq \|x_h(t) + x_s - e^{\{tA_+\}}A_+^{-1}C^*y_c + g(t, t_1) - x_s\| \\ &\leq \|x_h(t)\| + \|e^{\{tA_+\}}A_+^{-1}C^*y_c\| + \|g(t, t_1)\| \\ &\leq \text{const}(e^{\{t\lambda\}} + e^{\{(t_1-t)\lambda\}}). \end{aligned}$$

For the input we recall that by Theorem 2.8 the optimal input is given as $u(t) = -B^*(P(t)x(t) + w(t))$, where P is the solution to the differential Riccati equation (2.3) and w solves (2.4). With $P(t) = P_+ + P_\Delta(t)$ and with the formulas (3.3) and (3.4) for w we find that

$$u(t) = -B^*P_+x(t) - B^*P_\Delta x(t) - B^*A_+^*C^*y_c - B^*g_w(t, t_1),$$

where $g_w(t, t_1)$ collects all reminder terms of w and which is readily estimated by the decay of $e^{\{(t_1-t)A_+^*\}}$. With $u_s = -B^*P_+x_s - B^*A_+^*C^*y_c$ (see Lemma 2.7), we directly estimate

$$\begin{aligned} (3.6) \quad \|u(t) - u_s\| &= \| -B^*P_+(x(t) - x_s) - B^*P_+x_s \\ &\quad - B^*A_+^*C^*y_c - B^*P_\Delta x(t) - B^*g_w(t, t_1) - u_s \| \\ &\leq \|B^*P_+(x(t) - x_s)\| + \|B^*P_\Delta(t)x(t)\| + \|B^*g_w(t, t_1)\| \\ &\leq \|B^*P_+\| \|x(t) - x_s\| + \|B^*\| \|P_\Delta(t)\| (\|x_s\| + \|x(t) - x_s\|) + \\ &\quad \|B^*\| \|g_w(t, t_1)\| \end{aligned}$$

from where the turnpike estimate follows directly by the turnpike estimate for $x(t) - x_s$, the exponential decay of $g_w(t, t_1)$ with $t_1 \rightarrow \infty$, and the exponential decay of $P_\Delta(t)$ as $t_1 \rightarrow \infty$, see [7, Thm. 3]. \square

4. Linear Quadratic Optimal Control for Descriptor Systems. We now consider optimal control problems with differential algebraic equations (DAE) of the form

$$(4.1) \quad \mathcal{E}\dot{x}(t) = \mathcal{A}x(t) + \mathcal{B}u(t), \quad \mathcal{E}x(0) = \mathcal{E}x_0.$$

as constraints. If the coefficient \mathcal{E} is not invertible, then the equation (4.1) will be made of differential and algebraic equations for x , hence the name DAE.

Problem 4.1 (Finite horizon optimal control problem). For coefficients $\mathcal{A}, \mathcal{E} \in \mathbb{R}^{n \times n}$, $\mathcal{B} \in \mathbb{R}^{n \times m}$, $\mathcal{C} \in \mathbb{R}^{k \times n}$, and $\mathcal{F} \in \mathbb{R}^{\ell \times n}$, for an initial value $x_0 \in \mathbb{R}^n$, for target outputs $y_c \in \mathbb{R}^k$ and $y_e \in \mathbb{R}^\ell$ and a terminal time $t_1 > 0$, consider

$$\frac{1}{2} \int_0^{t_1} \|\mathcal{C}x(s) - y_c\|^2 + \|u(s)\|^2 ds + \frac{1}{2} \|\mathcal{F}x(t_1) - y_e\|^2 \rightarrow \min_u$$

subject to the DAE (4.1).

For DAEs, the steady state optimal control problem is not simply obtained via considering solutions to $0 = \mathcal{A}x + \mathcal{B}u$ as this does not respect the nature of the dynamical and algebraic parts at all. Below, we will show that under certain conditions, the solutions to the finite time optimal control problem tend exponentially towards a turnpike. Once this turnpike is determined, we will get back to the question of what is the corresponding steady state optimal control problem.

Problem 4.1 is a convex problem with affine linear constraints, which implies that if a candidate solution satisfies first order necessary optimality conditions, then it is an optimal solution.

For $y_c = 0$ and $y_e = 0$, the *formal* first order necessary conditions [19] for 4.1 read

$$(4.2) \quad \begin{bmatrix} \mathcal{E} & 0 \\ 0 & \mathcal{E}^* \end{bmatrix} \frac{d}{dt} \begin{bmatrix} x \\ p \end{bmatrix} = \begin{bmatrix} \mathcal{A} & -\mathcal{B}\mathcal{B}^* \\ -\mathcal{C}^*\mathcal{C} & -\mathcal{A}^* \end{bmatrix} \begin{bmatrix} x \\ p \end{bmatrix}, \quad \mathcal{E}x(0) = \mathcal{E}x_0, \quad \mathcal{E}^*p(t_1) = \mathcal{F}^*\mathcal{F}x(t_1),$$

and define the optimal control as $u(t) = -\mathcal{B}^*p(t)$.

Remark 4.2. The optimality conditions (4.2) are called formal, because they are formally derived through a variation of the original problem formulation. However, it is known that the optimal control problem can have a solution while the formal optimality conditions do not have a solution [19]. Thus, one should either use an equivalent reformulation of the optimal control problem (as proposed in [19]) or make sure that the formal optimality conditions are solvable [11].

One can confirm directly that, if \mathcal{P} solves the generalized differential Riccati equation (gDRE)

$$(4.3) \quad -\mathcal{E}^*\dot{\mathcal{P}} = \mathcal{A}^*\mathcal{P} + \mathcal{P}^*\mathcal{A} - \mathcal{P}^*\mathcal{B}\mathcal{B}^*\mathcal{P} + \mathcal{C}^*\mathcal{C} = 0, \quad \mathcal{E}^*\mathcal{P}(t_1) = \mathcal{F}^*\mathcal{F},$$

then the ansatz $p = \mathcal{P}x$ decouples the optimality conditions (4.2) and defines a solution.

As in the ODE case, we will consider stabilizing solutions of an associated generalized algebraic Riccati equation (gARE)

$$(4.4) \quad \mathcal{A}^*X + X^*\mathcal{A} - X^*\mathcal{B}\mathcal{B}^*X + \mathcal{C}^*\mathcal{C} = 0, \quad \mathcal{E}^*X = X^*\mathcal{E}.$$

Next, we provide the basic nomenclature and fundamental results for DAEs with inputs and outputs.

DEFINITION 4.3. *A matrix pair $(\mathcal{E}, \mathcal{A})$ or a matrix pencil $s\mathcal{E} - \mathcal{A}$ is called regular, if there exists an $s \in \mathbb{C}$ such that $s\mathcal{E} - \mathcal{A}$ is invertible.*

To introduce stability concepts we refer to the following lemma which is a direct consequence of the canonical form that can be derived for regular DAEs; see [17, Thm. I.2.7].

LEMMA 4.4. *If $(\mathcal{E}, \mathcal{A})$ is regular, then the associated DAE is equivalent to the decoupled system*

$$(4.5) \quad \begin{bmatrix} I & 0 \\ 0 & N \end{bmatrix} \frac{d}{dt} \begin{bmatrix} x_{\text{sss}} \\ x_{\text{fss}} \end{bmatrix} = \begin{bmatrix} J & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} x_{\text{sss}} \\ x_{\text{fss}} \end{bmatrix} + \begin{bmatrix} B_{\text{sss}} \\ B_{\text{fss}} \end{bmatrix} u,$$

where J and N are square matrices in Jordan canonical form and where N is nilpotent which means that there exists a $\nu \in \mathbb{N}$ such that $N^\nu = 0$.

The part with the state x_{sss} is called the *slow subsystem* or the *finite dynamics* and the part of x_{fss} is called the *fast subsystem*.

DEFINITION 4.5 (Finite dynamics stability). *Let $(\mathcal{E}, \mathcal{A})$ be regular.*

1. *The DAE (4.1) with coefficients $(\mathcal{E}, \mathcal{A})$ is called finite dynamics stable if its slow subsystem is stable, i.e., if all eigenvalues of J in the associated canonical form (4.5) have negative real part.*
2. *The triple $(\mathcal{E}, \mathcal{A}, \mathcal{B})$ is called finite dynamics stabilizable, if there exists a feedback matrix \mathcal{K} such that $(\mathcal{E}, \mathcal{A} - \mathcal{BK})$ is finite dynamics stable.*

For equivalent algebraic characterizations and for the duality with detectability, see [9, Ch. 3-1.2].

From the solution formula ([17, Lem. I.2.8]) for the *fast subsystem*

$$(4.6) \quad x_{\text{fss}}(t) = - \sum_{i=1}^{\nu-1} N^i B_{\text{fss}} \frac{d^i}{dt^i} u(t)$$

one finds that an initial condition for x_{fss} that does not equal the expression of (4.6) at $t = 0$ generates impulses in the solution; cp. [9, Eqn. (2-2.9)]. If any such impulse can be compensated by an input that is piecewise $\nu - 1$ -times differentiable, then the system is called *impulse controllable*. To circumvent the technicalities that come with distributions and to express *impulse controllability* in terms of the original coefficients $(\mathcal{E}, \mathcal{A}, \mathcal{B})$, we will use an equivalent algebraic characterization; see [9, Thm. 2-2.3].

DEFINITION 4.6. *Let $(\mathcal{E}, \mathcal{A})$ be regular. The DAE (4.1) with coefficients $(\mathcal{E}, \mathcal{A}, \mathcal{B})$ is called impulse controllable, if*

$$\text{rank} \begin{bmatrix} \mathcal{E} & 0 & 0 \\ \mathcal{A} & \mathcal{E} & \mathcal{B} \end{bmatrix} = n + \text{rank } \mathcal{E}.$$

A matrix pencil $s\mathcal{E} - \mathcal{A}$ is called *impulse-free* if no impulses occur in the DAE solution regardless of the initial value. This means that it is trivially *impulse controllable*. In line with Definition 4.6, this can be characterized as follows

DEFINITION 4.7. *Let $(\mathcal{E}, \mathcal{A})$ be regular. The DAE (4.1) with coefficients $(\mathcal{E}, \mathcal{A})$ is called impulse-free, if*

$$\text{rank} \begin{bmatrix} \mathcal{E} & 0 \\ \mathcal{A} & \mathcal{E} \end{bmatrix} = n + \text{rank } \mathcal{E}.$$

Remark 4.8. As for standard systems, the notions of *finite time detectability* and *impulse observability* of a DAE with output matrix \mathcal{C} can be defined by duality, i.e., via the *finite time stability* and *impulse controllability* of $(\mathcal{E}^*, \mathcal{A}^*, \mathcal{C}^*)$; see [9, Thm. 2-4.1].

For semi-explicit *impulse-free* systems, *finite-dynamics stability* can be characterized as follows:

LEMMA 4.9. *Let*

$$\left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \right)$$

be a regular impulse-free matrix pair. Then it is finite dynamics stable if, and only if, $A_{11} - A_{12}A_{22}^{-1}A_{21}$ is stable.

Proof. By the index 1 assumption it follows that A_{22} is invertible. From the equality

$$\begin{bmatrix} I & -A_{12}A_{22}^{-1} \\ 0 & I \end{bmatrix} \begin{bmatrix} -sI + A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} I & 0 \\ -A_{22}^{-1}A_{21} & I \end{bmatrix} = \begin{bmatrix} -sI + A_{11} - A_{12}A_{22}^{-1}A_{21} & 0 \\ 0 & I \end{bmatrix},$$

we find that

$$\left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \right) \text{ is equivalent to } \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} A_{11} - A_{12}A_{22}^{-1}A_{21} & 0 \\ 0 & I \end{bmatrix} \right)$$

from where we deduce that the *slow subsystem* is stable if, and only if, the matrix $A_{11} - A_{12}A_{22}^{-1}A_{21}$ is stable. \square

Next, we state the underlying assumptions for our analysis and some immediate consequences.

Assumption 4.10. The coefficients \mathcal{E} , \mathcal{A} , \mathcal{B} , and \mathcal{C} in Problem 4.1 and (4.1) are such

1. that the pair $(\mathcal{E}, \mathcal{A})$ is regular and
2. that the gARE (4.4) has a stabilizing solution \mathcal{P}_+ , i.e., the pair

$$(\mathcal{E}, \mathcal{A}_+) := (\mathcal{E}, \mathcal{A} - \mathcal{B}\mathcal{B}^*\mathcal{P}_+)$$

is regular, *impulse-free*, and *finite dynamics stable*.

Assumption implies that the system $(\mathcal{E}, \mathcal{A}, \mathcal{B})$ is *finite dynamics stabilizable* and *impulse controllable*. We will show below, that *impulse observability* of $(\mathcal{E}, \mathcal{A}, \mathcal{B})$ is a necessary condition for existence of a stabilizing Riccati solution \mathcal{P}_+ . As for the ODE case, (*finite time*) *detectability* is not necessary for the existence of \mathcal{P}_+ ; cp. Remark 2.6.

For existence of solutions to the necessary optimality conditions (4.2) in general, we make the following assumption

Assumption 4.11. The matrices \mathcal{E} and \mathcal{F} in Problem 4.1 are compatible in the sense that

$$\text{range } \mathcal{F}^* \subset \text{range } \mathcal{E}^*.$$

Looking at the terminal condition $\mathcal{E}^*p(t_1) = \mathcal{F}^*\mathcal{F}x(t_1)$, one can find that Assumption 4.11 is necessary for existence of solutions to the optimality conditions (4.2). Also it is an implicit assumption made in [4, cp. Equation (1)] and the base for more general results (see, e.g., [18, Thm. 13]). Still it is not a necessary condition for existence of optimal solutions; cp. Remark 4.2.

In order to simplify the formulas, we further assume that \mathcal{E} has a *semi-explicit* structure:

Assumption 4.12. The matrix $\mathcal{E} \in \mathbb{R}^{n,n}$ in (4.1) is of the form

$$(4.7) \quad \mathcal{E} = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$$

where $I \in \mathbb{R}^{d,d}$ is the identity matrix.

Remark 4.13. In theory, this assumption is not restrictive since a regular transformation of the system can always provide such a form of \mathcal{E} . In practice, to actually solve the Riccati equations, this semi-explicit realization of the state equations might be helpful. In this sense we point out that for many applications, this assumption readily holds or can be achieved in a computationally feasible way.

Remark 4.14. Assumption 4.12 and the symmetry constraint $\mathcal{E}^* \mathcal{P}_+ = \mathcal{P}_+^* \mathcal{E}$ imply that \mathcal{P}_+ is a block lower-triangular matrix, i.e.

$$(4.8) \quad \mathcal{P}_+ = \begin{bmatrix} P_{+;1} & 0 \\ P_{+;21} & P_{+;2} \end{bmatrix}$$

with $P_{+;1}$ being symmetric, i.e. $P_{+;1}^* = P_{+;1}$. Moreover, Assumptions 4.12 and 4.11 together imply that

$$(4.9) \quad \mathcal{F}^* \mathcal{F} = \begin{bmatrix} S_1 & 0 \\ 0 & 0 \end{bmatrix}.$$

Remark 4.15. For \mathcal{E} in semi-explicit form, several concepts can be made more explicit. Let

$$(4.10) \quad \mathcal{A} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \quad \mathcal{B} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \quad \text{and} \quad \mathcal{C} = [C_1 \quad C_2],$$

then $(\mathcal{E}, \mathcal{A}, \mathcal{B}, \mathcal{C})$ are impulse controllable or impulse observable if, and only if,

$$(4.11) \quad \begin{bmatrix} A_{22} & B_2 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} A_{22}^* & C_2^* \end{bmatrix}$$

have full rank, respectively. And $(\mathcal{E}, \mathcal{A})$ is impulse-free if, and only if, A_{22} is invertible.

The following lemma relates the associated Hamiltonian matrix pencil to the existence of stabilizing solutions of the generalized algebraic Riccati equation (4.4). Although it is the direct extension of the standard state space result, it has not been stated explicitly so far.

LEMMA 4.16. *Let $(\mathcal{E}, \mathcal{A})$ be regular. The gARE (4.4) has a stabilizing solution if, and only if, $(\mathcal{E}, \mathcal{A}, \mathcal{B})$ is finite dynamics stabilizable and the matrix pencil*

$$\mathcal{H}(s) = \begin{bmatrix} -s\mathcal{E} + \mathcal{A} & -\mathcal{B}\mathcal{B}^* \\ -\mathcal{C}^*\mathcal{C} & -s\mathcal{E}^* - \mathcal{A}^* \end{bmatrix}$$

is regular, impulse-free, and has no finite eigenvalues on the imaginary axis.

Proof. The necessity is stated and proved in the first lines of the proof of [13, Lem. 1]. The sufficiency follows by the arguments of [25, Sec. 3] as follows. With \mathcal{E} in semi-explicit form, the absence of impulses in $\mathcal{H}(s)$ implies that

$$\begin{bmatrix} A_{22} & -B_2 B_2^* \\ -C_2^* C_2 & A_{22}^* \end{bmatrix}$$

is invertible so that $(\mathcal{E}, \mathcal{A}, \mathcal{B}, \mathcal{C})$ must be impulse controllable and impulse observable; cp. (4.11). Thus, the condition of [25, Thm. 3.2] are fulfilled up to the finite dynamics observability of $(\mathcal{E}, \mathcal{A}, \mathcal{C})$. Still, one can apply [25, Lem. 3.10] since the needed invertibility is guaranteed by $\mathcal{H}(s)$ having no finite modes on the imaginary axis which implies that $\begin{bmatrix} C^* & A^* \end{bmatrix}$ has full rank (see [24, Thm. 4]) as it is needed in the proof of [25, Lem. 3.8]. Thus, existence of the relevant stabilizing solution, which is denoted by Y in [25], follows as laid out in [25, Sec. 3.2]. □

5. Existence and Asymptotic Behavior of Structured Solutions to the Differential Riccati Solution. In this section, we establish the existence of a particularly structured solution to the generalized differential Riccati equation gDRE (4.3) under the assumption that the associated algebraic Riccati equation gARE (2.1) has a stabilizing solution.

We start with adding another assumption that will be shown to be a sufficient criterion for existence of solutions to the (gDRE) (4.3) and that we will justify by considering its necessity for particular cases.

Assumption 5.1. Let Assumptions 4.10 and 4.12 hold and let $(\mathcal{E}, \mathcal{A}, \mathcal{C})$ and the stabilizing solution \mathcal{P} to the gARE (4.4) be partitioned as in (4.8) and (4.10). Then with the $P_{+,2}$ block of \mathcal{P} and with $K_2 := A_{22}^* - P_{+,2}B_2B_2^*$ being regular (cp. [13, Lem. 1]):

$$(5.1) \quad C_1^*C_1 - (C_1^*C_2 + A_{21}^*P_{+,2})K_2^{-*}B_2B_2^*K_2^{-1}(C_2^*C_1 + P_{+,2}^*A_{21}) \geq 0.$$

Remark 5.2. We note that the $P_{+,2}$ block of \mathcal{P}_+ is not uniquely defined, it only has to fulfill the quadratic equation

$$(5.2) \quad A_{22}^*P_{22} + P_{22}^*A_{22} - P_{22}^*B_2B_2^*P_{22} + C_2^*C_2 = 0$$

and the condition that $A_{22}^* - P_{22}^*B_2B_2^*$ is regular. See [13, Lem. 1] or the solution representation provided in [25, Lem. 3.10] for the semi-explicit \mathcal{E} . Also, cp. the nonuniqueness of the feedback law provided in [12, Eqn. (3.43)].

Before we state global existence of solutions to the generalized differential Riccati equations, we show that Assumption 5.1 generalizes the general assumption of a positive definite cost functional for problems that are impulse-free.

For that we consider a system that is impulse free and that, without loss of generality, can be assumed in the form of

$$(5.3) \quad \mathcal{E} = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathcal{A} = \begin{bmatrix} A_{11} & 0 \\ 0 & -I \end{bmatrix}, \quad \mathcal{B} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \quad \text{and} \quad \mathcal{C} = [C_1 \quad C_2].$$

Like for every system with $(\mathcal{E}, \mathcal{A})$ impulse free, the optimal control problem Problem 4.1 with system (5.3) as constraint is equivalent to a standard LQR problem. In this case, if the state $x = (x_1, x_2)$ is partitioned accordingly, one can express x_2 as $x_2 = B_2u$ and finds that the cost functional is positive definite if, and only if,

$$C_1^*C_1 - C_1^*C_2B_2B_2^*C_2^*C_1 \geq 0 \quad \text{or} \quad I - C_2B_2B_2^*C_2^* \geq 0$$

which is equivalent to the largest singular vector of C_2B_2 being less than one, i.e. $\bar{\sigma}(C_2B_2) \leq 1$. Thus, for systems in the form (5.3), the condition $\bar{\sigma}(C_2B_2) \leq 1$ is necessary to be in line with the standard theory (cp. [35, Eqn. (14.2)] or [23, Rem. 3.4]).

LEMMA 5.3. *Consider a system $(\mathcal{E}, \mathcal{A}, \mathcal{B}, \mathcal{C})$ in the form of (5.3). If $\bar{\sigma}(C_2B_2) \leq 1$, then there exists a P_{22} that solves (5.2), such that $A_{22}^* - P_{22}^*B_2B_2^*$ is regular and such that (5.1) holds.*

Proof. For a system in the form of (5.3), i.e. $A_{22} = -I$, by standard theory, the Riccati equation (5.2) has a symmetric positive definite or positive semi-definite

solution P_2 such that $-I - P_2^* B_2 B_2^*$ is stable and, thus, invertible. With $A_{21} = 0$, condition (5.1) reads

$$C_1^* C_1 - C_1^* C_2 (-I - B_2 B_2^* P_2)^{-1} B_2 B_2^* (-I - P_2^* B_2 B_2^*)^{-1} C_2^* C_1 \geq 0$$

or

$$(5.4) \quad I - C_2 (I + B_2 B_2^* P_2)^{-1} B_2 B_2^* (I + P_2^* B_2 B_2^*)^{-1} C_2 \geq 0.$$

With the identity $(I + B_2 B_2^* P_2)^{-1} B_2 = B_2 (I + B_2^* P_2 B_2)^{-1}$, with $P_2 \geq 0$ which implies that all eigenvalues of $I + B_2^* P_2 B_2$ are larger than one. Accordingly, all eigenvalues of $(I + B_2 B_2^* P_2)^{-1}$ are smaller than one. Since for symmetric positive definite matrices, the eigenvalues coincide with the singular values and since $\bar{\sigma}$ has all the properties of a norm, we can estimate

$$\begin{aligned} \bar{\sigma}(C_2 (I + B_2 B_2^* P_2)^{-1} B_2) &= \bar{\sigma}(C_2 B_2 (I + B_2 B_2^* P_2)^{-1}) \\ &\leq \bar{\sigma}(C_2 B_2) \bar{\sigma}((I + B_2 B_2^* P_2)^{-1}) \leq \bar{\sigma}(C_2 B_2) \leq 1 \end{aligned}$$

from where we conclude (5.4). \square

By Lemma 5.3, for impulse-free systems, validity of Assumption 5.1 is implied by the assumption that the underlying cost functional is positive definite.

THEOREM 5.4. *Consider the DAE (4.1) and the optimal control problem Problem 4.1. Assume that \mathcal{E} is semi-explicit and that \mathcal{F} is compatible (Assumptions 4.12 and 4.11). Assume that $(\mathcal{E}, \mathcal{A})$ is regular and that a stabilizing solution to the gARE exists (Assumption 4.10). Let Assumption 5.1 hold. Then the gDRE (4.3) has a solution \mathcal{P} for $t \leq t_1$.*

Proof. Since $\mathcal{E}^* \dot{\mathcal{P}}(t)$ is symmetric and $\mathcal{E}^* \mathcal{P}(t_1) = \mathcal{F}^* \mathcal{F}$ is symmetric, it holds that $\mathcal{E}^* \mathcal{P}(t)$ is symmetric or, due to the semi-explicit form of \mathcal{E} , that

$$\mathcal{P} = \begin{bmatrix} P_1 & 0 \\ P_{21} & P_2 \end{bmatrix}$$

with $P_1(t)$ being symmetric. With this block triangular structure and the partition of the coefficients $(\mathcal{A}, \mathcal{B}, \mathcal{C})$ as in (4.10), the gDRE (4.3) can be written in terms of the following four coupled matrix valued equations:

$$\begin{aligned} -\dot{P}_1 &= A_{11}^* P_1 + A_{21}^* P_{21} + P_1 A_{11} + P_{21}^* A_{21} \\ &\quad - P_1 B_1 B_1^* P_1 - P_{21}^* B_2 B_1^* P_1 - P_1 B_1 B_2^* P_{21} - P_{21}^* B_2 B_2^* P_{21} + C_1^* C_1, \\ (5.5a) \quad P_1(t_1) &= S, \\ (5.5b) \quad 0 &= A_{12}^* P_1 + A_{22}^* P_{21} + P_2^* A_{21} - P_2^* B_2 B_1^* P_1 - P_2^* B_2 B_2^* P_{21} + C_2^* C_1, \\ (5.5c) \quad 0 &= P_1 A_{12} + P_{21}^* A_{22} + A_{21}^* P_2 - P_1^* B_1 B_2^* P_2 - P_{21}^* B_2 B_2^* P_2 + C_1^* C_2, \\ (5.5d) \quad 0 &= A_{22}^* P_2 + P_2^* A_{22} - P_2^* B_2 B_2^* P_2 + C_2^* C_2. \end{aligned}$$

Note that (5.5c) is the transpose of and, thus, equivalent to (5.5b).

Since (5.5d) does not differ from the left-lower block of the gARE (4.4), Assumption 4.10 implies the existence of a (constant) matrix (function) P_2 that solves (5.5d) such that

$$K_2 := A_{22}^* - P_2^* B_2 B_2^*$$

is invertible. Accordingly, the matrix valued function P_{21} is defined by virtue of (5.5c) or (5.5b) as

$$(5.6) \quad P_{21}(t) = -K_2^{-1}(A_{12}^*P_1(t) + P_2^*A_{21} - P_2^*B_2B_1^*P_1(t) + C_2^*C_1)$$

and existence of \mathcal{P} relies on the existence of a Riccati solution to (5.5a) which, with P_{21} expressed in terms of a linear relation with P_1 and a constant term as in (5.6), reads

$$(5.7) \quad -\dot{P}_1 = \tilde{A}^*P_1 + P_1\tilde{A} - P_1\tilde{R}P_1 + \tilde{Q}, \quad P_1(t_1) = S,$$

where

$$\begin{aligned} \tilde{A} &:= A_{11} - (A_{21} - B_1B_2^*P_2)K_2^{-*}A_{21} + B_1B_2^*K_2^{-1}(P_2A_{21} + C_2^*C_1) \\ \tilde{R} &:= [B_1 \quad -(B_1B_2^*P_2 - A_{12}^*)K_2^{-*}B_2] \begin{bmatrix} B_1^* \\ -B_2^*K_2^{-1}(P_2^*B_2B_1^* - A_{12}) \end{bmatrix} \\ \tilde{Q} &:= C_1^*C_1 - (C_1^*C_2 + A_{21}^*P_2)K_2^{-*}B_2B_2^*K_2^{-1}(C_2^*C_1 + P_2^*A_{21}). \end{aligned}$$

With $\tilde{R} \geq 0$, for arbitrary $S \geq 0$, global existence of the unique solution to (5.7) is ensured (cp. [1, Thm. 4.1.6]), if also \tilde{Q} is positive semi-definite which it is by Assumption 5.1 and with the choice $P_2 = P_{+;2}$. \square

For this solution to the gDRE, in analogy to the standard ODE case [7], we can show the exponential decay towards the gARE solution.

To prepare the arguments, we consider the associated Hamiltonian boundary value problem

$$(5.8) \quad \begin{bmatrix} \mathcal{E} & 0 \\ 0 & \mathcal{E}^* \end{bmatrix} \frac{d}{dt} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \mathcal{A} & -\mathcal{B}\mathcal{B}^* \\ -\mathcal{C}^*\mathcal{C} & -\mathcal{A}^* \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}, \quad \mathcal{E}V_1(t_1) = \begin{bmatrix} I \\ 0 \end{bmatrix}, \quad \mathcal{E}V_2(t_1) = \begin{bmatrix} S \\ 0 \end{bmatrix},$$

with $V_1(t), V_2(t) \in \mathbb{R}^{n,d}$, where d is the size of identity block in \mathcal{E} (cp. Assumption 4.12) and where the initial conditions already anticipate the semi-explicit form of \mathcal{E} .

With \mathcal{P}_+ solving the gARE (4.4) and being partitioned as in (4.8), we can make use of the transformation

$$(5.9) \quad \begin{bmatrix} I & 0 \\ -\mathcal{P}_+^* & I \end{bmatrix} \begin{bmatrix} -s\mathcal{E} + \mathcal{A} & -\mathcal{B}\mathcal{B}^* \\ -\mathcal{C}^*\mathcal{C} & -s\mathcal{E}^* - \mathcal{A}^* \end{bmatrix} \begin{bmatrix} I & 0 \\ \mathcal{P}_+ & I \end{bmatrix} = \begin{bmatrix} -s\mathcal{E} + A_+ & -\mathcal{B}\mathcal{B}^* \\ 0 & -s\mathcal{E}^* - A_+^* \end{bmatrix}$$

to write (5.8) as

$$(5.10) \quad \begin{bmatrix} \mathcal{E} & 0 \\ 0 & \mathcal{E}^* \end{bmatrix} \frac{d}{dt} \begin{bmatrix} V_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} \mathcal{A}_+ & -\mathcal{B}\mathcal{B}^* \\ 0 & -\mathcal{A}_+^* \end{bmatrix} \begin{bmatrix} V_1 \\ \tilde{V}_2 \end{bmatrix}, \quad \mathcal{E}V_1(t_1) = \begin{bmatrix} I \\ 0 \end{bmatrix}, \quad \mathcal{E}\tilde{V}_2(t_1) = \begin{bmatrix} S_1 - P_{+;1} \\ 0 \end{bmatrix},$$

with

$$\begin{bmatrix} V_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} I & 0 \\ -\mathcal{P}_+ & I \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}.$$

In line with the semi explicit structure of \mathcal{E} , we further differentiate

$$(5.11) \quad \mathcal{A}_+ = \begin{bmatrix} A_{+;1} & A_{+;12} \\ A_{+;21} & A_{+;2} \end{bmatrix}, \quad \mathcal{B}\mathcal{B}^* = \begin{bmatrix} B_1B_1^* & B_1B_2^* \\ B_2B_1^* & B_2B_2^* \end{bmatrix}, \quad \begin{bmatrix} V_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} V_{11} \\ V_{12} \\ \tilde{V}_{21} \\ \tilde{V}_{22} \end{bmatrix}.$$

With this partitioning and with the swap of the third and second line and column, respectively, the system reads

$$(5.12) \quad \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \\ V_{12} \\ \tilde{V}_{22} \end{bmatrix} = \begin{bmatrix} A_{+;1} & -B_1 B_1^* & A_{+;12} & -B_1 B_2^* \\ 0 & -A_{+;1}^* & 0 & -A_{+;21}^* \\ A_{+;21} & -B_2 B_1^* & A_{+;2} & -B_2 B_2^* \\ 0 & -A_{+;12}^* & 0 & -A_{+;2}^* \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \\ V_{12} \\ \tilde{V}_{22} \end{bmatrix},$$

$$V_{11}(t_1) = I, \quad \tilde{V}_{21}(t_1) = S - P_{+;1}.$$

Since A_+ is of index 1, the block $A_{+;2}$ is invertible so that with the relation

$$(5.13) \quad \begin{aligned} \begin{bmatrix} V_{12} \\ \tilde{V}_{22} \end{bmatrix} &= - \begin{bmatrix} A_{+;2} & -B_2 B_2^* \\ 0 & -A_{+;2}^* \end{bmatrix}^{-1} \begin{bmatrix} A_{+;21} & -B_2 B_1^* \\ 0 & -A_{+;12}^* \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} \\ &= - \begin{bmatrix} A_{+;2}^{-1} & -A_{+;2}^{-1} B_2 B_2^* A_{+;2}^{-*} \\ 0 & -A_{+;2}^* \end{bmatrix} \begin{bmatrix} A_{+;21} & -B_2 B_1^* \\ 0 & -A_{+;12}^* \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} \\ &= - \begin{bmatrix} A_{+;2}^{-1} A_{+;21} & -A_{+;2}^{-1} B_2 B_1^* + A_{+;2}^{-1} B_2 B_2^* A_{+;2}^{-*} A_{+;12}^* \\ 0 & A_{+;2}^* A_{+;12}^* \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} \end{aligned}$$

we get the reduced system

$$(5.14) \quad \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \frac{d}{dt} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} = \begin{bmatrix} A_{+;1} - A_{+;12} A_{+;2}^{-1} A_{+;21} & -[B_1 - A_{+;12} A_{+;2}^{-1} B_2][B_1 - A_{+;12} A_{+;2}^{-1} B_2]^* \\ 0 & -(A_{+;1}^* - A_{+;21}^* A_{+;2}^{-*} A_{+;12}^*) \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix},$$

$$V_{11}(t_1) = I, \quad \tilde{V}_{21}(t_1) = S - P_{+;1}.$$

as it can be derived by means of the explicit representation of the Schur complement

$$S := \begin{bmatrix} A_{+;12} & -B_1 B_2^* \\ 0 & -A_{+;21}^* \end{bmatrix} \begin{bmatrix} A_{+;2} & -B_2 B_2^* \\ 0 & -A_{+;2}^* \end{bmatrix}^{-1} \begin{bmatrix} A_{+;21} & -B_2 B_1^* \\ 0 & -A_{+;12}^* \end{bmatrix} = \begin{bmatrix} A_{+;12} A_{+;2}^{-1} A_{+;21} & A_{+;12} A_{+;2}^{-1} B_2 B_2^* A_{+;2}^{-*} A_{+;12}^* - A_{+;12} A_{+;2}^{-1} B_2 B_1^* - B_1 B_2^* A_{+;2}^{-*} A_{+;12}^* \\ 0 & -A_{+;21}^* A_{+;2}^{-*} A_{+;12}^* \end{bmatrix}. \blacksquare$$

In what follows, we will use the abbreviations

$$\bar{A} := A_{+;1} - A_{+;12} A_{+;2}^{-1} A_{+;21} \quad \text{and} \quad \bar{B} := [B_1 - A_{+;12} A_{+;2}^{-1} B_2].$$

THEOREM 5.5. *Consider the gDRE (4.3) with \mathcal{E} semi-explicit as in Assumptions 4.12 and let \mathcal{F} be compatible as in Assumption 4.11. Let the coefficients $(\mathcal{A}, \mathcal{B}, \mathcal{C})$ be partitioned as in (4.10) in accordance with \mathcal{E} . Let Assumption 4.10 hold, let \mathcal{P}_+ be the stabilizing solution to the gARE (4.4), and let $\mathcal{A}_+ := \mathcal{A} - \mathcal{B} \mathcal{B}^* \mathcal{P}_+$ be partitioned as in (5.11). Let Assumption 5.1 hold and let \mathcal{P} be the solution to the gDRE (4.3). Then system (5.10) has a unique solution*

$$\begin{bmatrix} V_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} V_{11} \\ V_{12} \\ \tilde{V}_{21} \\ \tilde{V}_{22} \end{bmatrix}$$

with $V_{11}(t)$ being invertible for $t \leq t_1$ and such that for $\mathcal{P}_\Delta(t) := \mathcal{P}(t) - \mathcal{P}_+$ it holds that

$$(5.15) \quad \begin{aligned} \mathcal{P}_\Delta(t) &= \begin{bmatrix} P_{\Delta;1}(t) & 0 \\ P_{\Delta;21}(t) & 0 \end{bmatrix} = \begin{bmatrix} P_{\Delta;1}(t) & 0 \\ -A_{+;2}^{-*} A_{+;12}^* P_{\Delta;1}(t) & 0 \end{bmatrix} \\ &= \begin{bmatrix} \tilde{V}(t)_{21} V(t)_{11}^{-1} & 0 \\ -A_{+;2}^{-*} A_{+;12}^* \tilde{V}(t)_{21} V(t)_{11}^{-1} & 0 \end{bmatrix}. \end{aligned}$$

Proof. By Assumption 2.5 and Theorem 5.4 the existence of \mathcal{P}_Δ is ensured for $t \leq t_1$. A direct computation that realizes the transformation of (5.9) for the associated Riccati equation reveals that \mathcal{P}_Δ solves the generalized *difference* Riccati equation (cp. [7, p. 994]), i.e.

$$-\mathcal{E}^* \dot{\mathcal{P}}_\Delta = \mathcal{A}_+^* \mathcal{P}_\Delta + \mathcal{P}_\Delta^* \mathcal{A}_+ - \mathcal{P}_\Delta^* \mathcal{B} \mathcal{B}^* \mathcal{P}_\Delta, \quad \mathcal{E}^* \mathcal{P}_\Delta(t_1) = \mathcal{F}^* \mathcal{F} - \mathcal{E}^* \mathcal{P}_+.$$

Since the second block column of \mathcal{P}_Δ is zero – as it follows directly from $\mathcal{P}_\Delta = \mathcal{P} - \mathcal{P}_+$ – and $A_{+;2}$ is invertible, equation (4.3) implies that the left-lower block of \mathcal{P}_Δ is given as $-A_{+;2}^{-*} A_{+;12}^* P_{\Delta;1}(t)$ and that $P_{\Delta;1}$ is the solution to the Riccati equation

$$-\dot{P}_{\Delta;1} = \bar{A}^* P_{\Delta;1} + P_{\Delta;1} \bar{A} - P_{\Delta;1} \bar{B} \bar{B}^* P_{\Delta;1}, \quad P_{\Delta;1}(t_1) = S - P_{+;1}$$

which in particular means that this Riccati equation has a global solution for $t \leq t_1$ despite the possibly indefinite initial condition.

From the existence of the Riccati solution $P_{\Delta;1}$, we can infer the invertibility of $V_{11}(t)$ from the relation

$$-\dot{V}_{11}(t) = (\bar{A} - \bar{B} \bar{B}^* P_{\Delta;1}(t)) V_{11}(t), \quad V_{11}(t_1) = I,$$

which is a consequence of *Radon's Lemma* (see, e.g. [1, Thm. 4.1.1]).

Uniqueness follows from V_{11} and \tilde{V}_{21} being solutions to an ordinary linear differential equation, namely (5.14).

Thus, \mathcal{P}_Δ as defined in (5.15) is well-defined.

Following the lines of a proof for a standard result for ODEs [6, 180 Theorem], we directly confirm that it \mathcal{P}_Δ solves the generalized difference Riccati equation (4.3).

For that we find that the summands of the left upper block of $-\mathcal{E}^* \dot{\mathcal{P}}_\Delta$ which are given as

$$-\frac{d}{dt} V_{21} V_{11}^{-1} = -\dot{V}_{21} V_{11}^{-1} + \tilde{V}_{21} V_{11}^{-1} \dot{V}_{11} V_{11}^{-1},$$

and which, by means of the equations for \dot{V}_{21} and \dot{V}_{11} in (5.12) with V_{12} and V_{22} resolved via (5.13), rewrite as

$$\begin{aligned} -\dot{V}_{21} V_{11}^{-1} &= (A_{+;1}^* V_{21} - A_{+;21}^* A_{+;2}^{-*} A_{+;12}^* V_{21}) V_{11}^{-1} \\ &= (A_{+;1}^* - A_{+;21}^* A_{+;2}^{-*} A_{+;12}^*) P_{\Delta;1} \\ &= A_{+;1}^* P_{\Delta;1} + A_{+;21}^* A_{+;2}^{-*} A_{+;12}^* P_{\Delta;21} \end{aligned}$$

and

$$\begin{aligned}
V_{21}V_{11}^{-1}\dot{V}_{11}V_{11}^{-1} &= \\
&= V_{21}V_{11}^{-1}([A_{+,1} - A_{+,12}A_{+,2}^{-1}A_{+,21}]V_{11} \\
&\quad - [B_1 - A_{+,12}A_{+,2}^{-1}B_2][B_1 - A_{+,12}A_{+,2}^{-1}B_2]^*V_{21})V_{11}^{-1} \\
&= P_{\Delta;1}[A_{+,1} - A_{+,12}A_{+,2}^{-1}A_{+,21}] \\
&\quad - P_{\Delta;1}[B_1 - A_{+,12}A_{+,2}^{-1}B_2][B_1 - A_{+,12}A_{+,2}^{-1}B_2]^*P_{\Delta;1} \\
&= P_{\Delta;1}A_{+,1} + P_{\Delta;21}^*A_{+,21} \\
&\quad - P_{\Delta;1}B_1B_1^*P_{\Delta;1} - P_{\Delta;1}B_1B_2^*P_{\Delta;21} - P_{\Delta;21}^*B_2B_1^*P_{\Delta;1} - P_{\Delta;21}^*B_2B_2^*P_{\Delta;1},
\end{aligned}$$

sum up to the left upper block of

$$A_+^*P_{\Delta} + P_{\Delta}^*A_+ - P_{\Delta}^*\mathcal{B}\mathcal{B}^*P_{\Delta}.$$

By the zero pattern of \mathcal{P}_+ , the other blocks of $P_{\Delta}^*\mathcal{B}\mathcal{B}^*P_{\Delta}$ are zero, whereas the other possibly nonzero blocks of $A_+^*P_{\Delta}$ and $P_{\Delta}^*A_+$ sum up to zero, respectively, because of how the blocks of P_{Δ} are related. Thus,

$$-\mathcal{E}^*\dot{P}_{\Delta} = A_+^*P_{\Delta} + P_{\Delta}^*A_+ - P_{\Delta}^*\mathcal{B}\mathcal{B}^*P_{\Delta}$$

is fulfilled. Finally, by the structure of \mathcal{E} , \mathcal{F} , and, \mathcal{P}_{Δ} , the initial condition $\mathcal{E}^*\mathcal{P}_{\Delta}(t_1) = \mathcal{F}^*\mathcal{F} - \mathcal{E}^*\mathcal{P}_+$ reduces to $P_{\Delta;1}(t_1) = S - P_{+,1}$ which is fulfilled as $\tilde{V}_{21}(t_1)V_{11}(t_1) = \tilde{V}_{21}(t_1) = S - P_{+,1}$. \square

From Theorem 5.5, we can directly deduce necessary conditions for the convergence of $\mathcal{P}(t)$ towards \mathcal{P}_+ as $t_1 \rightarrow \infty$; cp. Lemma 2.9 for the standard ODE case.

COROLLARY 5.6 (of Theorem 5.5). *The left upper block $P_{\Delta;1}$ of \mathcal{P}_{Δ} as defined in (5.15) satisfies the relation*

$$(5.16) \quad P_{\Delta;1}(t) = e^{\{(t_1-t)\bar{A}^*\}}\bar{\tilde{S}}(t_1-t)e^{\{(t_1-t)\bar{A}\}}$$

where

$$(5.17) \quad \bar{\tilde{S}}(\tau) := (S - P_{+,1})[I + \bar{W}(\tau)(S - P_{+,1})]^{-1}$$

with

$$\bar{W}(\tau) := \int_0^{\tau} e^{\{s\bar{A}\}}\bar{B}\bar{B}^*e^{\{s\bar{A}^*\}} ds$$

being well-defined. Moreover, $P_{\Delta;1}(t) \rightarrow 0$ exponentially as $t_1 \rightarrow \infty$, if, and only if,

$$I + \bar{W}(S - P_{+,1})$$

is nonsingular, where

$$\bar{W} := \lim_{\tau \rightarrow \infty} \bar{W}(\tau).$$

Proof. Relation (5.16) and (5.17) follow from the *variation of constants* formula applied to (5.14) that gives

$$\tilde{V}_{21}(t) = e^{\{-(t-t_1)\bar{A}^*\}}(S - P_{+,1})$$

and

$$\tilde{V}_{11}(t) = e^{\{(t-t_1)\bar{A}\}} \left(I + \int_{t_1}^t e^{\{-(s-t_1)\bar{A}\}} \bar{B}\bar{B}^* e^{\{-(s-t_1)\bar{A}^*\}} ds (S - P_{+;1}) \right)$$

and the invertibility of $V_{11}(t)$. By stability of \bar{A} (cp. Lemma 4.9) well posedness of the improper integral that defines \bar{W} is ensured, and the equivalence of $P_{\Delta;1}(t) \rightarrow 0$ and invertibility of $I + \bar{W}(S - P_{+;1})$ follows by [7, Lem. 3]. \square

The condition for the convergence motivates the following assumption:

Assumption 5.7. Consider Problem 4.1, let Assumption 4.10 hold and let \mathcal{E} be semi-explicit as in Assumption 4.12 and \mathcal{A}_+ and $\mathcal{B}\mathcal{B}^*$ be partitioned as in (5.11) and let \mathcal{F} be compatible with \mathcal{E} as in Assumption 4.11. The matrix

$$I + \bar{W}(S - P_{+;1})$$

is nonsingular, where

$$\bar{W} := \int_0^\infty e^{\{s\bar{A}\}} \bar{B}\bar{B}^* e^{\{s\bar{A}^*\}} ds$$

is the closed loop *finite dynamics* reachability Gramian and where S is the left upper block of $\mathcal{F}^*\mathcal{F}$; cp. (4.9).

Another outcome of the existence of this structured solution to the gDRE is that the corresponding closed loop system does not generate impulses. Since, the closed loop system is time varying, the definition of *impulse freeness* (Def. 4.7) does not apply. Instead, we use the concept of *strangeness freeness* [17] that is closely connected to and has the same implications as *impulse freeness*.

COROLLARY 5.8 (of Theorem 5.5). *The closed loop system*

$$\mathcal{E}\dot{x}(t) = (\mathcal{A} - \mathcal{B}\mathcal{B}^*\mathcal{P}(t))x(t), \quad \mathcal{E}x(0) = \mathcal{E}x_0,$$

is strangeness free.

Proof. By the particular structure of P_Δ , it follows that the left lower block of $\mathcal{A} - \mathcal{B}\mathcal{B}^*\mathcal{P}(t) = \mathcal{A} - \mathcal{B}\mathcal{B}^*(P_+ + P_\Delta)$ equals the left lower block of A_+ , namely $A_{+;2}$. Since $A_{+;2}$ is invertible, the DAE defined by the (time-dependent) coefficients $(\mathcal{E}, \mathcal{A} - \mathcal{B}\mathcal{B}^*\mathcal{P})$ is strangeness free; cp. [17, Thm. 3.17]. \square

With this assumption, we can show the turnpike property of the homogeneous optimal control problem with DAE constraints with respect to the zero state and zero control action.

THEOREM 5.9. *Under the assumptions of Theorem 5.5 and under Assumption 5.7, the optimal control problem Problem 4.1 with $y_c = 0$ and $y_e = 0$ has a solution (x, u) which fulfills the estimate*

$$\|x(t)\| \leq \text{const}(e^{\{t\bar{\sigma}\}} + e^{\{(t_1-t)\bar{\sigma}\}})$$

and

$$\|u(t)\| \leq \text{const}(e^{\{t\bar{\sigma}\}} + e^{\{(t_1-t)\bar{\sigma}\}})$$

with *const* independent of t_1 and where $\bar{\sigma} < 0$ is the spectral abscissa of \bar{A} .

Proof. With $(V_{11}, V_{12}, \tilde{V}_{21}, \tilde{V}_{22})$ solving (5.10), with the relation (5.13), and with $V_{11}(t)$ being invertible, we have that

$$\begin{aligned} \begin{bmatrix} x_1 \\ x_2 \\ \tilde{p}_1 \\ \tilde{p}_2 \end{bmatrix} &= \begin{bmatrix} V_{11} \\ V_{12} \\ \tilde{V}_{21} \\ \tilde{V}_{22} \end{bmatrix} V_{11}^{-1}(t_0)x_0 = \begin{bmatrix} I & 0 \\ s_{11} & s_{12} \\ 0 & I \\ 0 & s_{22} \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} V_{11}^{-1}(t_0)x_0 \\ &= \begin{bmatrix} I & 0 \\ A_{+;2}^{-1}A_{+;21} & -A_{+;2}^{-1}B_2B_1^* + A_{+;2}^{-1}B_2B_2^*A_{+;2}^{-*}A_{+;12}^* \\ 0 & I \\ 0 & A_{+;2}^{-*}A_{+;12}^* \end{bmatrix} \begin{bmatrix} V_{11} \\ \tilde{V}_{21} \end{bmatrix} V_{11}^{-1}(t_0)x_0. \end{aligned}$$

defines the solution to (5.10), and, in particular, the optimal state as in (5.8). Multiplication of the first row gives that

$$V_{11}^{-1}(t)x(t) = V_{11}^{-1}(t_0)x(t_0)$$

so that, with $P_{\Delta;1} = V_{21}V_{11}^{-1}$ (cp. Thm. 5.5), we get the following formula for the optimal state

$$\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} V_{11}(t)V_{11}(t_0)^{-1}x_1(t_0) \\ A_{+;2}^{-1}A_{+;21}x_1(t) - [A_{+;2}^{-1}B_2B_1^* + A_{+;2}^{-1}B_2B_2^*A_{+;2}^{-*}A_{+;12}^*]P_{\Delta;1}(t)x_1(t) \end{bmatrix}.$$

Then the turnpike property for x_1 follows by the arguments for the ODE case [7, Thm. 4] as follows: From

$$\|x_1(t) - e^{\{\bar{A}t\}}\| \leq \text{const} e^{\{t_1\bar{\lambda}\}} e^{\{(t_1-t)\bar{\lambda}\}},$$

cp. [7, Eqn. (63)], we conclude with $e^{\{t_1\bar{\lambda}\}} \leq 1$ independent of t_1 , \bar{A} being stable, and an application of the triangle inequality as in (2.2) that

$$\|x_1(t)\| \leq \text{const}(e^{\{(t_1-t)\bar{\lambda}\}} + e^{\{t\bar{\lambda}\}}).$$

The same type of estimate for x_2 follows from the turnpike of x_1 since $P_{\Delta;1}$ is bounded by Corollary 5.6.

The turnpike estimate for $u(t) = -\mathcal{B}\mathcal{B}^*\mathcal{P}(t)x(t) = -\mathcal{B}\mathcal{B}^*\mathcal{P}_+x(t) - \mathcal{B}\mathcal{B}^*\mathcal{P}_\Delta(t)x(t)$ follows as in (3.6). \square

We summarize and comment on the assumptions and the results of this chapter on the optimal control of the linear descriptor system (4.1) with a quadratic costfunctional defined in Problem 4.1.

Assumptions:

1. Without loss of generality: \mathcal{E} is semi-explicit (Assumption 4.12).
2. To enable existence of solutions to the first order optimality conditions (4.2): Compatibility of \mathcal{F} and \mathcal{E} (Assumption 4.11).
3. In line with the basic assumption for the ODE case: Existence of a stabilizing solution to the generalized algebraic Riccati equation (4.4) including regularity of the matrix pair (Assumption 4.10).
4. To ensure existence of global solutions to the reduced closed loop Riccati equation (5.7): A spectral condition on the coefficients (Assumption 5.1).
5. In line with the relevant condition in the ODE case: Compatibility of the terminal constraint S , the solution to the gARE (4.4), and the relevant *reachability Gramian* (Assumption 5.7).

Certainly, Assumption 5.1 is somewhat unpleasant and, because of its dependency on P_2 not readily confirmed or discarded for a given system. Nonetheless, it generalizes the standard assumption for ODE systems that ensures the definiteness of the cost functional in the presence of cross terms in the costs or a feedthrough term in the system.

With these assumptions, the following results have been derived:

Summary of results:

1. Existence of solutions to the generalized differential Riccati equation (Theorem 5.4).
2. Representation of the difference $\mathcal{P}(t) - \mathcal{P}_+$ that implies that the closed loop system is *impulse free* (Theorem 5.5 and Corollary 5.8).
3. Convergence of $\mathcal{P}(t) \rightarrow \mathcal{P}_+$ as $t_1 \rightarrow \infty$ and turnpike property of the *homogeneous* optimal control problem with DAE constraints (Corollary 5.6 and Theorem 5.9).

6. The Affine DAE LQR Problem. In this section, we study the optimal control problem with nonzero target states y_c and y_e and get back to the question of what *the* steady-state optimal control problem is for a descriptor system.

Similarly to the ODE case, the feedthrough w is defined via

$$-\mathcal{E}\dot{w} = (\mathcal{A}^* - \mathcal{P}^*(t)\mathcal{B}\mathcal{B}^*)w - \mathcal{C}^*y_c, \quad \mathcal{E}^*w(t_1) = -\mathcal{F}^*y_e,$$

which we rewrite as

$$-\mathcal{E}\dot{w} = \mathcal{A}_+^*w - \mathcal{P}_\Delta^*(t)\mathcal{B}\mathcal{B}^*w - \mathcal{C}^*y_c, \quad \mathcal{E}^*w(t_1) = -\mathcal{F}^*y_e.$$

We partition the variables and coefficients

$$w = \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}, \quad \mathcal{C}^* = \begin{bmatrix} \mathcal{C}_1^* \\ \mathcal{C}_2^* \end{bmatrix}, \quad \text{and } \mathcal{F}^* = \begin{bmatrix} \mathcal{F}_1^* \\ 0 \end{bmatrix}$$

in accordance with \mathcal{E} , \mathcal{A}_+ , $\mathcal{B}\mathcal{B}^*$, and \mathcal{P}_Δ , as in (4.7), (5.11), and (5.15), respectively, and write

$$\begin{aligned} \mathcal{A}_+^* - \mathcal{P}_\Delta^*(t)\mathcal{B}\mathcal{B}^* &= \begin{bmatrix} A_{+;1}^* & A_{+;21}^* \\ A_{+;12}^* & A_{+;2}^* \end{bmatrix} - \begin{bmatrix} P_{\Delta;1}(t) & -P_{\Delta;1}(t)A_{+;12}A_{+;2}^{-1} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} B_1B_1^* & B_2B_1^* \\ B_1B_2^* & B_2B_2^* \end{bmatrix} \\ &= \begin{bmatrix} A_{+;1}^* - P_{\Delta;1}(t)\bar{B}B_1^* & A_{+;21}^* - P_{\Delta;1}(t)\bar{B}B_2^* \\ A_{+;12}^* & A_{+;2}^* \end{bmatrix}. \end{aligned}$$

In what follows, we will omit the time dependency of \mathcal{P}_Δ . With the relation

$$(6.1) \quad w_2 = -A_{+;2}^{-*} A_{+;21}^* w_1 + A_{+;2}^{-*} C_2^* y_c$$

we can eliminate w_2 from the equations and consider only

$$(6.2) \quad -\dot{w}_1 = (\bar{A}^* - P_{\Delta;1}(t) \bar{B} \bar{B}^*) w_1 - \bar{C}^* y_c + P_{\Delta;1}(t) \bar{B} B_2^* A_{+;2}^{-*} C_2^* y_c,$$

with the abbreviations

$$\bar{A} := A_{+;1} - A_{+;12} A_{+;2}^{-1} A_{+;21}, \quad \bar{B} := B_1 - A_{+;12} A_{+;2}^{-1} B_2, \quad \text{and} \quad \bar{C} := C_1 - C_2 A_{+;2}^{-1} A_{+;21}$$

as they have been used before.

By the same procedure, we derive the expressions for the parts of the optimal state as

$$(6.3) \quad x_2 = -A_{+;2}^{-1} A_{+;21} x_1 + A_{+;2}^{-1} B_2 \bar{B}^* (P_{\Delta;1} x_1 + w_1) + A_{+;2}^{-1} B_2 B_2^* A_{+;2}^{-*} C_2 y_c$$

and

$$(6.4) \quad \dot{x}_1 = (\bar{A} - \bar{B} \bar{B}^* P_{\Delta;1}(t)) x_1 - \bar{B} \bar{B}^* w_1 - \bar{B} B_2^* A_{+;2}^{-*} C_2 y_c.$$

The preceding derivations show that if the Riccati solution exists, then the optimal states $x = (x_1, x_2)$ decouple such that x_1 reads like a solution to an optimal control problem with ODE constraints, and x_2 is in a direct algebraic relation with x_1 . Accordingly, we can state the turnpike property for Problem 4.1 with similar arguments as for the standard LQR case.

THEOREM 6.1. *Consider the optimal control problem Problem 4.1 with the costs defined through t_1 , \mathcal{C} , \mathcal{F} , and target states y_c and y_e , and subject to the DAE (4.1) with coefficients $(\mathcal{E}, \mathcal{A}, \mathcal{B})$.*

Assume that \mathcal{E} is semi-explicit, that $(\mathcal{E}, \mathcal{A})$ is regular, and that the gARE (4.4) has a stabilizing solution \mathcal{P}_+ (Assumptions 4.10 and 4.12).

Assume that \mathcal{F} is compatible with \mathcal{E} so that with Assumptions 5.1 the gDRE (4.3) has a solution \mathcal{P} with $\mathcal{P}_\Delta = \mathcal{P} - \mathcal{P}_+$ as in (5.15).

Assume that the relevant part of \mathcal{F} is compatible with the relevant part of \mathcal{P}_+ such that Assumption 5.7 is fulfilled.

Then the optimal control has a solution (x, u) with x and u satisfying the estimates

$$\|x(t) - x_s\| \leq \text{const}(e^{\{t\bar{\lambda}\}} + e^{\{(t_1-t)\bar{\lambda}\}}),$$

and

$$\|u(t) - u_s\| \leq \text{const}(e^{\{t\bar{\lambda}\}} + e^{\{(t_1-t)\bar{\lambda}\}}),$$

with const independent of t_1 and where $\bar{\lambda} < 0$ is the spectral abscissa of \bar{A} and

$$(6.5) \quad x_s = \begin{bmatrix} x_{s;1} \\ -A_{+;2}^{-1} A_{+;21} x_{s;1} + A_{+;2}^{-1} B_2 (\bar{B}^* \bar{A}^{-*} \bar{C}^* + B_2^* A_{+;2}^{-*} C_2^*) y_c \end{bmatrix}$$

with $x_{s;1} := (\bar{A}^{-1} \bar{B} \bar{B}^* \bar{A}^{-*} \bar{C}^* + \bar{A}^{-1} \bar{B} B_2^* A_{+;2}^{-*} C_2^*) y_c$ and

$$(6.6) \quad u_s = -\bar{B}^* \mathcal{P}_+ x_s - \bar{B}^* \bar{A}^{-*} \bar{C}^* y_c - B_2^* A_{+;2}^{-*} C_2^* y_c.$$

Proof. We consider equations (6.2) and (6.4) for the parts w_1 and x_1 , respectively. As laid out in the proof of Theorem 5.5, the part \mathcal{P}_Δ solves the differential Riccati equation

$$-\dot{P}_{\Delta;1} = \bar{A}^* P_{\Delta;1} + P_{\Delta;1} \bar{A} - P_{\Delta;1} \bar{B} \bar{B}^* P_{\Delta;1}, \quad P_{\Delta;1}(t_1) = S_1 - P_{+;1}$$

and exists for all $t \leq t_1$. Thus, Lemma 3.1 applies and provides the formulas for the relevant fundamental solution as

$$U(t) = e^{\{-(t_1-t)\bar{A}\}} (I - [\bar{W} - e^{\{(t_1-t)\bar{A}\}} \bar{W} e^{\{(t_1-t)\bar{A}^*}\}]) (P_{+;1} - S_1).$$

As for the ODE case, we conclude that the feedthrough can be written as

$$(6.7) \quad w_1(t) = \bar{A}^{-*} \bar{C}^* y_c + g(t, t_1)$$

with a remainder term $g(t, t_1)$ that is dominated by $e^{\{(t_1-t)\bar{A}\}}$; cp. (3.3) and (3.4). The only difference to the ODE case lies in the additional term $P_{\Delta;1}(t) \bar{B} A_{+;2}^{-*} C_2^* y_c$ to w_1 as defined (6.7) which, however, can be included in the estimates by the decaying behavior of $P_{\Delta;1}$ as it is ensured by Assumption 5.7 and Corollary 5.6. And again, that part of x_1 that cannot be bounded by $e^{\{(t_1-t)\bar{\sigma}\}}$, where $\bar{\sigma}$ is the spectral abscissa of \bar{A} , is given by the integral operator I_1 (cp. (3.5)) applied to the constant parts in the right-hand side of (6.4). Thus, the turnpike for x_1 is given by the constant part of

$$\begin{aligned} & - \int_0^t e^{\{(t-s)\bar{A}\}} (\bar{B} \bar{B}^* \bar{A}^{-*} \bar{C}^* y_c + \bar{B} B_2^* A_{+;2}^{-*} C_2^* y_c) ds \\ & = (I - e^{\{t\bar{A}\}}) \bar{A}^{-1} [\bar{B} \bar{B}^* \bar{A}^{-*} \bar{C}^* y_c + \bar{B} B_2^* A_{+;2}^{-*} C_2^* y_c]. \end{aligned}$$

which is as in the first component of (6.5). The turnpike for x_2 as in the second component of (6.5) follows from formula (6.3) in combination with the decaying behavior of $P_{\Delta;1}$ and the estimate for w_1 given in (6.7).

With the formulas (6.7) and (6.1) for w_1 and w_2 , the optimal writes as

$$\begin{aligned} u(t) &= -\mathcal{B}^*(\mathcal{P}x(t) + w(t)) \\ &= -\mathcal{B}^* \mathcal{P}_+ x(t) - \mathcal{B}^* \mathcal{P}_\Delta(t) x(t) - B_1^* w_1(t) - B_2^* w_2(t) \\ &= -\mathcal{B}^* \mathcal{P}_+(x(t) - x_s) - \bar{B}^* P_{\Delta;1}(t) x_1(t) - \bar{B}^* g(t, t_1) \\ &\quad - \bar{B}^* \bar{A}^{-*} \bar{C}^* y_c - B_2^* A_{+;2}^{-*} C_2^* y_c - \mathcal{B}^* \mathcal{P}_+ x_s \\ &= -\mathcal{B}^* \mathcal{P}_+(x(t) - x_s) - \bar{B}^* P_{\Delta;1}(t) x_1(t) - \bar{B}^* g(t, t_1) + u_s \end{aligned}$$

from where the estimate (6.6) for $u(t) - u_s$ follows with the same arguments as for (3.6). \square

Now that the turnpike for the linear-quadratic optimization problem with DAE constraints has been determined, we return to the question of what the associated steady state problem is. For that we observe that with $p_s := \mathcal{P}_+ x_s + w_s$ and w_s being the time constant parts of w and w_s and u_s as defined in Theorem 6.1, the triple (x_s, p_s, u_s) is a critical point of the *Lagrange function*

$$\mathcal{L}(x, p, u) = \frac{1}{2} \|Cx - y_c\|^2 + \frac{1}{2} \|u\|^2 + p^*(Ax + \mathcal{B}u)$$

as it can be confirmed by considering the gradient of \mathcal{L} with respect to x , p , and u and the ansatz $u_s = -\mathcal{B}^*p_s$ and $p_s = \mathcal{P}_+x_s + w_s$. Still, in general, the turnpike is not that solution that arises from

$$\frac{1}{2}\|\mathcal{C}x - y_c\|^2 + \frac{1}{2}\|u\|^2 \rightarrow \min_u, \text{ subject to } \mathcal{A}x + \mathcal{B}u = 0$$

as this does not respect the particular feedback structure $u_s = -\mathcal{B}\mathcal{B}^*\mathcal{P}_+x_s$ that makes the left-lower block of $\mathcal{A} - \mathcal{B}\mathcal{B}^*\mathcal{P}_+$ regular.

7. Conclusion and Discussion. The presented results show that classical system theoretic results well apply to prove turnpike properties for LQR problems constrained by standard linear state space systems. Under the assumption of impulse controllability, a descriptor system can be controlled such that it is basically an ODE with an additional but well separated algebraic part so that similar arguments can be used to confer turnpike properties of LQR problems with DAE constraints.

In line with the literature on turnpike in control systems, natural extensions of the presented results could consider periodic orbits as turnpikes (as in [32]), PDE formulations (as in, e.g., [10]), or particular nonlinear phenomena (as in [27, 31]) for the differential algebraic case.

As for the theory of control of DAEs, an immediate strengthening of the results could be achieved by removing the assumption on impulse controllability. A more general framework will also consider indefinite cost functionals and suitable replacements for the Riccati equations, as they are used recent works on singular feedback control [5] or infinite time horizon problems [29].

Another issue, in particular in view of numerical realizations, is the nonuniqueness of P_2 that, from an optimistic point of view, could be exploited for the design of optimal feedback laws; cp. also [12]. A general open research issue is the development of numerical schemes for the solution of the generalized algebraic and differential Riccati equations.

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