Model Predictive Control

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github.com/silvasta/summary-mpc

Contents

1 Introduction

Requirements for MPC

1. A model of the system
2. A state estimator
3. Define the optimal control problem
4. Set up the optimization problem
5. Get the optimal control sequence (solve the optimization problem)
6. Verify that the closed-loop system performs as desired

1.1 Exact ODE solution of a Linear System

$$x(t) = e^{A^c(t-t_0)}x_0 + \int_{t_0}^{t} e^{A^c(t-\tau)}B^c u(\tau)d\tau$$

Problem Most physical systems are nonlinear

Idea use First Order Taylor expansion $f(\bar{x}) + \frac{\partial f}{\partial x^\top}\Big|_{\bar{x}}(x-\bar{x})$

1.2 Linearization

$$\begin{aligned} \dot{x_s} &= g(x_s,u_s) = 0 & \Delta\dot{x} &= \dot{x} - \dot{x_s} = A^c\Delta x + B^c\Delta u \\ y_s &= h(x_s,u_s) & \Delta y &= y - y_s = C\Delta x + D\Delta u \end{aligned}$$

$$A^c = \frac{\partial g}{\partial x^T}\Big|_{\substack{x_s\\u_s}} \quad B^c = \frac{\partial g}{\partial u^T}\Big|_{\substack{x_s\\u_s}} \quad C = \frac{\partial h}{\partial x^T}\Big|_{\substack{x_s\\u_s}} \quad D = \frac{\partial h}{\partial u^T}\Big|_{\substack{x_s\\u_s}}$$

1.3 Discretization

For general nonlinear systems only approximate discretization methods exist, such as Euler, quality depends on sampling time

Approximation $\dot{x}^c \approx \frac{x^c(t+T_s) - x^c(t)}{T_s}$

Notation $x(k) := x^c(t_0 + kT_s)$, $u(k) := u^c(t_0 + kT_s)$

Exact Discretization of Linear Time-Invariant Models

$$x(t_{k+1}) = \underbrace{e^{A^cT_s}}_{=A}x(t_k) + \underbrace{\int_0^{T_s} e^{A^c(T_s-\tau)}B^c d\tau}_{B=(A^c)^{-1}(A-\mathbb{I})B^c}\,u(t_k)$$

$$x(k+N) = A^N x(k) + \sum_{i=0}^{N-1} A^i B u(k+N-1-i)$$

1.4 Analysis of LTI Discrete-Time Systems

Controllabe if $\text{rank}(\mathcal{C}) = n$, $\mathcal{C} = \begin{bmatrix} B & \cdots & A^{n-1}B \end{bmatrix}$

$\forall (x(0), x^*) \exists$ finite time N with inputs $\mathcal{U}$, s.t. $x(N) = x^*$

Stabilizable iff all uncontrollable modes stable

Observable if $\text{rank}(\mathcal{O}) = n$, $\begin{bmatrix} C^\top & \cdots & (CA^{n-1})^\top \end{bmatrix}^\top$

$\forall x(0) \exists$ finite time N, s.t. the measurements

$y(0), \dots, y(N-1)$ uniquely distinguish initial state $x(0)$

Detectablitiy iff all unobservable modes stable

1.5 Lyapunov

Stability is a property of an **equilibrium point** $\bar{\mathbf{x}}$ of a system

Definition 1 (Lyapunov Stability). $\bar{\mathbf{x}}$ is **Lyapunov stable** if:

$\forall\, \epsilon > 0\, \exists\, \delta(\epsilon)$ s.t. $||x(0) - \bar{x}|| < \delta(\epsilon) \rightarrow ||x(k) - \bar{x}|| < \epsilon$

Definition 2 (Globally asymptotic stability). If $\bar{\mathbf{x}}$ is Lyapunov stable and attractive, i.e., $\lim_{k\to\infty} ||x(k) - \bar{x}|| = 0,\ \forall x(0)$ then $\bar{\mathbf{x}}$ is **globally asymptotic stable**.

Definition 3 (Global Lyapunov function). For $\bar{\mathbf{x}} = 0$, function $V: \mathbb{R}^n \to \mathbb{R}$ is called **Lyapunov function** if it is continuous at the origin, finite $\forall\, x \in \mathbb{R}^n$,

$$||x|| \to \infty \Rightarrow V(x) \to \infty$$

$$V(x) > 0\, \forall\, x \in \mathbb{R}^n \setminus \{0\} \quad V(0) = 0$$

$$V(g(x)) - V(x) \leq -\alpha(x) \quad \forall x \in \mathbb{R}^n$$

where $\alpha: \mathbb{R}^n \to \mathbb{R}$ continuous positive definite

Lyapunov Theorem

Theorem 1. If a system admits a Lyapunov function $V(x)$, then $\bar{\mathbf{x}} = 0$ is **globally asymptotically stable**.

Theorem 2 (Lyapunov indirect method). For linearization of system around $\bar{\mathbf{x}} = 0$ and resulting matrix $A = \frac{\partial g}{\partial x^T}\Big|_{x=0}$ with eigenvalues

$$|\lambda_i| := \begin{cases} \forall i := |\lambda_i| < 1 & \text{x=0 is asymptotically stable} \\ \exists i := |\lambda_i| > 1 & \text{origin is unstable} \\ \exists i := |\lambda_i| = 1 & \text{no info about stability} \end{cases}$$

Discrete-Time Lyapunov equation

$$A^T P A - P = -Q, \quad Q \succ 0$$

Theorem 3 (Existence of solution of DT Lyapunov equation). The discrete-time Lyapunov equation (3) has a unique solution P > 0 if and only if A has all eigenvalues inside the unit circle, i.e. if and only if the system x(k + 1) = Ax(k) is stable.

1.6 Optimal Control

Unconstrained Finite Horizon Control Problem

$$\begin{aligned} J^\star(x(0)) := \min_U x_N^\top P x_N + \textstyle\sum_{i=0}^{N-1} x_i^\top Q x_i + u_i^\top R u_i \\ \text{subject to } x_{i+1} = Ax_i + Bu_i \quad i = 0, \dots, N-1 \\ x_0 = x(0) \end{aligned}$$

$P \succeq 0$, with $P = P^T$ terminal weight

$Q \succeq 0$, with $Q = Q^T$ state weight

$R \succ 0$, with $R = R^T$ input weight

1.7 Batch Approach

expresses cost function in terms of $x(0)$ and input sequence U

$$\begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} \mathbb{I} \\ A \\ \vdots \\ A^N \end{bmatrix} x(0) + \begin{bmatrix} 0 & \cdots & 0 \\ B & 0 & 0 \\ AB & B & 0 \\ \vdots & \ddots & 0 \\ A^{N-1}B & \cdots & B \end{bmatrix} \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

$\overline{Q} :=$ blockdiag$(Q, \dots, Q, P)$ $\quad \overline{R} :=$ blockdiag$(R, \dots, R)$

Optimal Input (from $\nabla_U J(x(0), U) = 2HU + 2F^\top x(0) = 0$)

$$U^\star(x(0)) = -\big(\underbrace{(\mathcal{S}^u)^\top \overline{Q}\mathcal{S}^u + \overline{R}}_{H(\text{Hessian})^{-1}}\big)\underbrace{(\mathcal{S}^u)^\top \overline{Q}\mathcal{S}^x}_{F^\top} x(0)$$

Optimal Cost

$$J^\star(x(0)) = x(0)^\top(\mathcal{S}_x^\top \overline{Q}\mathcal{S}_x - \mathcal{S}_x^\top \overline{Q}\mathcal{S}_u(\mathcal{S}_u^\top \overline{Q}\mathcal{S}_u + \overline{R})^{-1}\mathcal{S}_u^\top \overline{Q}\mathcal{S}_x)x(0)$$

1.8 Recursive Approach

uses dynamic programming to solve problem backwards from N

$$J_j^\star(x(j)) := \min_{U_{j\to N}} x_N^\top P x_N + \sum_{i=j}^{N-1} x_i^\top Q x_i + u_i^\top R u_i$$

Ricatti Equations

RDE - Riccati Difference Equation

$$P_i = A^\top P_{i+1} A + Q - A^\top P_{i+1} B(B^\top P_{i+1} B + R)^{-1} B^\top P_{i+1} A$$

RDE - Riccati Difference Equation solved recursively

$$P_i = A^\top P_{i+1} A + Q - A^\top P_{i+1} B(B^\top P_{i+1} B + R)^{-1} B^\top P_{i+1} A$$

ARE - Algebraic Riccati Equation solved analytically

$$P_\infty = A^\top P_\infty A + Q - A^\top P_\infty B(B^\top P_\infty B + R)^{-1} B^\top P_\infty A$$

From Principle Of Optimality $\quad$ **Optimal Cost-To-Go**

$$J_j^\star(x_j) = \min_{u_j} I(x_i, u_i) + J_{j+1}^\star(x_{j+1}) \qquad J_i^\star(x_i) = x_i^\top P_i x_i$$

Optimal Control Policy

$$u_i^\star = F_i x_i = -(B^\top P_{i+1} B + R)^{-1} B^\top P_{i+1} A \cdot x(i)$$

1.9 Comparison of Batch and Recursive Approaches

Batch optimization returns sequence $U^\star(x(0))$ of **numeric values** depending only on x(0), dynamic programming yields **feedback policies** $u_i^\star = F_i x_i$ depending on each x_i.

Choice of P

1. Match infinite solution, use ARE
2. Assume no control needed after N, use Lyapunov Equation (makes only sense when asymptotically stable, otherwise P not positive definite)
3. set constraint $x_{i+N} = 0$

1.10 Infinite Horizon LQR

LQR

$$J_\infty^\star(x(k)) = \min \sum_{i=0}^{\infty} x_i^\top Q x_i + u_i^\top R u_i$$

$$\text{subj. to } x_{i+1} = Ax_i + Bu_i, \quad x_0 = x(k)$$

Same u as for finite problem but with ARE Constant Feedback Matrix $F\infty$ asymptotically stable for.. Q,R,stabi,detect

1.11 Optimization

A mathematical optimization problem is generally formulated as:

Mathematical Optimization Problem

Decision variable $x \in \mathbb{R}^n$
Objectivce function $f : \text{dom}(f) \to \mathbb{R}$
Inequality constraints g_i $(i \in \#\text{constraints})$
Equality constraints h_i $(i \in \#\text{constraints})$
Fesabile set $\mathcal{X} := \{x | g(x) \leq 0, h(x) = 0\}$

minimize $f(x)$
subject to:
$g_i(x) \leq 0$
$h_i(x) = 0$

Feasible point $x \in \text{dom}(f)$ with $g_i(x) \leq 0, \ h_i(x) = 0$
Strictly feasible point x with strict inequality $g_i(x) < 0$
Optimal value $f^\star$ (or $p^\star$) $= \inf\{f(x) | g_i(x) \leq 0, h_j = 0\}$
$f^\star = +\infty$: OP infeasible, $f^\star = -\infty$: OP unbound below
Optimizer set: $\text{argmin}_{x \in \mathcal{X}} f(x) := \{x \in \mathcal{X} | f(x) = f^\star\}$

$x^\star$ is a **Global Minimum** if $f(x^\star) \leq f(x)$
$x^\star$ is a **Local Minimum** if $\exists\, \epsilon > 0$ s.t. $f(x^\star) \leq f(x)$
$\forall x \in \mathcal{X} \cap B_\epsilon(x^\star)$, open ball with center $x^\star$ and radius ϵ

1.12 Convex Sets

Definition 4 (Convex Set). Set $\mathcal{C}$ is convex if and only if

$$\theta x + (1-\theta) y \in \mathcal{C}, \ \forall\, x, y \in \mathcal{C}, \ \forall\, \theta \in [0,1]$$

Definition 5 (Hyperplanes). $\{x \in \mathbb{R}^n \mid a^\top x = b\}$
Definition 6 (Halfspaces). $\{x \in \mathbb{R}^n \mid a^\top x \leq b\}$
can be **open** (strict inequality) or **closed** (non-strict inequality)
Definition 7 (Polyhedra). intersection of **finite** number of closed halfspaces: polyhedra $\{x \in \mathbb{R}^n \mid A^{q \times n} x \preceq b^{q \times 1}, \}$
Definition 8 (Polytope). is a **bounded** polyhedron.
Definition 9 (Convex hull). for $\{v_1, \ldots, v_k\} \in \mathbb{R}^d$ is:
$\text{co}(\{v_1, \ldots, v_k\}) := \{x | x = \sum_i \lambda_i v_i, \lambda \geq 0, \sum_i \lambda_i = 1\}$
Definition 10 (Ellipsoid). set: $\{x | (x - x_c)^\top A^{-1} (x - x_c) \leq 1\}$
where x_c is center of ellipsoid, $A \succ 0$ (i.e. positive definite)
(Semi-axis lengths are square roots of eigenvalues of A)
Definition 11 (Norm Ball). $B_r(x) := \{\xi \in \mathbb{R}^n : |\xi - x|_p < r\}$
where p defines the l_p norm, $p = \{1|2|..|\infty\}$
Intersection $\mathcal{C}_1, \mathcal{C}_2$ cv $\Rightarrow \mathcal{C}_1 \cap \mathcal{C}_2$ convex **(cv)**
Image under affine map $\mathcal{C} \subseteq \mathbb{R}^n$ cv $\Rightarrow \{Ax + b \mid x \in \mathcal{C}\}$ cv
Inverse IoaM $\mathcal{C} \subseteq \mathbb{R}^m$ cv $\Rightarrow \{x \in \mathbb{R}^n \mid Ax + b \in \mathcal{C}\}$ cv

1.13 Convex Functions

Definition 12 (Convex Function). $f : \mathcal{C}_{cv} \to \mathbb{R}$ is convex iff

$$f(\theta x + (1-\theta) y) \leq \theta f(x) + (1-\theta) f(y), \ \forall\, x, y \in \mathcal{C}, \ \forall\, \theta \in [0,1]$$

f is strictly convex if this inequality is strict.
Definition 13 (Epigraph). $f : \mathbb{R}^n \to \mathbb{R}$ cv $\Leftrightarrow$ epi(f) is cv set

$$\text{epi}(f) := \{(x, t) \in \mathbb{R}^{n+1} | f(x) \leq t\}$$

Check Convexity f is convex if it is composition of simple convex function with convexity preserving operations or if
$f : \mathbb{R}^n \to \mathbb{R}$ twice differentiable, $\partial^2 f / \partial x^2 \succeq 0 \, \forall\, x \in \mathbb{R}^n$
$g : \mathbb{R} \to \mathbb{R}$ with $g(t) = f(x + tv)$ convex in $t \, \forall\, x, v \in \mathbb{R}^n$
$\to f$ convex (restriction to a line)
- the point wise maximum of convex functions is convex
- the sum of convex functions is convex
- $f(Ax + b)$ is convex if f is convex

Theorem 4. For a convex optimization problem, **any** locally optimal solution is globally optimal (local optima are global optima).

Linear Programming minimize $c^\top x$ s.t. $Ax - b \geq 0, \ x \geq 0$
Step 1: $\mathcal{L}(x, \lambda_1, \lambda_2) = c^\top x - \lambda_1^\top (Ax - b) - \lambda_2^\top x, \ \lambda_i \geq 0$
Step 2: $\inf_{x \in \mathbb{R}^n} \mathcal{L} = \lambda_1^\top b$, if $c - A^\top \lambda_1 - \lambda_2 = 0$, else $-\infty$
Step 3: Dual, maximize $b^\top \lambda$ s.t. $c - A^\top \lambda \geq 0, \lambda \geq 0$ (again LP)
Quadratic Programming min ...

1.14 Optimality Conditions

Lagrange Duality

Consider $f^\star = \inf_{x \in \mathbb{R}^n} f(x)$ s.t. $g(x) \leq 0, \ h(x) = 0$

Lagrangian $\mathcal{L}(x, \lambda, \nu) = f(x) + \lambda^\top g(x) + \nu^\top h(x)$

Dual Function $d(\lambda, \nu) = \inf_{x \in \mathbb{R}^n} \mathcal{L}(x, \lambda, \nu)$

Proposition 1 (Weak Duality). $d(\lambda, \nu) \leq f^\star, \forall \lambda \geq 0, \nu \in \mathbb{R}^h$
Definition 14 (Constraint qualification). **Slaters Condition** holds if $\exists$ at least one strictly feasible point $\hat{x}$ $(h(\hat{x}) = 0, \ g(\hat{x}) < 0)$
Proposition 2 (Strong Duality). If Slater's condition holds and OP is convex $\Rightarrow \exists \lambda \geq 0, \nu \in \mathbb{R}^{n_h}$ s.t. $d(\lambda, \nu) = f^\star$

KKT Conditions (Karush-Kuhn-Tucker)

Theorem 5 (KKT Conditions). If Slater's condition holds and (1.14) is convex $\to x^\star \in \mathbb{R}^n$ is a minimizer of the primal (1.14) and $(\lambda^\star \geq 0, \nu^\star) \in \mathbb{R}^{n_g} \times \mathbb{R}^{n_h}$ is a maximizer of the dual $\Leftrightarrow$ is equivalent to the following statements:

KKT-1 (Stationary Lagrangian) $\nabla_x \mathcal{L}(x^\star, \lambda^\star, \nu^\star) = 0$
KKT-2 (primal feasibility) $g(x^\star) \leq 0, h(x^\star) = 0$
KKT-3 (dual feasibility) $\lambda^\star, \nu^\star \in \mathbb{R}^{n_h} \geq 0$
KKT-4 (compementary slackness) $\lambda^{\star T} g(x^\star) = 0$, $\nu^{\star T} h(x^\star) = 0$

In addition we have: $\sup_{\lambda \geq 0, \nu \in \mathbb{R}^{n_h}} q(\lambda, \nu) = \inf_{x \in \mathcal{C}} f(x)$

Remark Without Slater, KKT1-4 still implies $x^\star$ minimizes (1.14) and λ, ν maximizes dual, but the converse is no longer true. There can be primal-minimizer/dual-maximizer not satisfy KKT.

2 Nominal-MPC

2.1 CFTOC

CFTOC Constrained Finite Time Optimal Control problem

$$J(x(k)) = x_N^\top P x_N + \sum_{i=0}^{N-1} x_i^\top Q x_i + u_i R u_i$$

$$J^\star(x(k)) = \min_U I_f(x_N) + \sum_{i=0}^{N-1} I(x_i, u_i)$$

$$\text{s.t} \quad x_{i+1} = Ax_i + Bu_i, \ i = 0, \ldots, N-1$$
$$x_i \in \mathcal{X}, \ u_i \in \mathcal{U}, \ \mathcal{X}_N \in \mathcal{X}_f, \ x_0 = x(k)$$

N is the time horizon and X , U, Xf are polyhedral regions

2.2 Transform Quadratic Cost CFTOC into QP

Goal $\min_{z \in \mathbb{R}^n} \frac{1}{2} z^\top H z + q^\top z + r$ s.t. $Gz \leq h, \ Az = b$

2.2.1 Substitute without substitution

Idea Keep state equations as equality constraints

Define variable $z = \begin{bmatrix} x_1^\top & \ldots x_N^\top & u_0^\top & \ldots u_{N-1}^\top \end{bmatrix}^\top$
Equalities from system dynamics $x_{i+1} = Ax_i + Bu_i$

$$G_{eq} = \left[\begin{array}{cccc|ccc} \mathbb{I} & & & & -B & & \\ -A & \mathbb{I} & & & & & \\ & \ddots & \ddots & & & \ddots & \\ & & -A & \mathbb{I} & & & -B \end{array}\right] \quad E_{eq} = \begin{bmatrix} A \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

Inequalities $G_{in} z \leq w_{in} + E_{in} x(k)$ from $\mathcal{X} = \{x \mid A_x x \leq b_x\}, \mathcal{U} = \{u \mid A_u u \leq b_u\}, \mathcal{X}_f = \{x \mid A_f x \leq b_f\}$

$$G_{in} = \left[\begin{array}{cccc|cccc} 0 & & & & 0 & & & \\ \hline A_x & & & & 0 & & & \\ & \ddots & & & & \ddots & & \\ & & A_x & & & & 0 & \\ & & & A_f & & & & 0 \\ \hline 0 & & & & A_u & & & \\ & \ddots & & & & \ddots & & \\ & & 0 & & & & A_u & \\ & & & 0 & & & & A_u \end{array}\right] \quad w_{in} = \left[\begin{array}{c} b_x \\ \hline b_x \\ \vdots \\ b_x \\ b_f \\ \hline b_u \\ \vdots \\ b_u \\ b_u \end{array}\right]$$

$$E_{in} = \begin{bmatrix} -A_x \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

Cost Matrix $\bar{H} = \text{diag}(Q, \ldots, Q, P, R, \ldots, R)$
Finally the resulting quadratic optimization problem

$$J^\star(x(k)) = \min_z \begin{bmatrix} z^\top & x(k)^\top \end{bmatrix} \begin{bmatrix} \bar{H} & 0 \\ 0 & Q \end{bmatrix} \begin{bmatrix} z^\top & x(k)^\top \end{bmatrix}^\top$$
$$\text{s.t} \quad G_{in} z \leq w_{in} + E_{in} x(k) \quad G_{eq} z = E_{eq} x(k)$$

2.2.2 Substitute with substitution

Idea Substitute the state equations.
Step 1 Rewrite cost as

$$J(x(k)) = UXXXX$$
$$= \begin{bmatrix} U^\top & x(k)^\top \end{bmatrix} \begin{bmatrix} H & F^\top \\ F & Y \end{bmatrix} \begin{bmatrix} U^\top & x(k)^\top \end{bmatrix}^\top$$

Step 2 Rewrite constraints compaclty as $GU \leq w + Ex(k)$
Step 3 Rewrite constrained problem as

$$J^\star(x(k)) = \min_U \begin{bmatrix} U^\top & x(k)^\top \end{bmatrix} \begin{bmatrix} H & F^\top \\ F & Y \end{bmatrix} \begin{bmatrix} U^\top & x(k)^\top \end{bmatrix}^\top$$
$$\text{subj. to } GU \leq w + Ex(k)$$

2.3 Invariance

Definition 15 (Positively Invariant Set $\mathcal{O}$). For an autonomous or closed-loop system, the set $\mathcal{O}$ is positively invariant if:

$$x(k) \in \mathcal{O} \Rightarrow x(k+1) \in \mathcal{O}, \quad \forall k \in \{0, 1, \ldots\}$$

Definition 16 (Maximal Positively Invariant Set $\mathcal{O}_\infty$). A set that contains all $\mathcal{O}$ is the maximal positively invariant set $\mathcal{O}_\infty \subset \mathcal{X}$
Definition 17 (Pre-Sets). The set of states that in the dynamic system $x(k+1) = g(x(k))$ in one time step evolves into the target set $\mathcal{S}$ is the **pre-set** of $\mathcal{S} \Rightarrow$ pre$(\mathcal{S}) := \{x \mid g(x) \in \mathcal{S}\}$

Theorem 6 (Geometric condition for invariance). Set $\mathcal{O}$ is positively invariant set iff $\mathcal{O} \subseteq$ pre$(\mathcal{O}) \Leftrightarrow$ pre$(\mathcal{O}) \cap \mathcal{O} = \mathcal{O}$

Proof. **Necessary** if $\mathcal{O} \not\subseteq$ pre$(\mathcal{O})$, then $\exists \bar{x} \in \mathcal{O}$ s.t $\bar{x} \notin$ pre$(\mathcal{O}) \rightsquigarrow \bar{x} \in \mathcal{O}, \bar{x} \notin$ pre$(\mathcal{O})$, thus $\mathcal{O}$ not positively invariant
Sufficient if $\mathcal{O}$ not pos invar set, then $\exists \bar{x} \in \mathcal{O}$ s.t $g(\bar{x}) \notin \mathcal{O}$ $\rightsquigarrow \bar{x} \in \mathcal{O}, \bar{x} \notin$ pre$(\mathcal{O})$ thus $\mathcal{O} \notin$ pre$(\mathcal{O})$ □

Computing Invariant Sets

Pre-Set Computation

System with constraints $x(k+1) = Ax(k) + Bu(k)$
$u(k) \in \mathcal{U} := \{u | Gu \leq g\}$
and set $\mathcal{S} := \{x | Fx \leq f\}$
pre$(\mathcal{S}) := \{x \mid Ax \in \mathcal{S}\}$
$= \{x \mid FAx \leq f\}$

Conceptual Algorithm

first line
$\Omega_0 \leftarrow \mathcal{X}$
loop
$\Omega_{i+1} \leftarrow$ pre$(\Omega_i) \cap \Omega_i$
if $\Omega_{i+1} = \Omega_i$ **then**
return
$\mathcal{O}_\infty = \Omega_i$
end if
end loop

(Same but much harder for control invariat sets)

Conceptual Algorithm

first line
$\Omega_0 \leftarrow \mathcal{X}$
loop
$\Omega_{i+1} \leftarrow$ pre$(\Omega_i) \cap \Omega_i$
if $\Omega_{i+1} = \Omega_i$ **then**
return $\mathcal{O}_\infty = \Omega_i$
end if
end loop

(Same but much harder for control invariat sets)

Conceptual Algorithm

```
@decorator()
# Example Python code
def hello_world():
  # This is a comment
      print("Hello, World!")
```

(Same but much harder for control invariat sets)

2.4 Control Invariance

Definition 18 (Control Invariant Set). $\mathcal{C} \subseteq \mathcal{X}$ control invariant if

$$x(k) \in \mathcal{C} \Rightarrow \ \exists u(k) \in \mathcal{U} \text{ s.t } g(x(k), u(k)) \in \mathcal{C} \, \forall k$$

Definition 19 (Maximal Control Invariant Set $\mathcal{C}_\infty$). A set that contains all $\mathcal{C}$ is the maximal positively invariant set $\mathcal{C}_\infty \subset \mathcal{X}$
Intuition For all states in $\mathcal{C}_\infty$ exists control law s.t constraints are never violated $\rightsquigarrow$ **The best any controller could ever do**
Pre-set pre$(\mathcal{S}) := \{x \mid \exists u \in \mathcal{U} \text{ s.t } g(x, u) \in \mathcal{S}\}$
Set $\mathcal{C}$ is control invariant iff: $\mathcal{C} \subseteq$ pre$(\mathcal{C}) \Leftrightarrow$ pre$(\mathcal{C}) \cap \mathcal{C} = \mathcal{C}$

Control Law from Control Invariant Set

Let $\mathcal{C}$ control invariant set for $x(k+1) = g(x(k), u(k))$
Control law $\kappa(x(k))$ will **guarantee** that system satisfies constraints **for all time** if: $g(x, \kappa(x)) \in \mathcal{C}\ \forall x \in \mathcal{C}$
We can use this fact to **synthesize** control law κ with f as any function (including $f(x, u) = 0$)

$$\kappa(x) := \text{argmin}\{f(x, u) \mid g(x, u) \in \mathcal{C}\}$$

Does not ensure that system will converge
Difficult because calculating control invariant sets is hard
MPC implicitly describes $\mathcal{C}$ s.t easy to represent/compute

Theorem 7. Minkowski-Weyl
The following statements are equivalent for $\mathcal{P} \subseteq \mathbb{R}^d$

- $\mathcal{P}$ is a polytope and there exists A, b s.t $\mathcal{P} = \{x \mid Ax \leq b\}$
- $\mathcal{P}$ finitely generated, $\exists$ finite set $\{v_i\}$ s.t $\mathcal{P} = \text{co}(\{v_1, \ldots, v_s\})$

MOST COMMON Polytopic

1

Lemma 1. Invariant Sets from Lyapunov Functions
If $V : \mathbb{R}^n \to \mathbb{R}$ is a Lyapunov function for $x(k+1) = g(x(k))$, then $Y := \{x \mid V(x) \leq \alpha\}$ is an invariant set for all $\alpha \geq 0$

Proof. Lyapunov property $V(g(x)) - V(x) < 0$ implies that once $V(x(k)) \leq \alpha, V(x(j)) < \alpha, \forall j \geq k \to$ Invariance □

Example System for $x(k+1) = Ax(k)$ with $P \succ 0$ that satisfies $A^\top PA - P \prec 0 \rightsquigarrow$ then $V(x(k)) = x(k)^\top Px(k)$ is Lyap. function

Goal – find largest α s.t set $Y_\alpha \in \mathcal{X}$
$$Y_\alpha := \{x \mid x^\top Px \leq \alpha\} \subset \mathcal{X} := \{x \mid Fx \leq f\}$$
Equivalent to $\max_\alpha \alpha$ subj. to $h_{Y_\alpha}(F_i) \leq f_i\ \forall i \in \{1 \ldots n\}$

2.5 Feasibility and Stability

What can go wrong with "standard" MPC?

- No feasibility guarantee, i.e., the MPC problem may not have a solution

- No stability guarantee, i.e., trajectories may not converge to the origin

MPC Mathematical Formulation

V1

$$J^\star(x(k)) = \min \sum_{i=0}^{N-1} x_i^\top Qx_i + u_i^\top Ru_i$$

V3

$$J^\star(x(k)) = \min \sum_{i=0}^{N-1} x_i^\top Qx_i + u_i^\top Ru_i$$

subj. to $x_{i+1} = Ax_i + Bu_i$
$x_0 = x(k) \quad x_i \in \mathcal{X}, \quad u_i \in \mathcal{U}$

Stability of MPC - Main Result

Theorem 8. The closed-loop system under the MPC control law $u_0^\star(x)$ is asymptotically stable and the set $\mathcal{X}_f$ is positive invariant for the system $x(k+1) = Ax(k) + Bu_0^\star(x(k))$ under the following assumptions:
1. Stage cost is positive definite, i.e. it is strictly positive and only zero at the origin
2. Terminal set is **invariant** under the local control law $\kappa_f(x_i)$:

$$x_{i+1} = Ax_i + B\kappa_f(x_i) \in \mathcal{X}_f \forall x_i \in \mathcal{X}_f$$

All state and input **constraints are satisfied** in $\mathcal{X}_f$:

$$\mathcal{X}_f \in X, \kappa_f(x_i) \in U \forall x_i \in \mathcal{X}_f$$

3. Terminal cost is a continuous **Lyapunov function** in the terminal set $\mathcal{X}_f$ and satisfies:

$$I_f(x_{i+1}) - I_f(x_i) \leq -I(x_i, \kappa_f(x_i)) \quad \forall x_i \in \mathcal{X}_f$$

Finite-horizon MPC may not satisfy constraints for all time!
Finite-horizon MPC may not be stable!
- An infinite-horizon provides stability and invariance.
- Infinite-horizon *faked* by forcing final state into an invariant set for which there exists invariance-inducing controller, whose infinite-horizon cost can be expressed in closed-form.
- Extends to non-linear systems, but compute sets is difficult!

3 Practical-MPC

3.1 Steady-state Target Problem

- Reference is achieved by the target state x_s if $z_s = Hx_s = r$
- Target state should be a steady-state, i.e. $x_s = Ax_s + Bu_s$

$$\begin{aligned} x_s &= Ax_s + Bu_s \\ z_s &= Hx_s = r \end{aligned} \iff \begin{bmatrix} \mathbb{I} - A & -B \\ H & 0 \end{bmatrix} \begin{bmatrix} x_s \\ u_s \end{bmatrix} = \begin{bmatrix} 0 \\ r \end{bmatrix}$$

$\nexists$ solution $\to \min(Hx_s - r)^\top Q_s(Hx_s - r)$ (closest x to r)
If $\exists$ multiple feasible $u_s \to$ compute min $u_s^\top R_s u_s$ (cheapest)

$$\min_U |z_N - Hx_s|_{P_z}^2 + \sum_{i=1}^{N-1} |z_i - Hx_s|_{Q_z}^2 + |u_i - u_s|_R^2$$

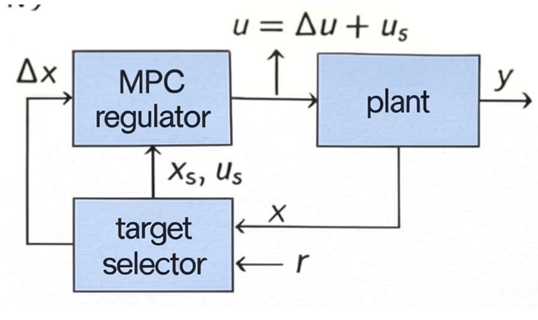
3.2 Reference Tracking

$$\begin{aligned} \Delta x &= x - x_s \\ \Delta u &= u - u_s \end{aligned} \Rightarrow \begin{aligned} \Delta x_{k+1} &= x_{k+1} - x_s \\ &= A\Delta x_k + Bu_k - (Ax_s + Bu_s) \\ &= A\Delta x_k + B\Delta u_k \end{aligned}$$

$$\begin{aligned} G_x x &\leq h_x \\ G_u u &\leq h_u \end{aligned} \Rightarrow \begin{aligned} G_x \Delta x &\leq h_x - G_x x_s \\ G_u \Delta u &\leq h_u - G_u u_s \end{aligned}$$

```
def get_next_u(y: Measurement, r: Reference):
    """
    System handler for offset-free tracking
    """
    # approximate state, disturbance
    x, d = estimator(y)
    # find steady state und generate delta
    x_s, u_s = target_selector(x, r, d)
    x_delta = x - x_s
    # call solver with new parameter
    u_delta = mpc_regulator(x_delta, x_s, u_s)
    u = u_delta + u_s

    return u
```



Assume target feasible with $x_s \in \mathcal{X}, u_s \in \mathcal{U}$, choose terminal weight $V_f(x)$ and constraint $\mathcal{X}_f$ as in regulation case satisfying

- $\mathcal{X}_f \subseteq \mathcal{X}, Kx \in \mathcal{U} \quad \forall x \in \mathcal{X}_f$
- $V_f(x(k+1)) - V_f(x(k)) \leq -l(x(k), Kx(k)) \quad \forall x \in \mathcal{X}_f$

If in addition the target reference x_s, u_s is such that

- $x_s \oplus \mathcal{X}_f \subseteq \mathcal{X}, K\Delta x + u_s \in \mathcal{U}, \quad \forall \Delta x \in \mathcal{X}_f$

then CL system converges to target reference

$$x(k) \to x_s, z(k) = Hx(k) \xrightarrow{k \to \infty} r$$

Proof.
- Invariance under local ctrol law inherited from regulation case
- Constraint satisfaction provided by extra conditions
  - $x_s \oplus \mathcal{X}_f \subseteq \mathcal{X} \to x \in \mathcal{X} \forall \Delta \in \mathcal{X}_f$
  - $K\Delta x + u_s \in \mathcal{U} \forall \Delta x \in \mathcal{X}_f \to u \in \mathcal{U}$
- Fron asympt stability of the regulation problem: $\Delta x(k) \xrightarrow{k \to \infty} 0$

□

Terminal set use $\mathcal{X}_f^{\text{scaled}} = \alpha \mathcal{X}_f$ (s.t. constraints satisfied)

3.3 Reference Tracking without Offset

Approach Model the disturbance, use the measurements and model to estimate the state and disturbance and find control inputs that use the disturbance estimate to remove offset.

Augmented Model

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + B_d d_k \\ y_k &= Cx_k + C_d d_k \end{aligned}$$

Constant disturbance $d_{k+1} = d_k$

Observable iff $\begin{bmatrix} A-\mathbb{I} & B_d \\ C & C_d \end{bmatrix}$ has full rank $(= n_x + n_d)$

Observer For Augmented Model

$$\begin{bmatrix} \hat{x}_{k+1} \\ \hat{d}_{k+1} \end{bmatrix} = \begin{bmatrix} A & B_d \\ 0 & \mathbb{I} \end{bmatrix} \begin{bmatrix} \hat{x}_k \\ \hat{d}_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + \begin{bmatrix} L_x \\ L_d \end{bmatrix} (C\hat{x}_k + C_d\hat{d}_k - y_k)$$

Error Dynamics $\Rightarrow$ choose L s.t error dynamics converge to 0

$$\begin{bmatrix} x_{k+1} - \hat{x}_{k+1} \\ d_{k+1} - \hat{d}_{k+1} \end{bmatrix} = \left(\begin{bmatrix} A & B_d \\ 0 & \mathbb{I} \end{bmatrix} + \begin{bmatrix} L_x \\ L_d \end{bmatrix} \begin{bmatrix} C & C_d \end{bmatrix} \right) \begin{bmatrix} x_k - \hat{x}_k \\ d_k - \hat{d}_k \end{bmatrix}$$

Lemma 2. Steady-state of an asym. stable observer satisfies:

$$\begin{bmatrix} A - \mathbb{I} & B \\ C & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_\infty \\ u_\infty \end{bmatrix} = \begin{bmatrix} -B_d\hat{d}_\infty \\ y_\infty - C_d\hat{d}_\infty \end{bmatrix} \text{ (for } n_y = n_d)$$

$\Rightarrow$ Observer output $C\hat{x}_\infty + C_d\hat{d}_\infty$ tracks y_∞ without offset

3.4 Offset-free Tracking

Goal Track constant reference: $Hy(k) = z(k) \to r, k \to \infty$

$$\begin{aligned} x_s &= Ax_s + Bu_s + B_d\hat{d}_\infty \\ z_s &= H(Cx_s + C_d\hat{d}_\infty) = r \end{aligned} \begin{bmatrix} A-I & B \\ HC & 0 \end{bmatrix} \begin{bmatrix} x_s \\ u_s \end{bmatrix} = \begin{bmatrix} 0 \\ r - HC_d\hat{d} \end{bmatrix}$$

Theorem 9 (Offset-free Tracking: Main Result). Assuming $n_d = n_y$, RHC recursively feasible, unconstrained for $k \geq j$, control law $\kappa(\cdot) = \kappa(\hat{x}(k), \hat{d}(k), r)$ and closed loop system

$$\begin{aligned} x(k+1) &= Ax(k) + B\kappa(\cdot) + B_d d \\ \hat{x}(k+1) &= (A + L_x C)\hat{x}(k) + (B_d + L_x C_d)\hat{d}(k) \\ &\quad + B\kappa(\cdot) - L_x y(k) \\ \hat{d}(k+1) &= L_d C\hat{x}(k) + (\mathbb{I} + L_d C_d)\hat{d}(k) - L_d y(k) \end{aligned}$$

converges, then $z(k) = Hy(k) \to r$ as $k \to \infty$

3.5 Soft Constraints

Input constraints are dictated by physical constraints on the actuators and are usually hard

- State/output constraints arise from practical restrictions on the allowed operating range and are **rarely hard**

- Hard state/output constraints always lead to **complications in the controller implementation**

Soft Constrained MPC Problem Setup

$$\min_u \sum_{i=0}^{N-1} x_i^\top Qx_i + u_i^\top Ru_i + l_\epsilon(\epsilon_i) + x_N^\top Px_i + l_\epsilon(\epsilon_N)$$

$$\begin{aligned} \text{subj. to } x_{i+1} &= Ax_i + Bu_i \\ H_x x_i &\leq k_x + \epsilon_i \\ H_u u_i &\leq k_u \\ \text{slack variable } \epsilon_i &\geq 0 \end{aligned}$$

Quadratic penalty $l_\epsilon(\epsilon_i) = \epsilon_i^\top S\epsilon_i$ (e.g $S = Q$)
Linear Penalty $v|\epsilon_i|_{1/\infty}$
Requirement on $l_\epsilon(\epsilon)$ If the original problem has a feasible solution $z^\star$, then the softened problem should have the same solution $z^\star$, and $\epsilon = 0$.
Theorem 10 (Exact Penalty Funtcion). $l_\epsilon(\epsilon) = v \cdot \epsilon$ satisfies requirement for any $v > \lambda^\star \geq 0$, where $\lambda^\star$ is optimal Lagrange multiplier for original problem

4 Robust-MPC

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5 Implementation

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