Riccati eq., Linear Quadratic Regulator

Control Theory, Lecture 8

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Content

- Hamilton-Jacobi-Bellman equation
  - Definitions
  - Cost, optimal cost
  - Differentiating optimal cost
- Algebraic Riccati equation
  - HJB for LTI
  - Linear Quadratic Regulator
  - Numerical methods

Let us define dynamics:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{1}$$

with initial conditions $\mathbf{x}(0) = \mathbf{x}_0$.

Additionally we define *control policy* as:

$$\mathbf{u} = \pi(\mathbf{x}, t) \tag{2}$$

To connect with the previous ways we talked about control, we can say that choosing different control gains and different feed-forward control amounts to choosing a different control policy.

Cost, optimal cost

Let J be an additive cost function:

$$J(\mathbf{x}_0, \pi(\mathbf{x}, t)) = \int_0^\infty g(\mathbf{x}, \mathbf{u}) dt \tag{3}$$

where $g(\mathbf{x}, \mathbf{u})$ is instantaneous cost and $\mathbf{x}_0 = \mathbf{x}(0)$ is the initial conditions. Notice that J depends on $\mathbf{x}_0$ rather than $\mathbf{x}(t)$, since initial conditions and control policy completely define the trajectory of the system $\mathbf{x}(t)$.

Let J^* be the optimal (lowest possible) cost. In other words:

$$J^*(\mathbf{x}_0) = \inf_\pi J(\mathbf{x}_0, \pi(\mathbf{x}, t)) \tag{4}$$

Optimal cost is attained when optimal policy is attained: $\pi = \pi^*(\mathbf{x}, t)$

Hamilton-Jacobi-Bellman equation, 1

With this, we can formulate *Hamilton-Jacobi-Bellman equation* (HJB):

$$\min_{\mathbf{u}} \left[g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u}) \right] = 0 \tag{5}$$

We can find control that delivers minimum to the function (5):

$$\mathbf{u}^* = \underset{\mathbf{u}}{\operatorname{argmin}} \left[g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u}) \right] \tag{6}$$

The term $\frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u})$ represents a derivative of J^* with respect to the vector field $\mathbf{f}(\mathbf{x}, \mathbf{u})$.

The core idea behind HJB is that for any sub-optimal control law the rate at which you incur cost $g(\mathbf{x}, \mathbf{u})$ outpaces the rate $\frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u})$ at which the "optimal cost-to-go from the current position to the goal" decreases:

$$g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u}) > 0 \tag{7}$$

and only for the optimal control policy the HJB holds:

$$g(\mathbf{x}, \mathbf{u}^*) + \frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u}^*) = 0 \tag{8}$$

Algebraic Riccati (LTI case), 1

For LTI, dynamics is:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{9}$$

We can choose quadratic cost:

$$g(\mathbf{x}, \mathbf{u}) = \mathbf{x}^\top \mathbf{Q}\mathbf{x} + \mathbf{u}^\top \mathbf{R}\mathbf{u} \tag{10}$$

where $\mathbf{Q} = \mathbf{Q}^\top \geq 0$ is a positive semidefinite matrix and $\mathbf{R} = \mathbf{R}^\top > 0$ is a positive-definite matrix.

There is a theorem that says that for LTI with quadratic cost, J^* has the form:

$$J^* = \mathbf{x}^\top \mathbf{S}\mathbf{x} \tag{11}$$

where $\mathbf{S} = \mathbf{S}^\top \geq 0$.

Algebraic Riccati (LTI case), 2

Let us compute the term $\frac{\partial J^*}{\partial \mathbf{x}}\mathbf{f}(\mathbf{x}, \mathbf{u})$ that appears in the HJB. Using the fact that $J^* = \mathbf{x}^\top \mathbf{S}\mathbf{x}$ we re-write it as:

$$\frac{\partial J^*}{\partial \mathbf{x}}\mathbf{f}(\mathbf{x}, \mathbf{u}) = \frac{d}{dt}(\mathbf{x}^\top \mathbf{S}\mathbf{x}) = \dot{\mathbf{x}}^\top \mathbf{S}\mathbf{x} + \mathbf{x}^\top \mathbf{S}\dot{\mathbf{x}} \tag{12}$$

Since $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$ we can continue the derivation:

$$... = (\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u})^\top \mathbf{S}\mathbf{x} + \mathbf{x}^\top \mathbf{S}(\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}) \tag{13}$$

Remembering that $g(\mathbf{x}, \mathbf{u}) = \mathbf{x}^\top \mathbf{Q}\mathbf{x} + \mathbf{u}^\top \mathbf{R}\mathbf{u}$ we write the HJB $\min_{\mathbf{u}} \left[g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}}\mathbf{f}(\mathbf{x}, \mathbf{u})\right] = 0$ as:

$$\min_{\mathbf{u}} \left[\mathbf{x}^\top \mathbf{Q}\mathbf{x} + \mathbf{u}^\top \mathbf{R}\mathbf{u} + \mathbf{x}^\top \mathbf{S}(\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}) + (\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u})^\top \mathbf{S}\mathbf{x}\right] = 0$$

We can simplify the expression
$\mathbf{x}^\top \mathbf{Q} \mathbf{x} + \mathbf{u}^\top \mathbf{R} \mathbf{u} + \mathbf{x}^\top \mathbf{S}(\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}) + (\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u})^\top \mathbf{S}\mathbf{x}$ as:

$$\min_{\mathbf{u}} \left[\mathbf{u}^\top \mathbf{R} \mathbf{u} + \mathbf{x}^\top (\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top \mathbf{S}) \mathbf{x} + \mathbf{x}^\top \mathbf{S}\mathbf{B}\mathbf{u} + \mathbf{u}^\top \mathbf{B}^\top \mathbf{S}\mathbf{x} \right] = 0$$

The minimum is achieved when the function is at an extremum, meaning $\frac{\partial}{\partial \mathbf{u}}(...) = 0$.

Setting the partial derivatives of
$\mathbf{u}^\top \mathbf{R} \mathbf{u} + \mathbf{x}^\top (\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top \mathbf{S}) \mathbf{x} + \mathbf{x}^\top \mathbf{S} \mathbf{B} \mathbf{u} + \mathbf{u}^\top \mathbf{B}^\top \mathbf{S} \mathbf{x}$ to zero:

$$2\mathbf{u}^\top \mathbf{R} + 2\mathbf{x}^\top \mathbf{S}\mathbf{B} = 0 \tag{14}$$

$$\mathbf{R}\mathbf{u} + \mathbf{B}^\top \mathbf{S}\mathbf{x} = 0 \tag{15}$$

$$\mathbf{u} = -\mathbf{R}^{-1}\mathbf{B}^\top \mathbf{S}\mathbf{x} \tag{16}$$

This is the desired control law. We can see that it is *proportional*. We can re-write it as:

$$\mathbf{u} = -\mathbf{K}\mathbf{x} \tag{17}$$

where $\mathbf{K} = \mathbf{R}^{-1}\mathbf{B}^\top \mathbf{S}$ is the controller gain. This control law is called *Linear Quadratic Regulator (LQR)*.

We substitute $\mathbf{u} = -\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S}\mathbf{x}$ into the Algebraic Riccati eq. $\mathbf{u}^\top\mathbf{R}\mathbf{u} + \mathbf{x}^\top(\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S})\mathbf{x} + \mathbf{x}^\top\mathbf{S}\mathbf{B}\mathbf{u} + \mathbf{u}^\top\mathbf{B}^\top\mathbf{S}\mathbf{x}$:

$$(\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S}\mathbf{x})^\top\mathbf{R}(\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S}\mathbf{x}) + \mathbf{x}^\top(\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S})\mathbf{x} - \\ -\mathbf{x}^\top\mathbf{S}\mathbf{B}(\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S}\mathbf{x}) - (\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S}\mathbf{x})^\top\mathbf{B}^\top\mathbf{S}\mathbf{x} = 0$$

$$\mathbf{x}^\top(\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S} + \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{R}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S} - \\ -\mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S} - \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S})\mathbf{x} = 0$$

Simplifying, we get:

$$\mathbf{x}^\top(\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S} - \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S})\mathbf{x} = 0 \tag{18}$$

The condition $\mathbf{x}^\top(\mathbf{Q} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S} - \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S})\mathbf{x} = 0$ holds for all $\mathbf{x}$ iff:

$$\mathbf{Q} - \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^\top\mathbf{S} + \mathbf{S}\mathbf{A} + \mathbf{A}^\top\mathbf{S} = 0 \tag{19}$$

This is the *Algebraic Riccati equation*.

There are a number of ways to solve LQR:

- In MATLAB there is a function `[K,S,P] = lqr(A,B,Q,R)`, where `P=eig(A-B*K)`
- In Python, there is `S = scipy.linalg.solve_continuous_are(A,B,Q,R)`

LQR and pole placement

- Pole placement upsides: allows to design exactly how fast the control error decays to zero; allows to design control error oscillations.
- Pole placement downsides: may require unreasonably high control gains. Easy to ask for "unreasonable" performance.
- LQR upsides: easy to produce "reasonable" control gains.
- LQR downsides: may produce very slow decaying control error with oscillations.

Consider discrete dynamics:

$$\mathbf{x}_{i+1} = \mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i \tag{20}$$

with a cost function:

$$J = \sum_{i=0}^{\infty} (\mathbf{x}_i^\top \mathbf{Q}\mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R}\mathbf{u}_i) \tag{21}$$

Let us find the optimal control policy for this case.

Cost-to-go, 1

Let us define cost-to-go as optimal cost for given initial conditions:

$$V_0 = \min_{\mathbf{u}} \sum_{i=0}^{\infty} (\mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R} \mathbf{u}_i) \tag{22}$$

If $\mathbf{x}_0$, $\mathbf{x}_1$, $\mathbf{x}_2$, ... is a sequence of states that form an optimal trajectory, let us define the cost-to-go starting from each of these states as:

$$V_i = \min_{\mathbf{u}} \sum_{k=i}^{\infty} (\mathbf{x}_k^\top \mathbf{Q} \mathbf{x}_k + \mathbf{u}_k^\top \mathbf{R} \mathbf{u}_k) \tag{23}$$

We can note that the optimal cost will take a form of a quadratic function:

$$V_i = \mathbf{x}_i^\top \mathbf{P}_i \mathbf{x}_i \tag{24}$$

Cost-to-go, 2

We can write cost-to-go as:

$$V_i(\mathbf{x}_i) = \min_{\mathbf{u}_i} \left(\mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R} \mathbf{u}_i + V_{i+1}(\mathbf{x}_{i+1}) \right) \tag{25}$$

where $V_{i+1}(\mathbf{x}_{i+1})$ is the optimal cost-to-go on the next step.

As the next step is closer to the goal, the optimal cost-to-go on the next step is both smaller than on the current step, and is contained in it.

The equation (25) is called *Bellman* equation.

Since $V_i = \mathbf{x}_i^\top \mathbf{P}_i \mathbf{x}_i$ and $V_{i+1} = \mathbf{x}_{i+1}^\top \mathbf{P}_{i+1} \mathbf{x}_{i+1}$ we can re-write Bellman equation as:

$$\mathbf{x}_i^\top \mathbf{P}_i \mathbf{x}_i = \min_{\mathbf{u}_i} \left(\mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R} \mathbf{u}_i + \mathbf{x}_{i+1}^\top \mathbf{P}_{i+1} \mathbf{x}_{i+1} \right) \tag{26}$$

To find minimum over $\mathbf{u}_i$ we set partial derivative to zero:

$$\begin{aligned}
\frac{\partial}{\partial \mathbf{u}_i} \left(\mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R} \mathbf{u}_i + (\mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i)^\top \mathbf{P}_{i+1} (\mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i) \right) &= 0 \\
2\mathbf{u}_i^\top \mathbf{R} + 2(\mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i)^\top \mathbf{P}_{i+1} \mathbf{B} &= 0 \\
\mathbf{R}\mathbf{u}_i + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B} \mathbf{u}_i + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A} \mathbf{x}_i &= 0 \\
(\mathbf{R} + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B}) \mathbf{u}_i &= -\mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A} \mathbf{x}_i \\
\mathbf{u}_i &= -(\mathbf{R} + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B})^{-1} \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A} \mathbf{x}_i
\end{aligned}$$

Let us define $\mathbf{M} = (\mathbf{R} + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B})^{-1}$ and $\mathbf{N} = \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A}$ we can re-write the control law:

$$\mathbf{u}_i = -\mathbf{M}\mathbf{N}\mathbf{x}_i \tag{27}$$

We can substitute the control law into the Bellman eq.:

$$\mathbf{x}_i^\top \mathbf{P}_i \mathbf{x}_i = \min_{\mathbf{u}} (\mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{u}_i^\top \mathbf{R} \mathbf{u}_i + (\mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i)^\top \mathbf{P}_{i+1} (\mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u}_i))$$

$$\mathbf{x}_i^\top \mathbf{P}_i \mathbf{x}_i = \mathbf{x}_i^\top \mathbf{Q} \mathbf{x}_i + \mathbf{x}_i^\top \mathbf{N}^\top \mathbf{M} \mathbf{R} \mathbf{M} \mathbf{N} \mathbf{x}_i + \\ +(\mathbf{A}\mathbf{x}_i - \mathbf{B}\mathbf{M}\mathbf{N}\mathbf{x}_i)^\top \mathbf{P}_{i+1} (\mathbf{A}\mathbf{x}_i - \mathbf{B}\mathbf{M}\mathbf{N}\mathbf{x}_i)$$

$$\mathbf{P}_i = \mathbf{Q} + \mathbf{N}^\top \mathbf{M} \mathbf{R} \mathbf{M} \mathbf{N} + \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{A} - \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{B} \mathbf{M} \mathbf{N} - \\ \mathbf{N}^\top \mathbf{M} \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A} + \mathbf{N}^\top \mathbf{M} \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B} \mathbf{M} \mathbf{N}$$

$$\mathbf{P}_i = \mathbf{Q} + \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{A} + \mathbf{N}^\top \mathbf{M} (\mathbf{R} + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B}) \mathbf{M} \mathbf{N} - \mathbf{N}^\top \mathbf{M} \mathbf{N} - \mathbf{N}^\top \mathbf{M} \mathbf{N}$$

$$\mathbf{P}_i = \mathbf{Q} + \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{A} - \mathbf{N}^\top \mathbf{M} \mathbf{N}$$

From $\mathbf{P}_i = \mathbf{Q} + \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{A} - \mathbf{N}^\top \mathbf{M} \mathbf{N}$ we obtain the final result:

$$\mathbf{P}_i = \mathbf{Q} + \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{A} - \mathbf{A}^\top \mathbf{P}_{i+1} \mathbf{B} (\mathbf{R} + \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{B})^{-1} \mathbf{B}^\top \mathbf{P}_{i+1} \mathbf{A}$$

This equation can be used to compute $\mathbf{P}_i$ from known $\mathbf{P}_{i+1}$.

Further reading

- Underactuated robotics. Linear Quadratic Regulators.
- Discrete LQR. Stanford, EE363.
- Discrete LQR (infinite horizon). Stanford, EE363.

Lecture slides are available via Github:

github.com/SergeiSa/Control-Theory-2025

Appendix A: Illustration of HJB

Consider the additive cost $J(\mathbf{x}_0, \pi(\mathbf{x})) = \int_0^\infty g(\mathbf{x}, \mathbf{u}) dt$, where $\mathbf{u} = \pi(\mathbf{x})$ is a control policy. The function $g(\mathbf{x}, \mathbf{u}) \geq 0$ can be interpreted as a rate of change of cost.

Let $\pi^*(\mathbf{x})$ be the optimal control policy. Applying the optimal policy to the dynamics $\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u})$ we obtain optimal dynamics:

$$\dot{\mathbf{x}} = f^*(\mathbf{x}) = f(\mathbf{x}, \pi^*(\mathbf{x})) \tag{28}$$

Given initial conditions $\mathbf{x}_0 = \mathbf{z}$ we generate an optimal trajectory $\mathbf{x}^* = \mathbf{x}^*(t, \mathbf{z})$. Given optimal trajectory and optimal control policy we find optimal cost:

$$J^*(\mathbf{z}) = J(\mathbf{z}, \pi^*(\mathbf{x})) \tag{29}$$

Equivalently, we find optimal instantenious cost:

$$g^*(\mathbf{x}) = g(\mathbf{x}, \pi^*(\mathbf{x})) \tag{30}$$

Incurred cost

Since optimal cost depends on initial conditions only, we can find a function $J^* = J^*(\mathbf{z})$ defined over $\mathbb{R}^n$.

Lets us consider a trajectory $\mathbf{x}^* = \mathbf{x}^*(t, \mathbf{z})$ and sequence of points on this trajectory $\mathbf{x}_0$, $\mathbf{x}_1$, $\mathbf{x}_2$, etc. associated with the time stamps t_0, t_1, t_2, etc. We can define incurred cost (incurred while moving from the initial state $\mathbf{z} = \mathbf{x}_0$ to the given point) for each of these points S_0, S_1, S_2, etc. as:

$$S_i = \int_0^{t_i} g^*(\mathbf{x}) dt \tag{31}$$

Since $g^*(\mathbf{x}) \geq 0$, we observe that $S_0 \leq S_1 \leq S_2 \leq ....$ Moving along a trajectory $\mathbf{x}^*(t, \mathbf{z})$ we incur monotonically increasing cost. We can describe it as a time function $S(t)$. The rate of increace of this function is given by instantenious cost $g^*(\mathbf{x})$.

We know that the optimal cost from the point $\mathbf{z}$ is given as $J^*(\mathbf{z})$. For each sequential point on the trajectory we can define *cost-to-go* V_i as a difference between the optimal cost and the incurred cost:

$$V_i = J^*(\mathbf{z}) - S_i \tag{32}$$

For a given trajectory, we can describe cost-to-go as a time function $V(t) = J^*(\mathbf{z}) - S(t)$. Where as $S(t)$ is monotonically increasing, the function $V(t)$ is monotonically decreasing, with a rate of change given as $-g^*(\mathbf{x})$.

Note that the cost-to-go can be equivalently found as:

$$V(t) = J^*(\mathbf{x}^*(t)) \tag{33}$$

since the optimal cost we incur by starting from the point $\mathbf{x}_i$ is equivalent to the cost "have left to incur" when we reach $\mathbf{x}_i$ from $\mathbf{x}_0$.

With that, we can make an observation: for an optimal policy we see the rate of change of the cost-to-go function equal to $-g^*(\mathbf{x})$. But this rate of change can be found by taking a derivative of $J^*(\mathbf{x})$ with respect to the vector field $\dot{\mathbf{x}} = f^*(\mathbf{x})$:

$$-g^*(\mathbf{x}) = \frac{\partial J^*}{\partial \mathbf{x}} f^*(\mathbf{x}) \tag{34}$$

For sub-optimal control policies, the incurred cost will outpace the decrease of the cost-to-go:

$$g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}} f(\mathbf{x}, \mathbf{u}) \geq 0 \tag{35}$$

Optimal policy recovers the sought equality:

$$\min_{\mathbf{u}} \left[g(\mathbf{x}, \mathbf{u}) + \frac{\partial J^*}{\partial \mathbf{x}} \mathbf{f}(\mathbf{x}, \mathbf{u}) \right] = 0 \tag{36}$$