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# Riccati Differential Equation

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# 1 RICCATI DIFFERENTIAL EQUATION

## 1.1 Definition

The finite-horizon linear quadratic regular (LQR) optimal control problem is defined as

$$\begin{aligned} & \underset{\mathbf{u}(t)}{\text{minimize}} && \int_{t_0}^T (\mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{u}^T \mathbf{R} \mathbf{u} + 2\mathbf{x}^T \mathbf{S} \mathbf{u}) dt + \mathbf{x}(T)^T \mathbf{P}_T \mathbf{x}(T) \\ & \text{subject to} && \dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u} \\ & && \mathbf{P}(T) = \mathbf{P}_T \end{aligned} \quad (1)$$

where  $\mathbf{x} \in \mathbb{R}^n$ ,  $\mathbf{u} \in \mathbb{R}^m$ ,  $\mathbf{Q} \in \mathbb{R}^{n \times n}$ ,  $\mathbf{R} \in \mathbb{R}^{m \times m}$ ,  $\mathbf{S} \in \mathbb{R}^{n \times m}$ ,  $\mathbf{x}(T) \in \mathbb{R}^n$ , and  $\mathbf{P}_T \in \mathbb{R}^{n \times n}$ . The solution to the finite-horizon LQR problem is

$$\mathbf{u}(t) = -\mathbf{K}(t)\mathbf{x}(t)$$

where

$$\mathbf{K}(t) = \mathbf{R}^{-1} [\mathbf{B}^T \mathbf{P}(t) + \mathbf{S}^T] \quad (2)$$

and where  $\mathbf{K} \in \mathbb{R}^{m \times n}$  and  $\mathbf{P} \in \mathbb{R}^{n \times n}$ . The matrix function  $\mathbf{P}(t)$  is found by solving the **Riccati differential equation backwards** in time (i.e. from  $t = T$  to  $t = t_0$ ) using the terminal condition  $\mathbf{P}(T) = \mathbf{P}_T$ . The Riccati differential equation is given by [5]

$$\dot{\mathbf{P}} = -[\mathbf{A}^T \mathbf{P} + \mathbf{P} \mathbf{A} - (\mathbf{P} \mathbf{B} + \mathbf{S}) \mathbf{R}^{-1} (\mathbf{B}^T \mathbf{P} + \mathbf{S}^T) + \mathbf{Q}] \quad (3)$$

## 1.2 Solving the IVP

The Riccati differential equation is a matrix-valued ODE of the form

$$\frac{d\mathbf{M}}{dt} = \mathbf{F}(t, \mathbf{M})$$

where  $\mathbf{M} \in \mathbb{R}^{p \times q}$  (where  $p$  and  $q$  are arbitrary scalars). However, MATLAB's ODE solvers are only equipped to solve *vector*-valued ODEs of the form

$$\frac{dy}{dt} = \mathbf{f}(t, \mathbf{y})$$

where  $\mathbf{y} \in \mathbb{R}^p$ .

We can transform a matrix-valued ODE to a vector-valued ODE using the `mat2vec_ode` and `mat2vec_IC` functions of the *IVP Solver Toolbox*, and then transform the results of the vector-valued IVP into the results of the corresponding matrix-valued IVP using the `vec2mat_sol` function of the *IVP Solver Toolbox* [3, pp. 38–45][2].

## 1.3 Conditions for Existence and Uniqueness

Let's define the matrix  $\mathbf{M}$  as

$$\mathbf{M} = \begin{bmatrix} \mathbf{Q} & \mathbf{S} \\ \mathbf{S}^T & \mathbf{R} \end{bmatrix} \quad (4)$$

A unique solution to the Riccati differential equation exists if and only if the following conditions are satisfied [1][4, p. 35]:

1.  $\mathbf{M}$  is symmetric positive semidefinite ( $\mathbf{M} \succeq 0$ ). If  $\mathbf{S} = \mathbf{0}$ , this condition reduces to the following two conditions:
  - (a)  $\mathbf{Q}$  is symmetric positive semidefinite ( $\mathbf{Q} \succeq 0$ ).
  - (b)  $\mathbf{R}$  is symmetric positive definite ( $\mathbf{R} \succ 0$ ).
2.  $\mathbf{P}_T$  is symmetric positive semidefinite ( $\mathbf{P}_T \succeq 0$ ).
3.  $(\mathbf{A}, \mathbf{B})$  stabilizable.
4.  $(\mathbf{A} - \mathbf{B} \mathbf{R}^{-1} \mathbf{S}^T, \mathbf{Q} - \mathbf{S} \mathbf{R}^{-1} \mathbf{S}^T)$  detectable.
  - If  $\mathbf{S} = \mathbf{0}$ , this condition reduces to  $(\mathbf{A}, \mathbf{Q}^{1/2})$  detectable.

## REFERENCES

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