GENERAL

an introduction to kalman filtering with matlab examples synthesis lectures on signal processing

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Introduction

In modern engineering, the ability to estimate hidden states from noisy measurements is indispensable. Whether you're tracking an aircraft, filtering a sensor signal, or reconstructing a signal in a communications system, Kalman filtering offers a mathematically rigorous, computationally efficient solution. This article provides a thorough introduction to Kalman filtering, complete with MATLAB examples, and explores how these concepts are woven into synthesis lectures on signal processing. By the end of this guide, you will understand the theory, implement a Kalman filter in MATLAB, and appreciate its role in advanced signal processing curricula.

What Is Kalman Filtering?

Kalman filtering is a recursive algorithm that estimates the internal state of a linear dynamic system from a series of noisy observations. The filter combines a predictive model—capturing how the system evolves over time—with real time sensor data, producing an optimal estimate in the sense of minimizing the mean square error. The algorithm was introduced by Rudolf Kalman in 1960 and has since become a cornerstone of control theory, robotics, aerospace, and digital signal processing.

Key Components

- State Vector (x): The set of variables that fully describe the system at a given time.
- Process Model (F): Describes how the state evolves from one time step to the next.
- Process Noise (Q): Accounts for uncertainty in the model.
- Measurement Model (H): Relates the state to observable measurements.
- Measurement Noise (R): Captures sensor inaccuracies.
- Covariance Matrices (P, S): Quantify uncertainty in state estimates.

Mathematical Foundations

At its core, the Kalman filter operates on the following two equations:

Kalman gain: **K_k = P_{k|k 1}·H^T·(H·P_{k|k 1}·H^T + R)¹**nState update: **x0#Ç7V#æ·Æ³Â÷7V#â Ò ƒ _{k|k 1} + K_k·(z_k – H·x0#Ç7V#æ·Æ² Â÷7V#â**Covariance update: **P_{k|k} = (I – K_k·H)·P_{k|k 1}**n

Kalman Filtering in MATLAB

MATLAB provides a rich toolbox for implementing Kalman filters. The kalman function, part of the Control System Toolbox, allows you to define system matrices and automatically generate the filter. For educational purposes, it's often instructive to code the algorithm manually, which deepens understanding and gives you fine control over each step.

Simple 1 D Constant Velocity Example

Consider a vehicle moving along a straight line with constant velocity. Its position is measured by a noisy GPS

sensor. We wish to estimate both position and velocity.

State vector: **x = [position; velocity]**\nProcess model: **F = [1 dt; 0 1]** (dt is the sampling interval)\nProcess noise: **Q = q·[dt⁴/4 dt³/2; dt³/2 dt²]** (q is acceleration noise intensity)\nMeasurement model: **H = [1 0]** (only position is measured)\nMeasurement noise: **R = r**(variance of GPS noise)

Below is a concise MATLAB script that implements the filter step by step. The code is written for clarity rather than speed.

dt = 1;\n**q = 0.01;**\n**r = 5;**\n**F = [1 dt; 0 1];**\n**Q = q*[dt^4/4 dt^3/2; dt^3/2 dt^2];**\n**H = [1 0];**\n**R = r;**\n**P = eye(2);**\n**x = [0; 1];** *% initial state*\n**for k = 1:50**\n   **z = x(1) + sqrt(r)*randn;** *% noisy measurement*\n   **% Prediction**\n   **x_pred = F*x;**\n   **P_pred = F*P*F' + Q;**\n   **% Update**\n   **K = P_pred*H'/(H*P_pred*H' + R);**\n   **x = x_pred + K*(z - H*x_pred);**\n   **P = (eye(2) - K*H)*P_pred;**\n   **% Store or plot results here**\n**end**

Running this script shows the estimated position and velocity converging to the true values despite measurement noise. The Kalman gain gradually decreases as the filter becomes more confident in its predictions.

Extending to 2 D Tracking

In many applications, you need to track an object in two dimensions. The state vector expands to include both x and y positions and velocities. The process and measurement matrices become block diagonal, simplifying the implementation.

x = [pos_x; vel_x; pos_y; vel_y]

F = [1 0 dt 0; 0 1 0 dt; 0 0 1 0; 0 0 0 1]

Assume we can observe both positions but not velocities:

H = [1 0 0 0; 0 0 1 0]

The MATLAB code follows the same pattern as the 1 D example, but with 4×4 matrices. The script below demonstrates the core loop.

dt = 0.1;\n**q = 0.05;**\n**r = 10;**\n**F = [1 0 dt 0; 0 1 0 dt; 0 0 1 0; 0 0 0 1];**\n**Q = q*diag([dt^4/4 dt^3/2 dt^4/4 dt^3/2]);**\n**H = [1 0 0 0; 0 0 1 0];**\n**R = r*eye(2);**\n**P = eye(4);**\n**x = [0; 0; 0; 0];**\n**for k = 1:200**\n   **z = [x(1); x(3)] + sqrt(r)*randn(2,1);** *% noisy measurement*\n   **% Prediction**\n   **x_pred = F*x;**\n   **P_pred = F*P*F' + Q;**\n   **% Update**\n   **K = P_pred*H'/(H*P_pred*H' + R);**\n   **x = x_pred + K*(z - H*x_pred);**\n   **P = (eye(4) - K*H)*P_pred;**\n   **% Plot or store results**\n**end**

Advanced Kalman Filter Variants

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