

## Exercise 8: Continuous-Time Optimal Control

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Consider the following continuous-time optimal control problem:

$$\begin{aligned} \min_{x(t), u(t)} \quad & \int_{t=0}^T L(x(t), u(t)) dt + E(x(T)) \\ \text{s.t.} \quad & x(0) = \bar{x}_0 \\ & \dot{x}(t) = f(x(t), u(t)), \quad t \in [0, T]. \end{aligned} \tag{1}$$

- (a) Discretize problem (1) using the explicit Euler integrator with step-size  $h$  over  $N$  intervals. Write on paper the obtained discrete-time optimal control problem.
- (b) Write the first-order optimality conditions for the discretized problem obtained in (a). Use the Hamiltonian function defined as

$$H(x, u, \lambda) := L(x, u) + \lambda^T f(x, u) \tag{2}$$

to simplify these conditions.

- (c) Now let  $N \rightarrow \infty$  and  $h \rightarrow 0$ . What type of problem do the conditions derived in (b) converge to?
- (d) Fix  $N = 2$  and apply the Newton method to the first-order optimality conditions for the discretized optimal control obtained in (b). Derive the form of the linear systems associated with the Newton steps. Order the variables as  $z = (\lambda_0, x_0, u_0, \lambda_1, x_1, u_1, \lambda_2, x_2)$  and the KKT conditions accordingly as  $F(z) = 0$  with  $F(z) := \nabla_z \mathcal{L}(z)$ , where  $\mathcal{L}(z)$  is the Lagrangian of the NLP.

For notational simplicity we suggest you use the abbreviations  $Q_k := h \nabla_x^2 H(x_k, u_k, \lambda_k)$ ,  $R_k := h \nabla_u^2 H(x_k, u_k, \lambda_k)$ ,  $S_k := h \nabla_{ux}^2 H(x_k, u_k, \lambda_k)$ ,  $A_k := I + h \nabla_x f(x_k, u_k)^\top$ ,  $B_k := h \nabla_u f(x_k, u_k)^\top$  for  $k \in \{0, \dots, N-1\}$  and  $Q_N := \nabla_x^2 E(x_N)$

- (e) **[Bonus]** The linear systems associated with the Newton steps in (d) can be solved exploiting the Riccati Difference Equation (equation 8.5 in the course's script). Derive this equation.
- (f) **[Bonus]** What kind of matrix ODE does the difference equation derived in (e) converge to for  $N \rightarrow \infty$  and  $h \rightarrow 0$ ?

*Hint: if you have not solved the bonus point (e) you can refer to equation 8.5 from the course's script.*