Introduction

Euklidian Norm: $\|x\|_2 = \sqrt{\sum_{i=1}^{n} x_i^2} = \sqrt{x^T x}$

$$\|x\|_2^2 = x^T \cdot x$$

Weighting Eukl. Norm: $\|x\|_Q^2 = x^T Q \cdot x$

Frobenius Norm: $\|x\|_F^2 = \text{trace}(AA^T) = \sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij}A_{ij}$

Jacobian: $\nabla f(x) = \frac{\partial f}{\partial x}(x)$ in $\mathbb{R}^{n\times m}$ Hessian: $\nabla^2 f(x)$

$$(AB)^\top = B^\top A^\top \quad (AB)^{-1} = B^{-1}A^{-1} \quad (A^\top)^{-1} = (A^{-1})^\top$$

Matrix derivates: $\frac{\mathrm{d}(c^T x)}{\mathrm{d}x} = c \qquad \frac{\mathrm{d}(x^T A x)}{\mathrm{d}x} = (A^T + A)x$

Linear and non-linear models:
- linear if parameters linear i.e. $(\theta_1 x^2 + \theta_2 x + \theta_3)$
- nonliniar if i.e $(\sin(\theta_1)x + \theta_2)$ or derivatives in other orders than 1

Table of Derivatives:

$\mathbf{f(x)}$	$\mathbf{f'(x)}$
$g(x)\cdot h(x)$	$g'(x)\cdot h(x) + g(x)\cdot h'(x)$
$g(h(x))$	$g'(h(x))\cdot h'(x)$
$\sin(x)$	$\cos(x)$
$\cos(x)$	$-\sin(x)$
$\tan(x) = \frac{\sin(x)}{\cos(x)}$	$\frac{1}{\cos^2(x)} = \sec^2(x)$
e^{kx}	$\frac{1}{k}e^{kx}$
$\ln(x)$	$\frac{1}{x}$
$\log_a x$	$\frac{1}{x\cdot \ln a}$
Ax	A
$x^\top A$	$A^\top$
$x^\top Bx$	$x^\top(B^\top + B)$
$x^\top Ax$	$x^\top(A + A^\top)$
$x^\top A^\top Ax$	$2x^\top A^\top A$

Random Variables and Probability

Dependent Probability: $P(A \vee B) = P(A) + P(B)$

Independent Prob.: $P(A, B) = P(A \wedge B) = P(A)\cdot P(B)$

Conditional Prob.: $P(A|B) = \frac{P(A,B)}{P(B)} = \frac{P(B|A)\cdot P(A)}{P(B)}$ (Bayes' theorem)

$$P(X \in [a,b]) = \int_a^b p_X(x)\mathrm{d}x \qquad p(x|y) = \frac{p(x,y)}{p(y)}$$

Mean/Expectation value: $\mathbb{E}\{\mu_X\} := \mu_X = \int_{-\infty}^{\infty} x \cdot p_X(x)dx$

$$\mathbb{E}\{a + bX\} := a + b\mathbb{E}\{X\}$$

$$\mathbb{E}\{XY\} = \mathbb{E}\{X\}\cdot\mathbb{E}\{Y\} \Leftrightarrow X, Y \text{ independent}$$

Variance: $\sigma_X^2 := \mathbb{E}\{(X-\mu_X)^2\} = \mathbb{E}\{X^2\} - \mu_X^2$

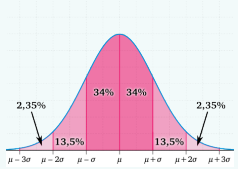
Standard deviation: $\sigma_X = \sqrt{\sigma_X^2}$

Distributions

Uniform distribution: $P_y(x) = \begin{cases} \frac{1}{b-a} & \text{if } x \in [a,b] \\ 0 & \text{else} \end{cases}$, $\text{var}(x) = \frac{(b-a)^2}{12}$

Mean: $\mu_X = \int_{-\infty}^{\infty} x\, p_X(x)\mathrm{d}x = \int_a^b \frac{x}{b-a}\mathrm{d}x = \frac{a+b}{2} =: \mu_X$

Normal distribution: $X \sim \mathcal{N}(\mu, \sigma^2) \quad \hat{\theta}_{LS} \sim \mathcal{N}(\theta_0, \Sigma_{\hat{\theta}})$



$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\cdot\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Multidimensional Normal Distribution:

$$p(x) = \frac{1}{\sqrt{(2\pi)^n\cdot\det(\Sigma)}}\cdot\exp\left(-\frac{1}{2}\cdot(x-\mu)^T\cdot\Sigma^{-1}\cdot(x-\mu)\right)$$

Weibull distribution: $F(x) = 1 - \exp\left(-(\lambda\cdot x)^k\right)$

Laplace distribution: $f(x|\mu, b) = \frac{1}{2b}\cdot\exp\left(-\frac{|x-\mu|}{b}\right)$

Useful statistic definitions

Covariance and Correlaton: $\sigma(X,Y) := \mathbb{E}(X-\mu_X)(Y-\mu_Y)$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x-\mu_X)(y-\mu_Y)\cdot p_{X,Y}(x,y)\,\mathrm{d}x\,\mathrm{d}y$$

Covariance Matrix: $\Sigma_x = cov(X) = \mathbb{E}\{XX^T\} - \mu_x\mu_x^T$ is PSD

$\Sigma = \begin{bmatrix}\sigma_x^2 & \sigma_{yx}\\ \sigma_{xy} & \sigma_y^2\end{bmatrix}$ $\sigma_{xy} = \sigma yx = \rho_{xy}\cdot\sigma_x\cdot\sigma_y$ where ρ is correlation

x and y are i.i.d. $\Rightarrow \Sigma$ is diagonal

Multidimensional Random Variables:

$$\mathbb{E}\{f(X)\} = \int_{\mathbb{R}^n} f(x)p_X(x)d^n x$$

$$\text{cov}(X) = \mathbb{E}\{(X-\mu_X)(X-\mu_X)^T\}$$

$$\text{cov}(X) = \mathbb{E}\{XX^T\} - \mu_X\mu_X^T$$

$$\text{cov}(Y) = \Sigma_y = A\Sigma_x A^T \quad for \quad y = A\cdot x$$

$$\mathbb{E}\{AX\} = A\cdot\mathbb{E}\{X\}$$

Rules for variance:

$$\text{var}(aX) = a^2\cdot\text{var}(X)$$

$$\text{var}(X+Y) = \text{var}(X) + \text{var}(Y) + 2\cdot\text{cov}(X,Y)$$

Formula for variance: $\text{var}(X) = \mathbb{E}((X-\mathbb{E}(X))^2) = \mathbb{E}(X^2) - (\mathbb{E}(X))^2$

Correlation:
uncorrelated if $\rho(X,Y) = 0$, $\rho(X,Y) := \frac{\text{cov}(X,Y)}{\sigma_x\sigma_y}$

Statistical estimators:

Biased- and Unbiasedness An estimator $\hat{\theta}_N$ is unbiased $\Leftrightarrow \mathbb{E}\{\hat{\theta}_N(y_N)\} = \theta_0$, where $\theta_0 \equiv$ "true" value of θ. Otherwise: biased.

Asymptotic Unbiasedness An estimator $\hat{\theta}_N$ is called asymptotically unbiased $\Leftrightarrow \lim_{n\to\infty}\mathbb{E}\{\hat{\theta}_N(y_N)\} = \theta_0$

Consistency An estimator $\hat{\theta}_N(y_N)$ is called consistent if, for any $\epsilon > 0$, the probability $P(\hat{\theta}_N(y_N) \in [\theta_0 - \epsilon, \theta_0 + \epsilon])$ tends to 1 for $N \to \infty$.

Unconstrainded Optimization

Theorem 1: (First Order Necessary Conditions)
If $x^* \in D$ is local minimizer of $f : D \to \mathbb{R}$ and $f \in C^1$ then $\nabla f(x^*) = 0$ Definition (Stationary Point) A point $\bar{x}$ with $\nabla f(\bar{x}) = 0$ is called a stationary point of f.

Theorem 2: (Second Order Necessary Conditions)
If $x^* \in D$ is local minimizer of $f : D \to R$ and $f \in C^2$ then $\nabla^2 f(x^*) \succeq 0$

Theorem 3: (Second Order Sufficient Conditions and Stability under Perturbations)
Assume that $f : D \to R$ is C^2. If $x^* \in D$ is a stationary point and $\nabla^2 f(x^*) \succ 0$ then x^* is a strict local minimizer of f. In addition, this minimizer is locally unique and is stable against small perturbations of f, i.e. there exists a constant C such that for sufficiently small $p \in \mathbb{R}^n$ holds

$$\|x^* - \underset{x}{\text{argmin}}(f(x) + p^T x)\| \le C\|p\|$$

Linear Least Squares Estimation

Preliminaries: i.i.d. and Gaussian noise

Overall Model: $y(k) = \phi(k)^T\theta + \varepsilon(k)$

LS cost function as sum: $\sum_{k=1}^{N}(y(k) - \phi(k)^T\theta)^2$

LS cost function: $f(\theta) = \|y_N - \Phi_N\theta\|_2^2$

Unique minimizers: $\hat{\theta}_{LS} = \underset{\theta\in\mathbb{R}}{\text{argmin}}\, f(\theta)\theta^* = \underbrace{(\Phi^T\Phi)^{-1}\Phi^T}_{:=\Phi^+} y$

Pseudo Inverse: $\Phi^+ = (\Phi^T\Phi)^{-1}\Phi^T$

Weighted Least Squares (unitless)

For i.i.d noise: Unweight Least Squares is optimal: $W = I$

$$f_{WLS}(\theta) = \sum_{k=1}^{N}\frac{(y(k) - \phi(k)^T\theta)^2}{\sigma_\epsilon^2(k)} = \|y_N - \Phi_N\theta\|_W^2$$

$$= \|W^{\frac{1}{2}}y - W^{\frac{1}{2}}\Phi_N\theta\|_2^2 = (y_N - \Phi\cdot\theta)^T\cdot W\cdot(y_N - \Phi\cdot\theta)$$

Solution for WLS:

$$\hat{\theta}_{WLS} = \tilde{\Phi}^+\tilde{y} \qquad \text{with } \tilde{\Phi} = W^{\frac{1}{2}}\Phi \text{ and } \tilde{y} = W^{\frac{1}{2}}y$$

$$= \underset{\theta\in\mathbb{R}}{\text{argmin}}\, f_{\text{WLS}}(\theta) = (\Phi^T W\Phi)^{-1}\Phi^T W y$$

Ill-Posed Least Squares

Singular Value Decomposition: $A = USV^T \in \mathbb{R}^{mxn}$
with $U \in \mathbb{R}^{mxm}$, $V \in \mathbb{R}^{nxn}$ and $S \in \mathbb{R}^{mxn}$ where S is a diagonal Matrix with non-negative elements $(\sigma_1, \ldots, \sigma_r, 0, \ldots, 0)$

Moore Penrose Pseudo Inverse:

$$\Phi^+ = VS^+U^T = V(S^TS + \alpha I)^{-1}S^TU^T$$

Φ^+ therefore selects $\theta^* \in S^*$ with minimal norm

Regularization for Least Squares:

$$\lim_{a\to 0}(\Phi^T\Phi + \alpha I)^{-1}\Phi^T = \Phi^+ \quad \text{with } \Phi^+ \; MPPI$$

$$\theta^* = (\Phi^T\Phi + \alpha\mathbb{I})^{-1}\Phi^T y$$

Statistical Analysis of WLS

Expectation of Least Squares Estimator:

$$E\{\hat{\theta}_{WLS}\} = E\{(\Phi_N^T W \Phi_N)^{-1} \Phi_N^T W y_N\} = \theta_0$$

Covariance of the least squares estimator:

$$\mathrm{cov}(\hat{\theta}_{\mathrm{WLS}}) = (\Phi^\top W\Phi)^{-1}\Phi^\top W\Sigma_\varepsilon^{-1} W\Phi(\Phi^\top W\Phi)^{-1} = \underbrace{(\Phi_N^\top \Sigma_\varepsilon^{-1}\Phi_N)^{-1}}_{\text{for } W=\Sigma_\varepsilon}$$

$$\mathrm{cov}(\hat{\theta}_{WLS}) \succeq (\Phi_N^T W \Phi_N)^{-1}$$

Example LLS

Example of the Linear Least Square Estimator for: $N = 2$

$$\varepsilon(1) \sim \mathcal{N}(0|\sigma_1^2) \qquad \varepsilon(2) \sim \mathcal{N}(0|\sigma_2^2)$$

$$N = 2; \quad \Sigma_{\varepsilon_N} = \begin{bmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{bmatrix} \qquad W^{OPT} = \Sigma_{\varepsilon_N}^{-1} = \begin{bmatrix} \frac{1}{\sigma_1^2} & 0 \\ 0 & \frac{1}{\sigma_2^2} \end{bmatrix}$$

$$\mathrm{cov}(\hat{\theta}_{WLS}) = (Y_N - \Phi_N\theta)^T \cdot W \cdot (Y_N - \Phi_N\theta)$$

$$= \sum_{k=1}^{2} (y(k) - \phi(k)^T\theta) \cdot \frac{1}{\sigma_k^2} \cdot (y(k) - \phi(k)^T\theta)$$

Measuring the goodness of Fit using: $R^2 \quad (0 \le R^2 \le 1)$

$$R^2 = 1 - \frac{\|y_N - \Phi_N\hat{\theta}\|_2^2}{\|y_N\|_2^2} = 1 - \frac{\|\epsilon_N\|_2^2}{\|y_N\|_2^2}$$

$$= \frac{\|y_N\|_2^2 - \|\epsilon_N\|_2^2}{\|y_N\|_2^2} = \frac{\|\hat{y}_N\|_2^2}{\|y_N\|_2^2}$$

Residual: $\epsilon_N \uparrow \rightarrow \quad R^2 \to 0 \ (\Rightarrow bad)$

Covariance estimation with a single experiment

Estimate $\hat{\sigma}_\varepsilon$

$$\hat{\sigma}_\varepsilon^2 = \frac{1}{N-d}\|y - \Phi_N\hat{\theta}\|_2^2, \quad \text{with } \hat{\theta} \in \mathbb{R}^d$$

$$\hat{\Sigma}_{\hat{\theta}} = \hat{\sigma}_\varepsilon(\Phi_N^\top\Phi_N)^{-1} = \frac{\|y - \Phi_N\hat{\theta}\|_2^2}{N-d}(\Phi_N^\top\Phi_N)^{-1}$$

Bayesian Estimation and the Maximum a Posteriori Estimate

Assumptions:

- Measurement: $y_N \in \mathbb{R}^N$ has i.i.d. noise
- Linear Model: $M(\theta) = \phi_N \cdot \theta$ and $\theta \in \mathbb{R}$

$$p(\theta|y_N) = \frac{p(y_N,\theta)}{p(y_N)} = \frac{p(y_N|\theta)\cdot p(\theta)}{p(y_N)}$$

$$\hat{\theta}_{MAP} = \underset{\theta\in\mathbb{R}}{\mathrm{argmin}}\{\underbrace{-\log(p(y_N|\theta))}_{\text{Max. Likelihood}} \underbrace{-\log(p(\theta))}_{\text{prev. knowledge}}\}$$

MAP Example: Regularised Least Squares

$$\theta = \bar{\theta} \pm \sigma_\theta \quad \text{with} \quad \bar{\theta} = \theta_{\text{a-priori}}$$

$$\hat{\theta}_{\mathrm{MAP}} = \underset{\theta\in\mathbb{R}}{\mathrm{argmin}} \frac{1}{2}\cdot\frac{1}{\sigma_{\varepsilon}2}\cdot\|y_N - \Phi_N\cdot\theta\|_2^2 + \frac{1}{2}\cdot\frac{1}{\sigma_\theta^2}\cdot(\theta-\bar{\theta})^2$$

Maximum Likelihood Estimation

L_2 **Estimation: Maximum Likelihood Estimation (ML)**:

- Measurement Errors assumed to be Normally distributed
- Model described by a non-linear function $M(\theta)$
- Every unbiased estimator needs to satisfy the Cramer-Rao inequality, which gives a lower bound on the covariance matrix.

Model: $y = M(\theta) + \varepsilon$

$$p(y|\theta) = C\prod_{i=1}^N \exp\left(\frac{-(y_i - M_i(\theta))^2}{2\cdot\sigma_i^2}\right) \qquad C = \prod_{i=1}^N \frac{1}{\sqrt{2\cdot\pi\sigma_i^2}}$$

Positive log-Likelihood: (log changes products into sums)

$$\log p(y|\theta) = \log(C) + \sum_{i=1}^N -\frac{(y_i - M_i(\theta))^2}{2\cdot\sigma_i^2}$$

Negative log-Likelihood:

$$\hat{\theta}_{ML} = \arg\max_{\theta\in\mathbb{R}^d} p(y|\theta) = \arg\min_{\theta\in\mathbb{R}^d} \sum_{i=1}^N \frac{(y_i - M_i(\theta))^2}{2\sigma_i^2}$$

$$= \arg\min_{\theta\in\mathbb{R}^d} \frac{1}{2}\sum_{i=1}^N \left(\frac{y_i - M_i(\theta)}{\sigma_i}\right)^2$$

$$= \arg\min_{\theta\in\mathbb{R}^d} \frac{1}{2}\|S^{-1}(y - M(\theta))\|_2^2 \qquad \text{with: } S = \begin{bmatrix} \sigma_1 & & \\ & \ddots & \\ & & \sigma_N \end{bmatrix}$$

L_1 **Estimation:**

- Measurement Errors assumed to be Laplace distributed and more robust against outliers.

$$\min_\theta \|y - M(\theta)\|_1 = \min_\theta \sum_{i=1}^N |y_i - M_i(\theta)|$$

$$\Rightarrow \text{ median of } \{Y_1, \cdots, Y_N\}$$

Recursive Linear Least Squares

$$Q_{N+1} = \alpha\cdot Q_N + \varphi(N+1)\cdot\varphi(N+1)^T, \ \alpha \mathrel{\widehat{=}} \text{“forgettingfactor”}$$

$$\hat{\theta}_{ML}(N+1) = \hat{\theta}_{ML}(N) + Q_{N+1}^{-1}\cdot\varphi(N+1)$$

$$\cdot[\underbrace{y(N+1)}_{\text{new measurement}} - \underbrace{\varphi(N+1)^T\cdot\hat{\theta}_{ML}(N)}_{\text{old prediction}}]$$

Q_0 and $\hat{\theta}_0$ have to be chosen.
Q_0 should be **non-singular, small and positive definite**. (e.g. $10^{-3}\cdot I$)
$Q_N \approx \Sigma^{-1}_{\hat{\theta}_{\mathrm{ML}}(N)}$

Cramer-Rao-Inequality (Fisher information Matrix M)

$$\mathrm{cov}(\hat{\theta}(y_N)) = \Sigma_{\hat{\theta}} \succeq M^{-1} \quad \underbrace{= (\Phi_N^T\cdot\Sigma^{-1}\cdot\Phi_N)^{-1}}_{\text{for lin. model w. } \varepsilon\sim\mathcal{N}(\mu,\sigma)}$$

$$M = \int_{y_n} \nabla_\theta^2 L(\theta_0, y_n)\cdot p(y_n|\theta_0)\mathrm{d}y_n$$

Assumptions:

- Minimising a Linear Model
- Gaussian Noise: $X \sim \mathcal{N}(0,\Sigma)$)

$$L(\theta, y_N) = -\log(p(y_N|\theta))$$

$$(\text{if lin. model, etc.}) = \frac{1}{2}\cdot(\Phi_N\cdot\theta - y_N)^T\cdot\Sigma^{-1}\cdot(\Phi_N\cdot\theta - y_N)$$

$$M = \mathbb{E}\{\nabla_\theta^2 L(\theta, y_N)\} = \nabla_\theta^2 L(\theta, y_N)(= \Phi_N^T\cdot\Sigma^{-1}\cdot\Phi_N)$$

$$\Rightarrow W = \Sigma^{-1} \text{ is the optimal weighting Matrix for WLS.}$$

Continuous Time Systems

Ordinary Differential Equations (ODE):

$$\dot{x} = f(x(t), u(t), \epsilon(t), p)$$

Differential Algebraic Equations(DAE):

$$\dot{x} = f(x(t), u(t), \epsilon(t), p)$$
$$0 = g(x, z).$$

LTI Sytem (ODE):

$$\dot{x} = Ax + Bu \quad y = Cx + Du$$

$$G(s) = C(sI - A)^{-1}B + D$$

Numerical Integration Methods

Euler Integration Step

$$\tilde{x}(t; x_0, u_{\text{const}}) = x_0 + tf(x_0, u_{\text{const}}), \quad t \in [0, \Delta t]$$

$$\tilde{x}_{j+1} = \tilde{x}_j + hf(\tilde{x}_j, u_{\text{const}}), \quad j = 0, \ldots, M-1$$

- Approximation becomes better by decreasing the step size h.
- Concistency Error: h^2
- Total Number of steps: $\Delta t/h$
- Error in the final step of order $h\Delta t$
- Linear in step size $\rightarrow$ order one
- Taking more steps is more accurate but needs more computation

Runge-Kutta Method of Order Four (RK4)

$$k_1 = f(\tilde{x}_j, u_{\text{const}})$$

$$k_2 = f(\tilde{x}_j, \frac{h}{2}k_1, u_{\text{const}})$$

$$k_3 = f(\tilde{x}_j, \frac{h}{2}k_2, u_{\text{const}})$$

$$k_4 = f(\tilde{x}_j, hk_3, u_{\text{const}})$$

$$\tilde{x}_{j+1} = \tilde{x}_j + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$

One Step of RK4 is thus as expensive as four steps of euler
accurency of final approximation is of order $h^4\Delta$ t
$\rightarrow$ RK4 needs fewer functions to obtain the same accuracy level as euler

Discrete Time Systems

Det. Model as State Space	Stoch. Model as State Space
Det. Model as Input-Output	Stoch. Model as Input-Output

State Space Model
$x_{k+1} = f_k(x_k, u_k), k = 0, 1, \ldots, N-1$ with input vector u_k and state vector x_k

Input-Output Model
$y(k) = h(u(k), \ldots, u(k-n), y(k-1), \ldots, y(k-n))$

LTI system as State-Space Model:

$$x_{k+1} = Ax_k + Bu_k, \quad k = 0, 1, \ldots, N-1.$$

LTI system as Input-Output Model:

$$G(s) = \frac{b_0 + b_1 s + \ldots + b_n s^n}{a_0 + a_1 s + \ldots + a_{n-1}s^{n-1} + s^n} \quad |\cdot s = z^{-1}$$

$$G(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_n z^{-n}}{a_0 + a_1 z^{-1} + \ldots + a_n z^{-n}}$$

$$= \frac{b_0 z^n + b_n z^{n-1} + \ldots + b_n}{a_0 z^n + a_1 z^{n-1} + \ldots + a_n} \quad \Rightarrow \text{Also called "polynomial model".}$$

Deterministic Model

The output of the system can be obtained with absolute certainty. The Output y or the state x, depend on the known inputs $u(1), \dots, u(N)$, the previous Outputs $y(1), \dots, y(N)$ or state $x(n-1)$ and initial conditions. All deterministic models are **time invariant**.

State Space Model:

$$x(k+1) = f(x(k), u(k))$$
$$y(k) = g(x(k), u(k))$$

Initial conditions: $x(1) = x_0$

Input-Output Model

$$y(k) = h(u(k), ..., u(k-n), y(k-1), ..., y(k-n))$$

Initial conditions: $y(1) = y_1, \dots, y(n) = y_n \quad u(1) = u_1, \dots, u(n) = u_n$

Finite Impulse Response (FIR):

$$y(k) = b_0 u(k) + ... + b_{n_b} u(k-n_b)$$

$$G(z) = b_0 + b_1 z^{-1} + ... + b_{n_b} z^{-n_b} \quad | \cdot \frac{z^{n_b}}{z^{n_b}}$$

$$= \frac{b_0 z^{n_b} + b_1 z^{n_b-1} + ... + b_{n_b}}{z^{n_b}}$$

Auto Regressive model with eXogenous inputs (ARX/IRR):

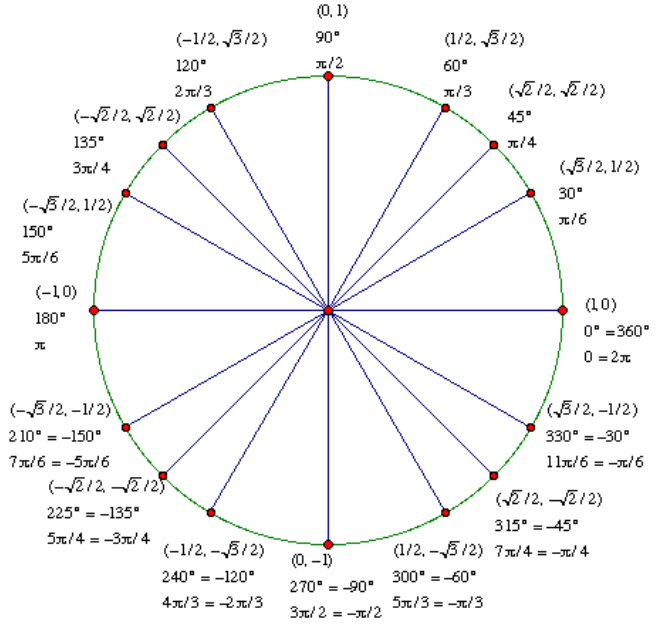
$$a_0 y(k) + \cdots + a_{n_a} y(k-n_a) = b_0 u(k) + \cdots + b_{n_b} u(k-n_b)$$

$$G(z) = \frac{b_0 z^n + b_1 z^{n-1} + \cdots + b_n}{a_0 z^n + a_1 z^{n-1} + \cdots + a_n}$$

The next output depends on the previous output. Also called **IIR** (infinite impulse response)

Auto Regressive model(AR):

$$y(k) = a_1 y(k-1) - ... - a_{n_a} y(k-n_a)$$



Stochastic Model

Real systems are far from deterministic.

- there is stochastic noise $\varepsilon(k)$
- there are constant and unknown parameters p
- measured outputs $y(k)$ depend in both, $\varepsilon(k)$ and p

Assumptions: noise is **i.i.d** and enters the model like a normal input, but as a random variable

State Space Model

$$x(k+1) = f(x(k), u(k), \varepsilon(k))$$
$$y(k) = g(x(k), u(k), \varepsilon(k))$$

Input-Output Model

Only interested in input and output, not the whole model state

$$y(k) = h(u(k), ..., u(k-n), y(k-1), ..., y(k-n), \varepsilon(k), ..., \varepsilon(k-n))$$

for $\quad k = n+1, n+2, ...$

Measurement Noise (Output Error Model)

$$y(k) = M(k; U, x_0, p) + \varepsilon(k)$$

Stochastic Disturbance (Equation Errors)

$$y(k) = h(p, u(k), ..., u(k-n), y(k-1), ..., y(k-n)) + \varepsilon(k)$$

for $k = n+1, n+2, \dots$

Linear In the Parameters models (LIP):

$$y(k) = \sum_{i=1}^{d} \theta_i \phi_i(u(k), \dots, y(k-1), \dots) + \varepsilon(k)$$

$$y(k) = \varphi(k)^T \theta + \varepsilon(k) \quad \text{where } \varphi = (\phi_1(\cdot), ..., \phi_d(\cdot))$$

LIP-LTI Models with Equation Errors (ARX)[a]

- Combining best of two worlds (LTI and LIP)

$$a_0 y(k) + \dots + a_{n_a} y(k-n_a) = b_0 u(k) + \dots + b_{n_b} u(k-n_b) + \varepsilon(k)$$

Auto-Regressive Moving Average with eXogeneous input (ARMAX):

$$a_0 y(k) + ... + a_{n_a} y(k-n_a) = b_0 u(k) + ... + b_{n_b} u(k-n_b) + \varepsilon(k) + c_1 \varepsilon(k-1) + ... + c_{n_x} \varepsilon(k-n_c)$$

Auto-Regressive Moving Average without inputs (ARMA):

$$a_0 y(k) + ... + a_{n_a} y(k-n_a) = \varepsilon(k) + c_1 \varepsilon(k-1) + ... + c_{n_x} \varepsilon(k-n_c)$$

Where c_i represent the noise coefficient, we have to use non-linear least squares with the unknown noise terms $\varepsilon(k-i)$

Difference between Deterministic and Stochastic Models

- stochastic noise $\varepsilon(k)$
- unknown but constant parameter p
- measured output $y(k)$ depend on both, $\varepsilon(k)$ and p

[a] additive noise is a special case

Example for State Space Model

$$\ddot{a} = m \cdot \dot{a} + g \cdot a + c \cdot u$$
$$y = \dot{a}$$

$$x = \begin{bmatrix} a \\ \dot{a} \end{bmatrix} \quad \dot{x} = \begin{bmatrix} \dot{a} \\ \ddot{a} \end{bmatrix} \quad \dot{x} = Ax + Bu \quad y = Cx + Du$$

$$A = \begin{bmatrix} 0 & 1 \\ g & m \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ c \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0 \end{bmatrix}$$

Pure Output Error (OE) Minimization

Assume: i.i.d. gaussian noise only affecting output
using non-linear least squares

$$\theta_{ML} = \min_\theta \sum_{k=1}^{N} (y(k) - M(k; U, x_0 p))^2$$

Output Error Minimization for FIR Models: lead to convex problems, therefore global minimum can be found

$$y(k) = (u(k), u(k-1), ..., u(k-n_{n_b})) \cdot \theta + \varepsilon(k)$$

$$= \min_\theta \sum_{k=n_b+1}^{N} (y(k) - \underbrace{(u(k), u(k-1), ..., u(k-n_{n_b}))}_{\text{det. part is also } M(k;U,x_0,p)} \cdot \theta)^2$$

They often need a very high dimension n_b to obtain a reasonable fit. As a consequence ARX models are usually used instead.

Equation Error Minimization: Assume: i.i.d. $\varepsilon(k)$ noise enters the input-output equation as additive disturbance

$$y(k) = h(p, u(k), ..., u(k-n), y(k-1), ..., y(k-n)) + \varepsilon(k)$$

for $\quad k = n+1, n+2$

if the i.i.d noise is gaussian, a maximum likelihood formulation to estimate the unknown parameter vector $\theta = p$ is given:

$$\theta_{ML} = \min_\theta \sum_{k=n+1}^{N} (y(k) - h(p, u(k), ..., y(k-1), ...)))^2$$

u and k are known input and output measurements, and the algorithm minimises the so called **equation errors** or **prediction errors**.
This problem is also known as **Prediction error minimisation(PEM)**
Such a problem is convex if p enters linearly in f, i.e. if the model is **linear-in-the-parameters (LIP)**

PEM of LIP Models

$$y(k) = \varphi(k)^T \theta + \varepsilon(k)$$

where $\varphi = (\phi_1(\cdot), ..., \phi_d(\cdot))^T$ are the regressor variables

considering this last expression, the prediction error minimisation(PEM) problem can be formulated as:

$$\min_\theta \underbrace{\sum_{k=1}^{N} (y(k) - \varphi(k)^T \theta)^2}_{= \| y_N - \Phi_N \theta \|_2^2}$$

Which can be solved using LLS $\theta^* = \Phi_N^+ y_N$

Special Case: PEM of LIP-LTI Models with Equation Errors(ARX) General ARX model equation

$$a_0 y(k) + ... + a_{n_a} y(k-n_a) = b_0 u(k) + ... + b_{n_b} u(k-n_b) + \varepsilon(k)$$

In order to have a determined estimation problem, a_0 has to be fixed, otherwise the number of optimal solutions would be infinitive. Therefore we sually fix $a_0 = 1$ and use $\theta = (a_1, ..., a_{n_a}, b_0, ..., b_{n_b})^T$ as the parameter estimation vector. The regressor vector is given by:

$$\varphi = (-y(k-1), ..., -y(k-n_a), u(k), ..., u(k-n_b))^T$$

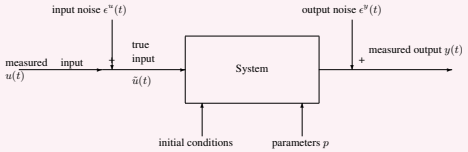
leading to the optimal solution provided by LLS:

$$y(k) = \varphi(k)^T \theta + \varepsilon(k)$$

Pure Output Error (OE) Minimization

Models with Input and Output Errors:

$$y(k) = M(k; U + \varepsilon_N^u, x_0, p) + \varepsilon^y(k)$$



Assume: i.i.d. gaussian noise on both input and output with variance σ_u^2 for the input and σ_y^2 for the output

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}} \sum_{k-1}^{N} \frac{1}{\sigma_y^2}(y(k) - M(k; U + \varepsilon_N^u, x_0, p))^2 + \frac{1}{\sigma_u^2}(\varepsilon_u(k))^2$$

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}} \sum_{k-1}^{N} \frac{1}{\sigma_y^2}(y(k) - M(k; \tilde{U}, x_0, p))^2 + \frac{1}{\sigma_u^2}(u(k) - \tilde{u}(k))^2$$

$$\tilde{U} := U + \varepsilon_N^u$$

Fourier Transformation

FT:

$$F\{F\}(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} \mathrm{d}t$$

$$G(j\omega) = \frac{Y_0}{U_0} e^{j\omega t}$$

iFT:

$$f(t) = F^{-1}\{F\}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{-j\omega t} d\omega$$

DFT:

$$U(m) := \sum_{k=0}^{N-1} u(t) e^{-j\frac{2\pi m k}{N}}$$

iDFT:

$$u(n) := \sum_{k=0}^{N-1} U(k) e^{j\frac{2\pi k n}{N}}$$

Useful frequency things

$$\omega = 2\pi f = \tfrac{2\pi}{T}, \quad f_s > 2f_{\max}, \quad T = N\Delta t = \tfrac{N}{f_s} = (f_{\text{res}})^{-1}$$

$$\sin(\varphi) = \tfrac{e^{j\varphi} - e^{-j\varphi}}{2}, \ \cos(\varphi) = \tfrac{e^{j\varphi} + e^{-j\varphi}}{2}$$

Aliasing and Leakage Errors

Aliasing Error: Due to sampling of continous signal to discrete signal. Avoid with Nyquist Theoreme:

$$f_{\text{Nyquist}} = \frac{1}{2\Delta t}[\text{Hz}] \quad or \quad \omega_{\text{Nyquist}} = \frac{2\pi}{2\Delta t}[\text{rad/s}]$$

Leakage Error: Due to windowing.

$$\omega_{\text{base}} := \frac{2\pi}{N \cdot \Delta t} = \frac{2\pi}{T} \rightarrow \omega = m \cdot \frac{2\pi}{N \cdot \Delta t}$$

Crest Factor (ger. = Scheitelfaktor)

$$\text{Crest Factor} = \frac{u_{\max}}{u_{\text{rms}}} \quad \text{with}: u_{\text{rms}} := \sqrt{\frac{1}{T}\int_0^T u(t)^2 \,\mathrm{d}t} \underbrace{\left(= \sqrt{\frac{u_1^2 + u_2^2}{2}}\right)}_{\text{symm. square wave}}$$

$$\text{and} \quad u_{\max} := \max_{t \in [0,T]} |u(t)|$$

Optimising Multisine for optimal crest factor

Frequency: Choose frequencies in logarithmic manner as multiples of the base frequency. $\omega_{k+1}/\omega_k \approx 1.05/1.01/1.03$ (round to $n \cdot \omega_{\text{base}}$!)

Phase: To prevent high peaks (Crest Factor): random algorithm for phase shifts

Multisine Identification Implementation procedure

Window Length: Integer multiple of sampling time: $T = N \cdot \Delta t$

Harmonics of base frequency: Are contained in multisine

$$\omega_{base} = \tfrac{2\pi}{T}$$

Highest contained Frequency: Is **half** of Nyquist frequency:

$$\omega_{\text{Nyquist}} = \tfrac{2\pi}{4\Delta T}$$

Experiment and Analysis: :

1. Insert Multisine periodically
2. Drop first Periods (till transients died out)
3. Record M Periods, with N samples, of input and output data
4. Average all windows and apply DFT (or vice versa)
5. Build transfer function: $\hat{G}_{j\omega_k} = \frac{\hat{Y}(k(p))}{\hat{U}(k(p))}$

Nonparametric and Frequency Domain Identification Models

Impulse response and transfer function:

$$y(t) = \int_0^{\infty} g(\tau) u(t-\tau)\,\mathrm{d}\tau$$

$$Y(s) = G(s) \cdot U(s)$$

$$G(s) = \int_0^{\infty} e^{-st} g(t)\,\mathrm{d}t$$

Bode diagram from frequency sweeps:

$$u(t) = A \cdot \sin(\omega \cdot t), \quad y(t) = \|G(j \cdot \omega)\| A \cdot \sin(\omega \cdot t + \alpha)$$

Bode Diagramm

Magnitude $\hat{=}$ Amplitude $|G(j\omega)| = \sqrt{\text{Re}(G)^2 + \text{Im}(G)^2}$

Phase $\hat{=}$ $\arg\, G(j\omega) = \arctan\left({}^{\text{Im}(G)}/_{\text{Re}(G)}\right)$

When to use what in frequency response

- In general: Multisines are a good approach
- Very fast system and transients $\Rightarrow$ Frequency sweep
- **Very** slow system $\Rightarrow$ Step response
- In the middle $\Rightarrow$ Multisines

Kalman Filter

Valid for Discrete and Linear!

If recursive least squares: $x_{k+1} = A_k \cdot x_k$

$x_{k+1} = A_k \cdot x_k + \omega_k$ and $y_k = C_k \cdot x_k + v_k$

Steps of Kalman Filter

1 Prediction

$$\hat{x}_{[k|k-1]} = A_{k-1} \cdot \hat{x}_{[k-1|k-1]}$$

$$P_{[k|k-1]} = A_{k-1} \cdot P_{[k-1|k-1]} \cdot A_{k-1}^T \cdot W_{k-1}$$

If RLS $\Rightarrow$ no W_{k-1}

2 Innovation update

$$P_{[k|k]} = (P_{[k|k-1]}^{-1} + C_k^T \cdot V^{-1} \cdot C_k)^{-1}$$

$$\hat{x}_{[k|k]} = \hat{x}_{[k|k-1]} + P_{[k|k]} \cdot C_k^T \cdot V^{-1} \cdot (y_k - C_k \cdot \hat{x}_{[k|k-1]})$$

Useful hints and practices

- Time invariant: t is only an argument of $u(*)$ or $y(*)$ i.e. **not**:
  $\dot{y}(t) = u(t) + \cos(t), \ \dot{y}(t) = t \cdot u(t) + y(t)$
- Linear: highest exponent of u and y is 1, i.e. **not**:
  $\dot{y}(t) = u(t)^2$
- Affine: linear and has additive term **independent** from u and y, i.e.:
  $\dot{y}(t) = y(t) + \cos(t), \ \dot{y}(t) = y(t) + C$
- Sample Mean: $\hat{\theta}_N(Y_N) = \frac{1}{N}\sum_{k=1}^{N} Y(k)$
- Sample Variance: $S^2 = \frac{1}{N-1}\sum_{k=1}^{N}(Y(k) - \mathbb{E}\{Y_N\})^2$

Magic Matrix for 8 point DFT:

$$W_r = \begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 0.7 & 0.0 & -0.7 & -1.0 & -0.7 & 0.0 & 0.7 \\ 1.0 & 0.0 & -1.0 & 0.0 & 1.0 & 0.0 & -1.0 & 0.0 \\ 1.0 & -0.7 & 0.0 & 0.7 & -1.0 & 0.7 & 0.0 & -0.7 \\ 1.0 & -1.0 & 1.0 & -1.0 & 1.0 & -1.0 & 1.0 & -1.0 \\ 1.0 & -0.7 & 0.0 & 0.7 & -1.0 & 0.7 & 0.0 & -0.7 \\ 1.0 & 0.0 & -1.0 & 0.0 & 1.0 & 0.0 & -1.0 & 0.0 \\ 1.0 & 0.7 & 0.0 & -0.7 & -1.0 & -0.7 & 0.0 & 0.7 \end{bmatrix}$$